united nations educational, scientific and cultural organization
international atomic energy agency

the
abdus salam
international centre for theoretical physics

ICTP 40th Anniversary

H4.SMR/1574-16

"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Detectors and Data Aquisition

D. Cowen

Pennsylvania State University
U.S.A.

Detectors and Data Acquisition in Non-accelerator astroparticle physics

- Please pick up a free copy of a book on PMTs kindly sent to us by Photonis (a PMT manufacturer in France). This book is yours to keep.

Detectors and Data Acquisition in Non-accelerator astroparticle physics

- Non-accelerator astroparticle physics experiments exhibit <u>tremendous</u> variation
  - Sizes: centimeters to kilometers
  - Locations: ocean, ice, balloons, satellite, plain old labs, deep underground labs…
  - Astronomical messengers: photons, neutrinos, protons, gravitons, WIMPs…
  - Energies: keV – ZeV

Outline

- First, we'll focus on the similarities & common threads in particle astrophysics experiments
  - These similarities are significant and make it reasonably easy for experimental particle astrophysicists to move between experiments
- Then, we'll focus on the differences, of which there are many
  - The variety and striking contrasts are indicative of the creativity and intellectual ferment driving this exciting & relatively new field

Similarities

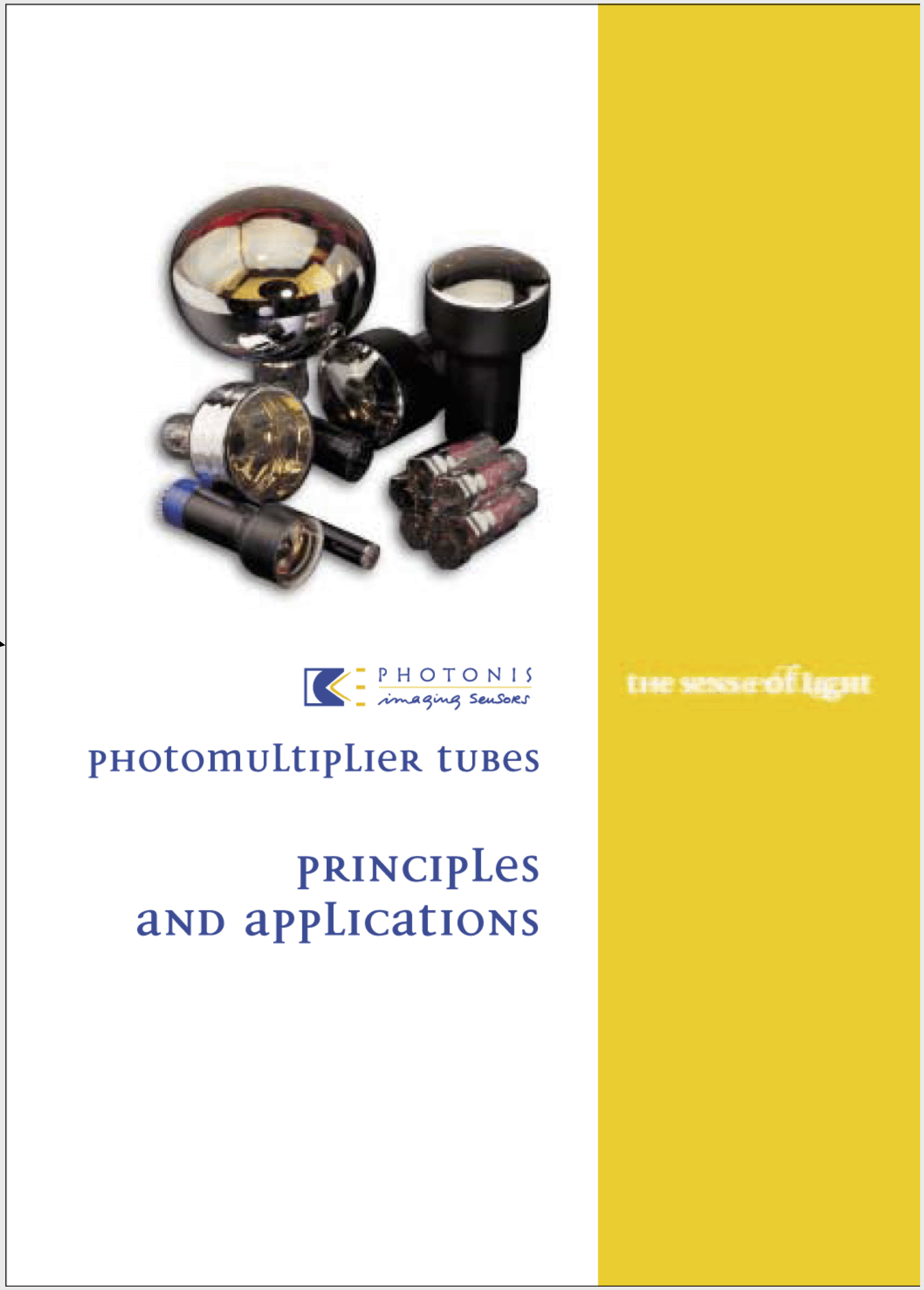
- Many use photomultiplier tubes (PMTs) to detect Cherenkov light
- Many use custom ASICs (application specific integrated circuits) in their data acquisition systems
- Most have low data rates compared to accelerator-based HEP experiments
- Many are very sensitive to backgrounds
- Many instrument large volumes
- Many use neutrinos as astronomical messengers

