Pop goes the neutrino: Acoustic detection of astrophysical neutrinos

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UC Berkeley

SLAC

Advanced Instrumentation Seminar

May 14, 2008

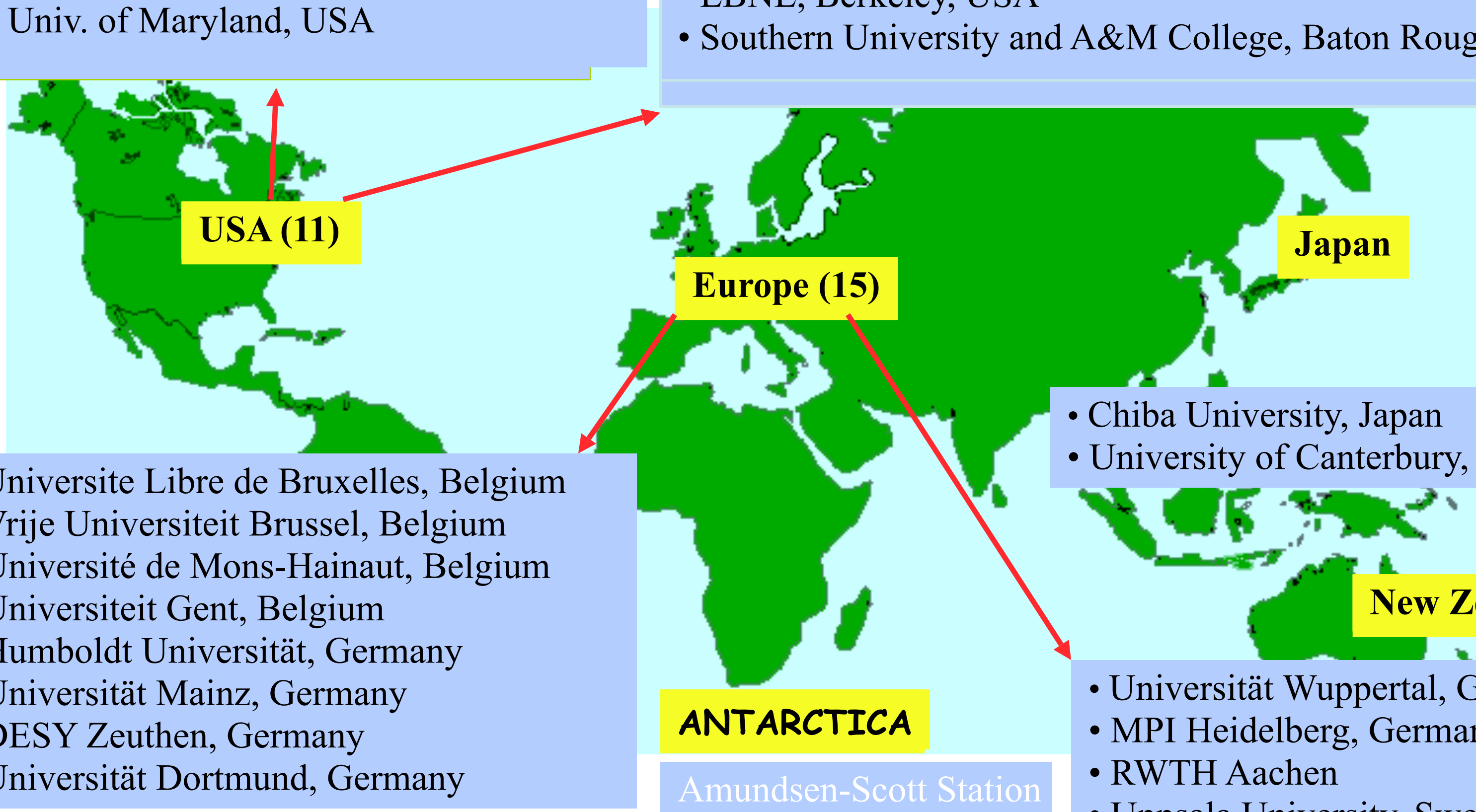
Thanks to my collaborators!

IceCube:

29 institutions
~250 people

- Bartol Research Institute, Delaware, USA
- Pennsylvania State University, USA
- UC Berkeley, USA
- UC Irvine, USA
- Clark-Atlanta University, USA
- University of Alaska, Anchorage, USA
- Univ. of Maryland, USA

- University of Wisconsin-Madison, USA
- University of Wisconsin-River Falls, USA
- LBNL, Berkeley, USA
- Southern University and A&M College, Baton Rouge, USA



- Chiba University, Japan
- University of Canterbury, Christchurch, NZ

- Universite Libre de Bruxelles, Belgium
- Vrije Universiteit Brussel, Belgium
- Université de Mons-Hainaut, Belgium
- Universiteit Gent, Belgium
- Humboldt Universität, Germany
- Universität Mainz, Germany
- DESY Zeuthen, Germany
- Universität Dortmund, Germany

- Universität Wuppertal, Germany
- MPI Heidelberg, Germany
- RWTH Aachen
- Uppsala University, Sweden
- Stockholm University, Sweden
- Oxford University, UK
- Utrecht University, Netherlands

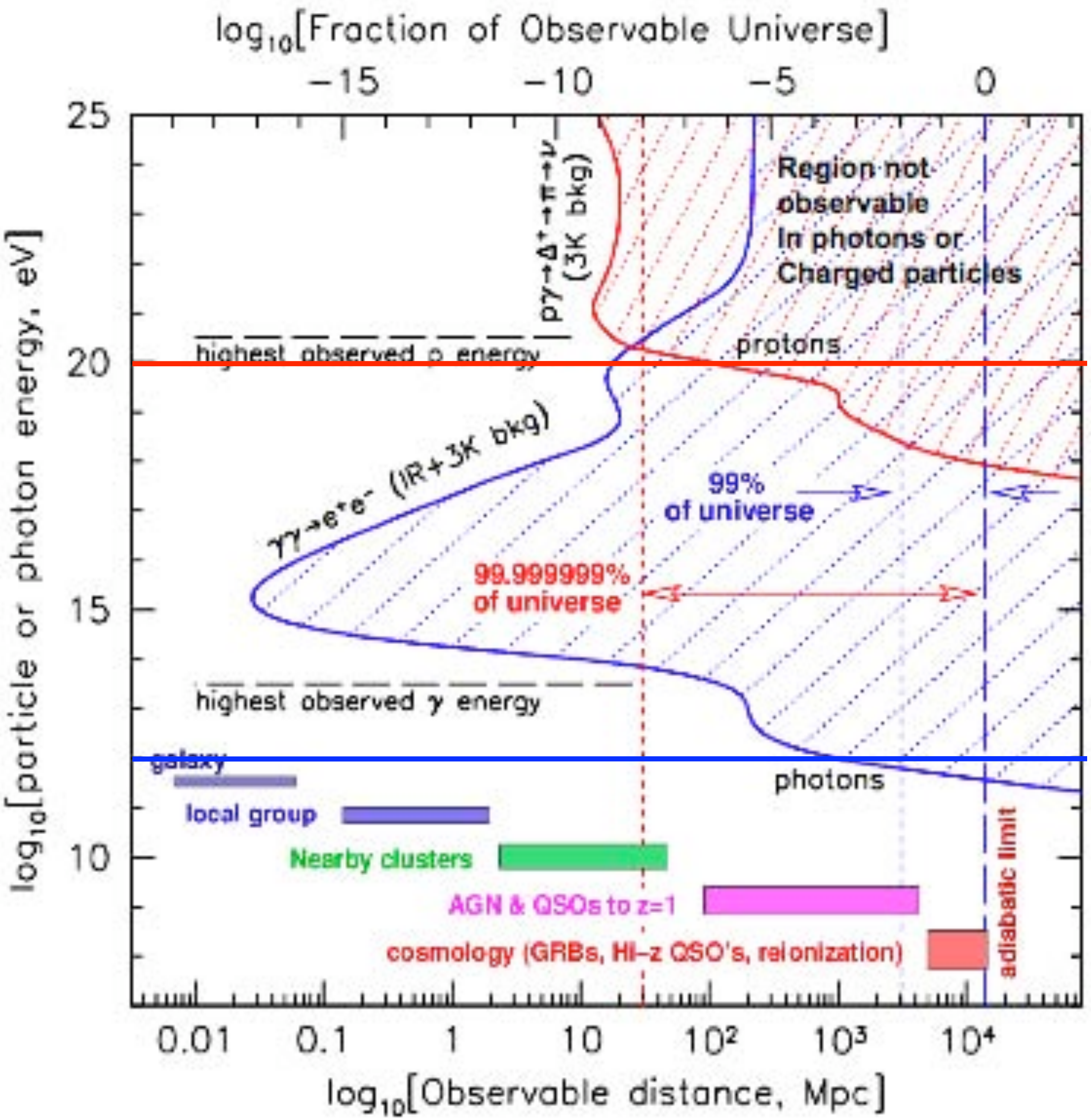
…and SAUND: Giorgio Gratta, Naoko

Outline

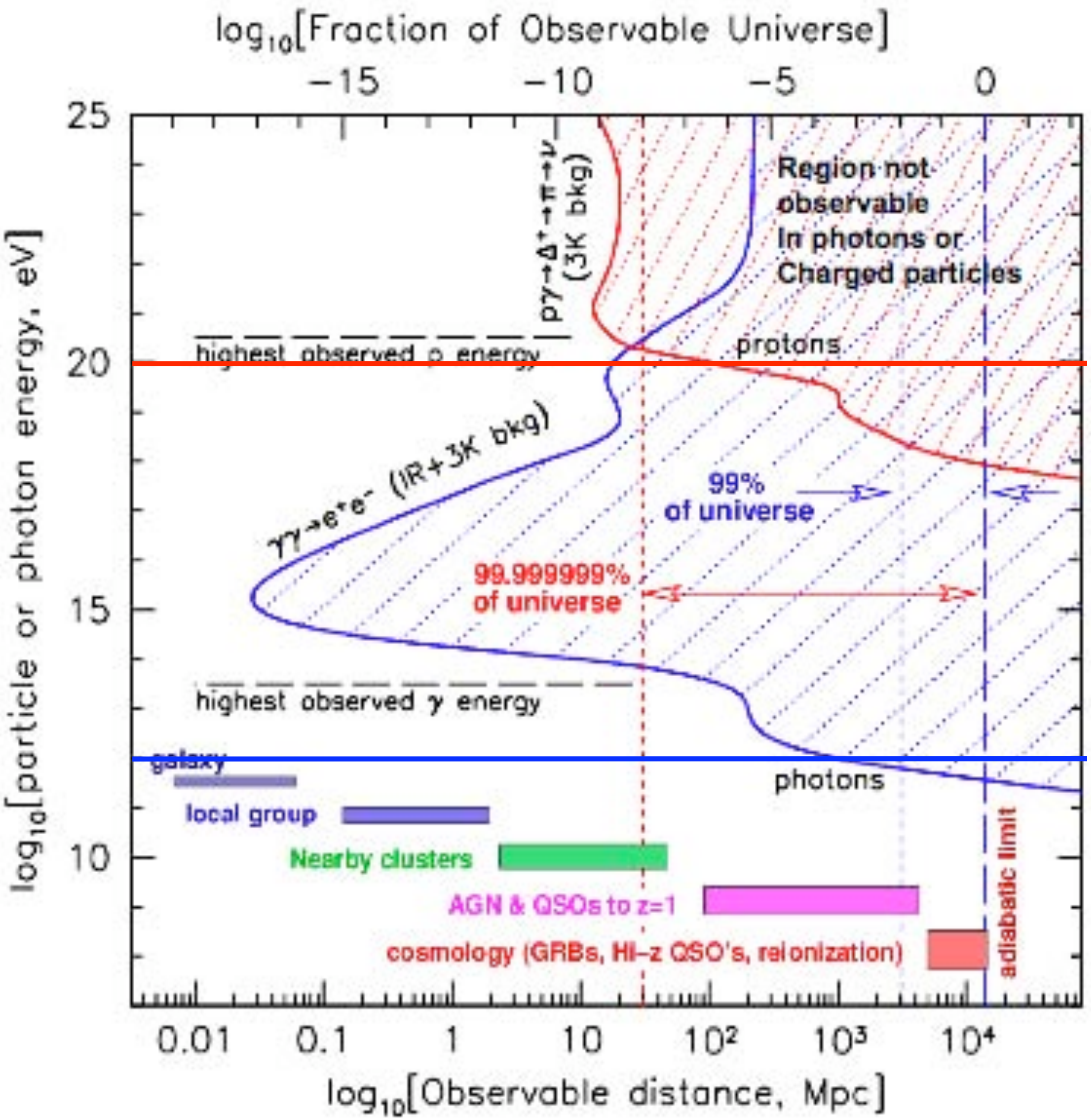
- Science motivation
- Acoustic technique
- Acoustic instrumentation at various sites
- Acoustics in ice: Go South!
- IceCube
- Acoustic instrumentation at South Pole
- Acoustic results from South Pole

Part 1: Science motivation

Astronomy and particle physics with high energy photons, cosmic rays, and neutrinos



Astronomy and particle physics with high energy photons, cosmic rays, and neutrinos



In addition to astronomy, we can study fundamental physics:

Lorentz invariance ($\gamma \approx 10^{11}$!)

quantum gravity

extra dimensions

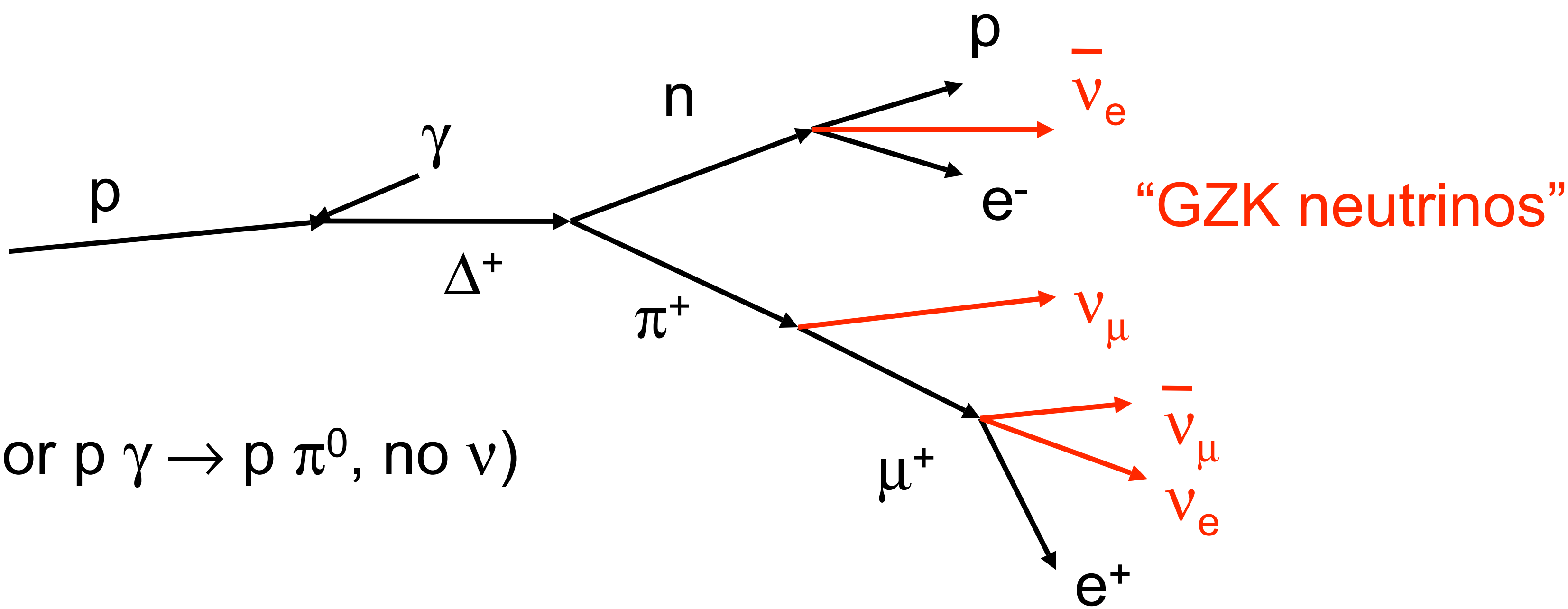
topological defects

GUT relics

Neutrino-nucleon cross section

Is there a GZK cutoff?

Above ~5 x 10^{19} eV, cosmic rays interact with CMB to produce pions:



(or $p\ \gamma \rightarrow p\ \pi^0$, no ν)

Basic test of our understanding of astronomy and particle physics:
Is there something unexpected in either?

AGASA did not see a cutoff, while HiRes did

GZK neutrinos especially interesting

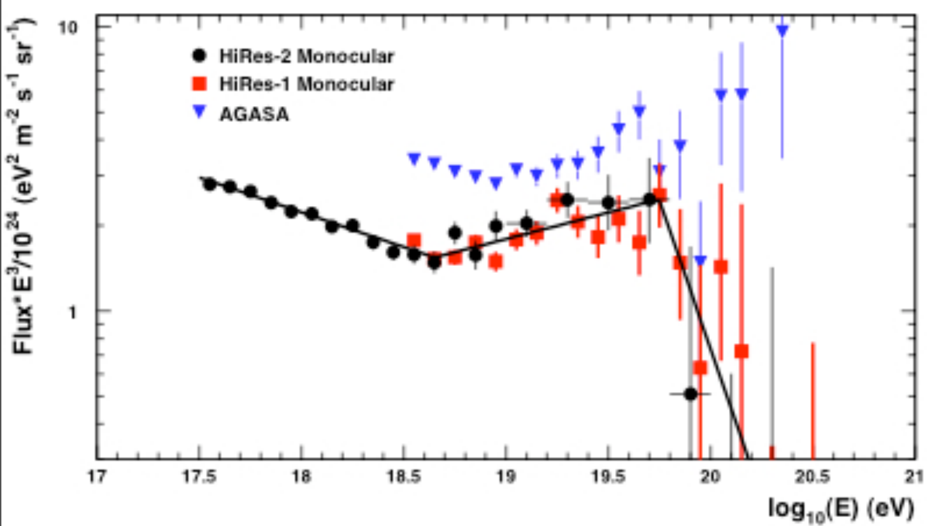
1) Identify UHECR sources

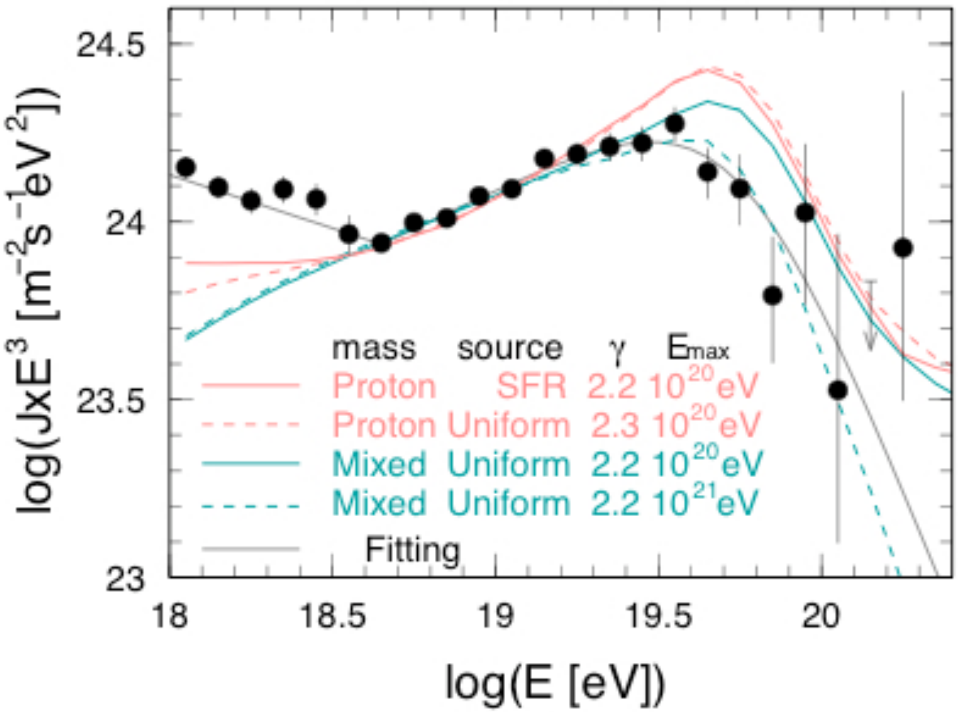
2) Measure a cross section at ~100 TeV center of mass

3) Test exotic models involving e.g. topological defects or relic neutrinos

4) They are cosmological

Observation of UHECR spectrum steepening at ~$10^{19.7}$ simplest interpretation is GZK cutoff



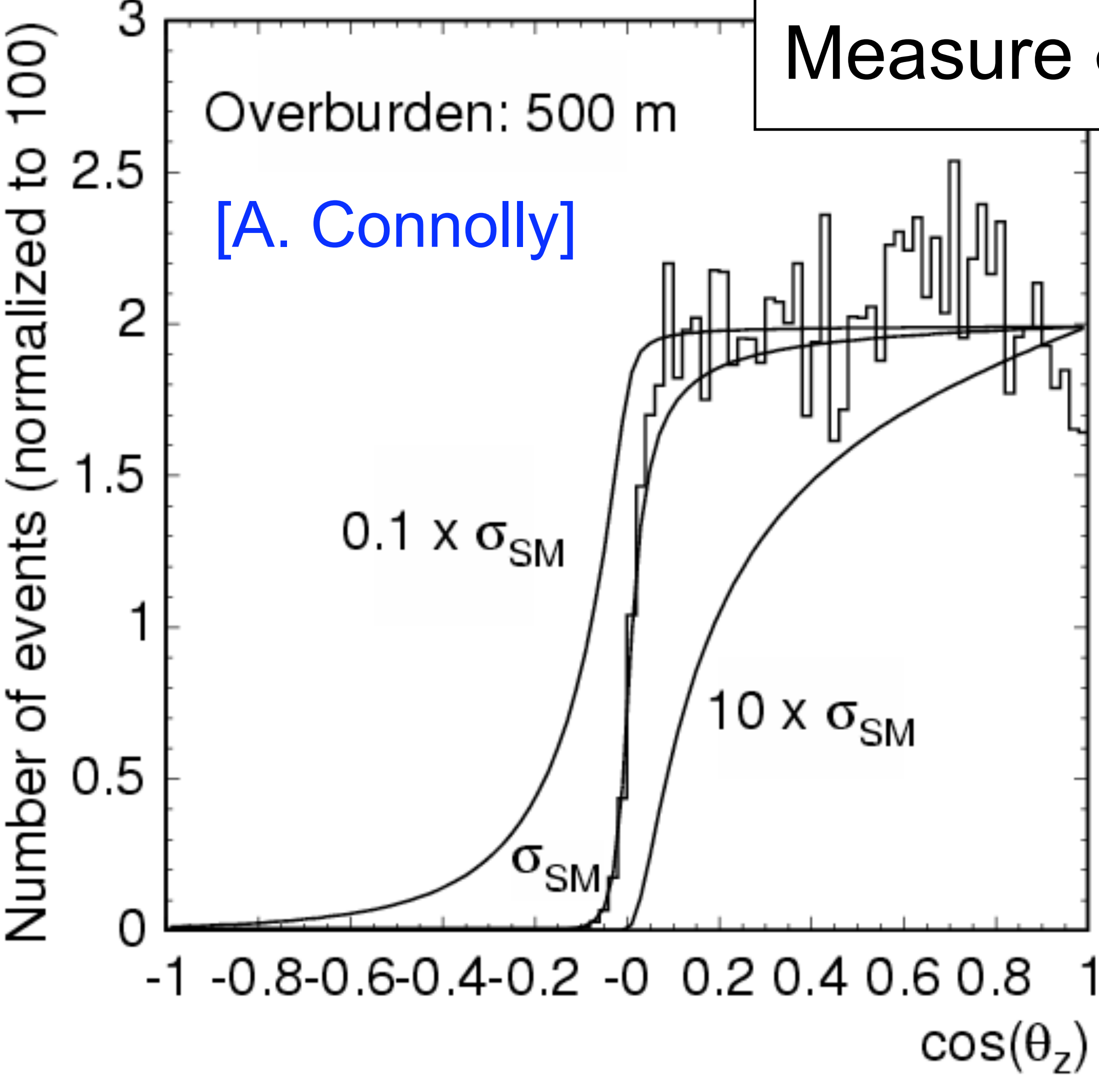


HiRes
5 sigma steepening

Auger
6 sigma steepening

Conclusion: GZK neutrinos exist!

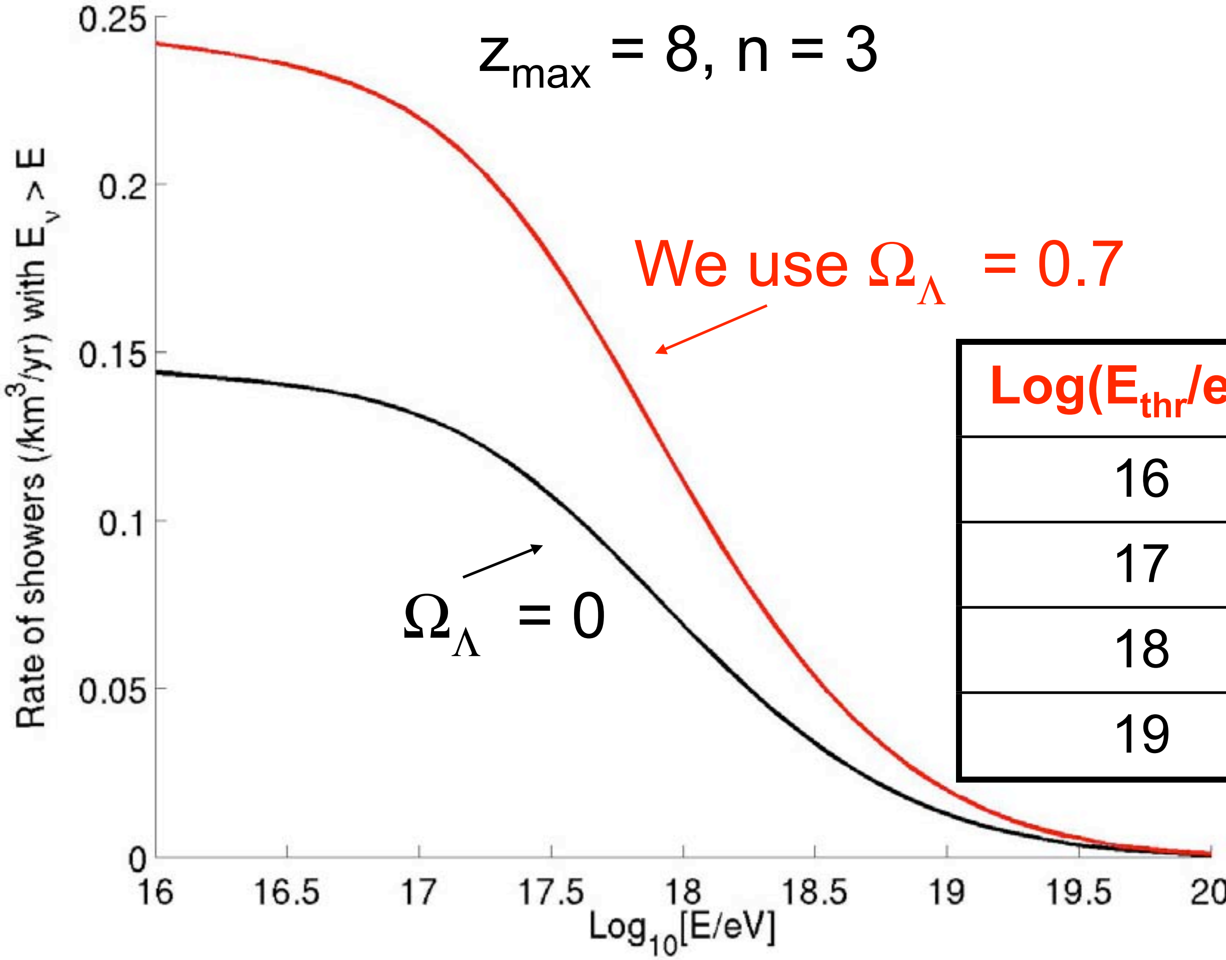
Particle physics with GZK ν: Measure $\sigma_{\nu N}$ @ E_{CM} ~100 TeV



100 events: measure L_{int} = 400 km ± 33%

tests e.g. models of extra dimensions

GZK ν event rates (Engel, Seckel, Stanev model)

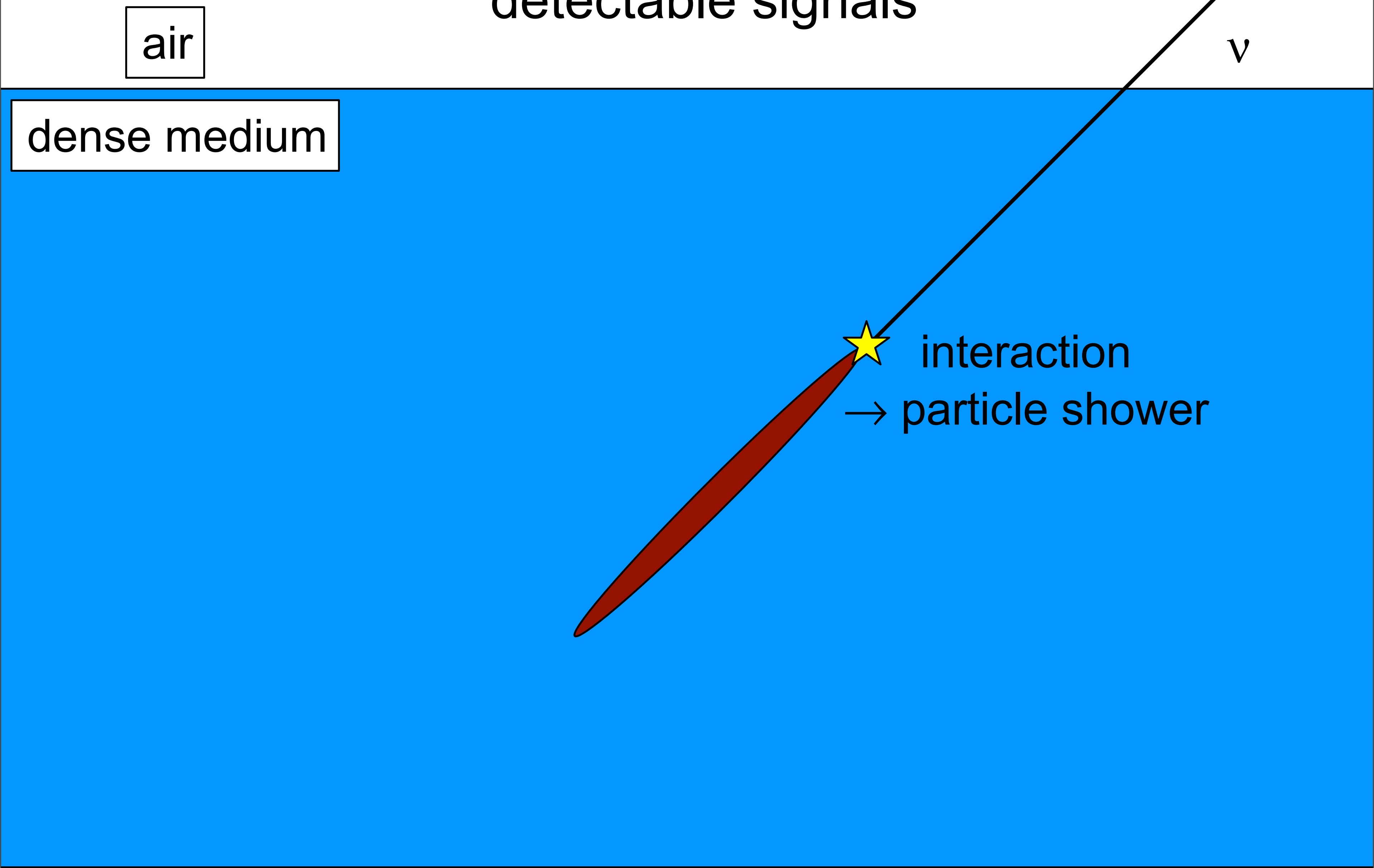


$Log(E_{thr}/eV)$	~V_{eff} for 1 evt/yr
16	4
17	5
18	9
19	50

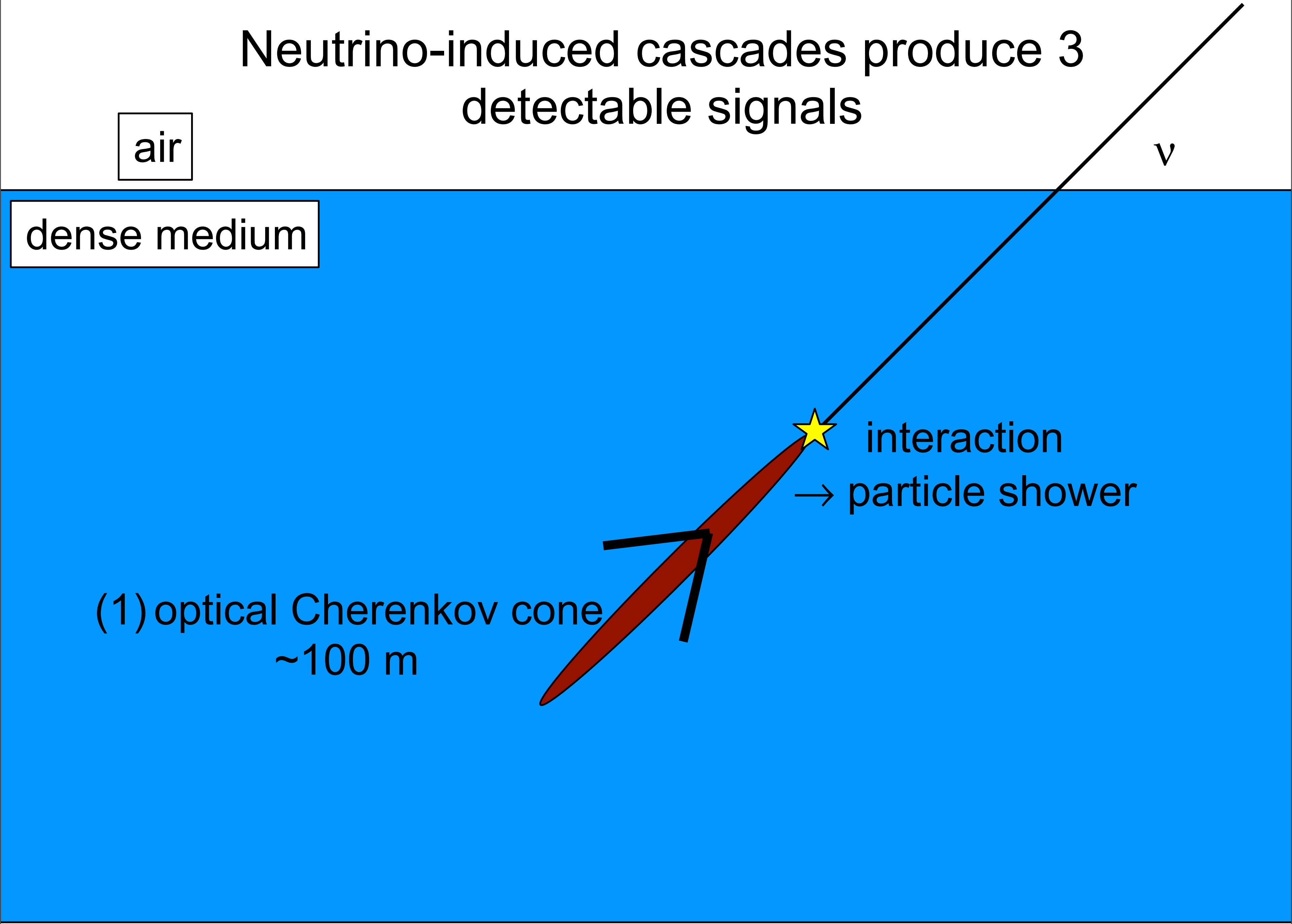
Need ~100 km³ effective volume to get ~10 evts/yr