Focus First on Similarities: PMTs

- Photomultiplier tubes (PMTs)
  - "A lightbulb run in reverse." -F. Halzen (Theorist, but now head of a large neutrino telescope experiment.)
    - Lightbulb: electrons go in, light comes out
    - PMT: photons go in, electrons come out
  - Of course, as theorists like to say, this is only "an approximation"

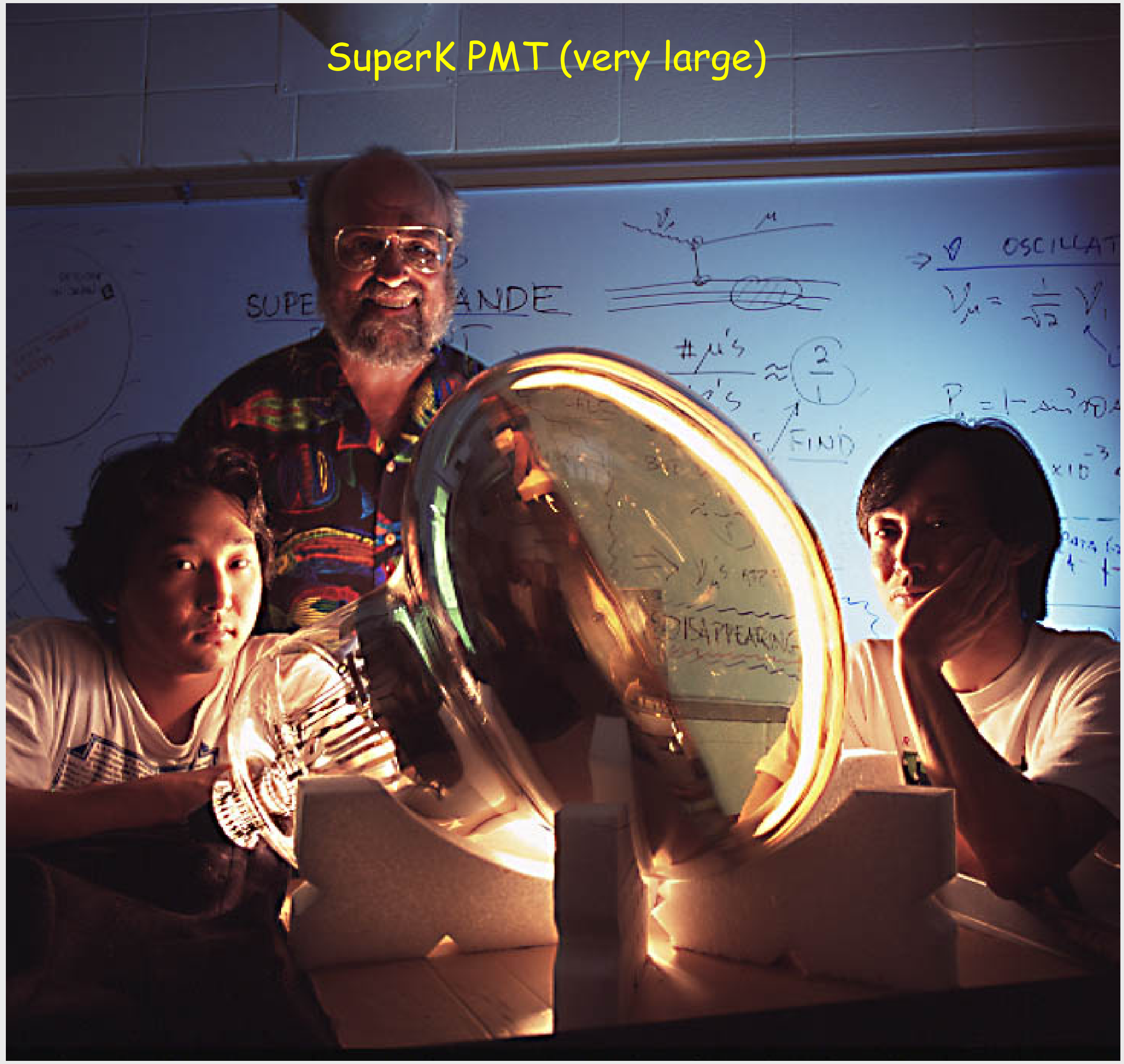
PMTs

- Much of the following information can be found in the Photonis book, *Photomultiplier Tubes, Principles and Applications*
  - Thanks to Photonis (and the Italian Post!), you now have your own personal copy



PMTs Come in all Shapes & Sizes

AMANDA PMT
(in a bathysphere)