Part 2: The acoustic technique

Neutrino-induced cascades produce 3 detectable signals



Neutrino-induced cascades produce 3 detectable signals



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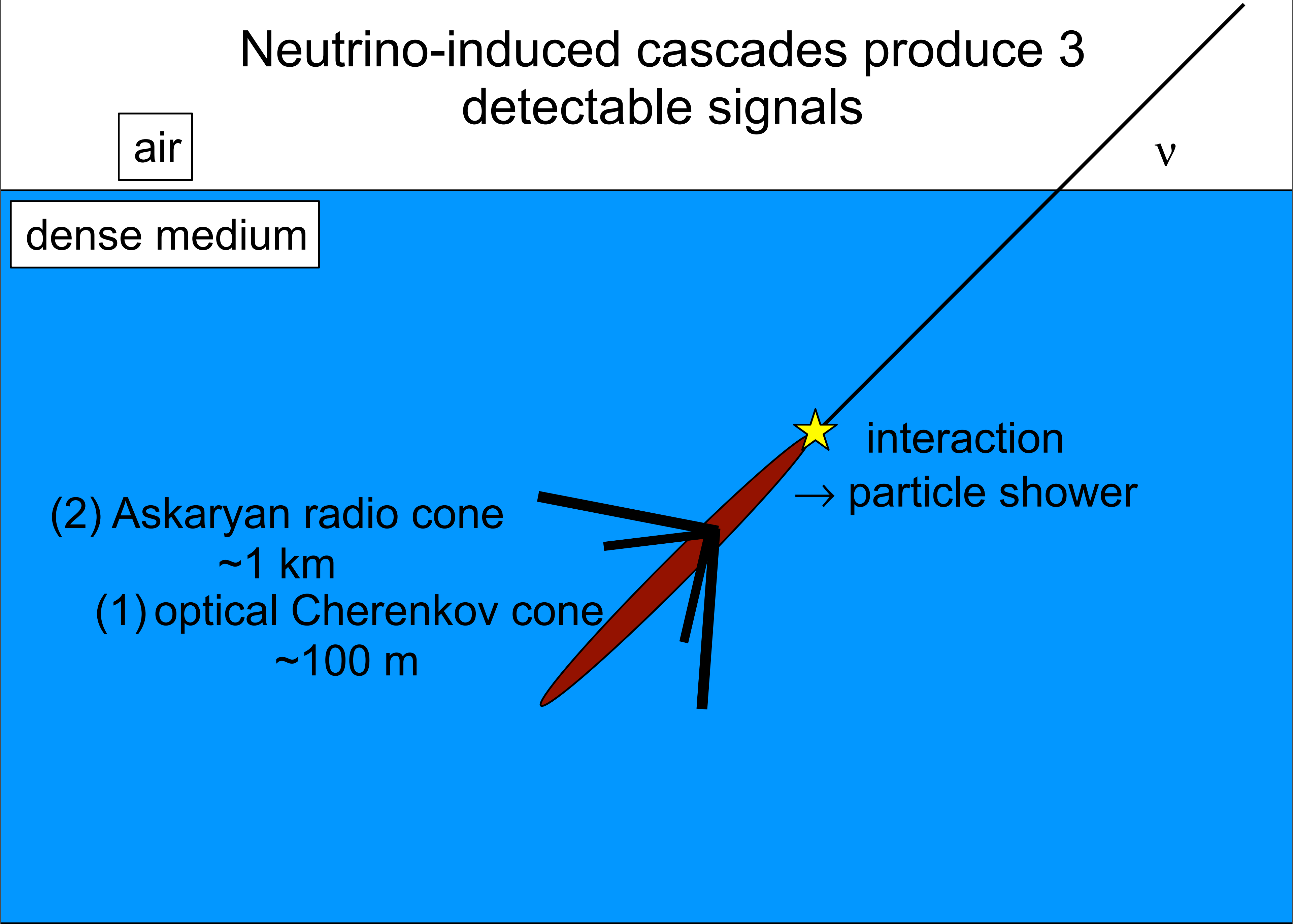
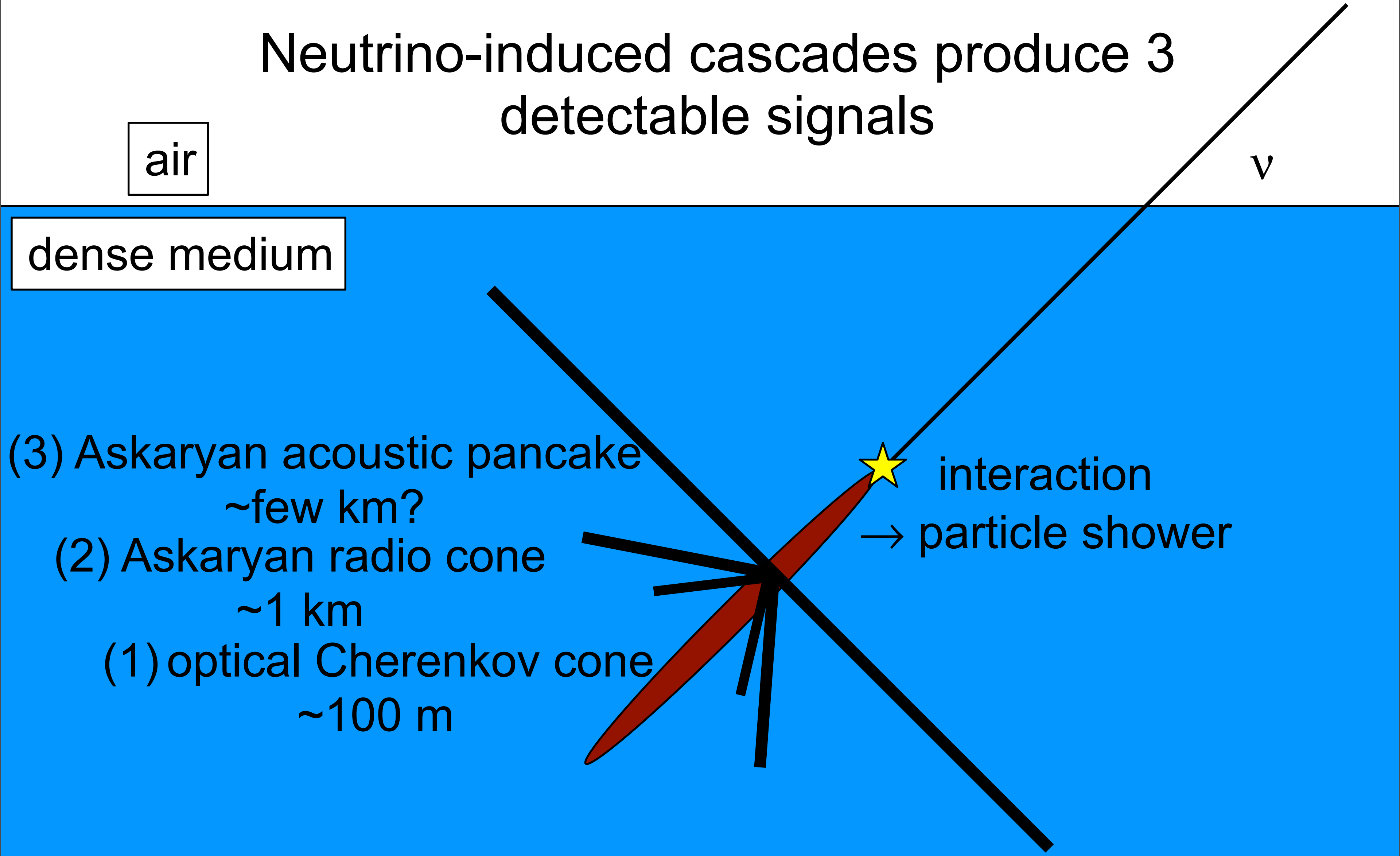
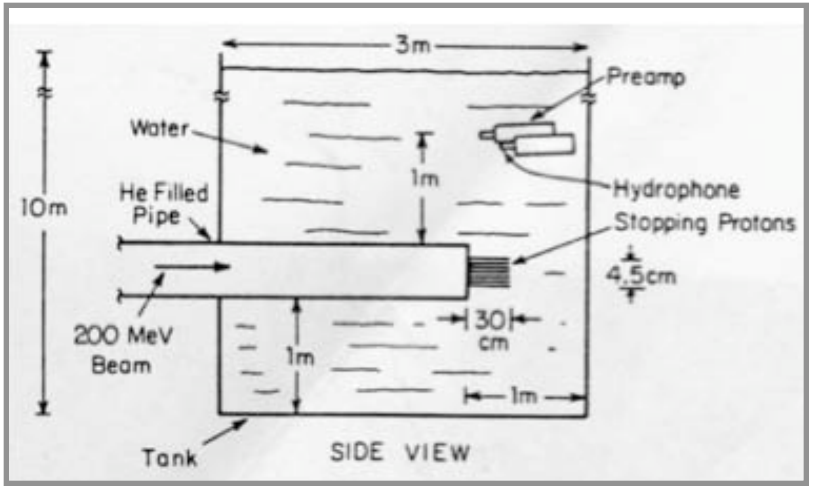


Neutrino-induced cascades produce 3 detectable signals



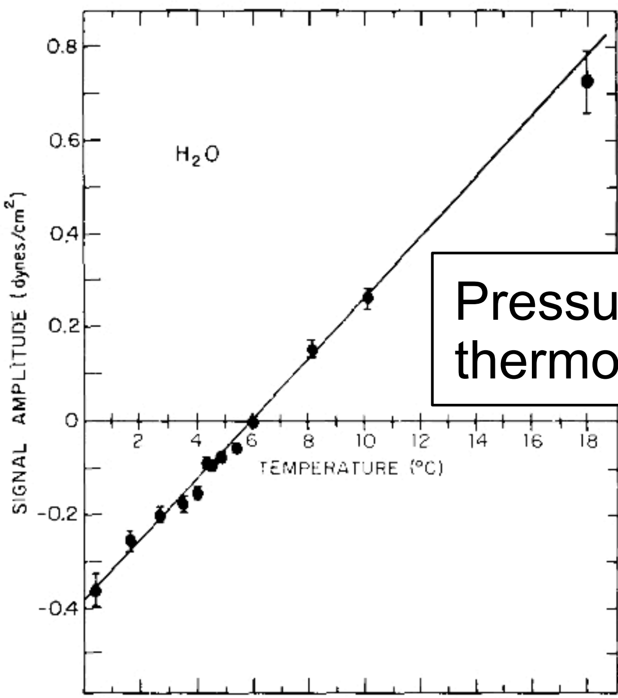
radio and acoustic (?) travel farther than optical in ice

Confirmation of acoustic technique

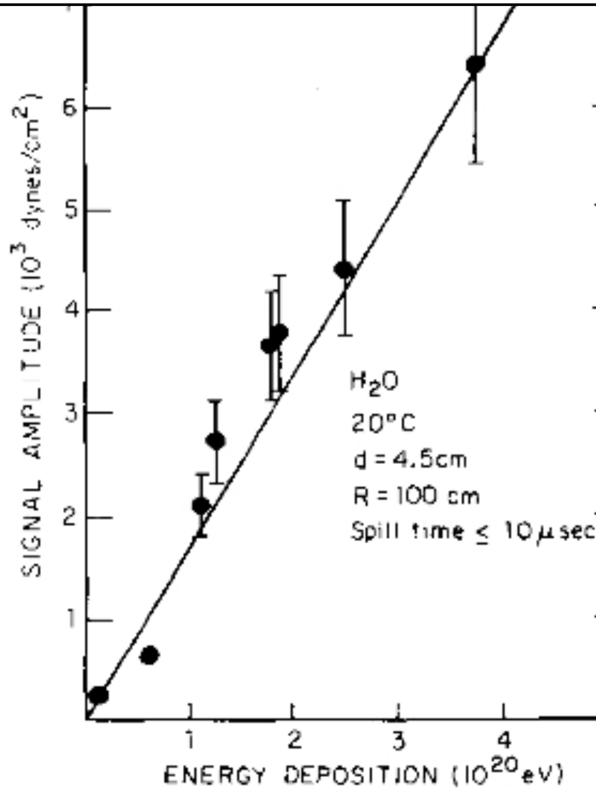


Bipolar pulse characteristics confirmed with Brookhaven proton beam
(Sulak et al NIM 1979)

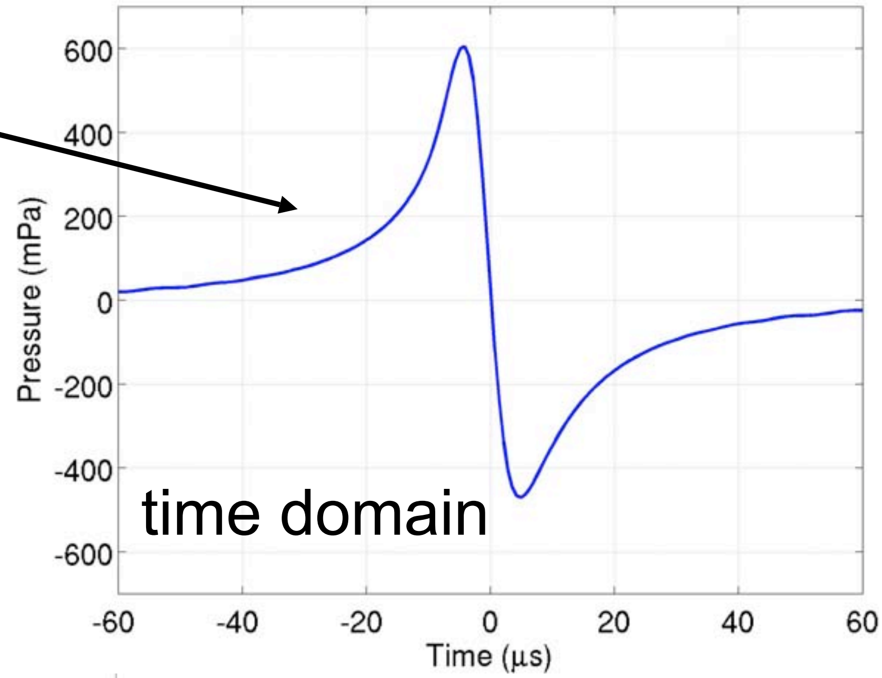
Pressure proportional to shower energy: coherence, calorimetry



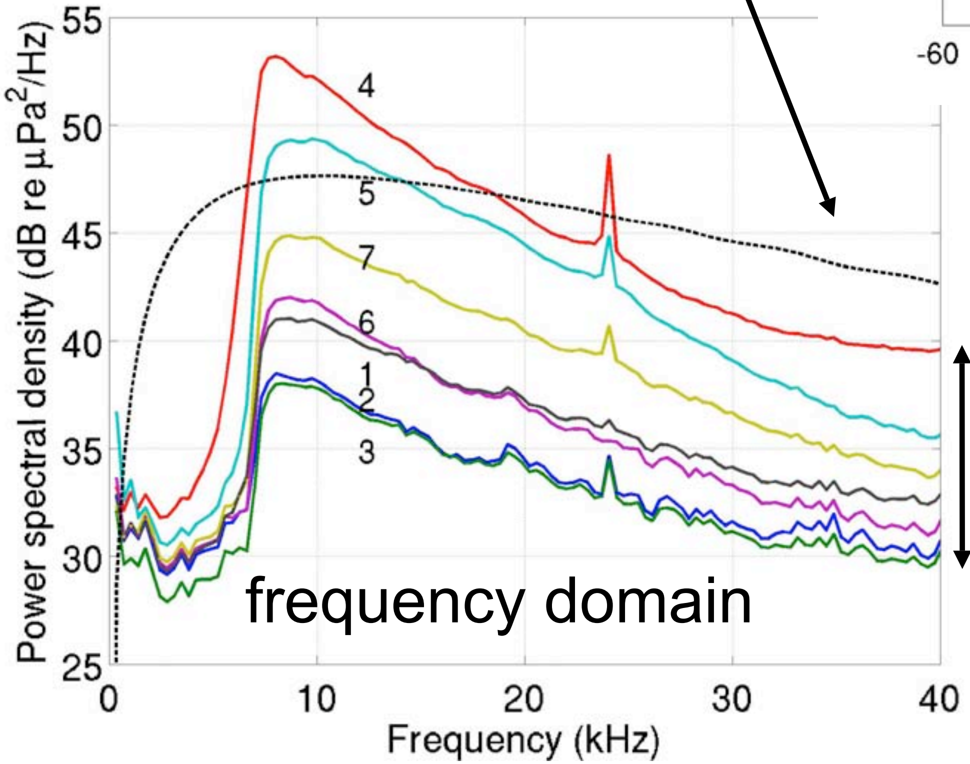
Pressure proportional to β(T): thermo-acoustic origin



The sound of one neutrino clapping



10^{21} eV shower
1.05 km distant
with ocean absorption



SAUND-I noise

Possible large volumes for acoustic neutrino detection: oceans, salt domes, polar ice caps

acoustic signal strength ~ Gruneisen parameter γ

	ocean	salt	South Pole ice
c (m/s)	1530	4560	3920
β (/K)	2.6E-04	1.2E-04	1.3E-04
C_P (J/kg/K)	3900	839	1720
f_{max} (kHz)	7.7	42	20
$\gamma = c^2\beta/C_P$	0.153	2.87	1.12

also need to consider background noise and attenuation length

conclusion:

ocean noisy

salt impure + expensive

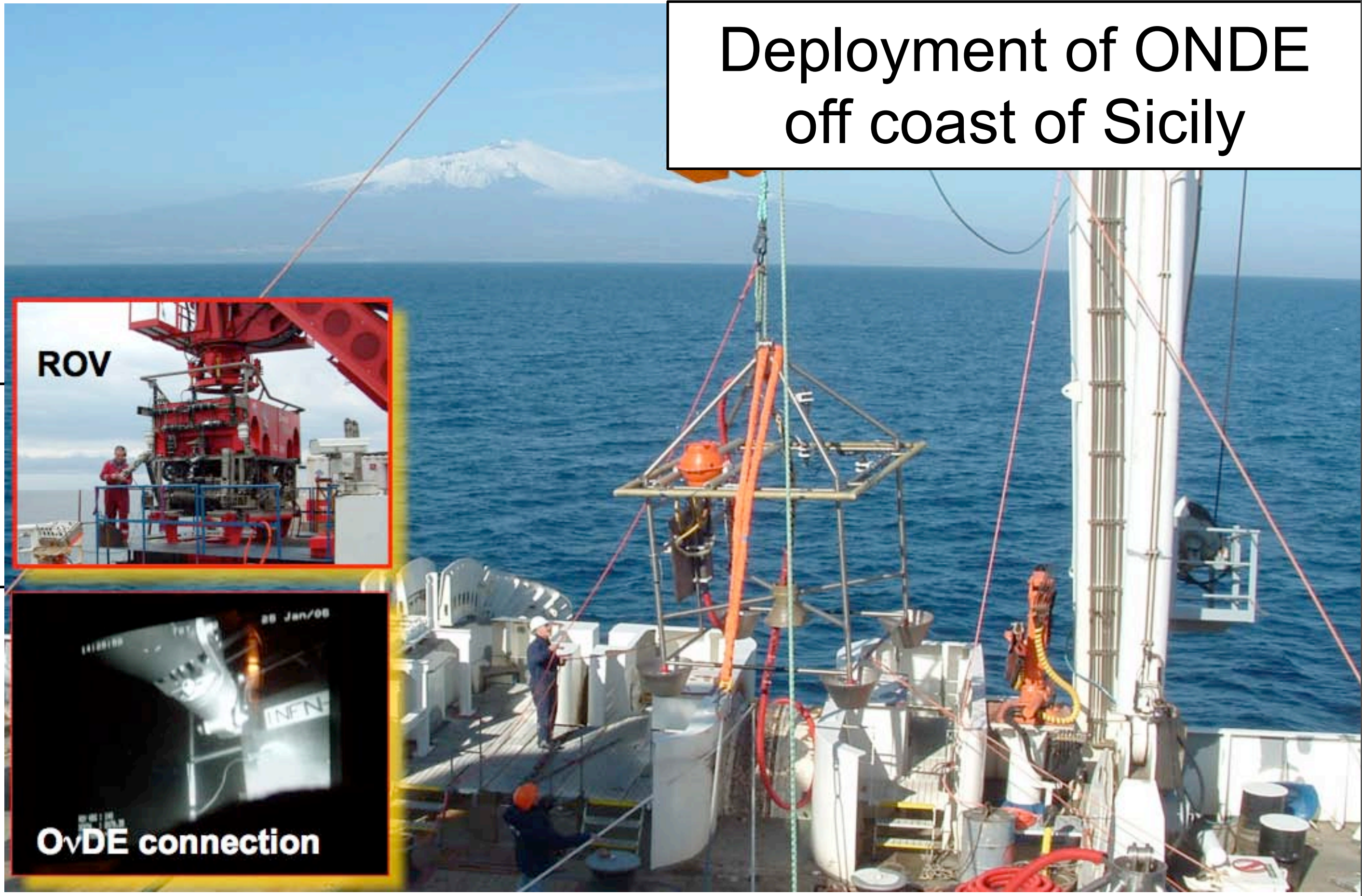
ice likely best

Part 3: Acoustic instrumentation

Current activities in acoustic neutrino detection

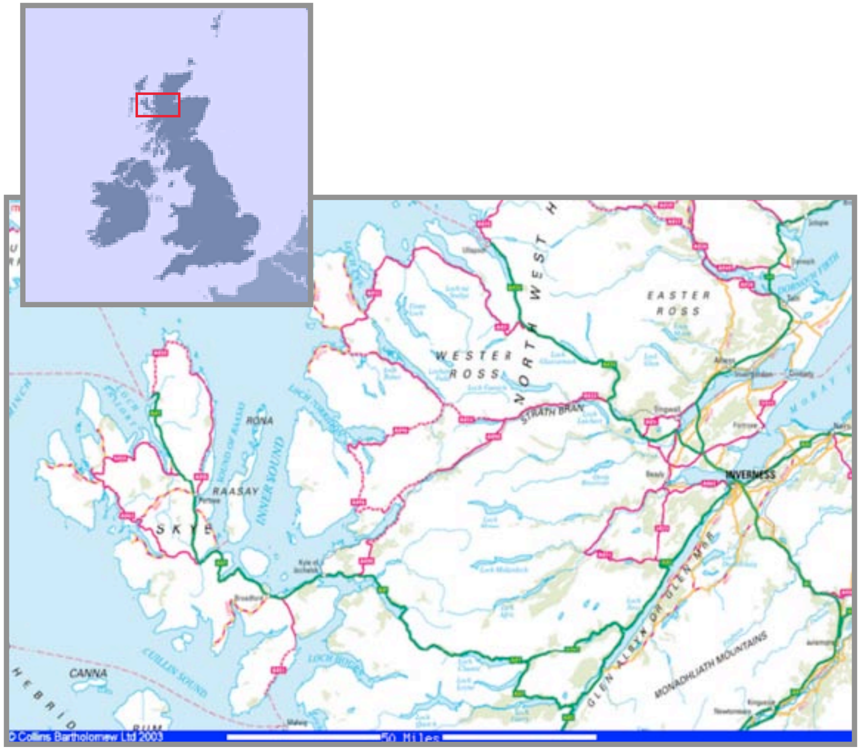
- Measurements in salt
- Arrays in water at Bahamas, Scottish Isles, Mediterranean Sea, Lake Baikal
- Array in ice at South Pole
- New ideas: Ross Ice Shelf, Dead Sea

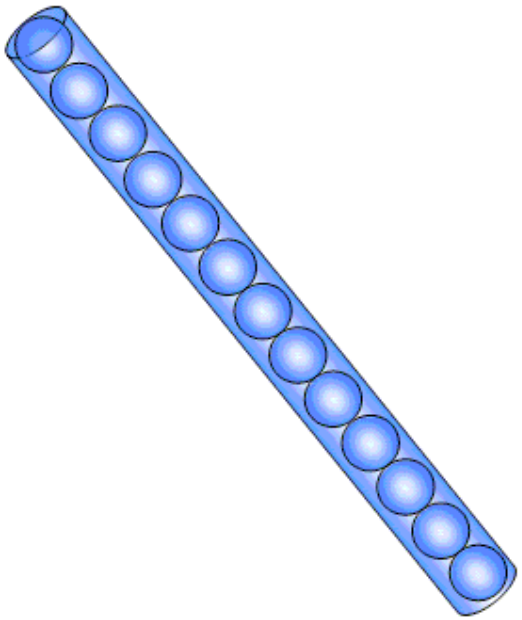
Deployment of ONDE off coast of Sicily



For a summary see J. Vandenbroucke astro-ph/0611503

Acoustic Cosmic Ray Neutrino Experiment (ACORNE)





British collaboration
Scottish military array
8 hydrophones
Running since 2005

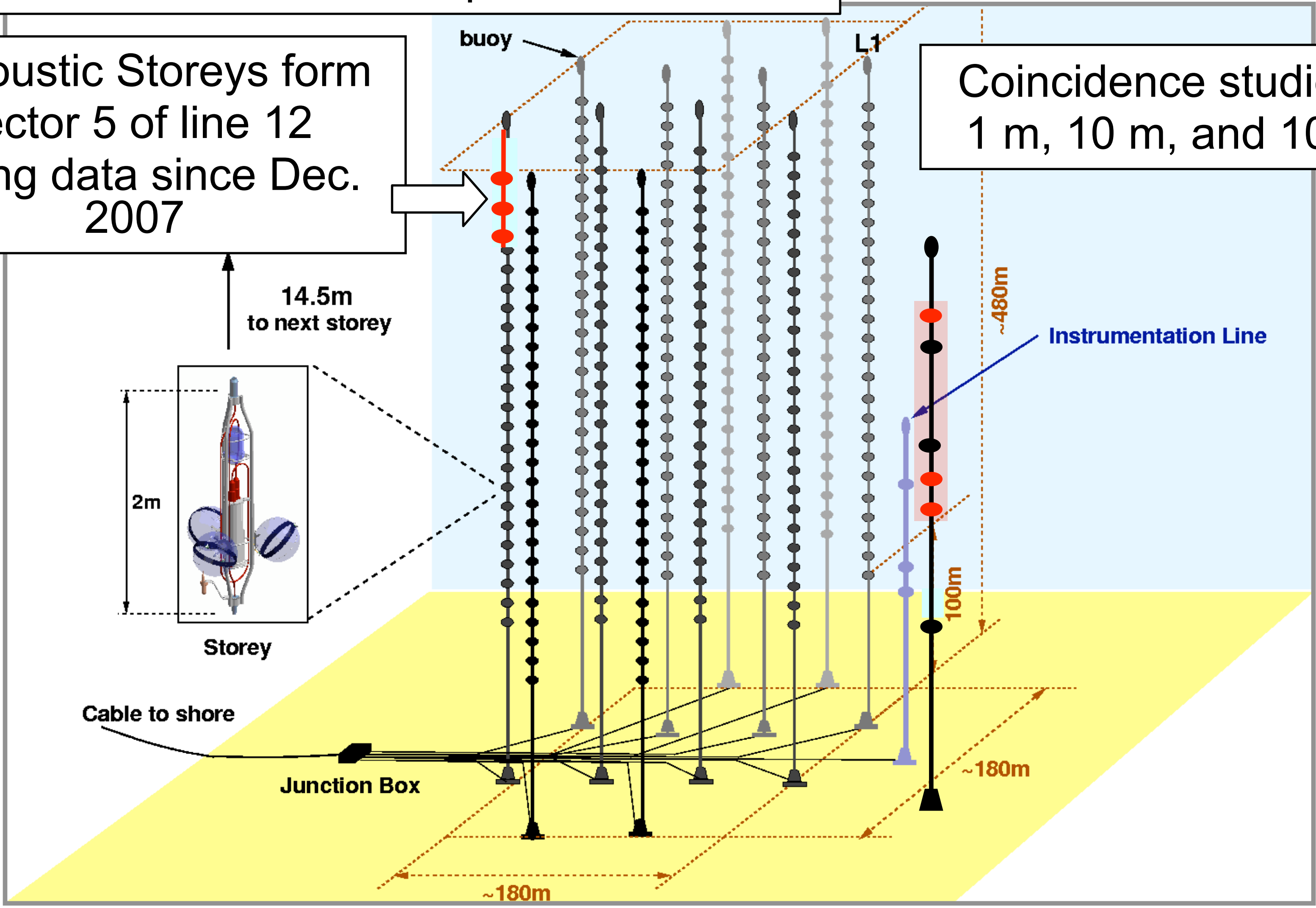
<u>Activities:</u>
Hadronic shower simulations
Careful calibration with pancake source
Full readout with offline filter studies

ANTARES Modules for Acoustic Detection Under the Sea (AMADEUS)

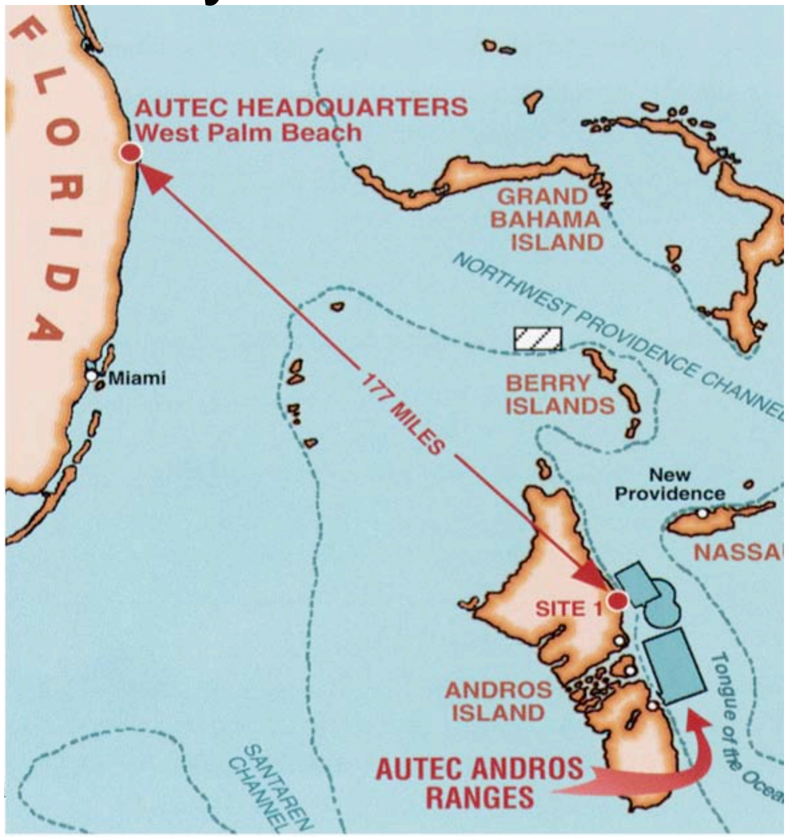
pathfinder for acoustic component in Km3Net

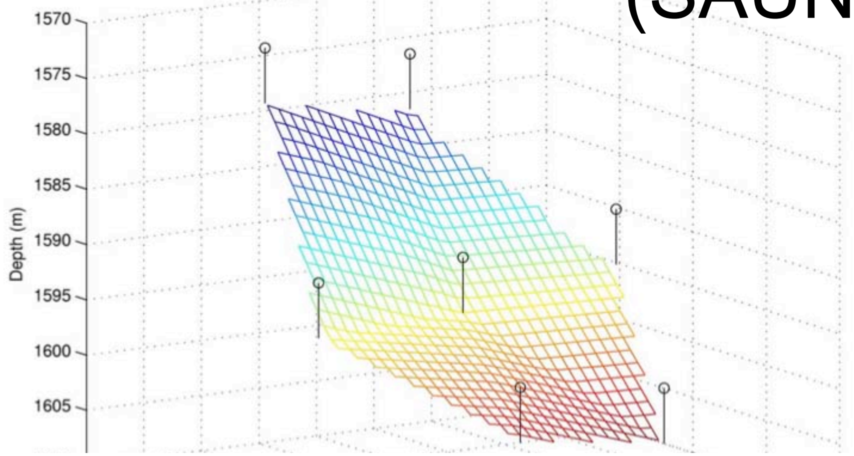
3 Acoustic Storeys form sector 5 of line 12
Taking data since Dec. 2007

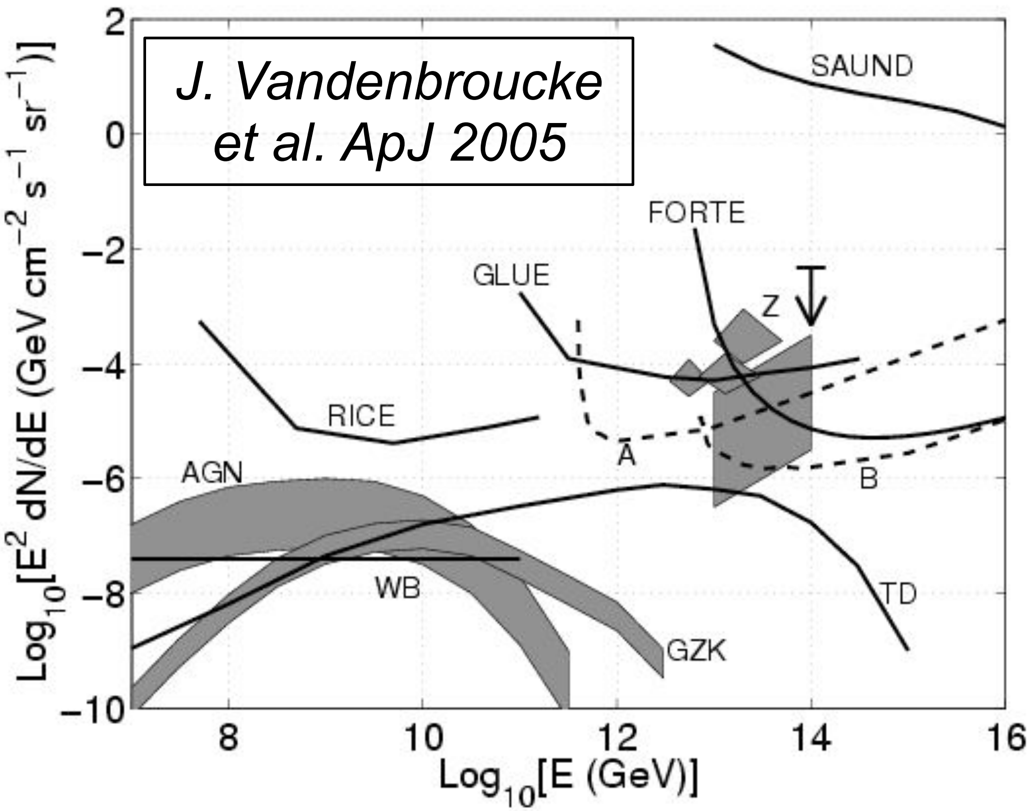
Coincidence studies at 1 m, 10 m, and 100 m



Study of Acoustic Ultra-high-energy Neutrino Detection (SAUND)



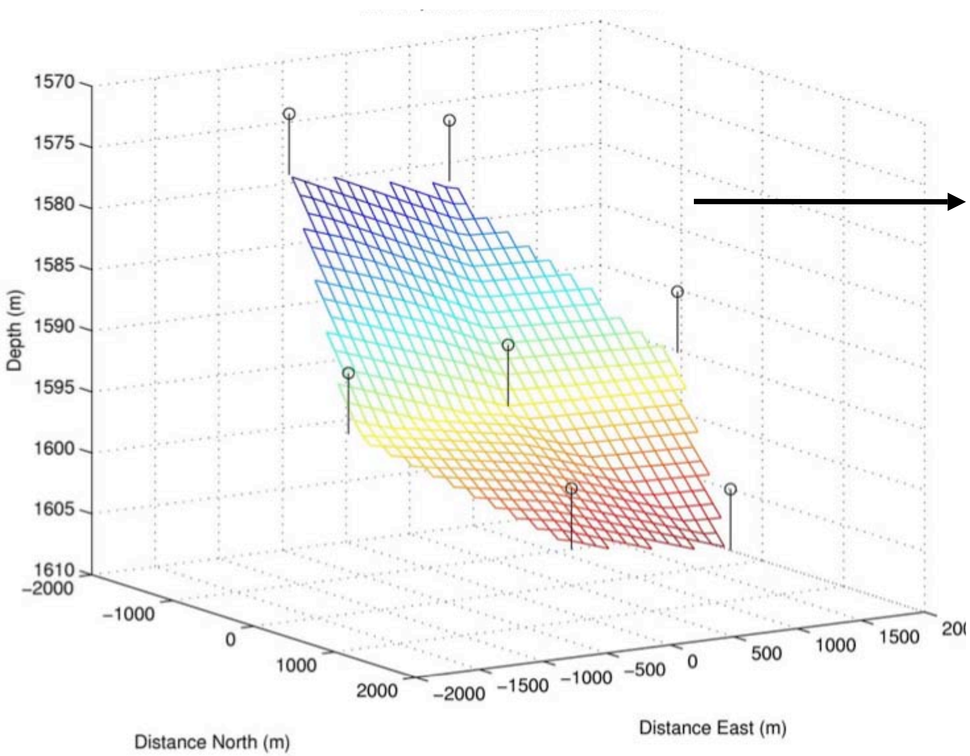


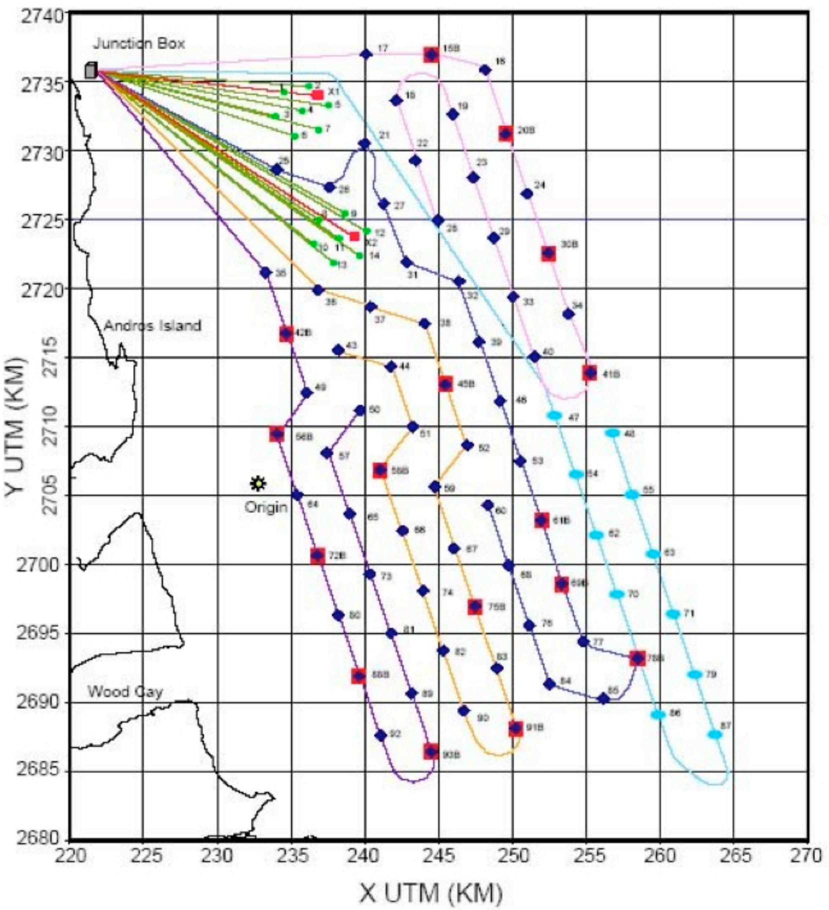


- 7 hydrophones at undersea Navy array in Bahamas
- Searched for neutrino signals in 195-day exposure
- First acoustic neutrino limit, not competitive with radio but new technique
- SAUND-II now underway, 49 hydrophones (10^3 km^2)

Tongue of the Ocean from space

From SAUND-I to SAUND-II

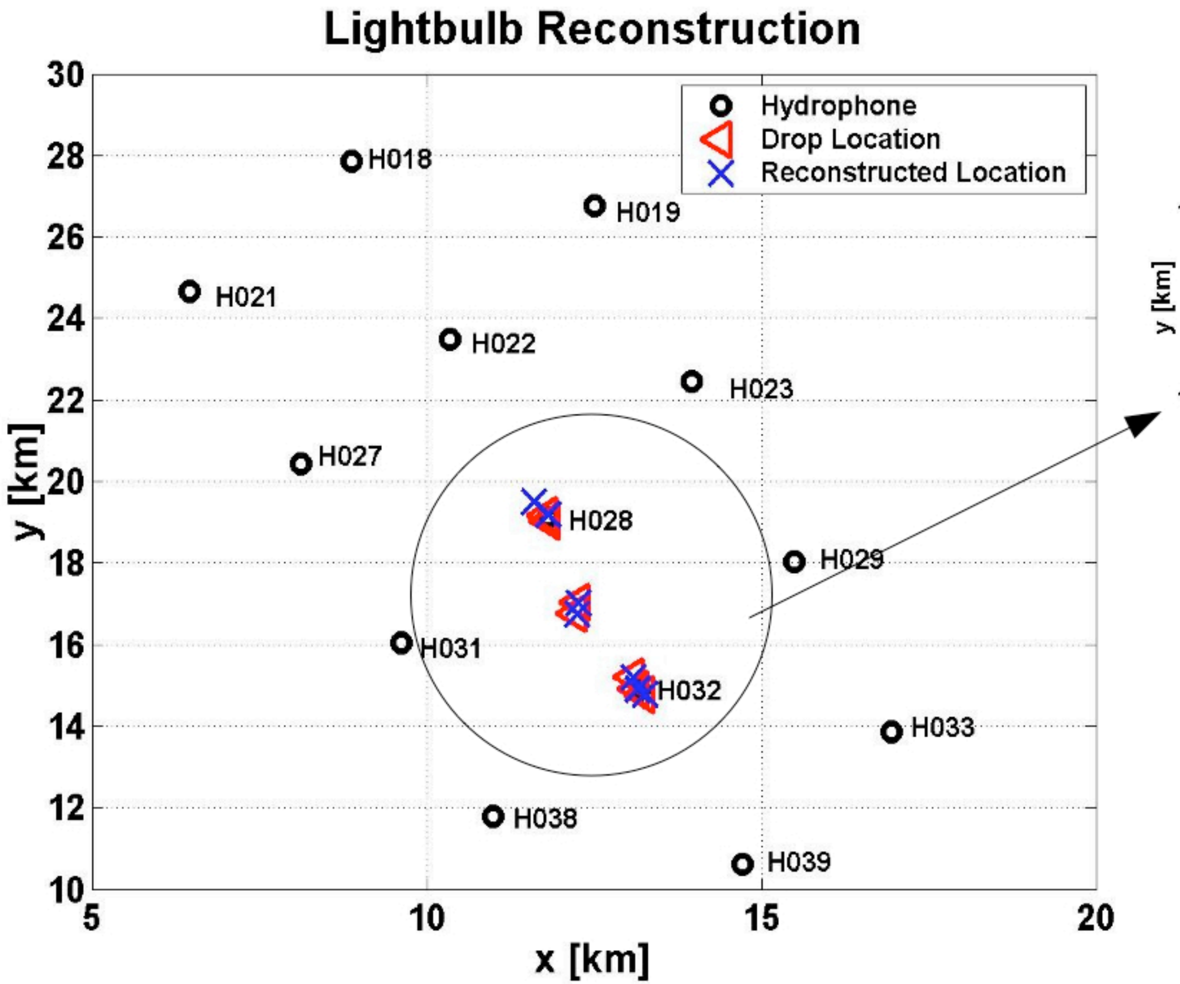


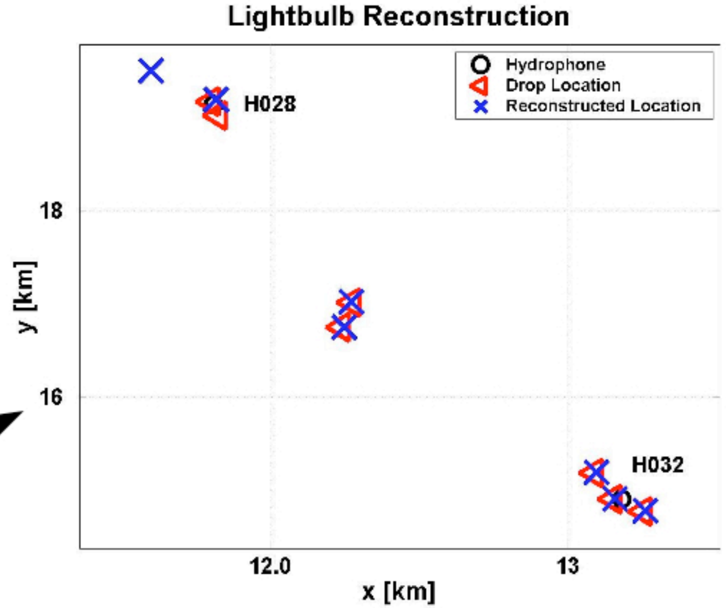


- 7 → 49 hydrophones
- Optical readout (significantly lower noise)
- Bandwidth starting at 0.1 kHz (was 7.5 kHz)
- Physics run started summer 2006

SAUND-II vertex reconstruction calibration

Lightbulbs dropped from a boat pop at ~100 m depth





blind analysis!

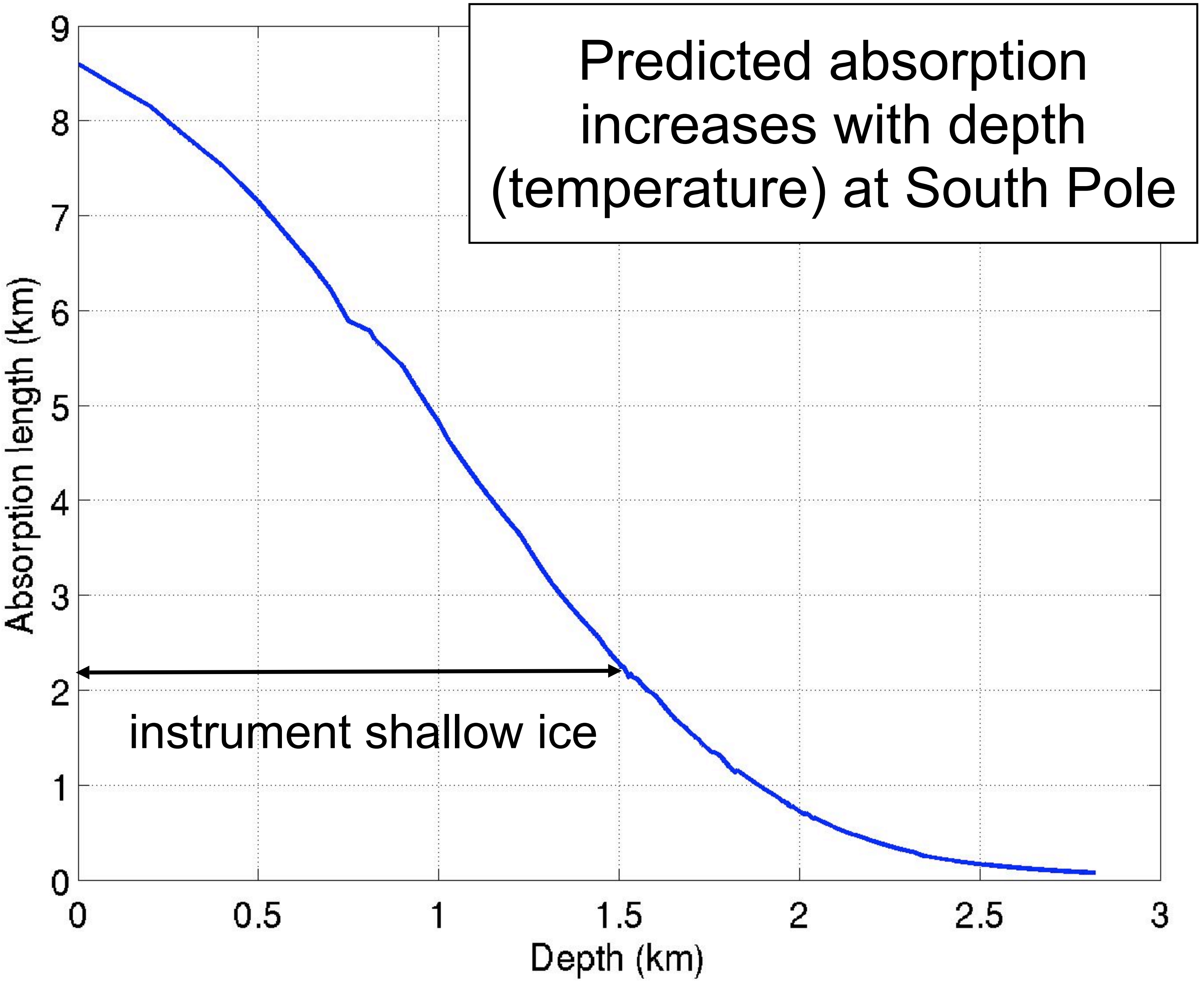
Part 4: Acoustics in ice: Go South!

Acoustic detection in *ice* predicted better than water

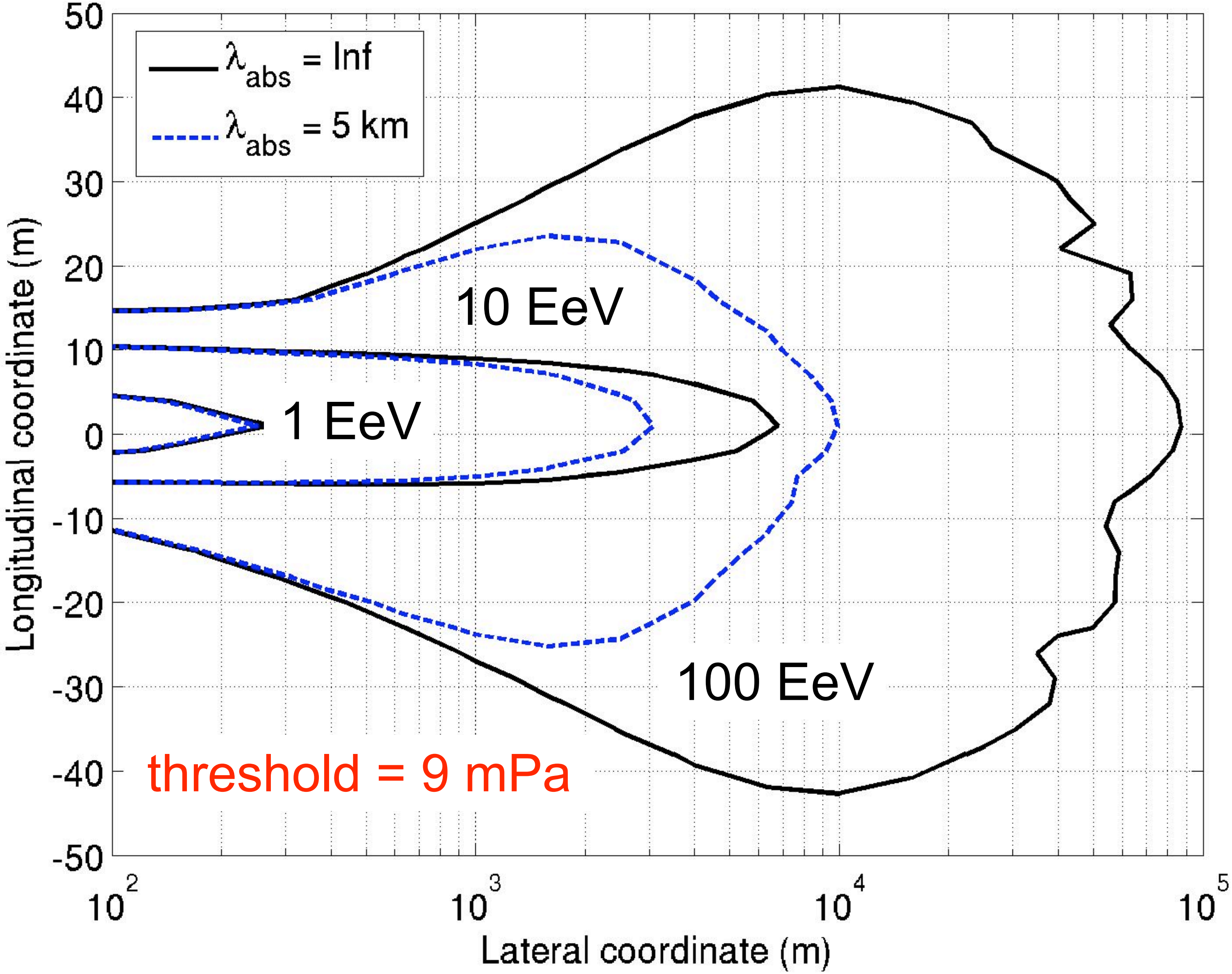
- Signal 7 times larger
- Refraction not an issue below firn (snow) layer ~200 m thick
- Lower noise?

  No waves, ships, dolphins, shrimp

  Surface noise blocked by firn waveguide?
- Attenuation lower (theoretical model based on lab data, *P. B. Price GRL 2006)*

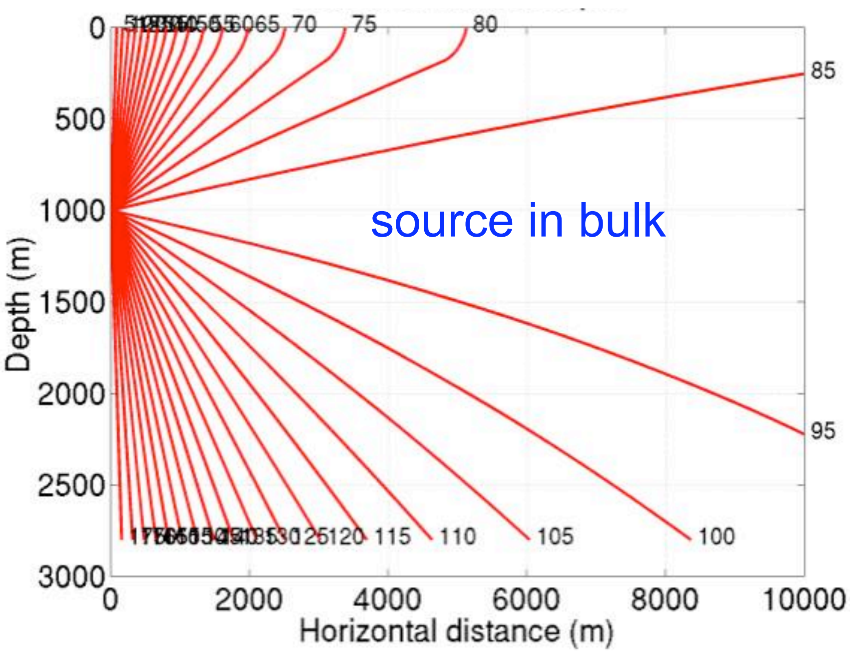

Predicted absorption increases with depth (temperature) at South Pole
instrument shallow ice
Absorption length (km)
Depth (km)
0
1
2
3
4
5
6
7
8
9
0
0.5
1
1.5
2
2.5
3

Acoustic radiation pattern in ice



Signals from bulk ice (neutrinos) somewhat refracted…

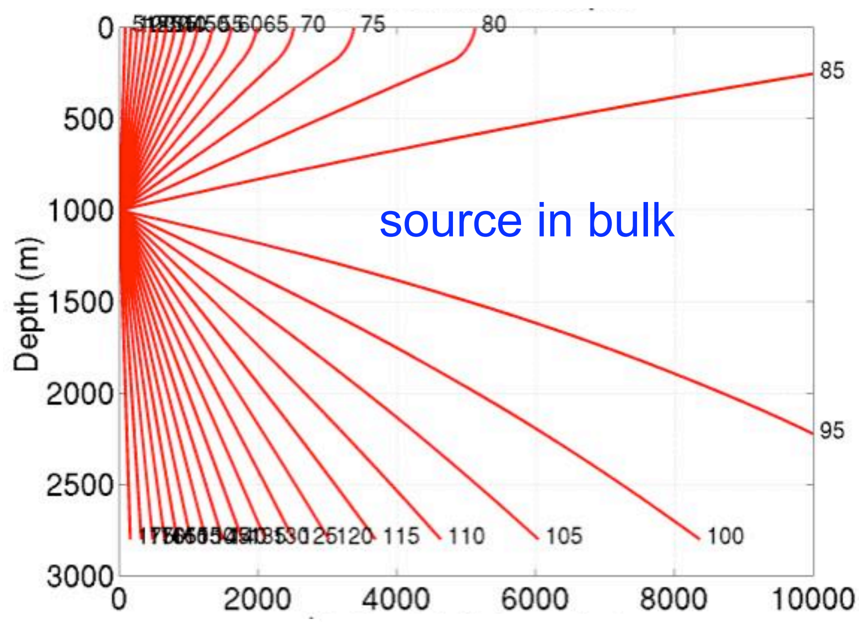
(emit a ray every 5°)

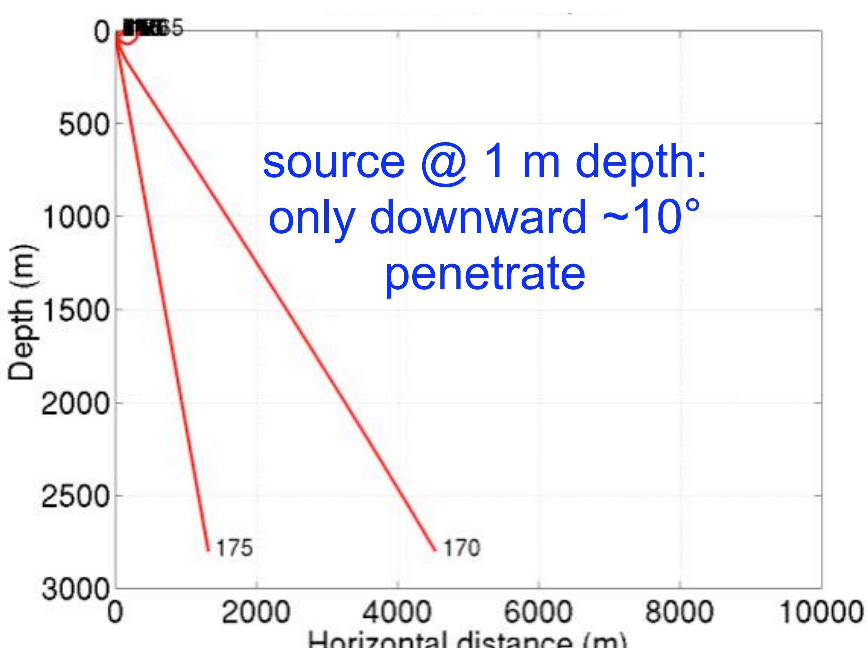


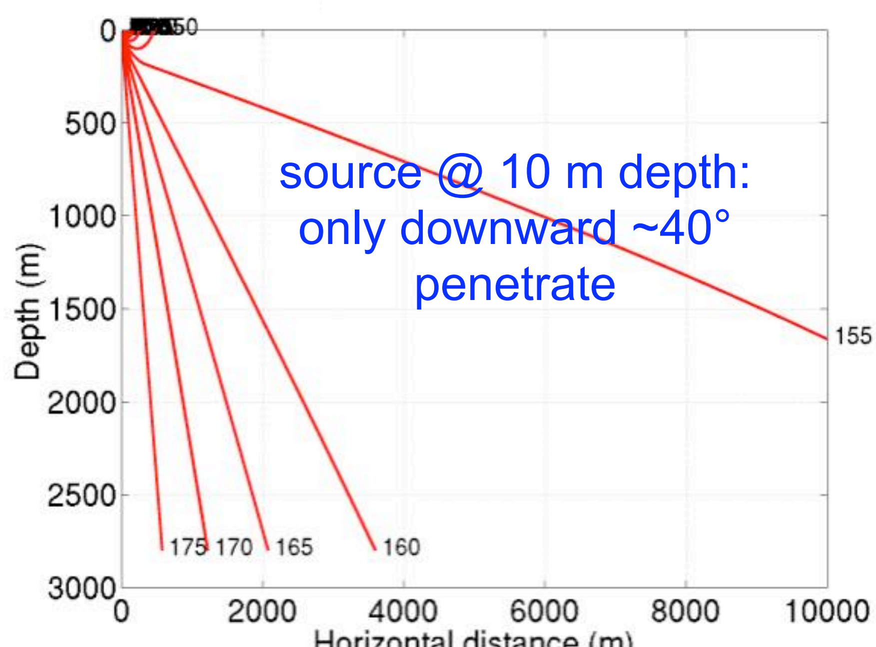
Signals from bulk ice (neutrinos) somewhat refracted…

(emit a ray every 5°)

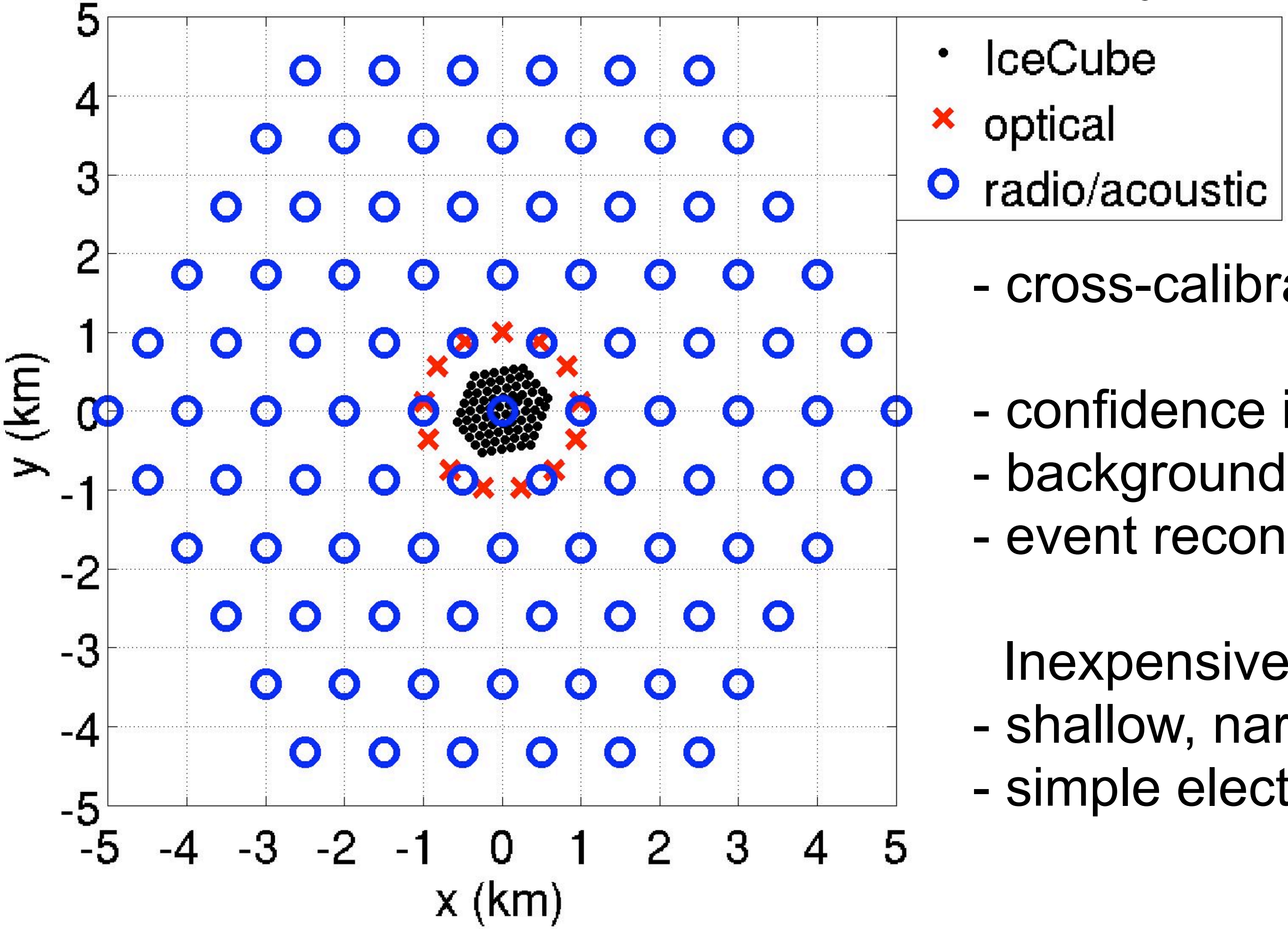
…signals from surface (noise) shielded by firn







South Pole good for all methods (optical, radio, acoustic)
Build a hybrid array!
Goal: detect ~100 GZK ν in a few years



- cross-calibration

- confidence in signals
- background rejection
- event reconstruction

Inexpensive:
- shallow, narrow holes
- simple electronics

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Build a hybrid array!
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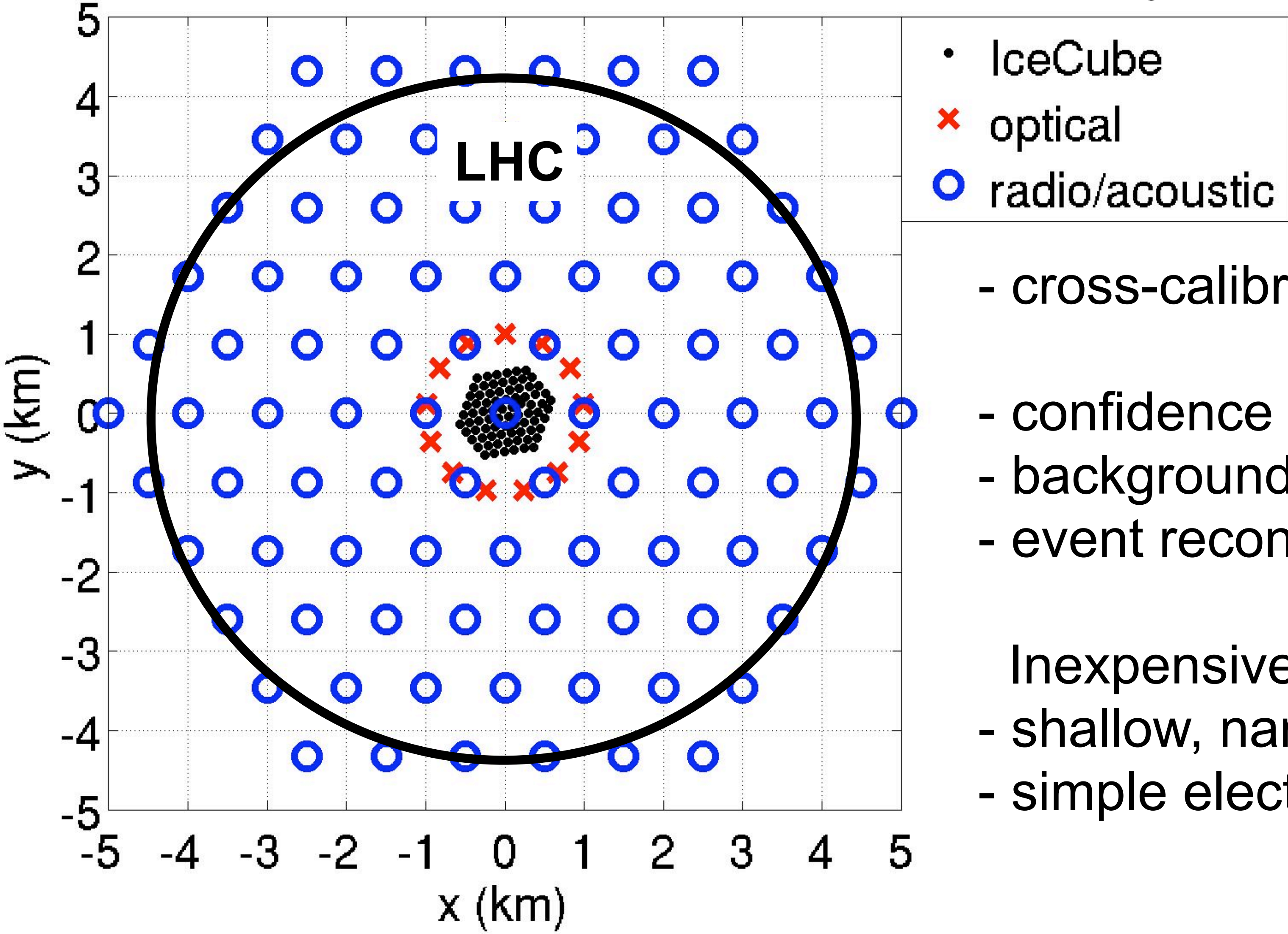

- cross-calibration

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Inexpensive:
- shallow, narrow holes
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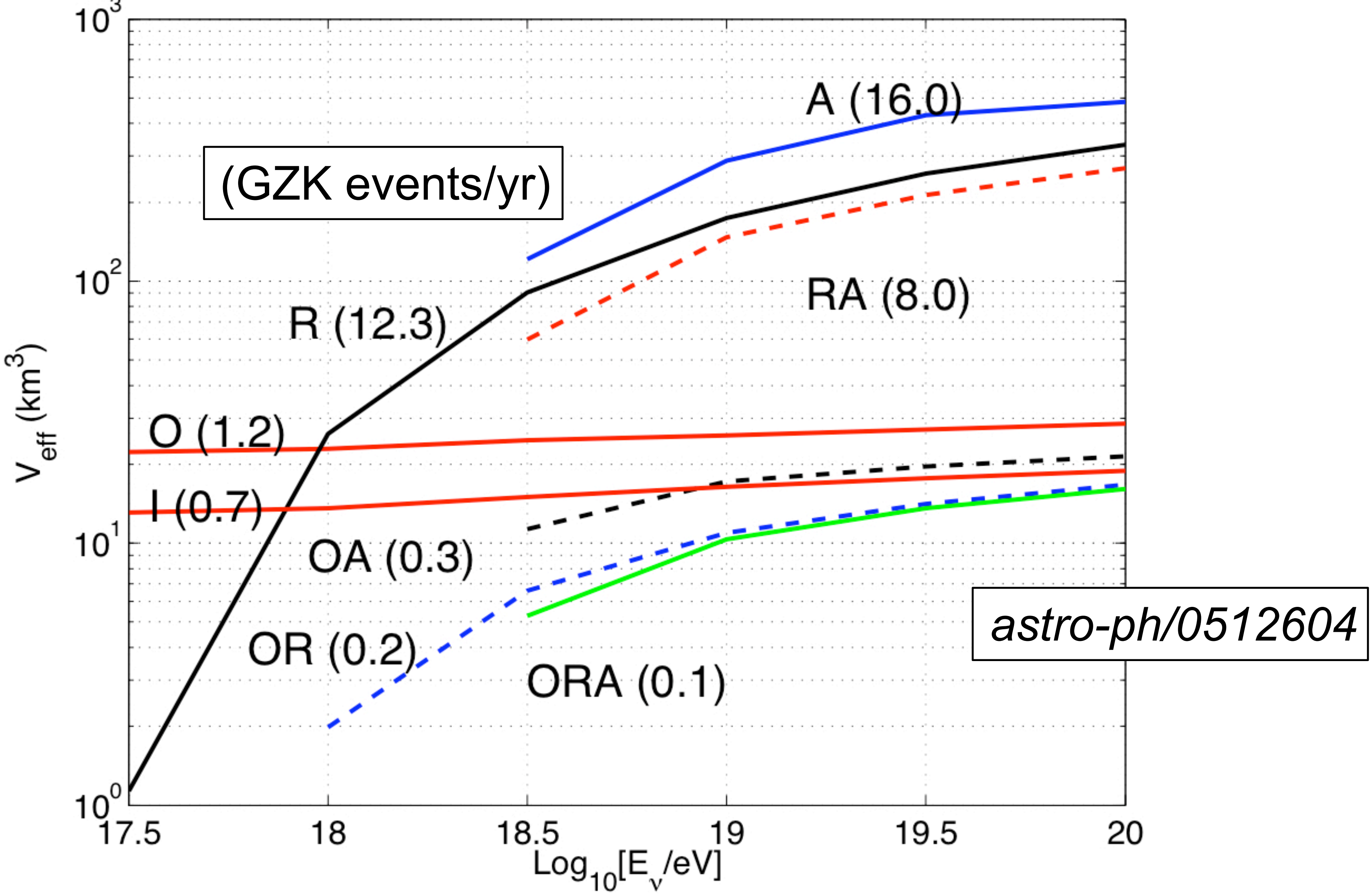
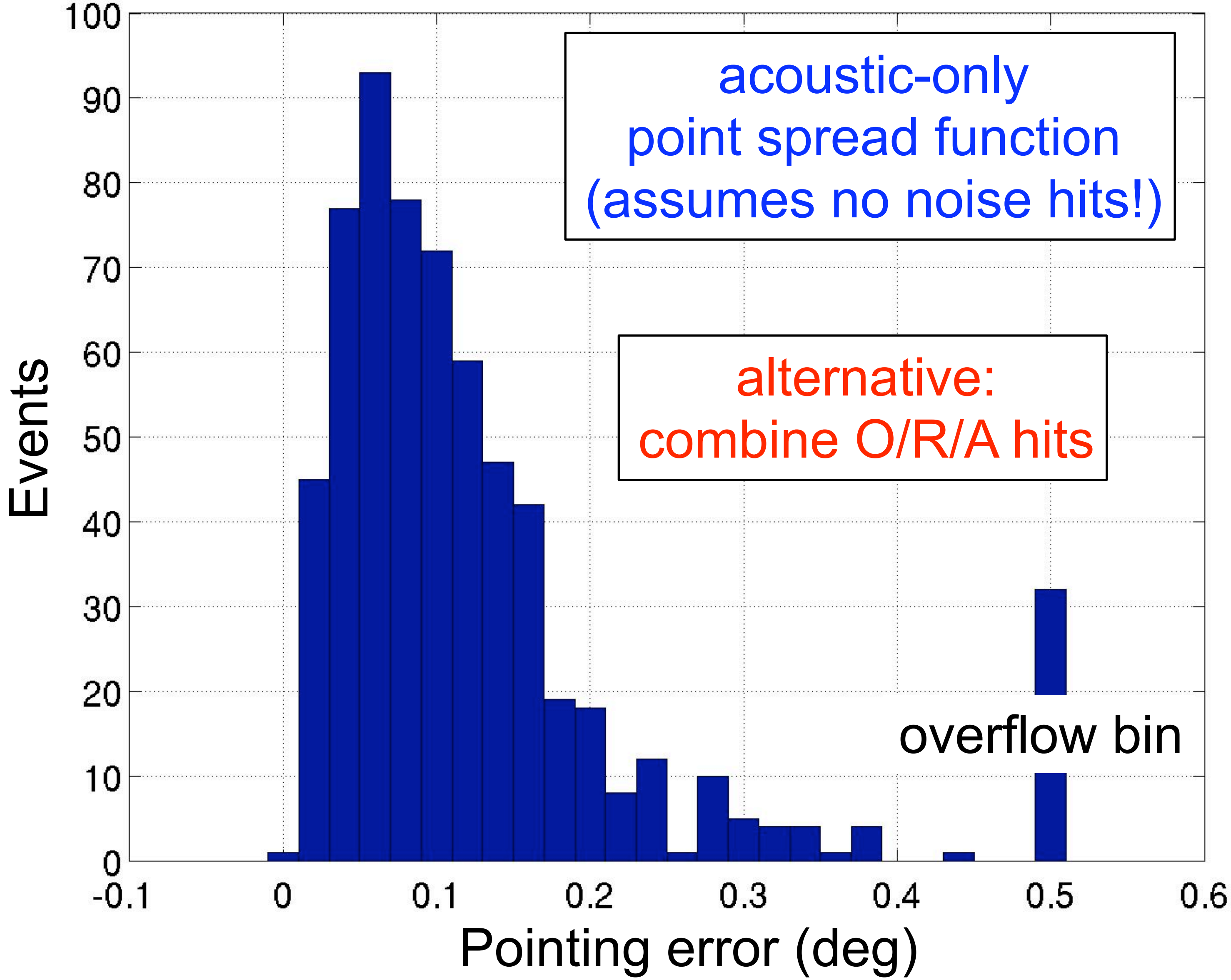
Simulated sensitivity of hybrid detector



Good neutrino pointing resolution (benefit of flat acoustic radiation pattern)



Part 5: IceCube

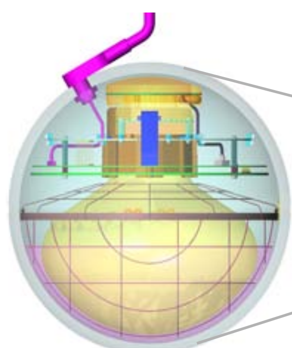
IceCube-AMANDA

<u>IceCube</u> : 4800 DOMs on 80 strings

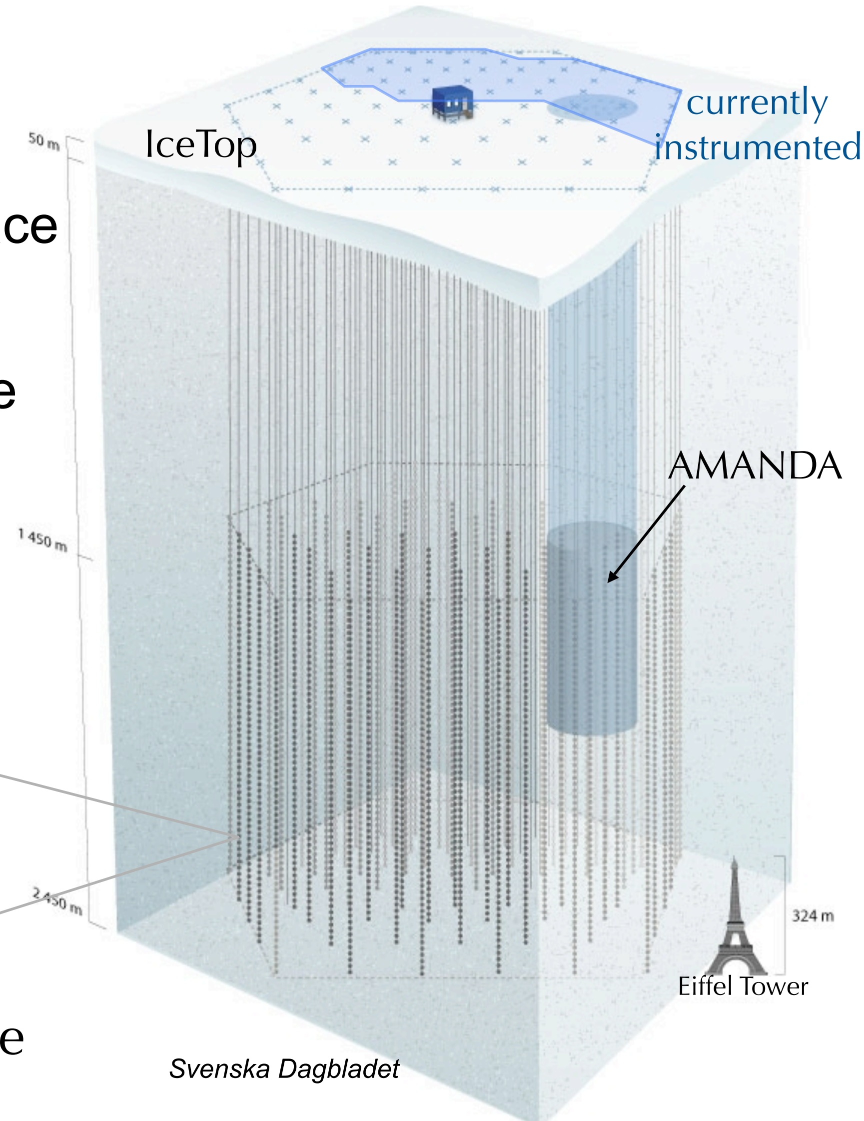
<u>IceTop</u> : 160 Ice Cherenkov tanks on surface

<u>AMANDA</u>: 677 OMs surrounded by IceCube

40 strings installed as of January 2008!

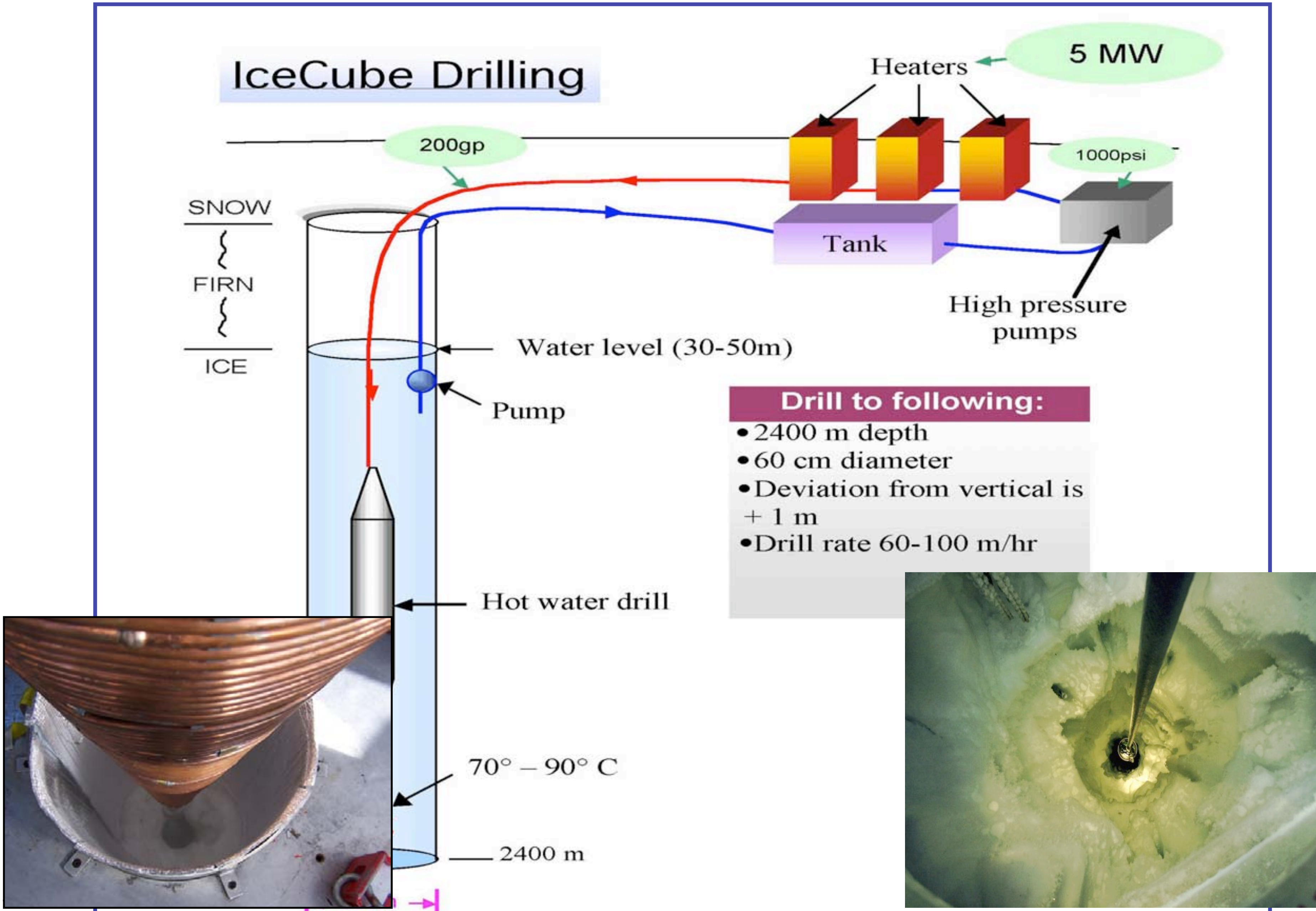


Digital Optical Module (DOM)



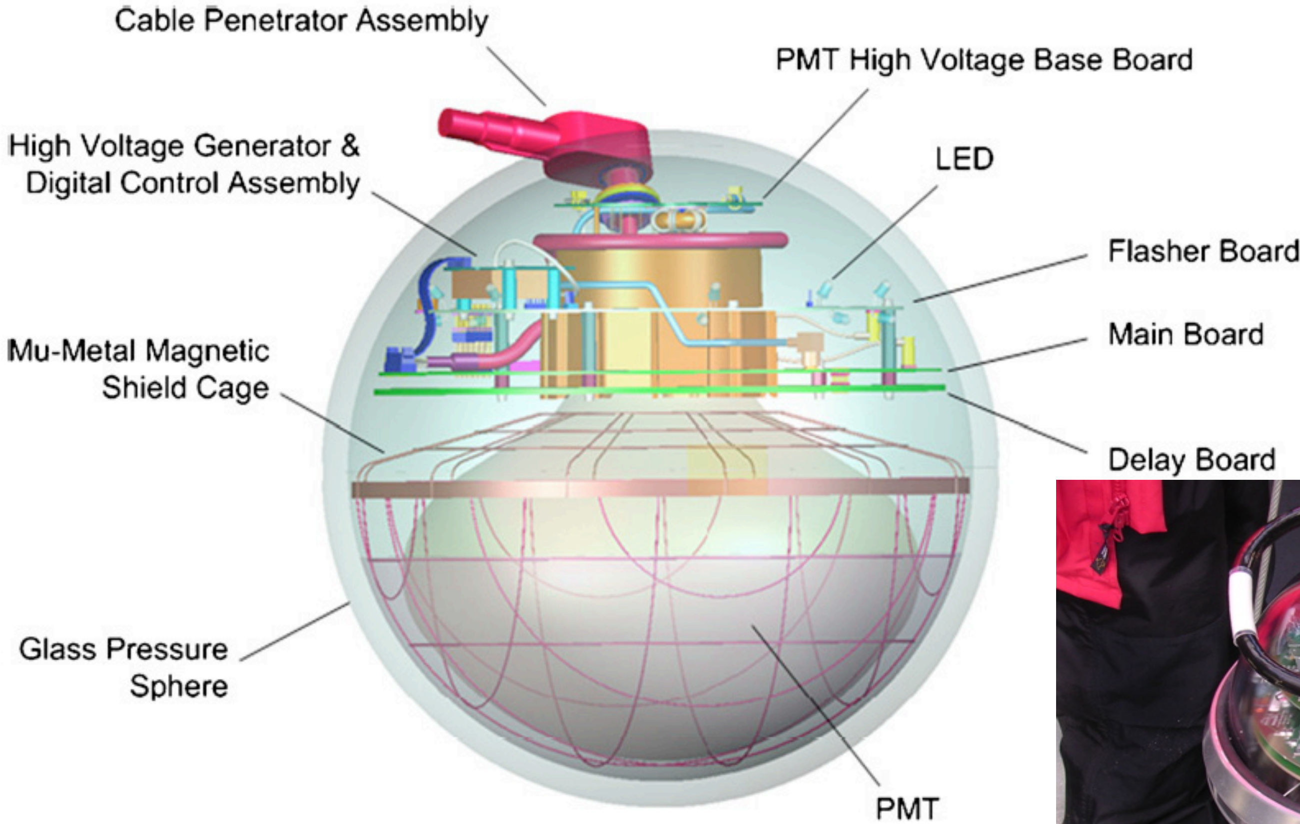
Svenska Dagbladet

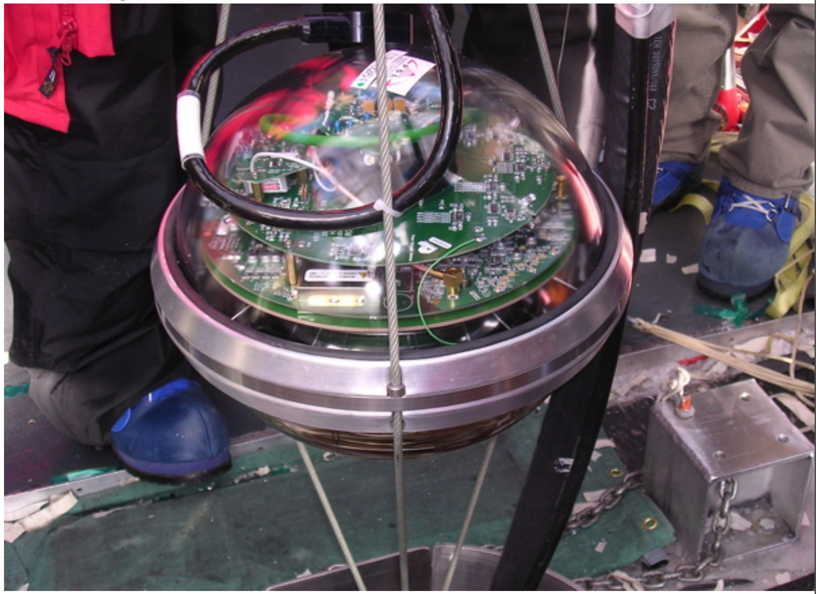
Drilling 2.5 km into a polar ice sheet with hot water




DEPLOYMENT
Hose reel
Drill tower
5 MW Hot water generator
Hot-water drilling
Drilling to 2500 m < 40h
String deployment ~ 12h
speed: ~90m/hr

IceCube Digital Optical Module = PMT + electronics

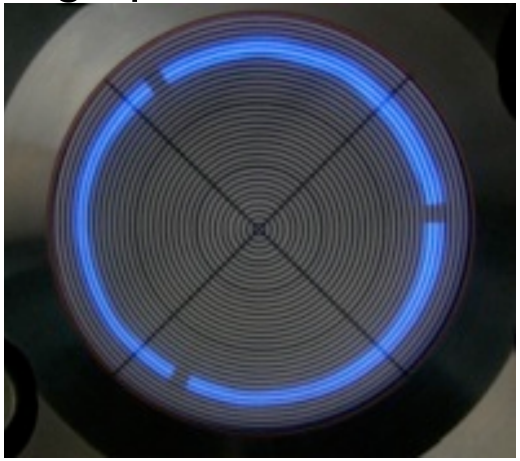




- Low intrinsic noise ~ 500 Hz
- Fast digitization 30 ms/channel
- Waveform: 4 channels/128 sample
- Low power consumption 5 W per DOM
- Up to 12 µs combined waveform length
- Variable sampling speed: 250 - 800 MHz
- Up to 200-300 p.e./10 ns charge resolution

IceCube "Standard Candle"

- Calibration device to simulate Cherenkov cones of known intensity in detector
- Pulsed N_2 laser @ 337 nm
- Beam focused on reflecting cone to produce light cone
- Steel pressure housing containing laser, monitor + control electronics, optics
- Mimics neutrino induced cascades
- Intensity dynamic range ~200
- 2 deployed: one pointing up and one down



Part 6: Acoustic

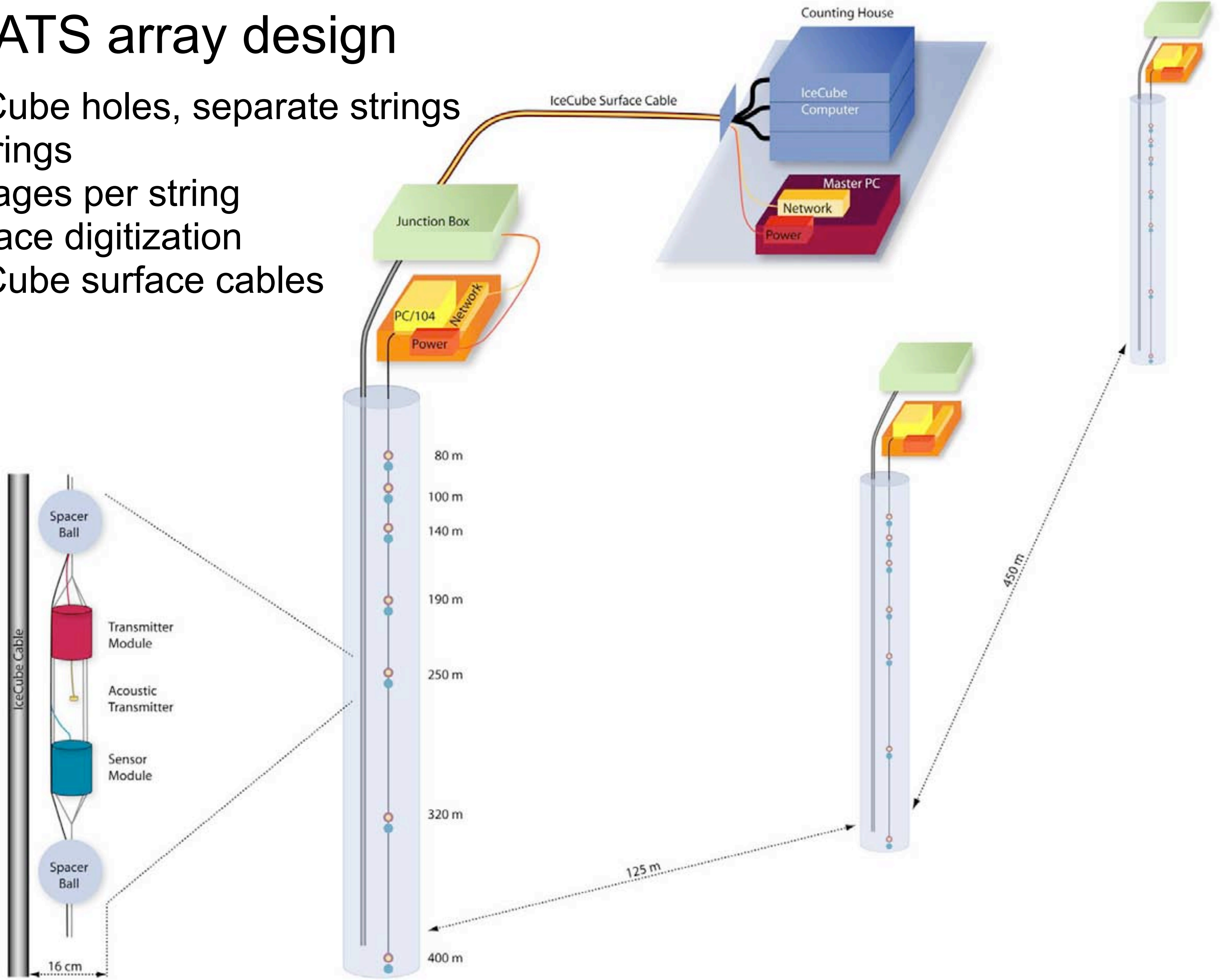
The South Pole Acoustic Test Setup (SPATS)

- First step toward large acoustic/hybrid detector at South Pole: measure ice properties in situ

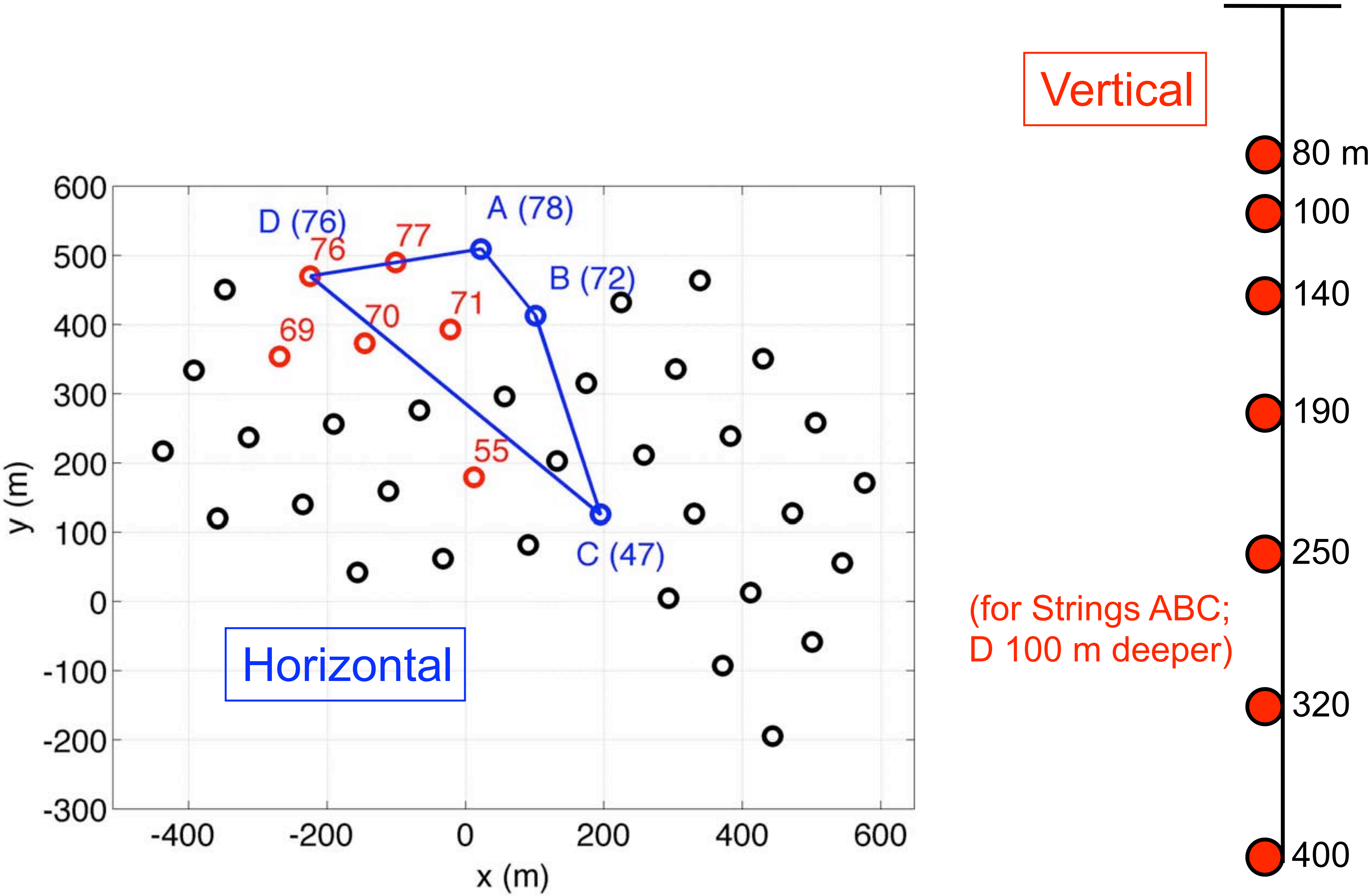
- Measurement goals:
  - Attenuation
  - Noise floor
  - Sound speed vs. depth
  - Transients
    - background for us
    - interesting for glaciologists?
      stick/slip glacier movement or bulk ice cracking?

SPATS array design

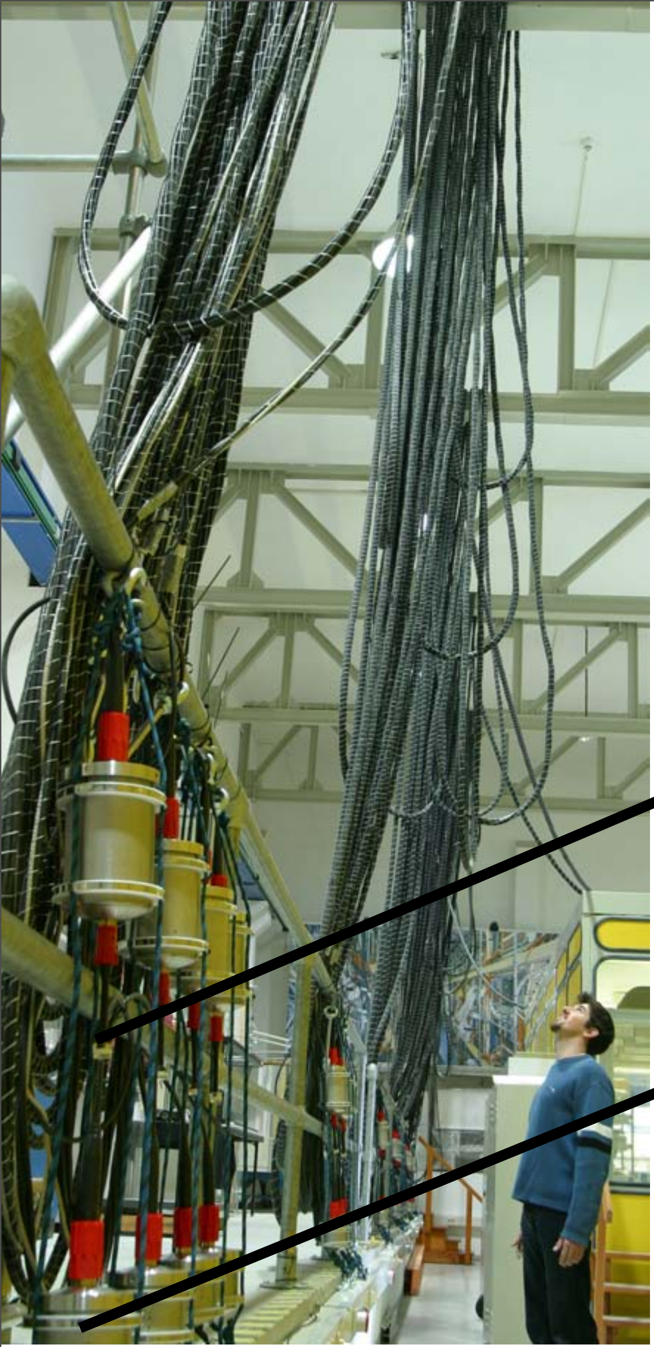
- IceCube holes, separate strings
- 4 strings
- 7 stages per string
- surface digitization
- IceCube surface cables

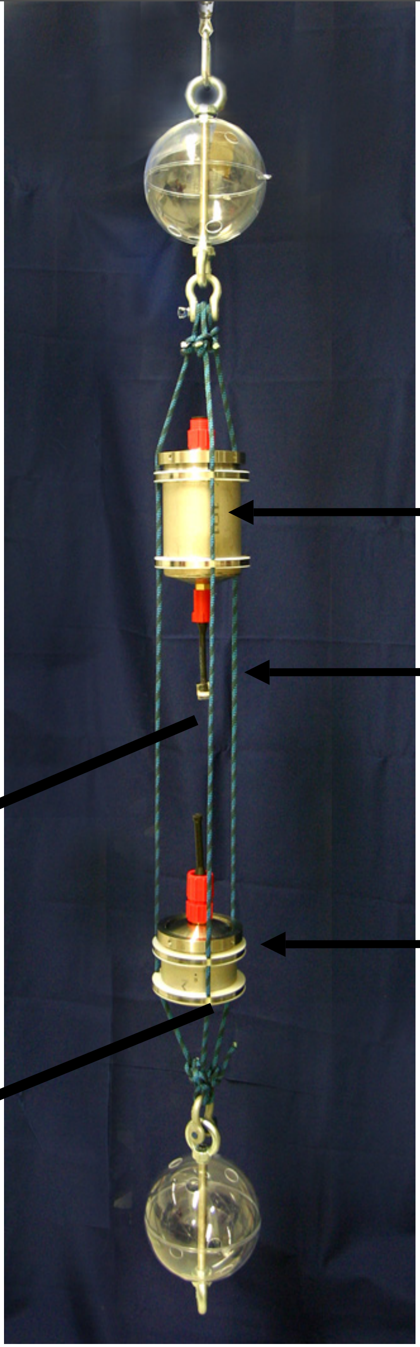


SPATS geometry



SPATS in-ice





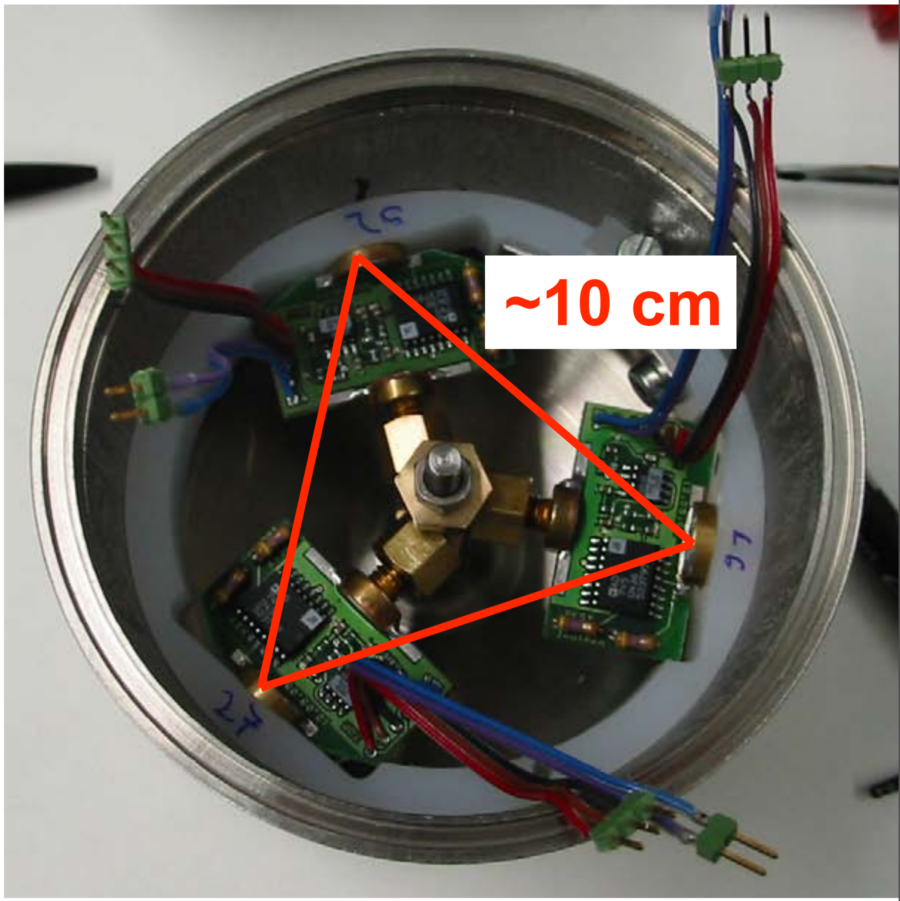
transmitter module
(electronics)

transmitter piezo-ceramic

sensor module
3 piezo-ceramics inside
for full azimuthal coverage

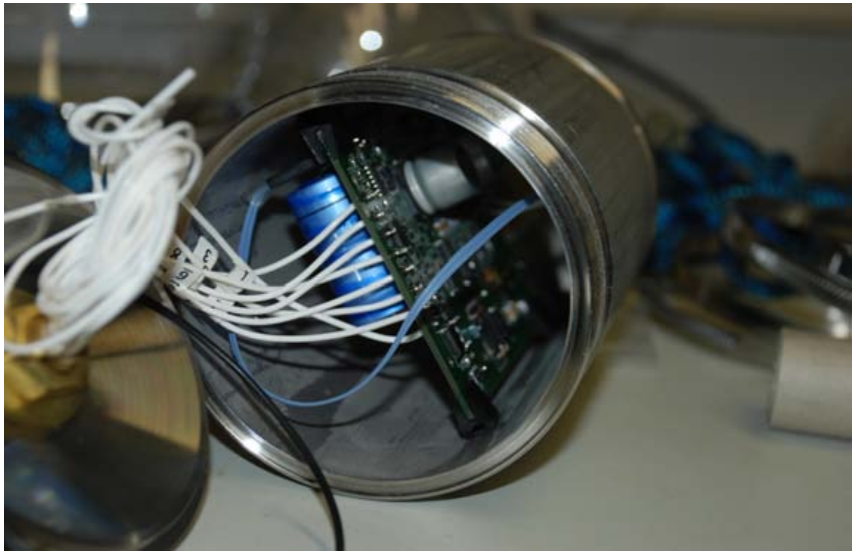
SPATS sensor module

- Steel pressure housing
- 3 independent channels per module
- Separated 120° in azimuth
- Few μs acoustic propagation delay between channels
- Transducer = one piezoelectric disk per channel
- One custom amplifier board per channel
- Differential analog output to surface

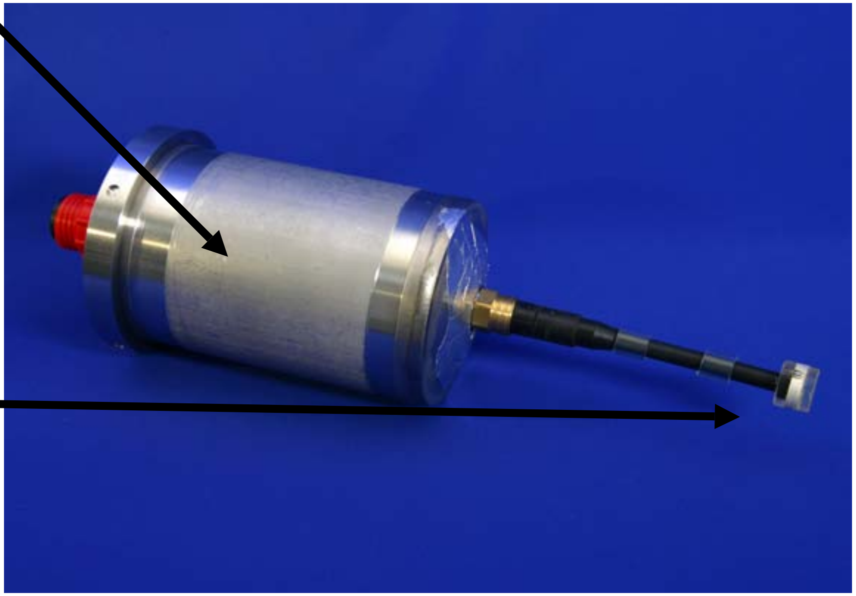


SPATS transmitter module

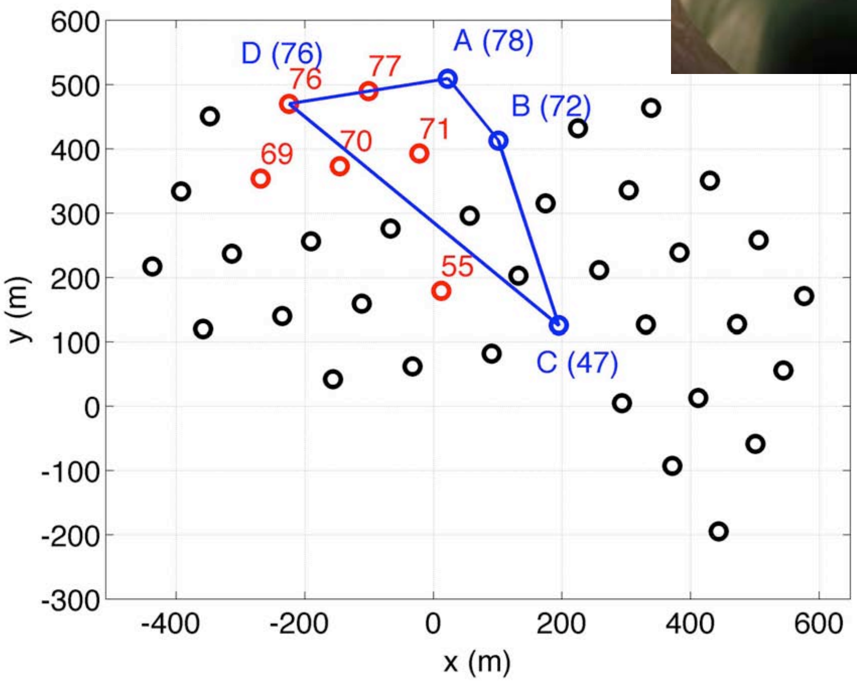
- HV pulser:
- ~ 30 μs pulse up to 1500 V gaussian-shape



- ring shaped piezo-ceramic



Retrievable



Retrievable pinger: technical design

In hole:

- Emitter: ITC1001 (isotropic)
- HV pulser (30 μs, fixed amplitude)
- Sea Star sensors

On surface ("Acoustic Pinger Box")

- Power (batteries)
- Trigger (PPS from GPS)

In between:

Robertson winch

SPATS data acquisition

1x master-pc
in IceCube Lab

4x embedded PC
buried in snow
above each string

power
digital comm.
GPS timing

triggered data

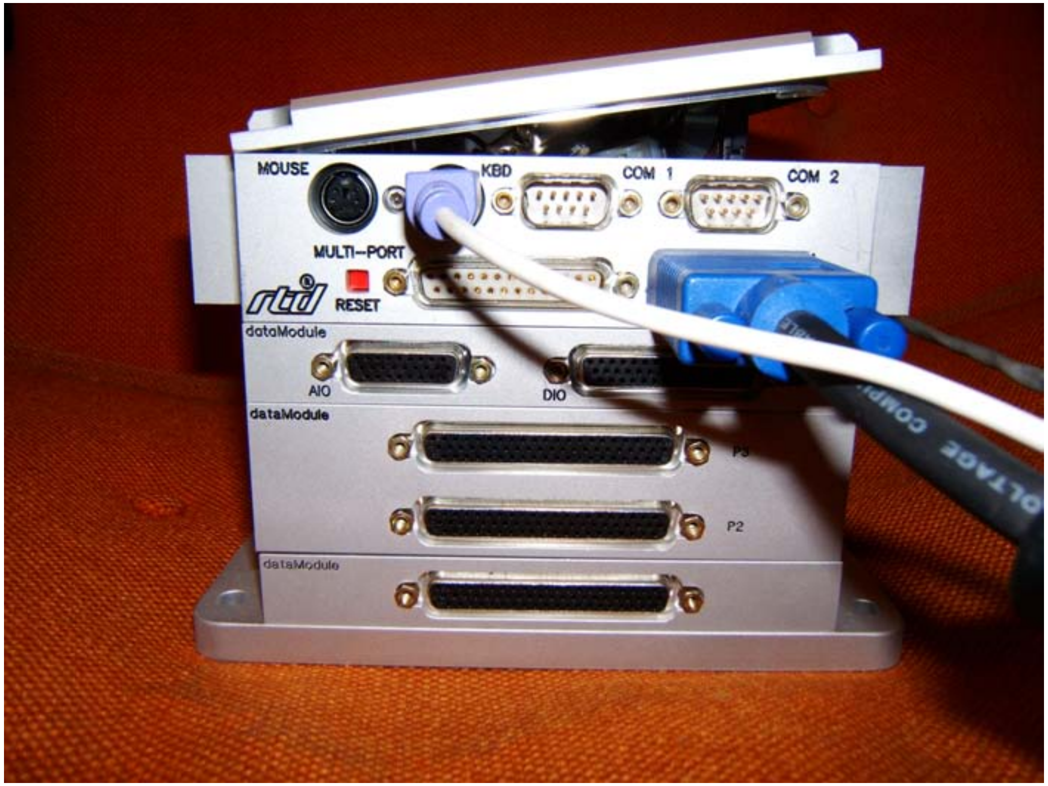
4x in-ice string

power
transmitter control

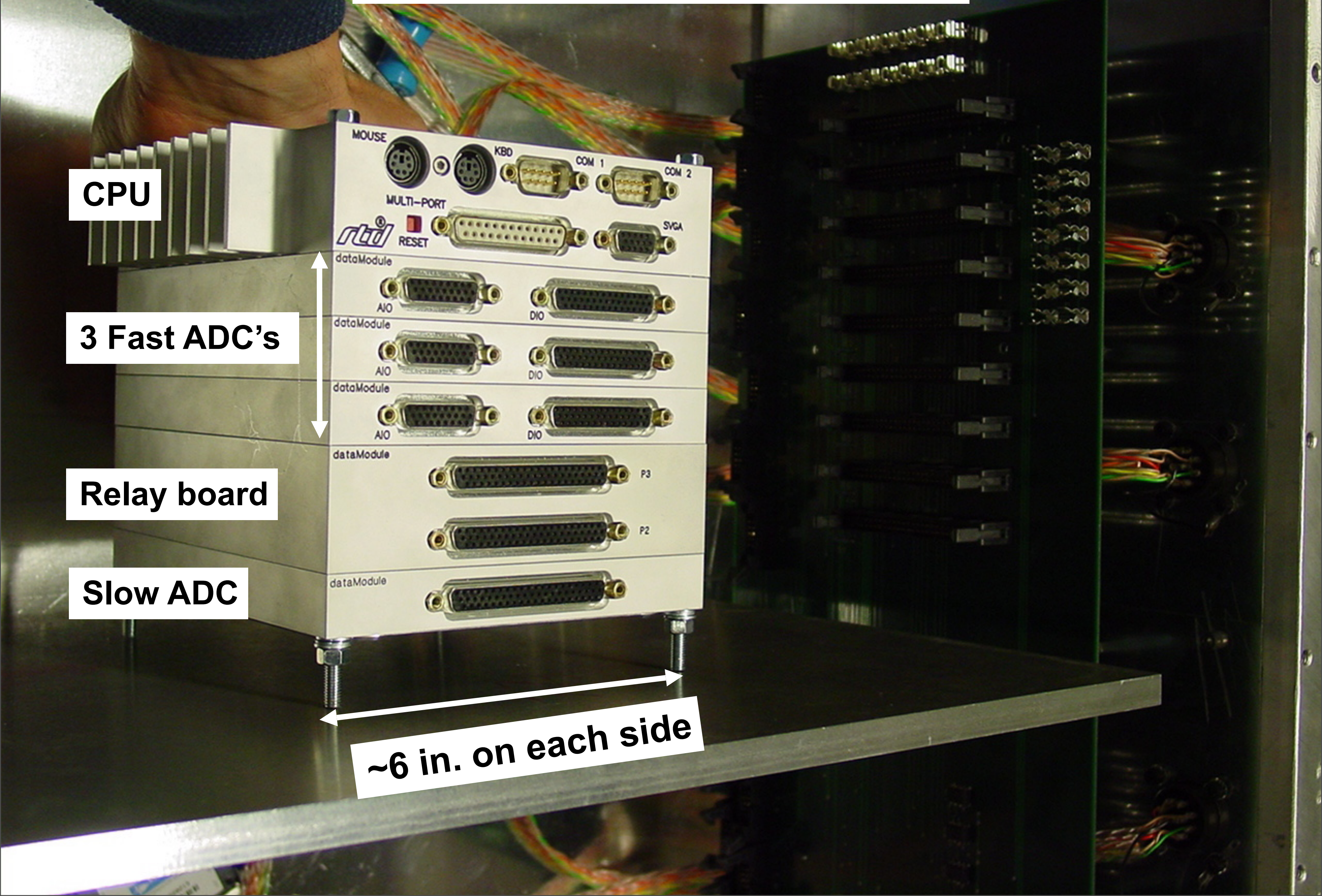
analog waveforms

String PC

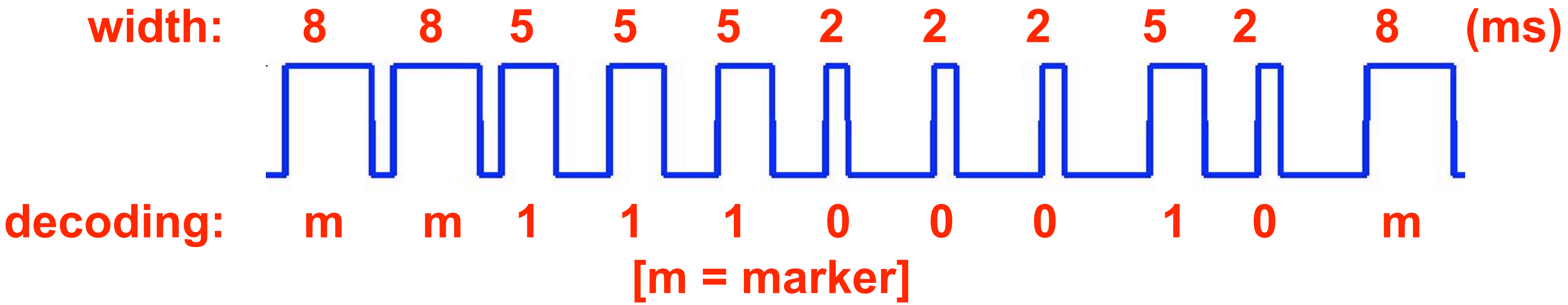
- A rugged computer in the IceTop trench, in a waterproof Acoustic Junction box next to the Surface Junction Box
- Use a PC104(+) modular embedded computing system from RealTime Devices
- Developed for military applications in extreme temperature and vibration conditions
- All components rated to -40 C and tested to -55 C
- All components take 5 VDC, total usage ~25 W



String PC: Components



Timing: Distribute IRIG-B

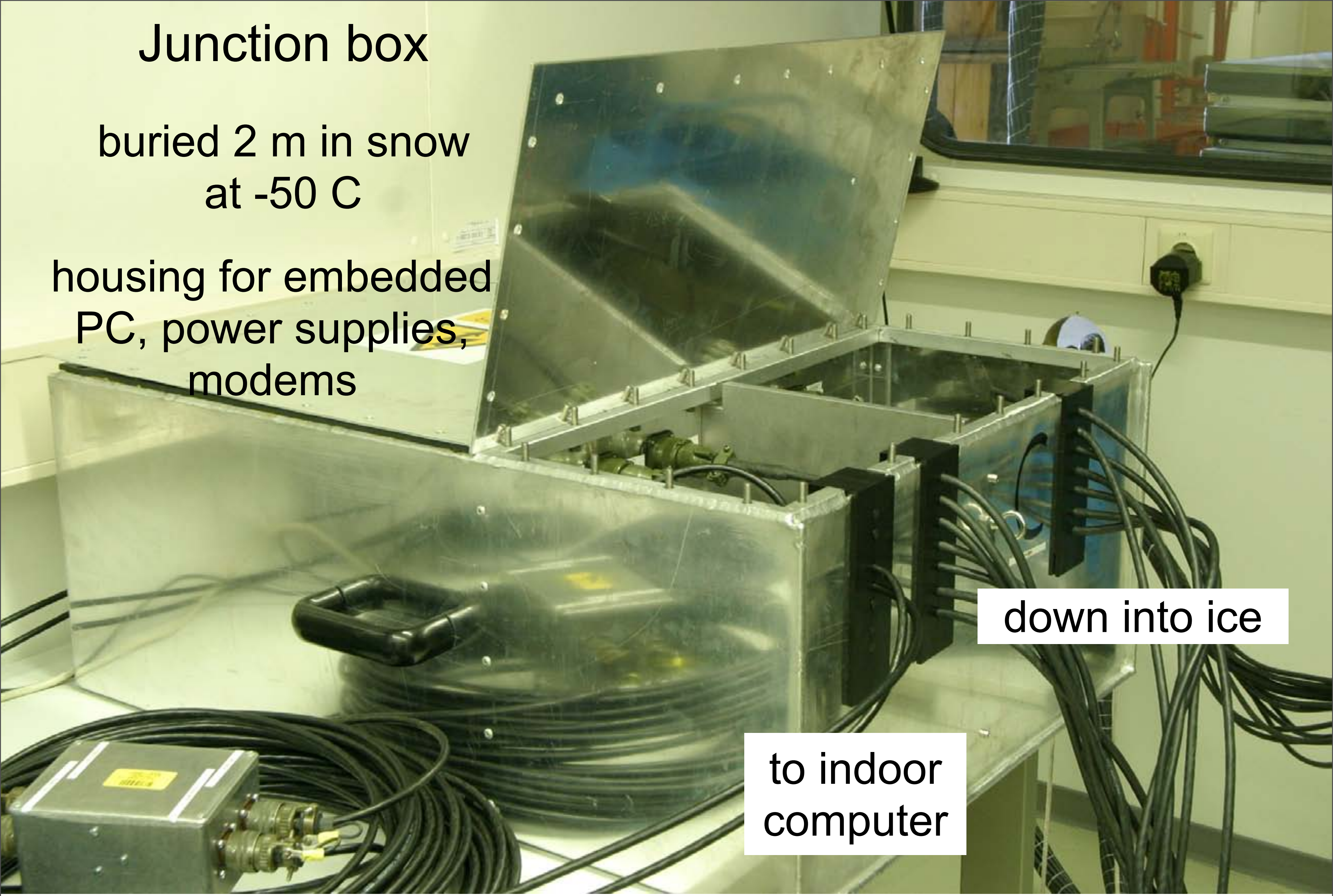


- From GPS clock in Master PC to all 4 strings:
  - absolute time specified in 1-second frames of digital pulses
  - 1 pulse every 10 ms, <1 μs risetime
  - pulse lengths encode bits to specify absolute time
- ADC boards can sample “marker” digital lines simultaneously with the analog
- We use IRIG-B as a marker line → match it with the acoustic signals to give 1-sample (~μs) timing resolution

Junction box

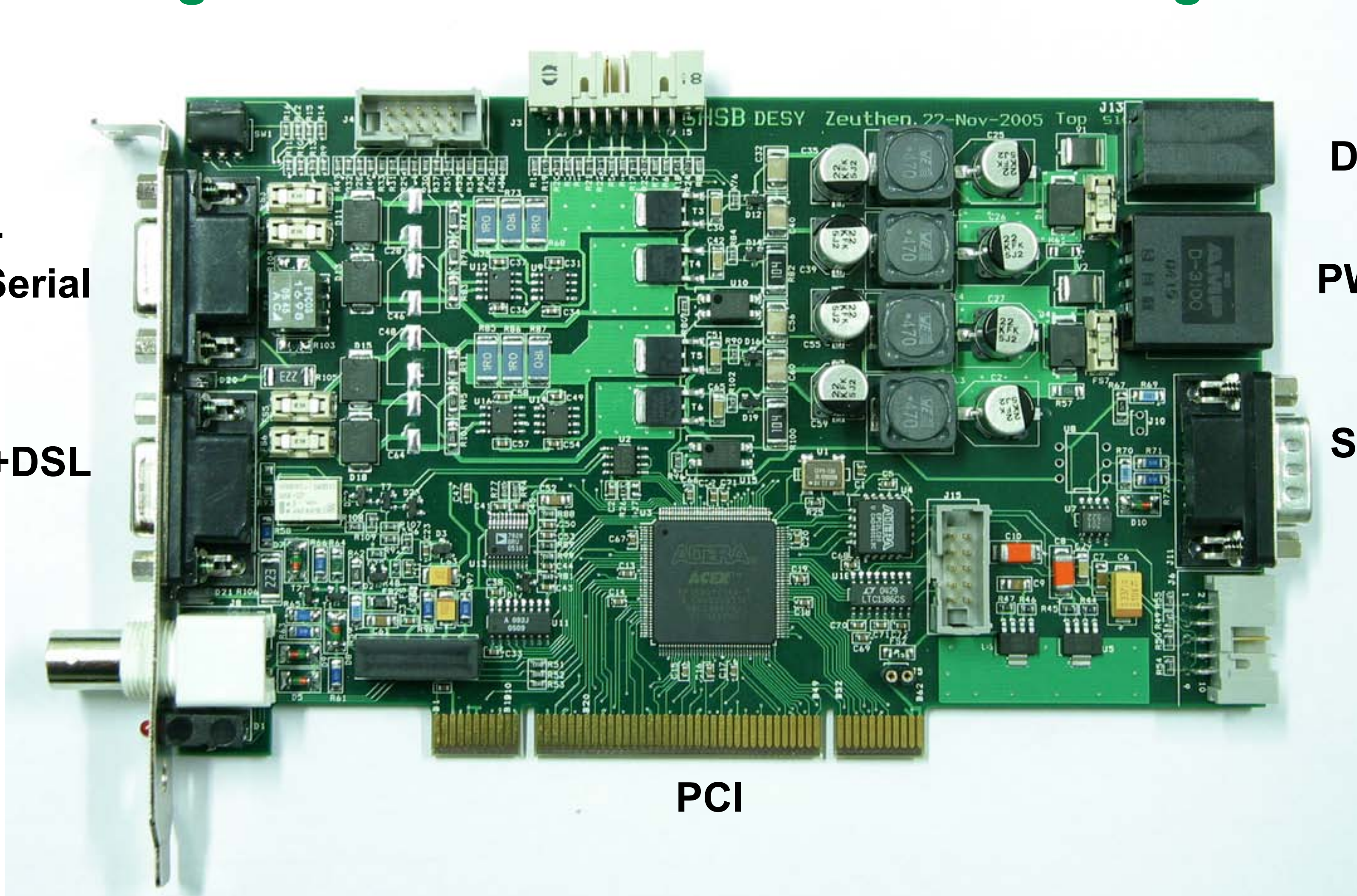
buried 2 m in snow
at -50 C

housing for embedded PC, power supplies, modems



SPATS Hub Service Board

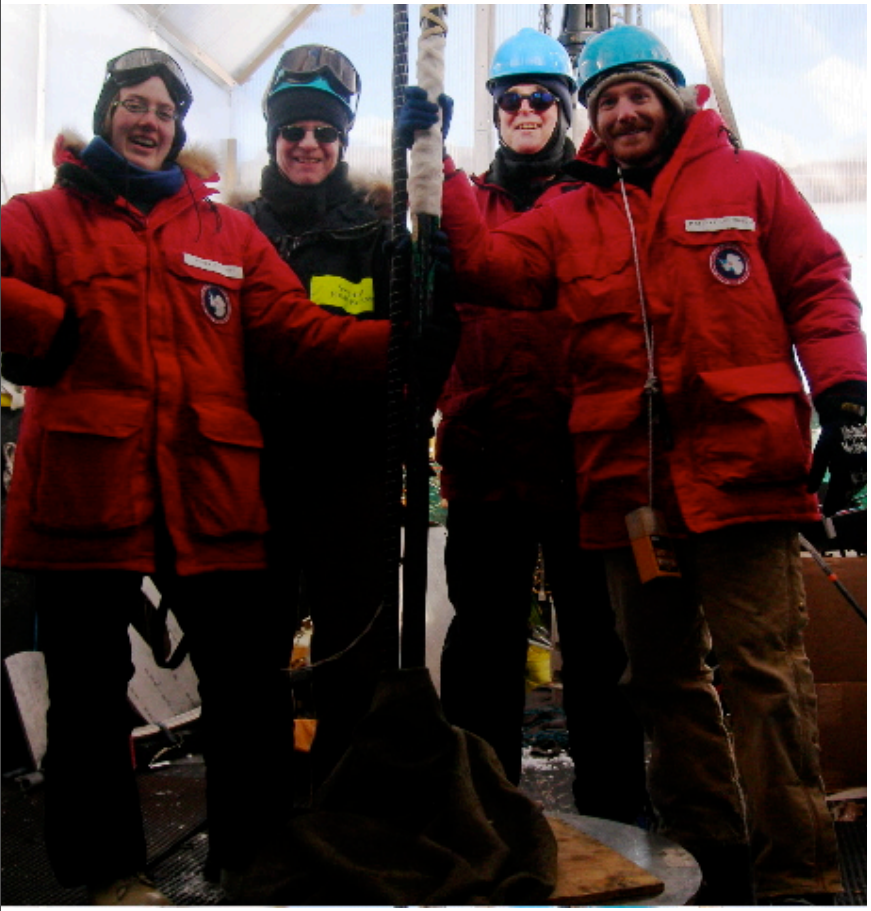
1 per string in Master PC: distribute PWR + timing + comm's



4 strings successfully deployed at Pole Jan. + Dec. 2007

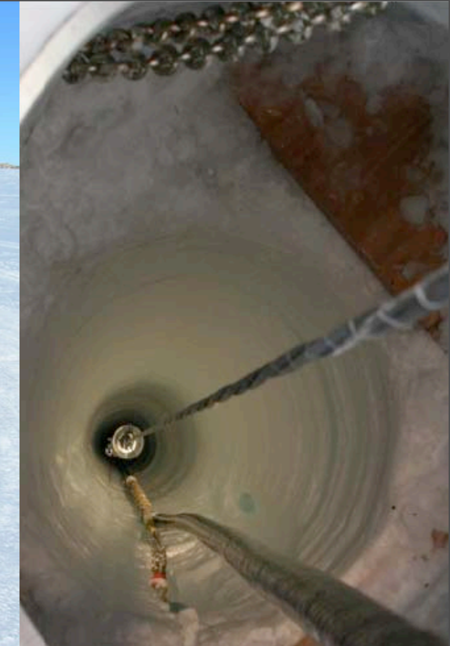
- SPATS B, hole 72, Jan. 11
- SPATS A, hole 78, Jan. 14
- SPATS C, hole 47, Jan. 22
- SPATS D, hole 68, Dec. 24

first hybrid optical/radio/acoustic string



Deployment preparation

Deployment

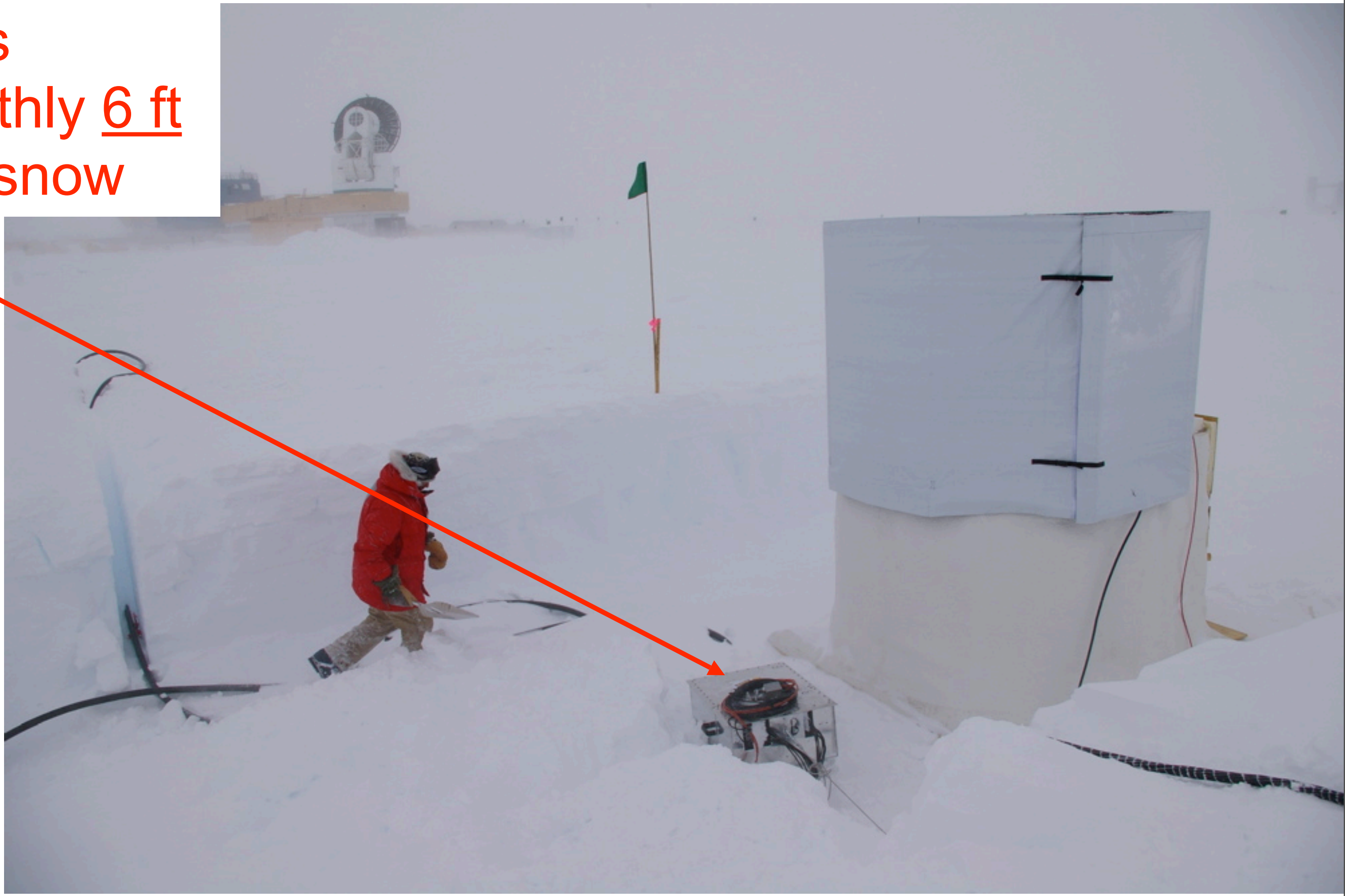



AED
AED

Commissioning and running

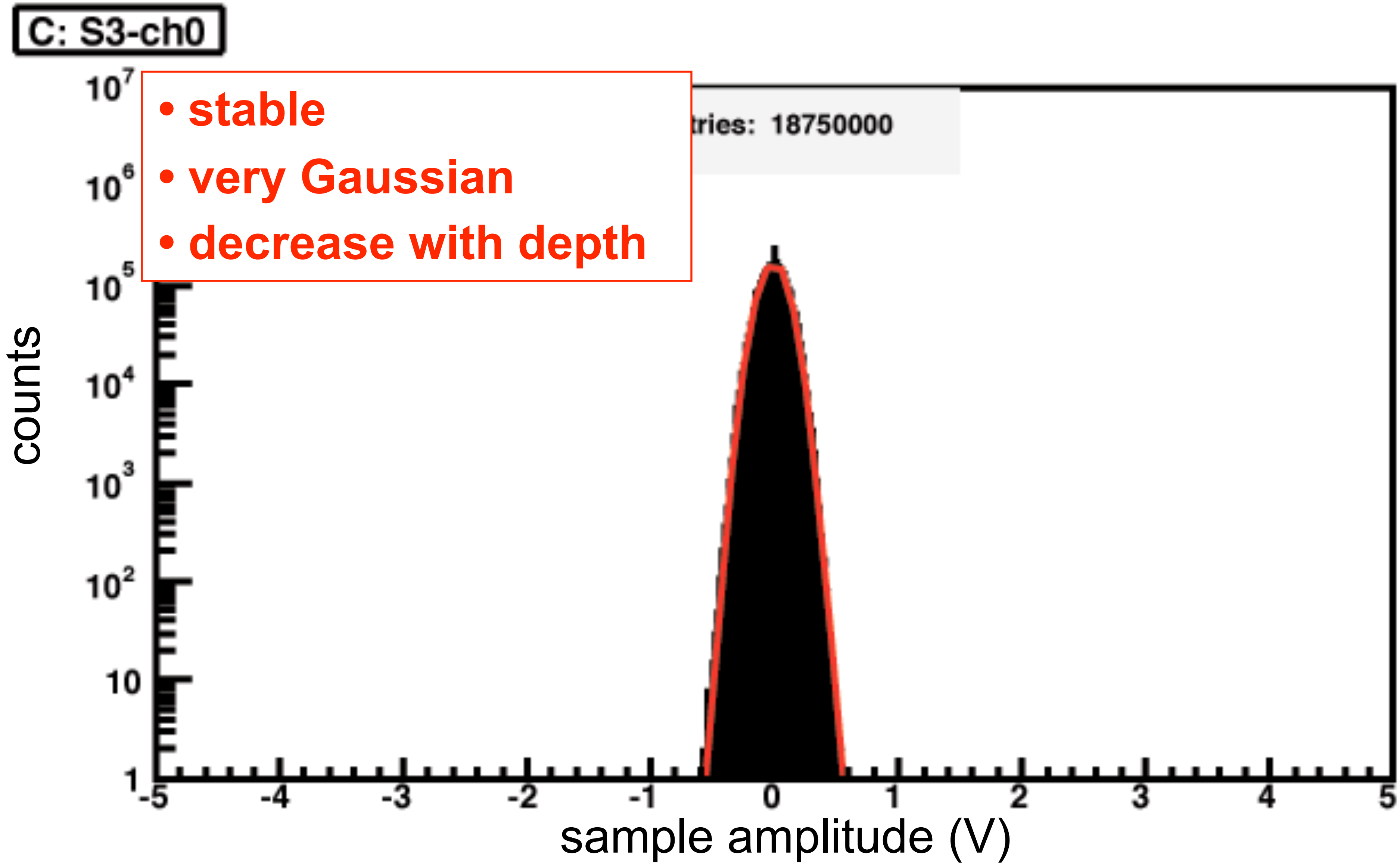
- All 28 transmitters working
- 72 of 80 sensor channels working normally
- Continuous running except a few power outages; recover fine

- 4 string-PC's running smoothly 6 ft under -50° C snow



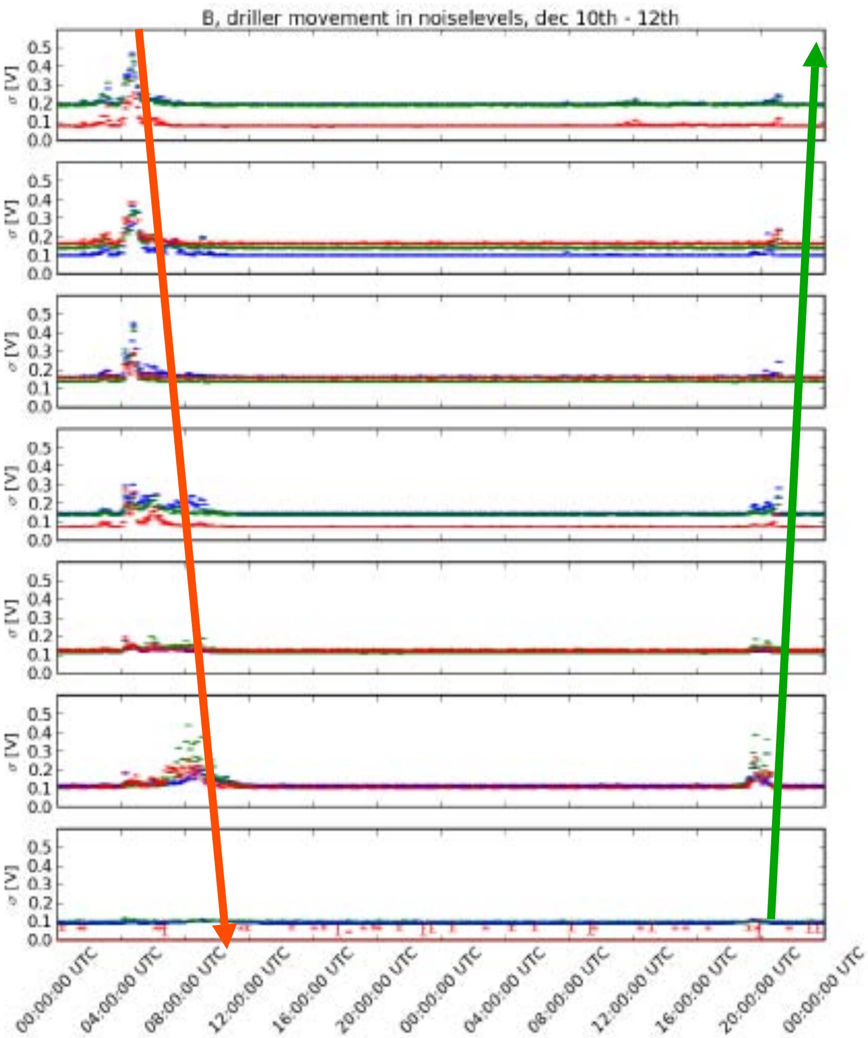
Part 7: Acoustic results from

Gaussian noise floor

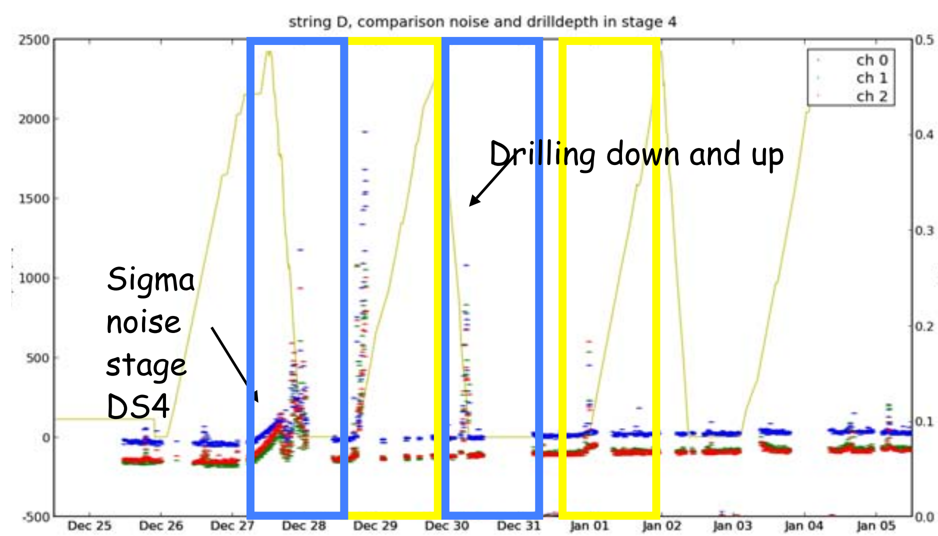


- stable
- very Gaussian
- decrease with depth

SPATS hears the IceCube drill!



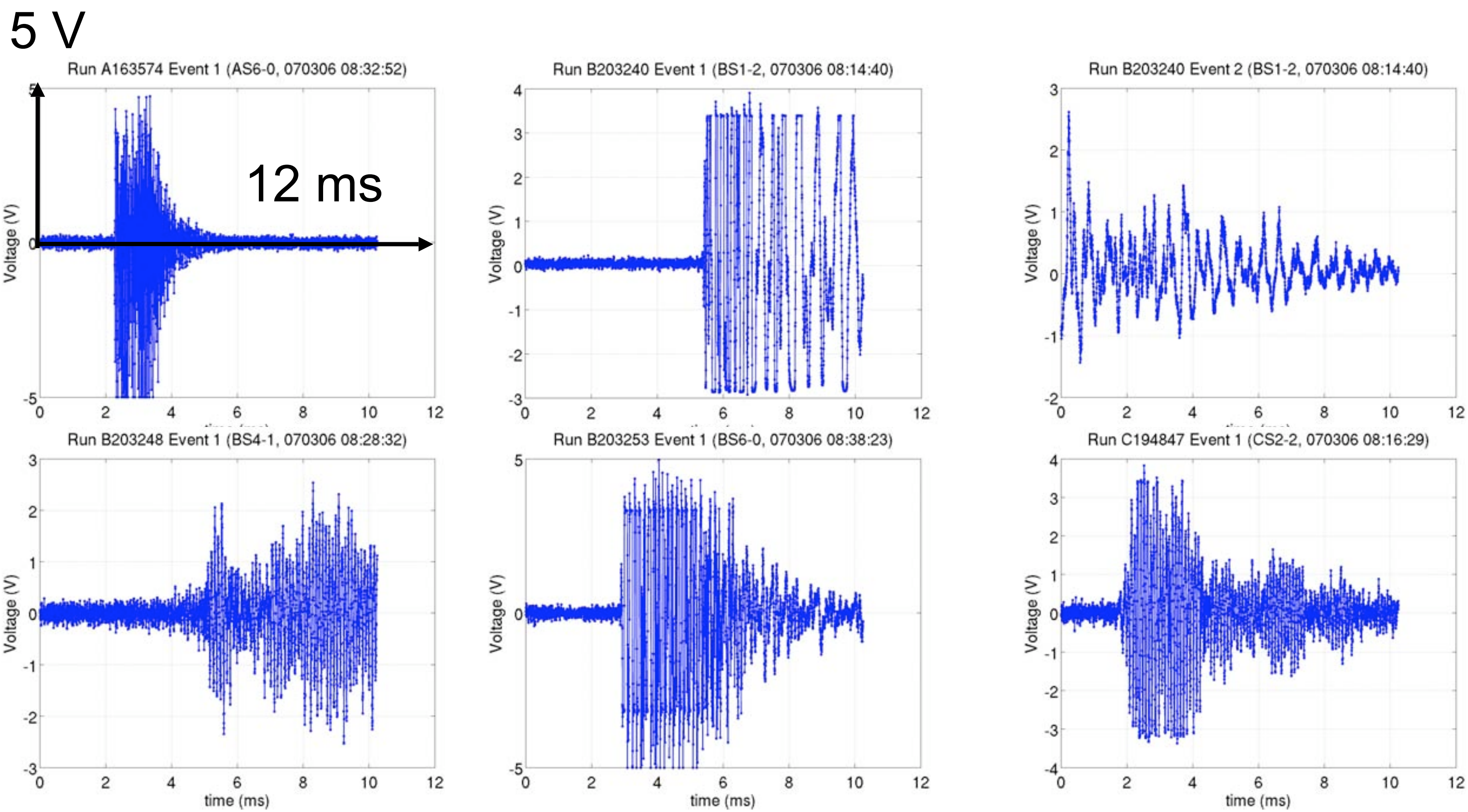
- SPATS running throughout 07/08 drilling season
- Drill in each hole heard
- On way down and up
- All instrumented distances (max 660 m)



Background transients

Rate: ~1/minute/channel

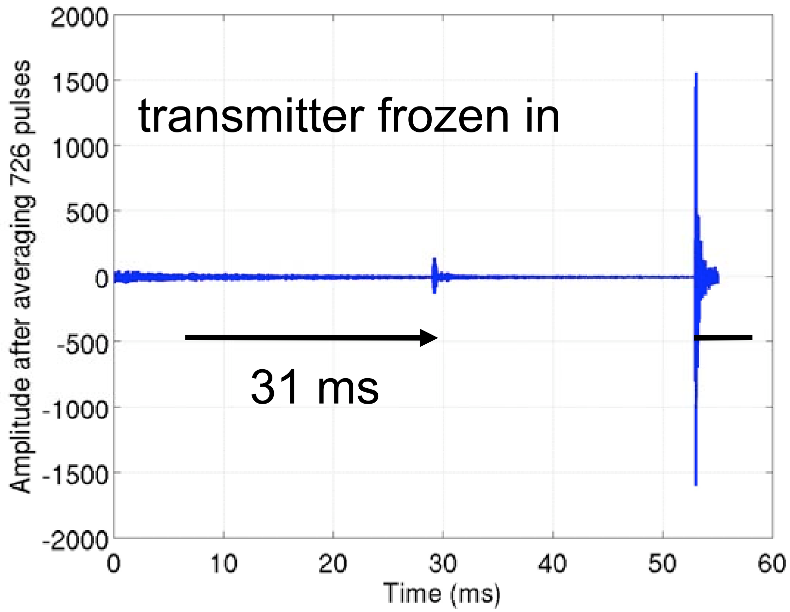
Loud examples:

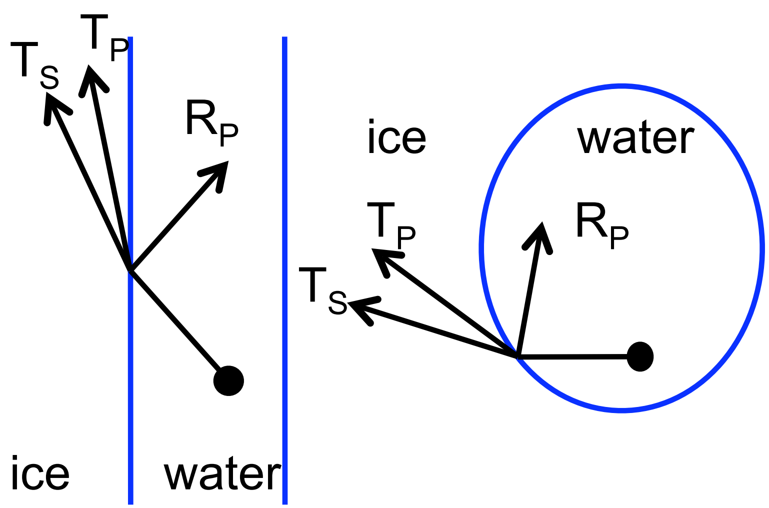


Discovery of shear waves

Mode conversion at interfaces: at larger incident angle, shear wave amplitude increases and P wave amplitude decreases

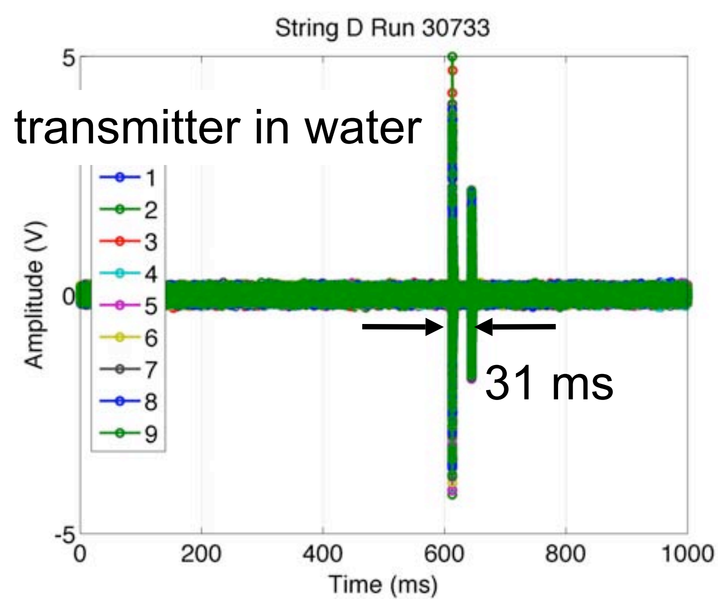
If neutrinos produce S waves: vertex distance; shower energy from one sensor!



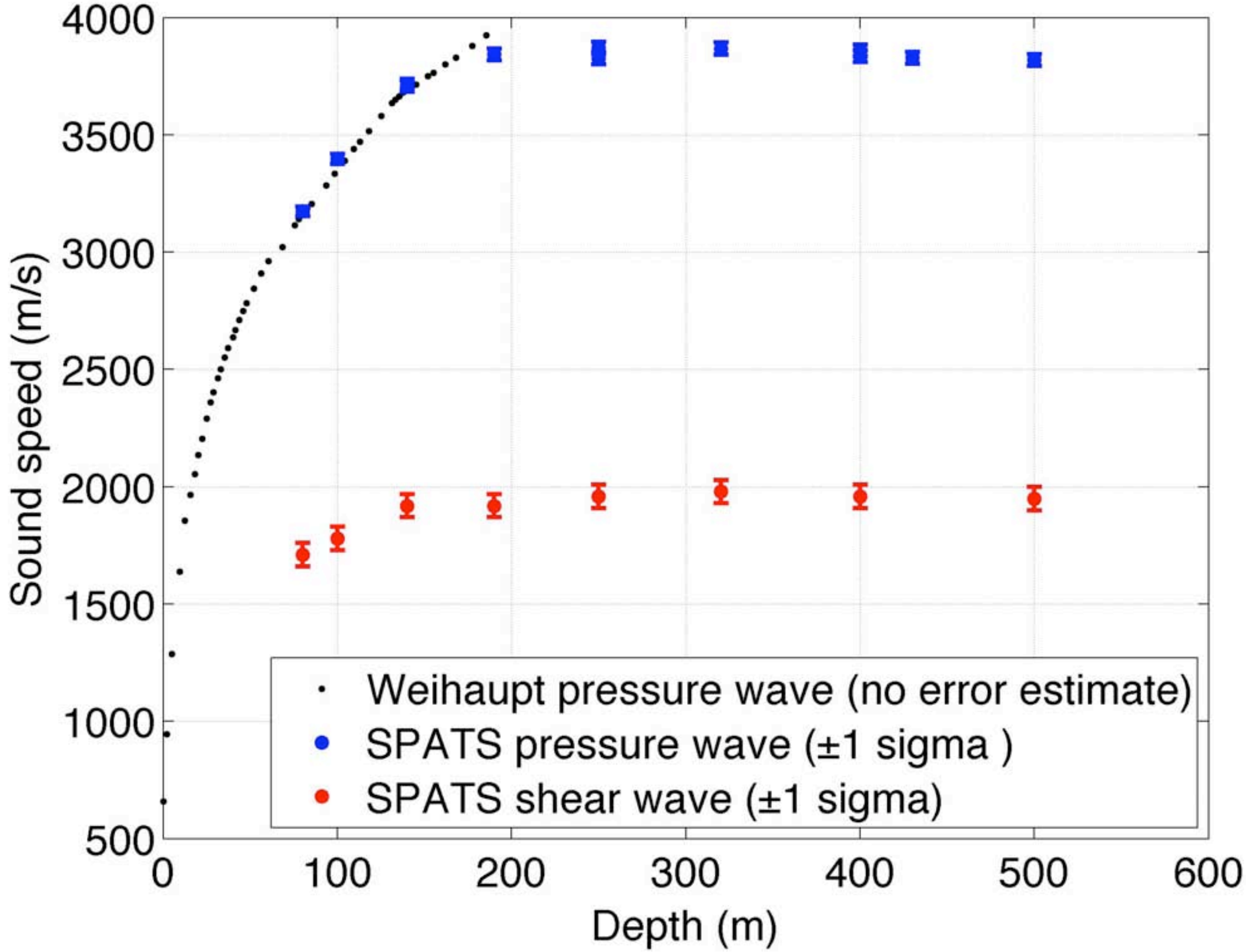


side view

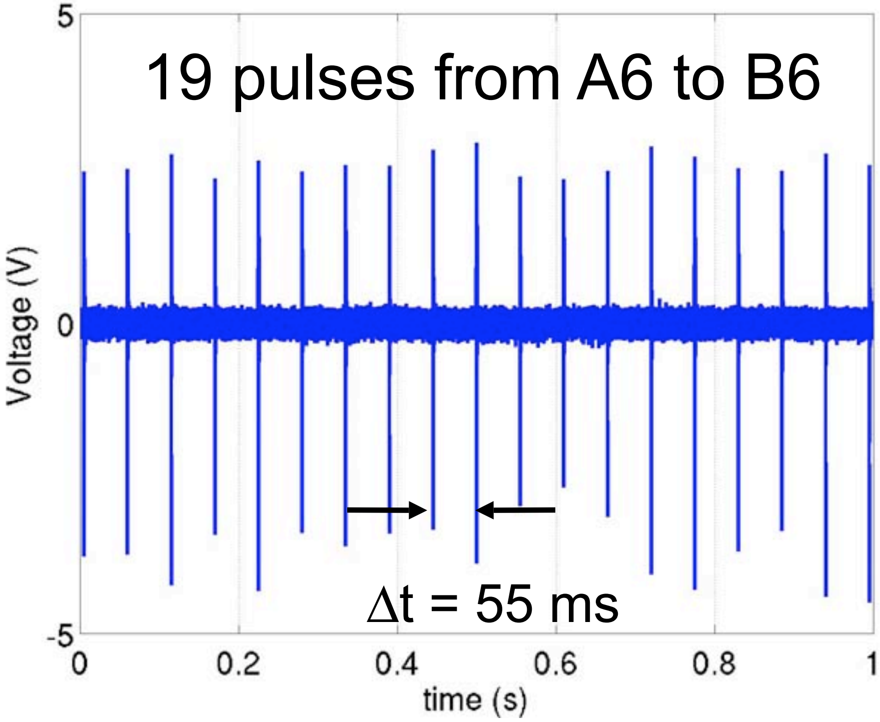
top view

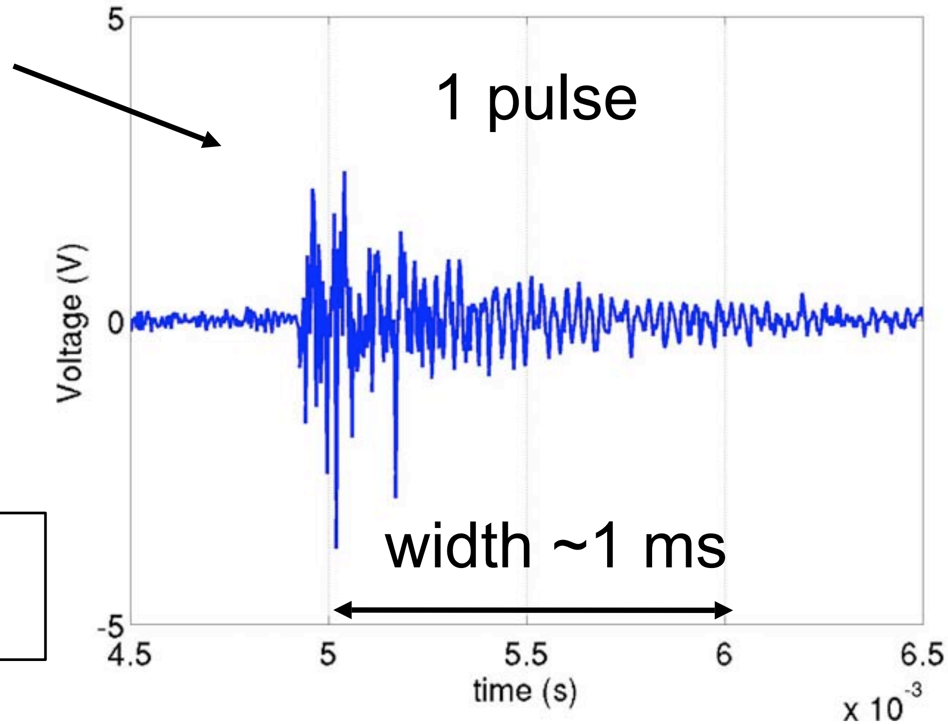


Measurement of pressure and shear wave speed vs. depth with SPATS + Pinger



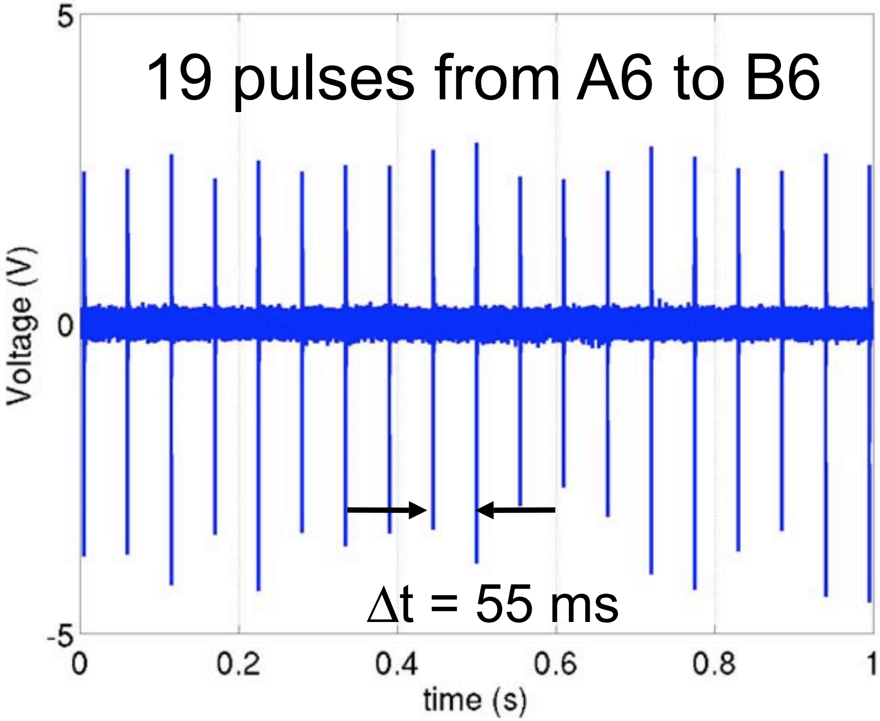
Inter-string transmitter pulses recorded through ≥125 m of South Pole ice

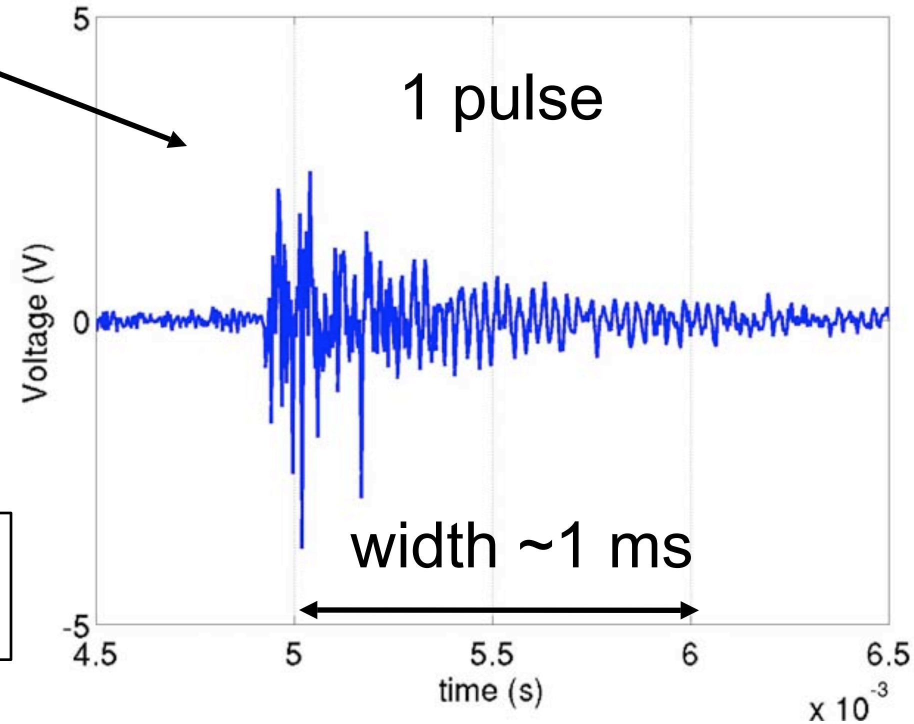




- signals detected from every string to every other string

Inter-string transmitter pulses recorded through ≥125 m of South Pole ice





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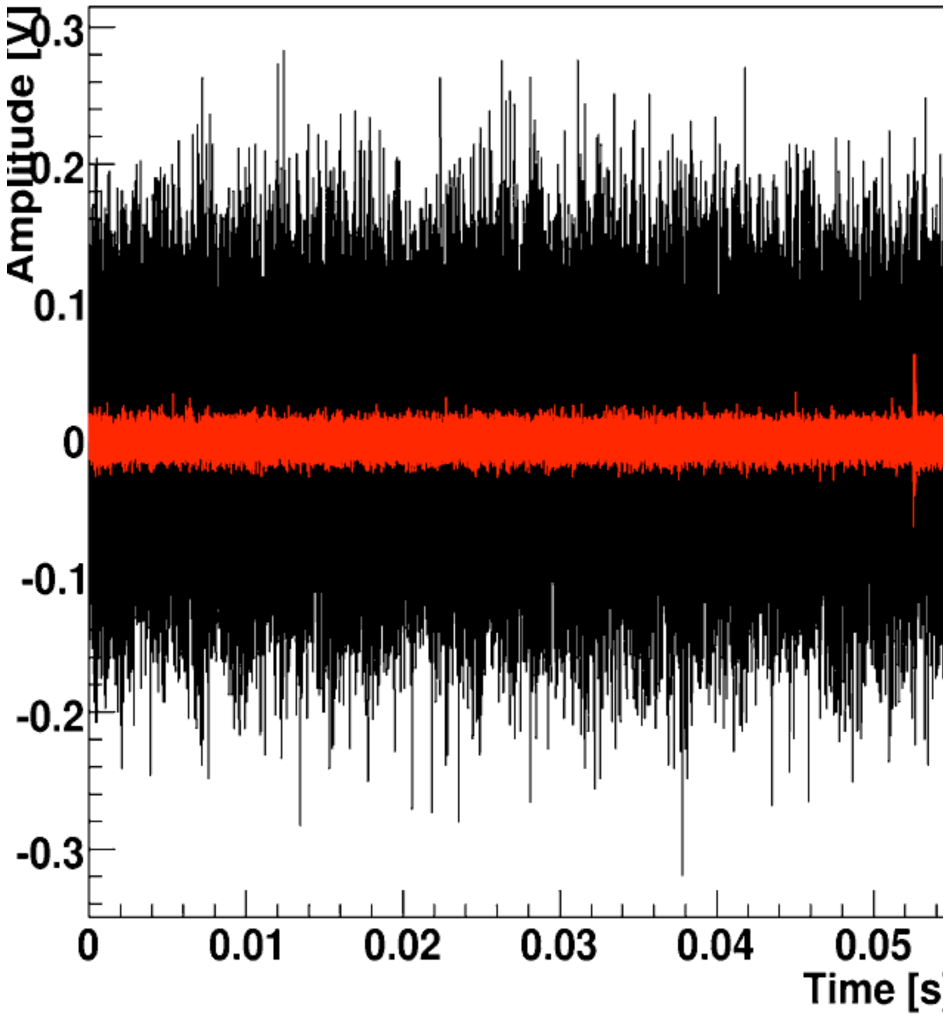
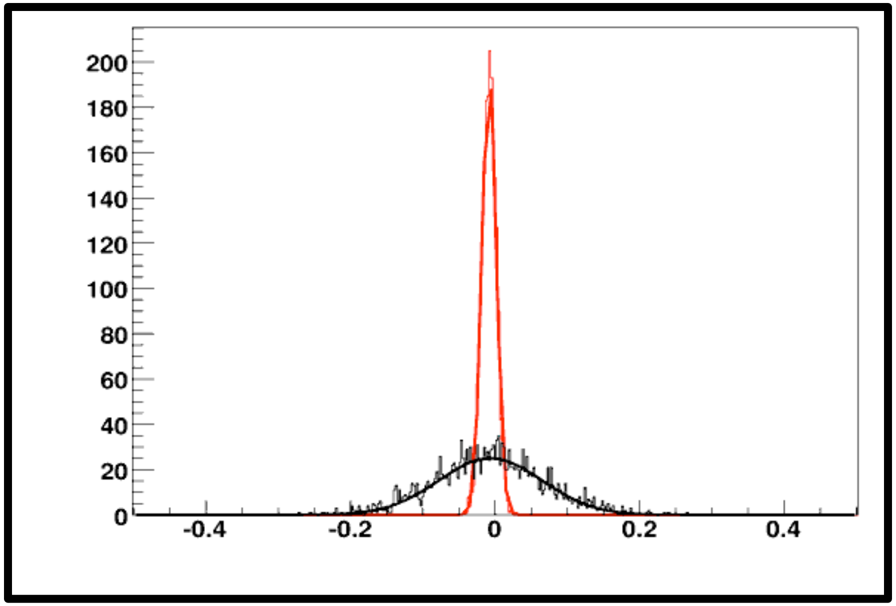
Inter-string transmitter pulses



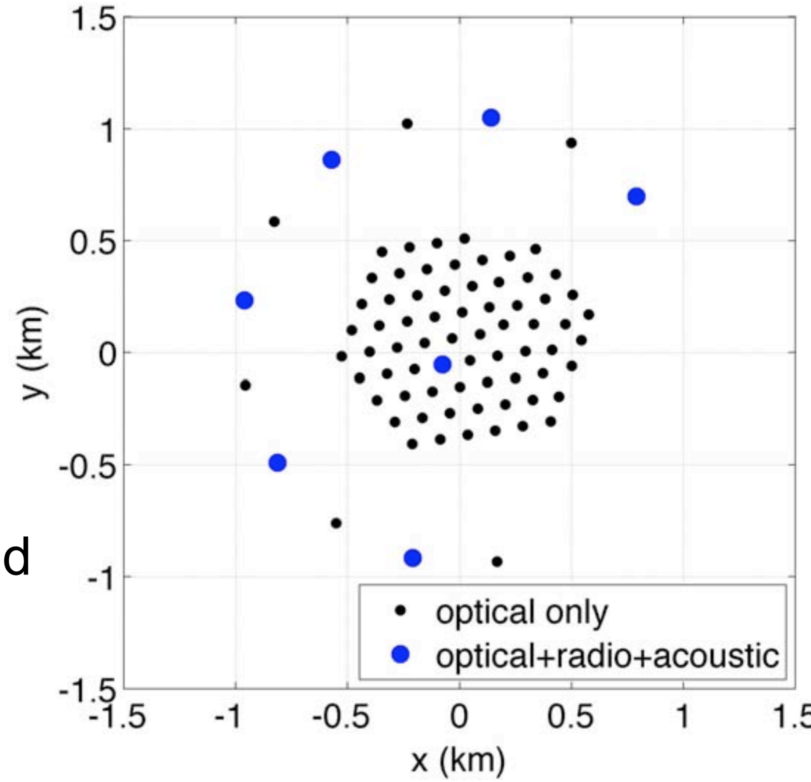
one pulse **average of 89 pulses**

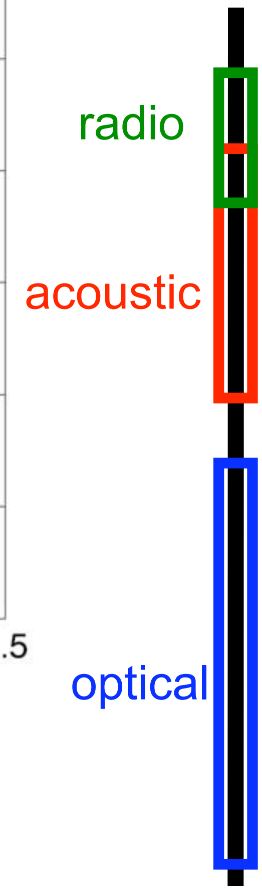
Can hear longest baseline:
DT4 to CS6 = 543m



IceCube high energy outer strings: an opportunity for hybrid (radio + acoustic) R&D (and hybrid ν!)

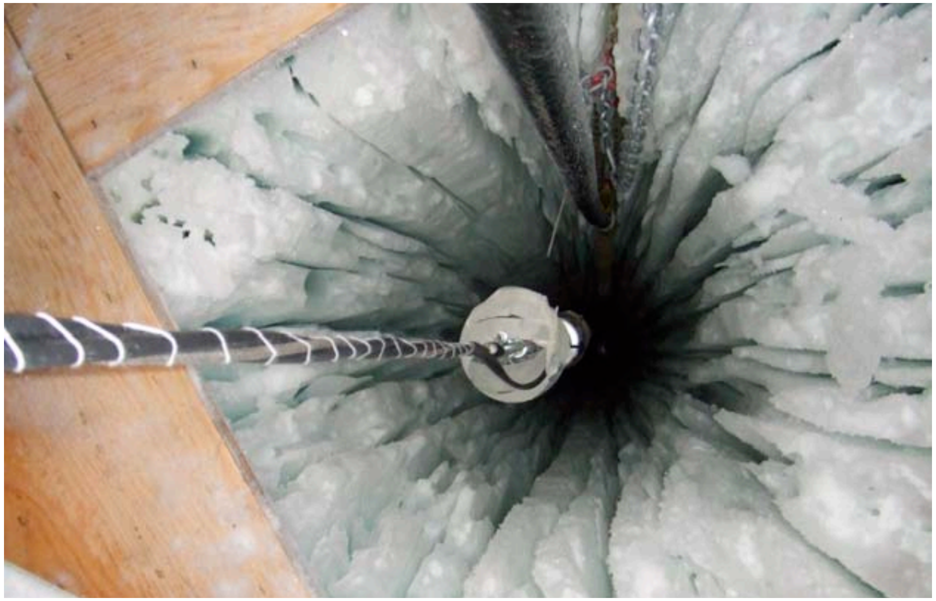
- Final strings of IceCube likely spaced to optimize ≥PeV response
- Radio and acoustic instrumentation could improve quantitatively and qualitatively
- An opportunity for both R&D and event detection
- Simulations underway
- Seeking interested collaborators!





Conclusions

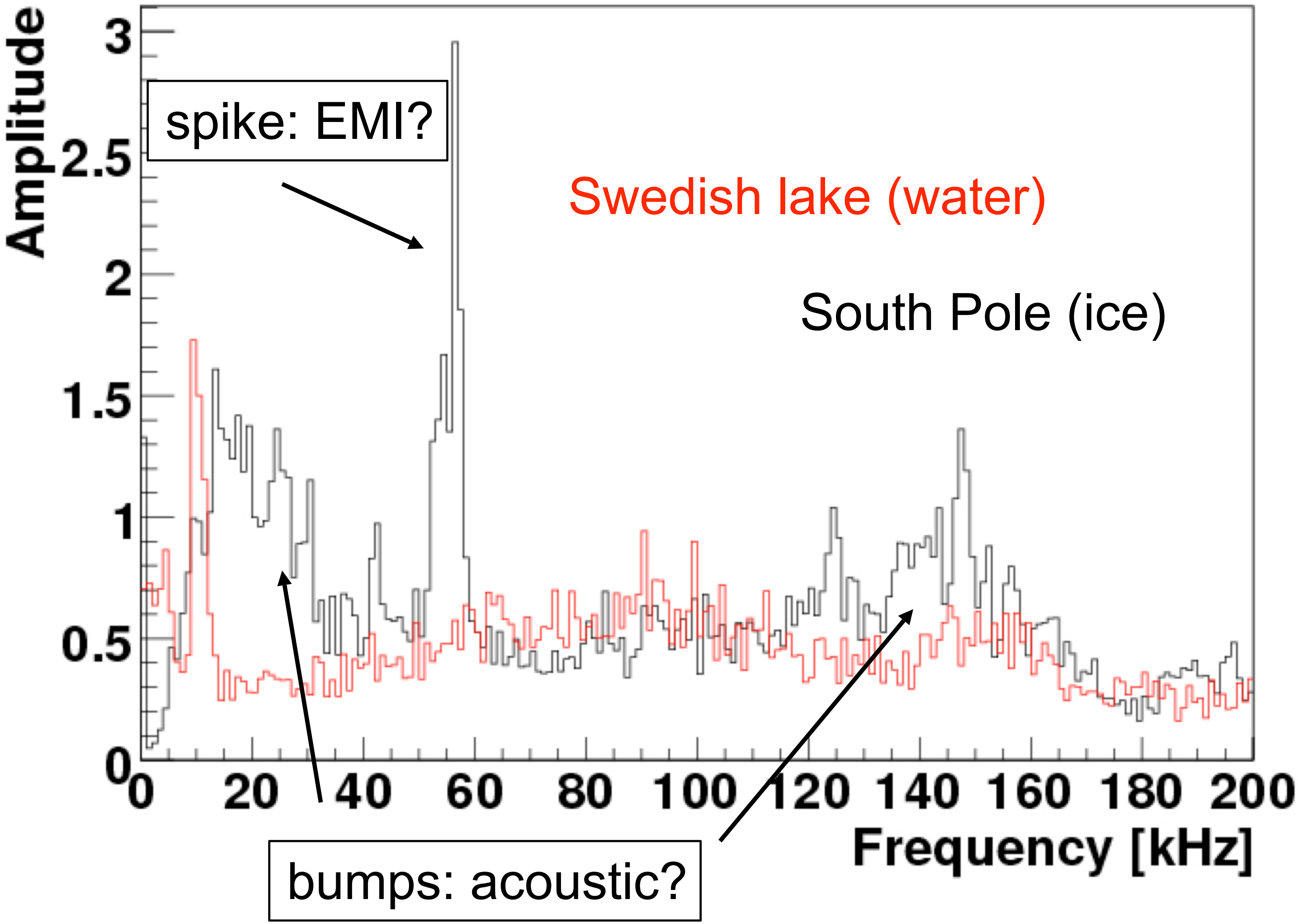
SAUND: **astro-ph/0406105**
Hybrid array: **astro-ph/0512604**
Review: **astro-ph/0611503**
SPATS: **arXiv:0708.2089**



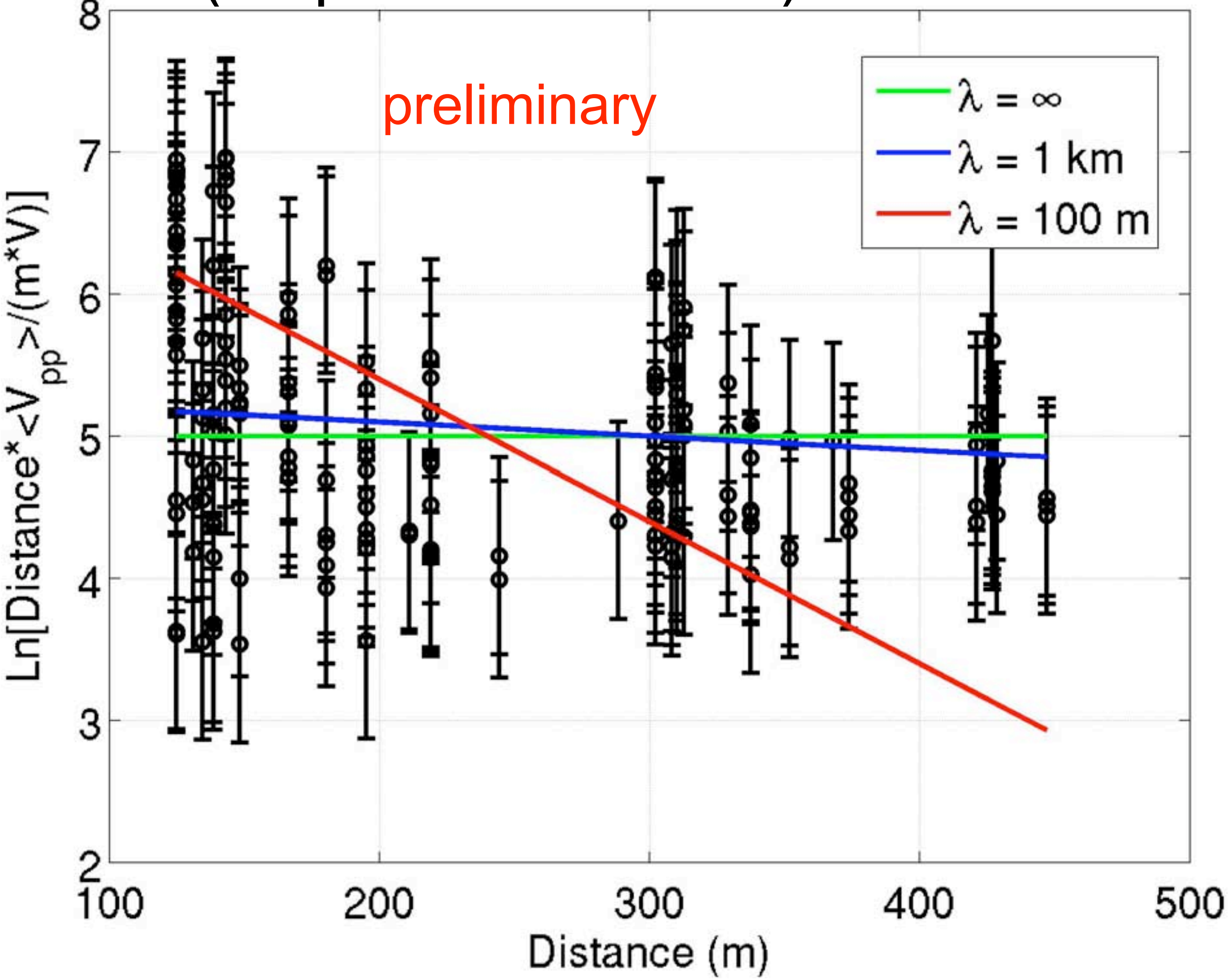
- EeV ν valuable for high energy physics and astronomy
- acoustic technique promising ~EeV
- projects underway in water, salt, and ice
- South Pole ice most promising
- SPATS installed in 2007 to determine feasibility in ice
- noise Gaussian and stable and decreases with depth; transients rare
- pressure and shear wave speed vs. depth measured
- attenuation analysis underway
- IceCube 1/2 constructed; 40 strings up and running
- future: a hybrid optical / radio / acoustic neutrino observatory at South Pole!

extra slides

Typical noise spectra



Attenuation analysis: work in progress
Ln(amplitude*distance) vs. distance



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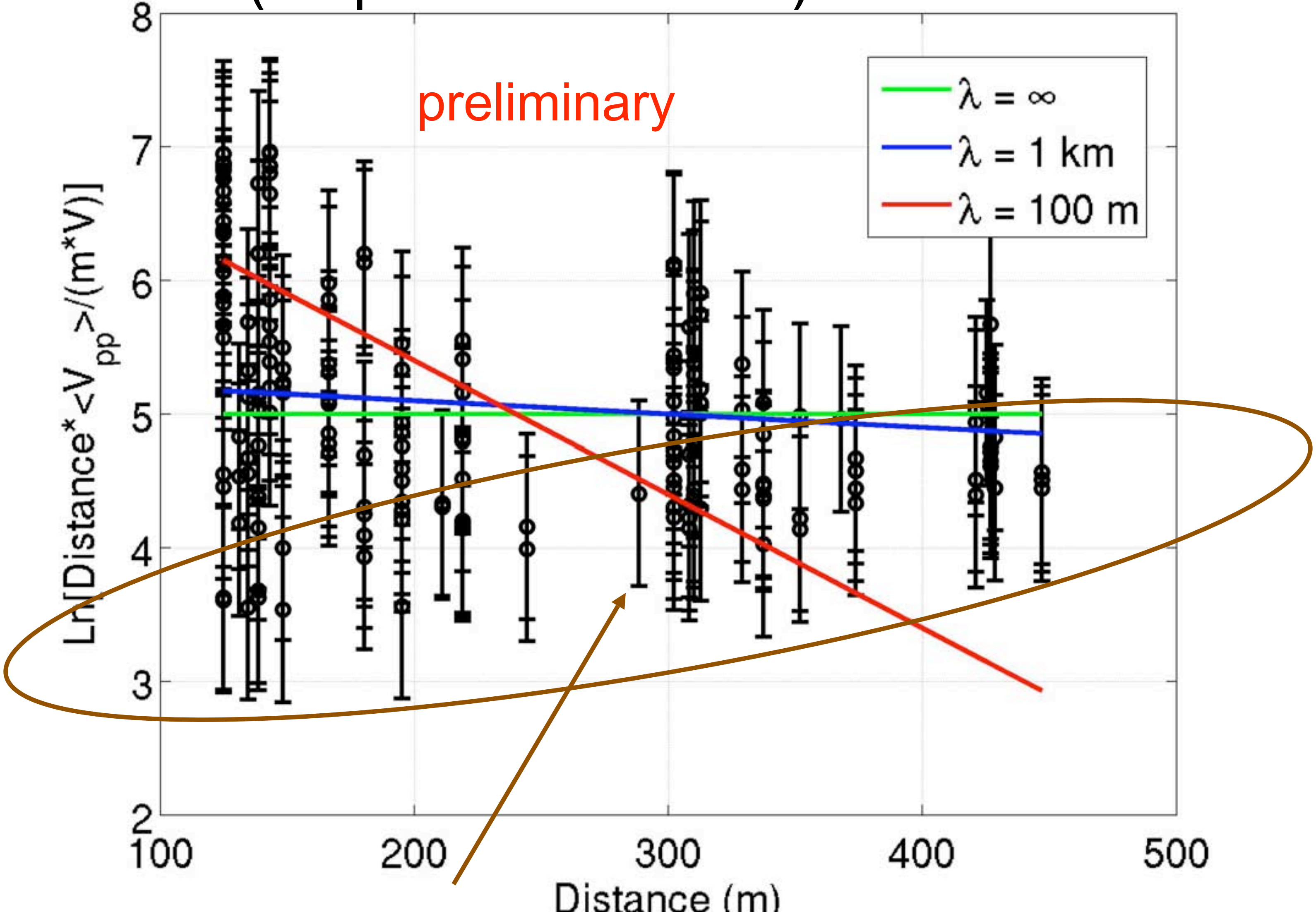

Missing many pairs in noise: overcome with pulse averaging

Hybrid event reconstruction

Acoustic, radio hits direct $\rightarrow$ easier than with highly scattered optical photons

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Acoustic and radio (or optical) hits can be combined:

$V_{sound} \sim 10^{-5}\, v_{light} \rightarrow T_{radio}$ or $T_{optical}$ gives acoustic emission time

Hybrid event reconstruction

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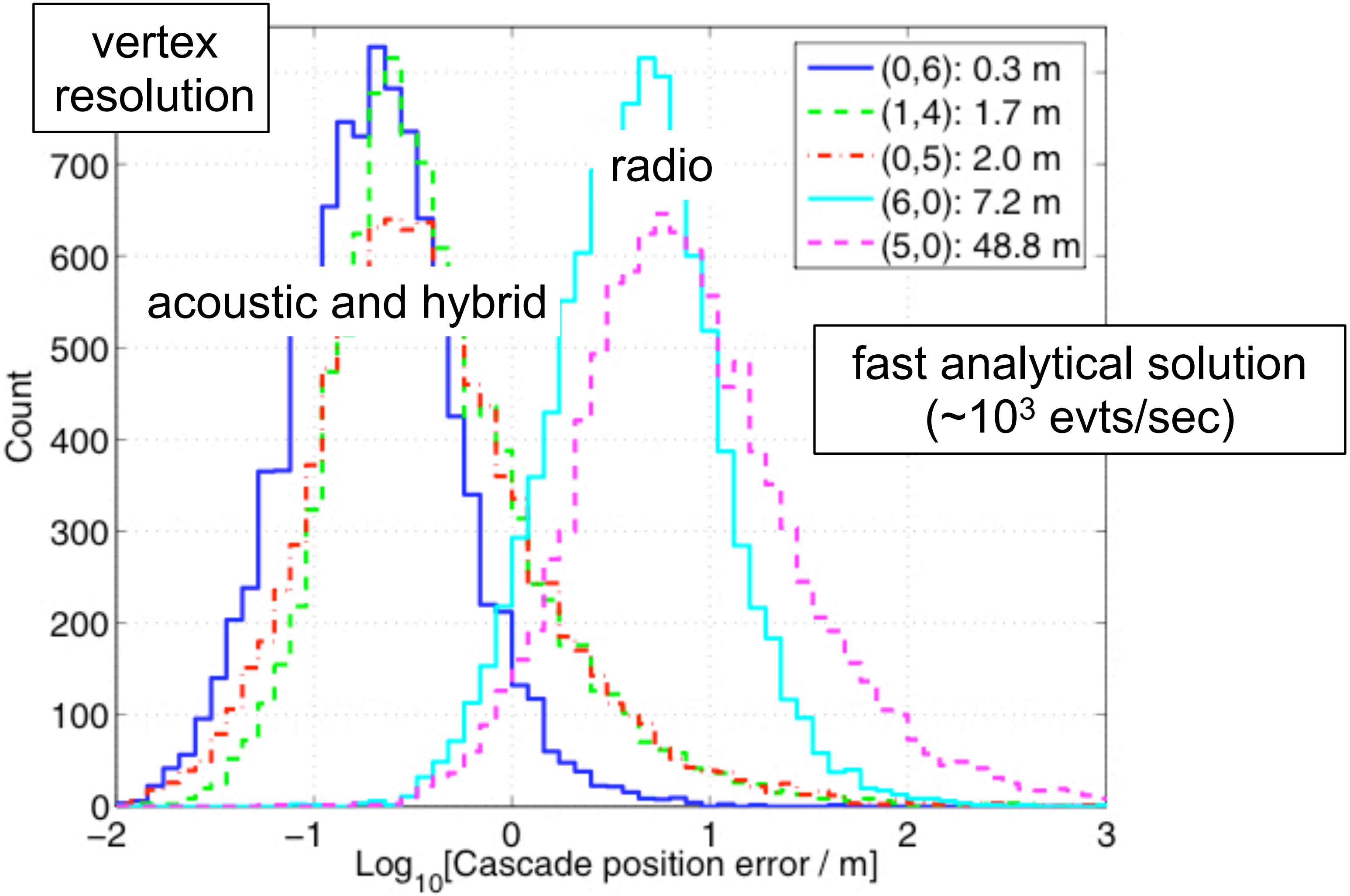
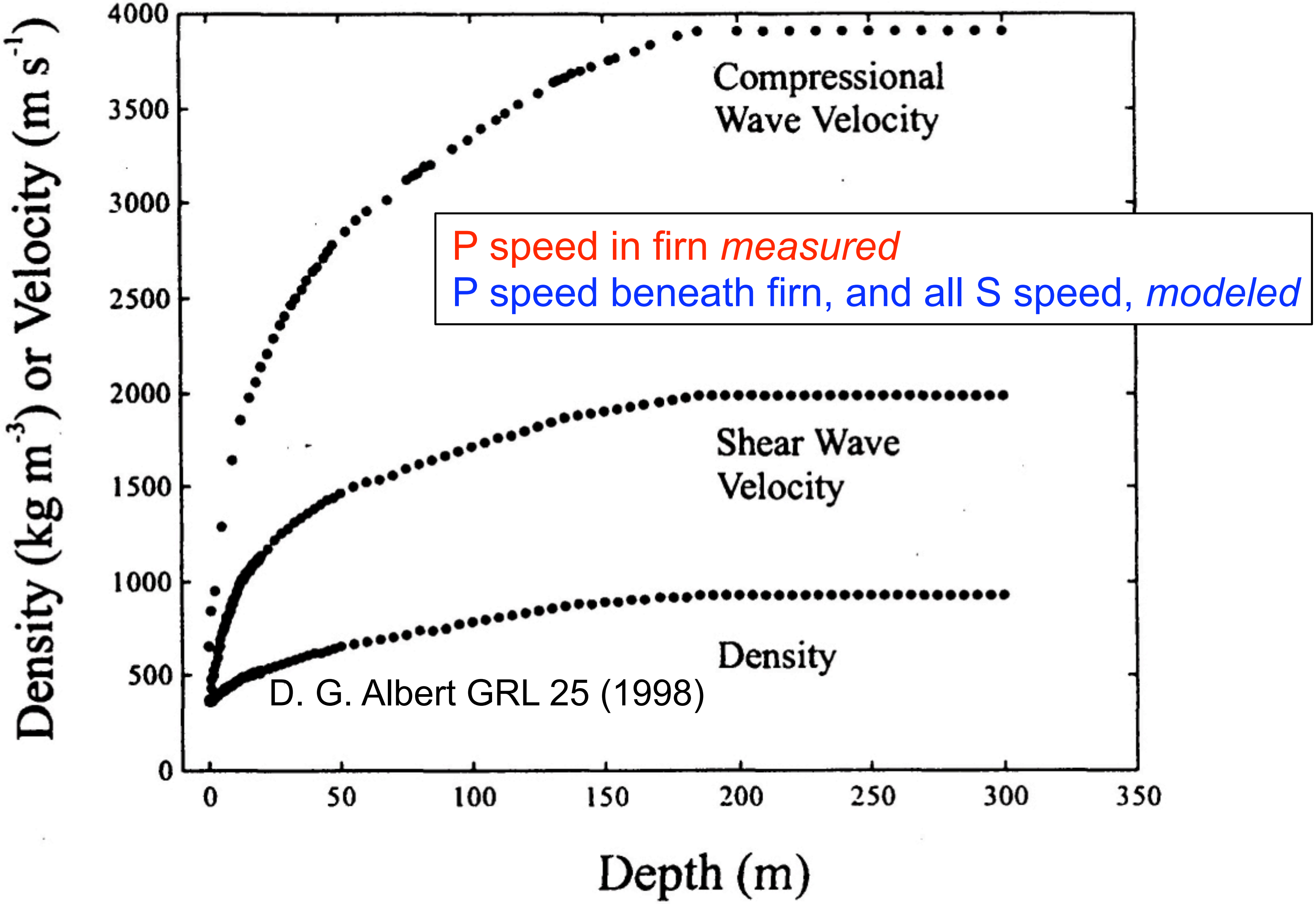


Previous sound speed work in literature

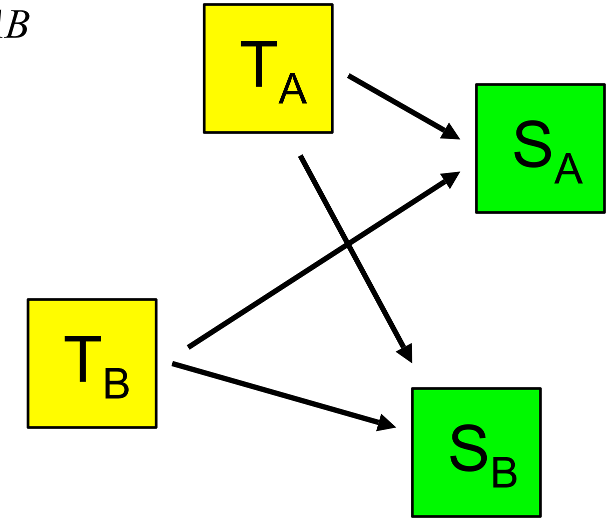


O(91) radio/acoustic strings for a fraction of the IceCube cost?

- **Holes**: ~3 times smaller in diameter (20 cm) and ~1.5 km deep
- Don LeBar (Ice Coring and Drilling Services) drilling estimate: $33k per km hole length after $400k drill upgrade to make it weatherproof and portable (cf. SalSA ~$600k/hole)
- **Sensors**: simpler than PMT's
- **Cables and DAQ**: Only ~5 radio channels per string (optical fiber). ~300 acoustic modules per string, *but*:
- Cable channel reduction: Send acoustic signals to local in-ice DAQ module (eg 16 sensor modules per DAQ module) which builds triggers and sends to surface
- Acoustic bandwidth and timing requirements are easy ($c_{sound} \sim 10^{-5} c_{light}$!)
- Acoustic data bandwidth per string = 0.1-1 Gbit, could fit on a single ethernet cable per string

Overcoming module to module variation with ratios

Model: $$A_{T_A S_B} = \frac{1}{d_{AB}} S_B T_A e^{-\alpha d_{AB}}$$

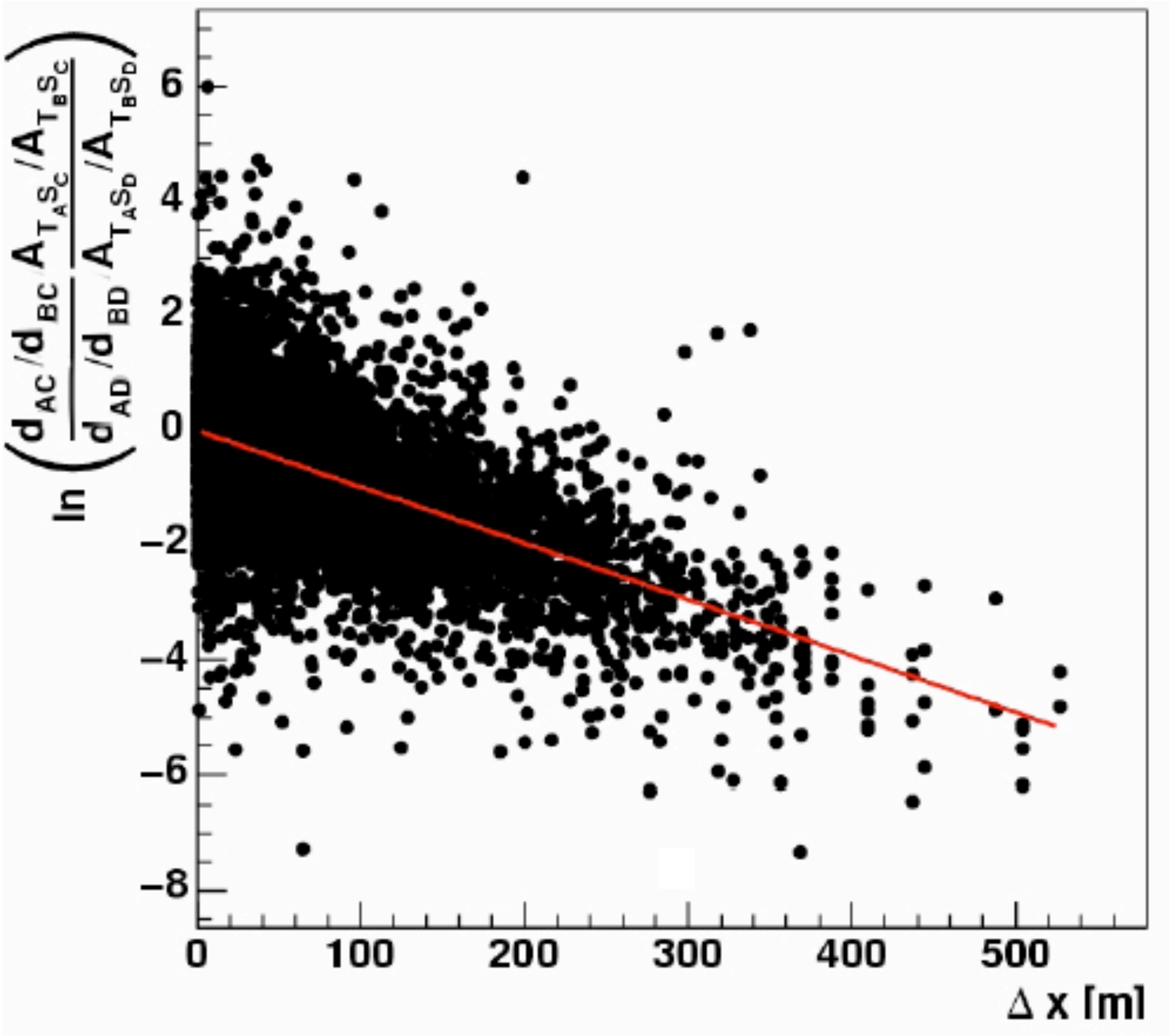


Assumes S, T independent of angle

2 T's + 2 S's → couplings divide out:

$$\frac{d_{AC}/d_{BC}}{d_{AD}/d_{BD}} \frac{A_{T_A S_C}/A_{T_B S_C}}{A_{T_A S_D}/A_{T_B S_D}} = e^{-\alpha((d_{AC}-d_{BC})-(d_{AD}-d_{BD}))} = e^{-x/\lambda}$$

One remaining unknown: λ



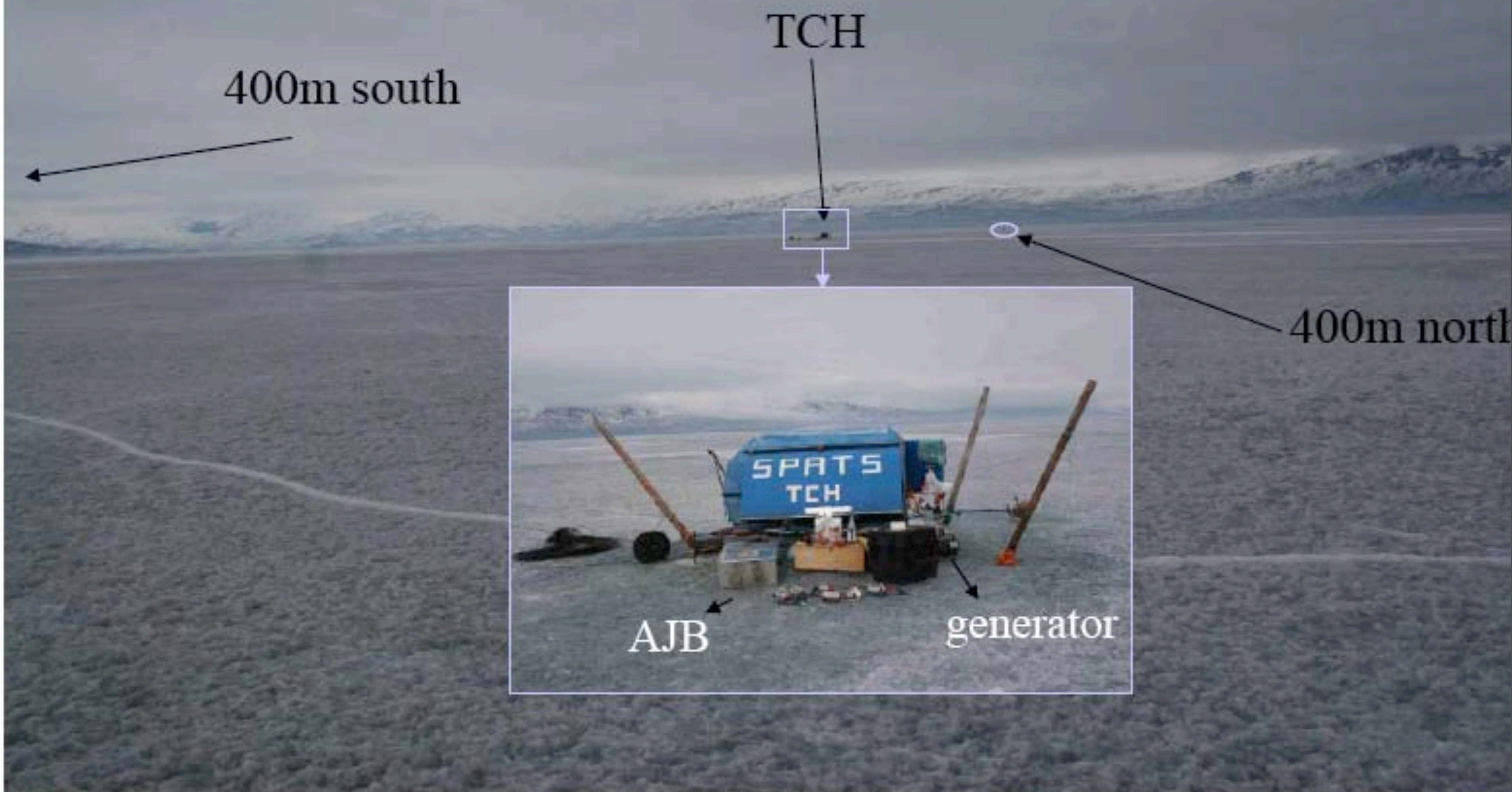
Ratio method (Monte Carlo)

Assume → measure λ = 100 m

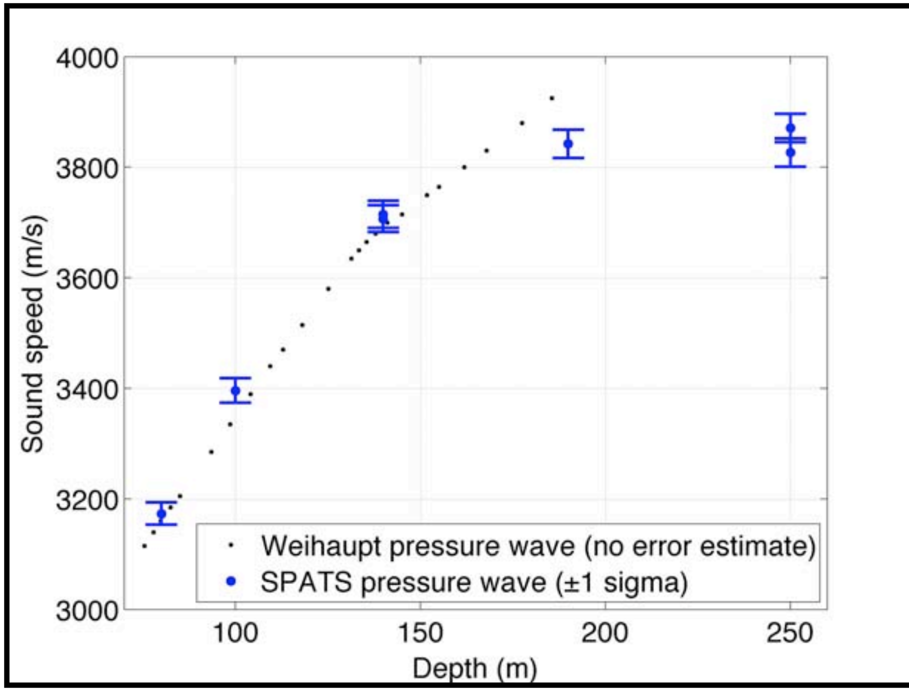
Treats angular variation (~40%) as uncorrelated variation in amplitudes

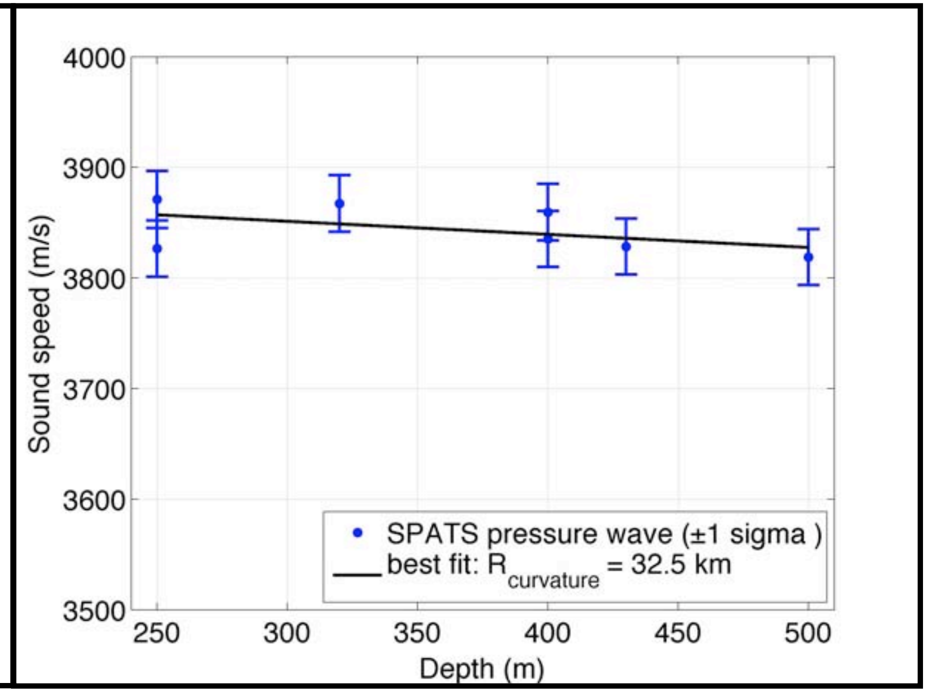
SPATS tested in frozen lake, Northern Sweden

100 km above Arctic Circle
April 2006



Close up of pressure wave speed results

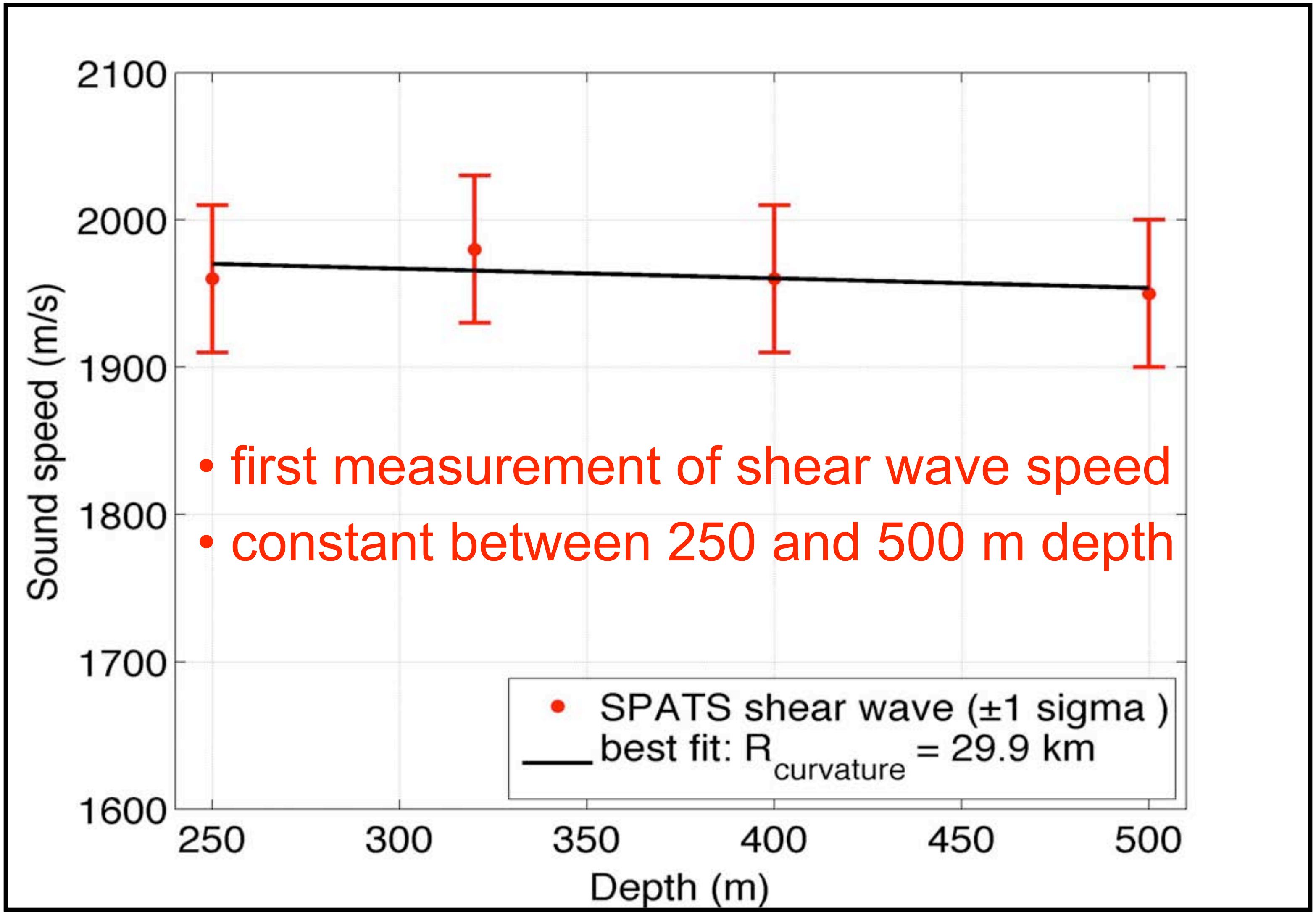




consistent with previous result in firn

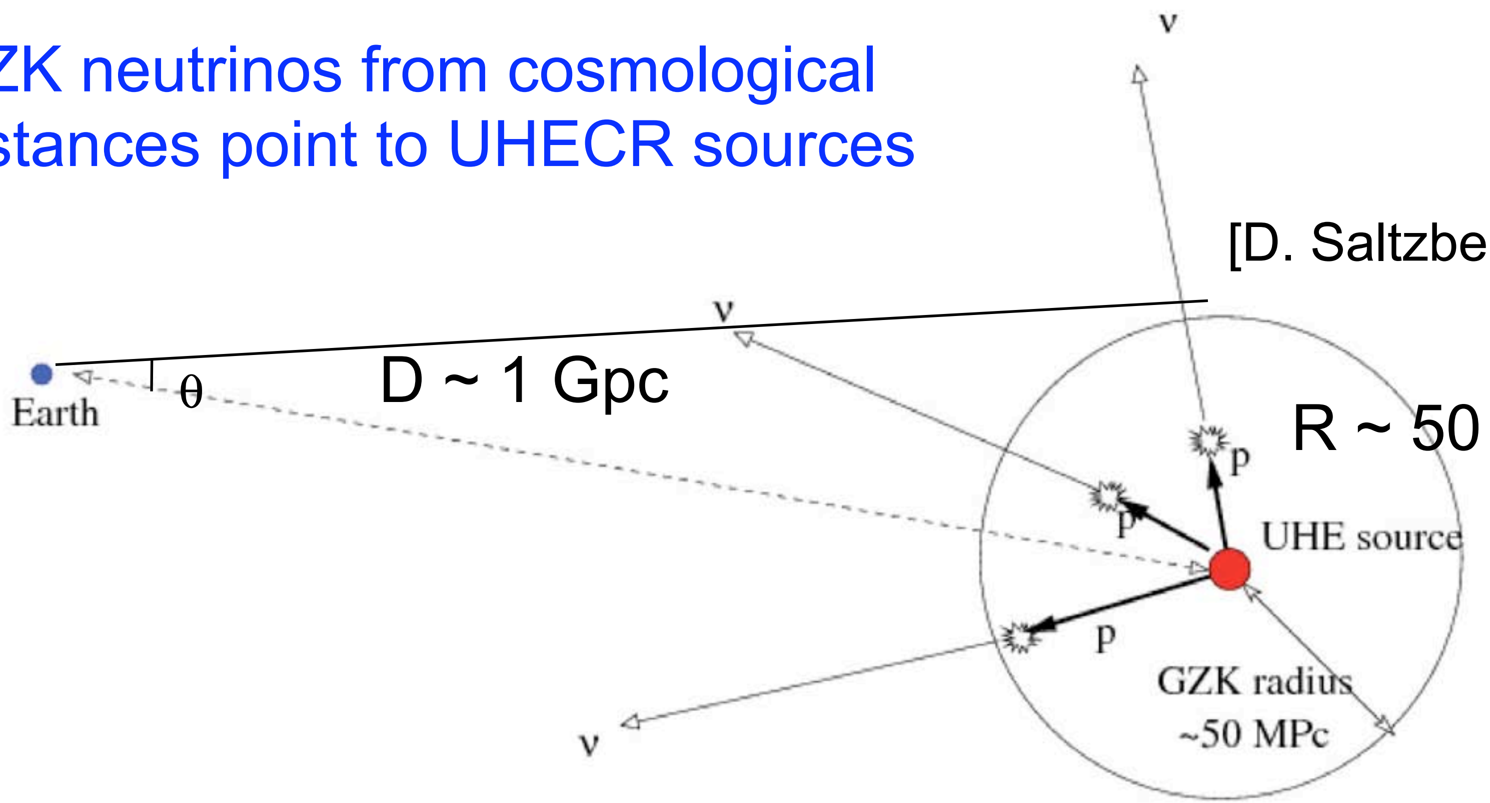
constant between 250 and 500 m depth

Close up of shear wave speed results



GZK ν point to UHECR sources

GZK neutrinos from cosmological distances point to UHECR sources



“GZK sphere”
of arbitrary B deflection/diffusion

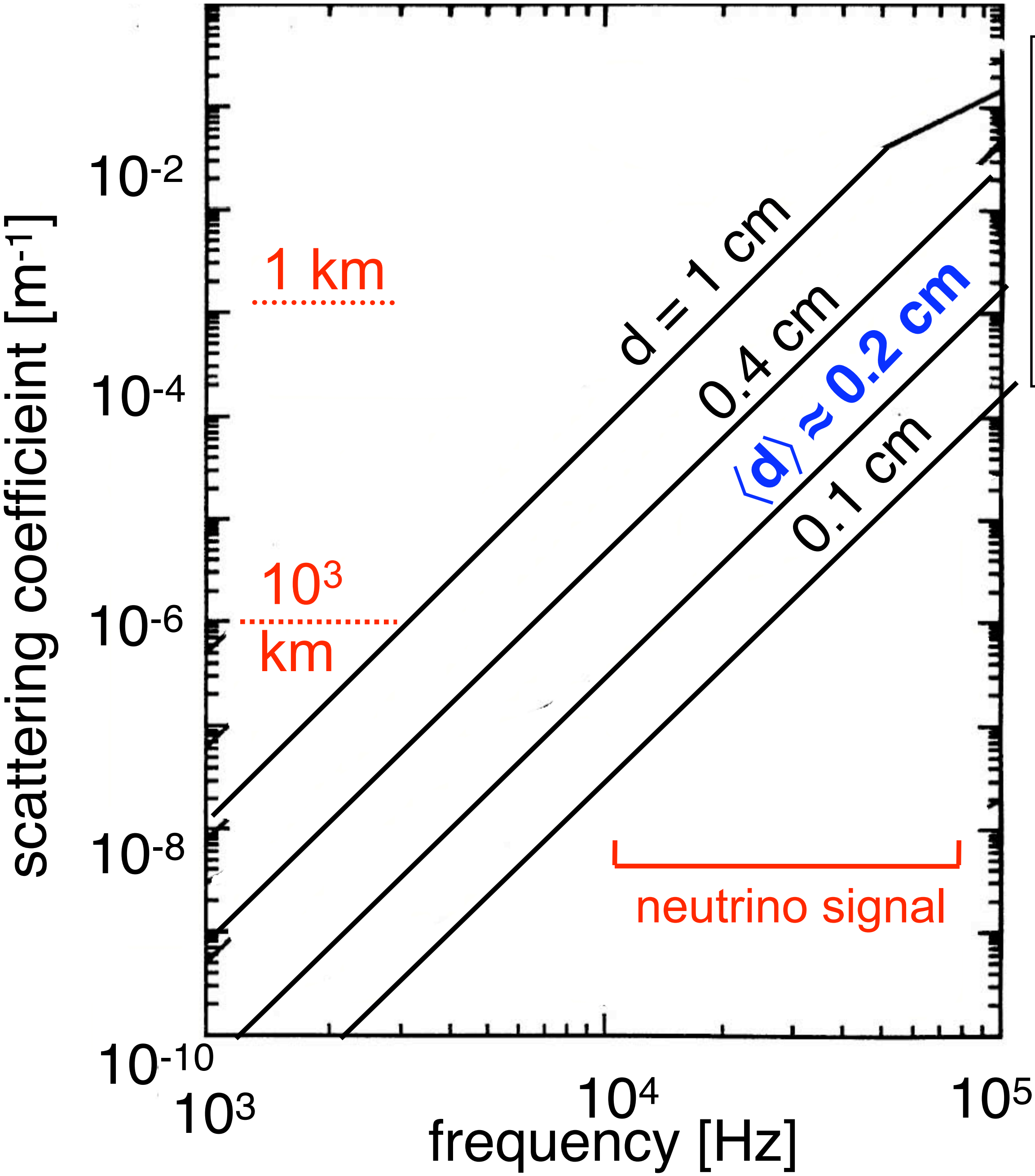
$\theta \sim R/D \sim 3°$





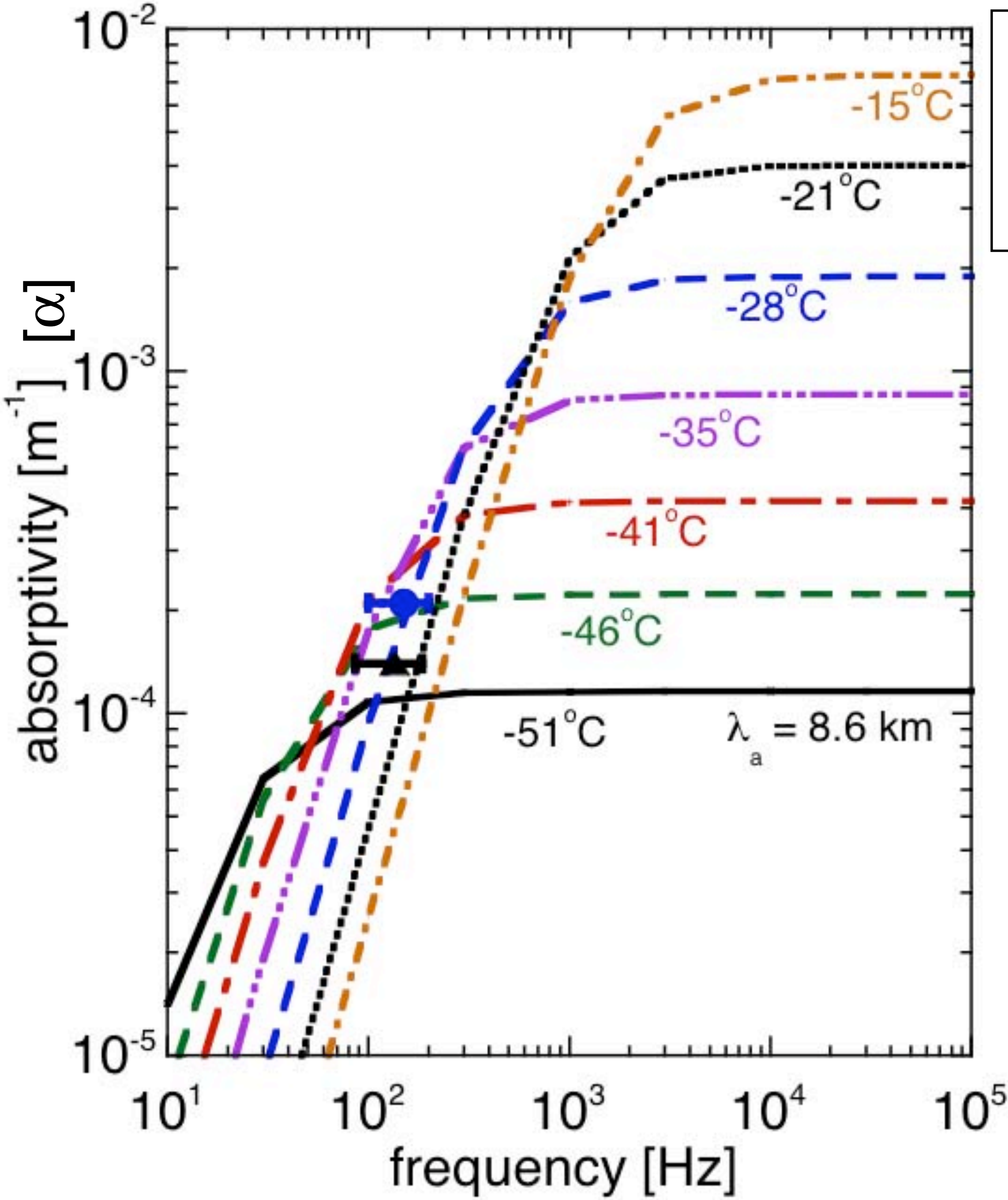

Attenuation (1)

Scattering: Rayleigh off ice grains



$\lambda_{scat} > 10^3$ km

Attenuation (2)
Absorption: by thermal phonons



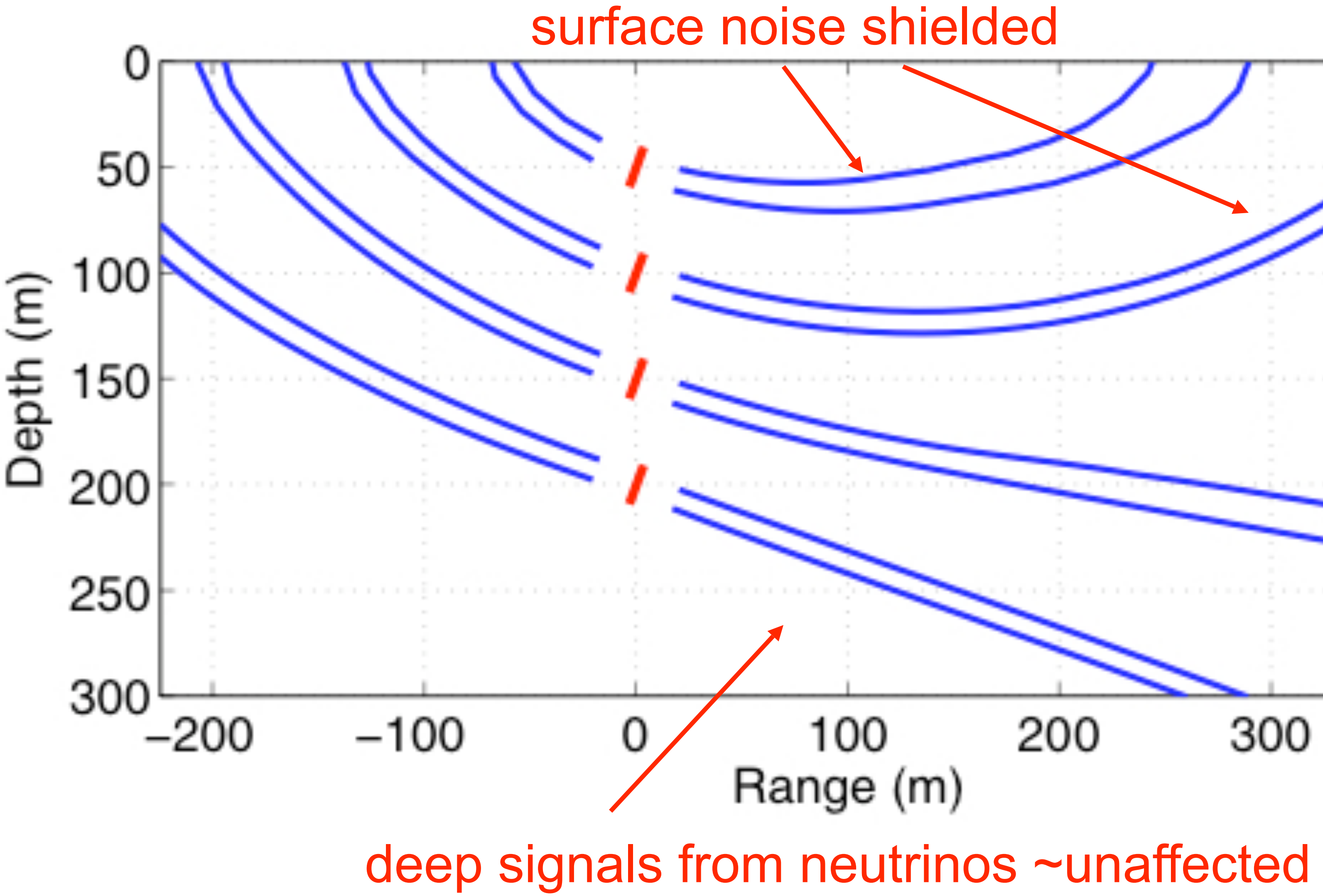
theoretical model fits lab data *(P. B. Price GRL 2006)*

$$\alpha \propto \frac{f^2 e^{U/kT}}{1+(f/f_0)^2 e^{2U/kT}}$$

λ_{abs} ~ few km

to be measured *in situ*

Refracted ray paths



Ultra-high energy cosmic rays, gamma rays, and neutrinos

3 legs to stand on
to reach the highest energy particle physics and astrophysics

Cosmic particles have been detected well above 10^{18} eV (UHECR). What are they and where are they from?

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Bottom-up models
active galactic nuclei
gamma ray bursts
galaxy clusters
magnetars

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Top-down/exotic models
- topological defects
- GUT scale relics
- Lorentz invariance violation
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The answer will lie in
spatial, temporal, and spectral distributions of our 3 legs

At high energy and distance, ν leg strongest
(gammas attenuated, protons attenuated and deflected)

String PC Connected in Acoustic Junction Box

Standard Candle II event seen on 22 strings