SuperK PMT (very large)

Photonis PMTs

Real PMTs from Photonis

- Be careful handling them; if dropped they will implode
- These models are (clearly) at the smaller end of the PMT size scale

How a PMT Works (an Experimentalist's Perspective)

- Photons hit photocathode, releasing an electron
- Electron is accelerated through electric field and focussed toward a dynode
- Electron crashes into dynode, causing more electrons to be released
- Newly-released electrons are all accelerated to next dynode, etc.
- At last dynode, a large dollop of electrons is collected, enough to make a detectable pulse that standard electronics can discern

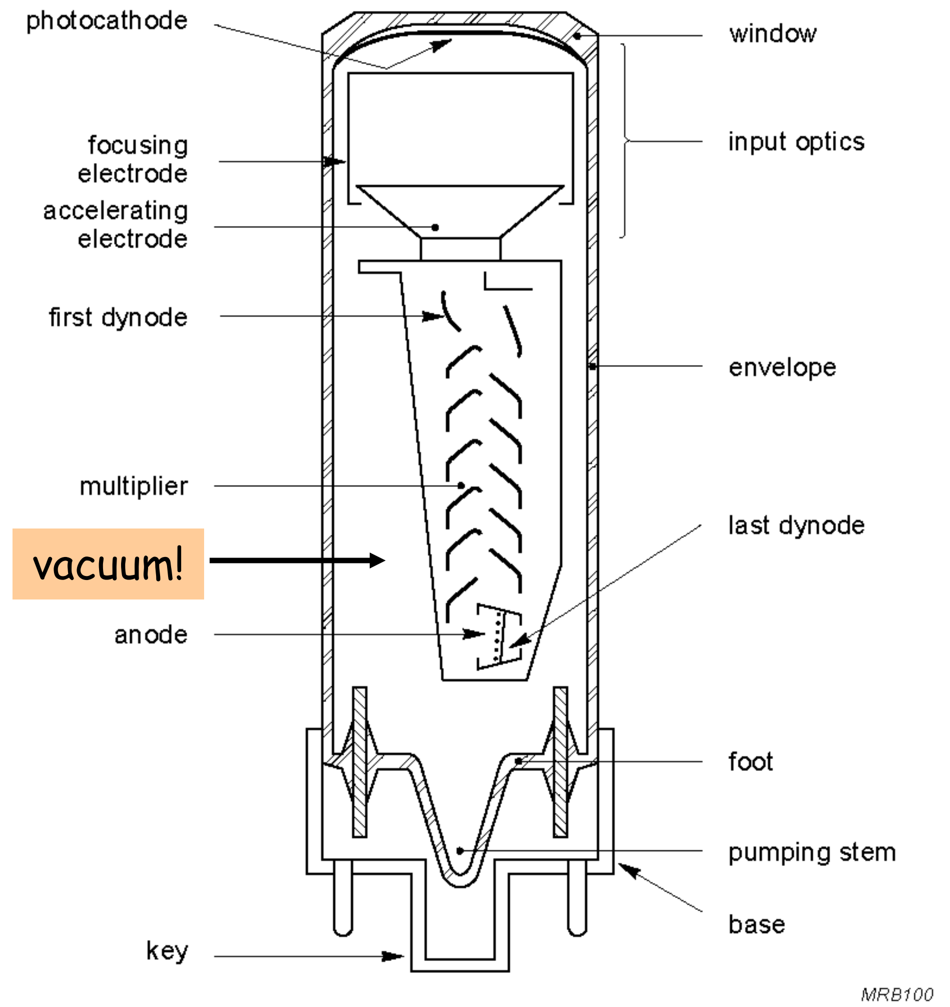
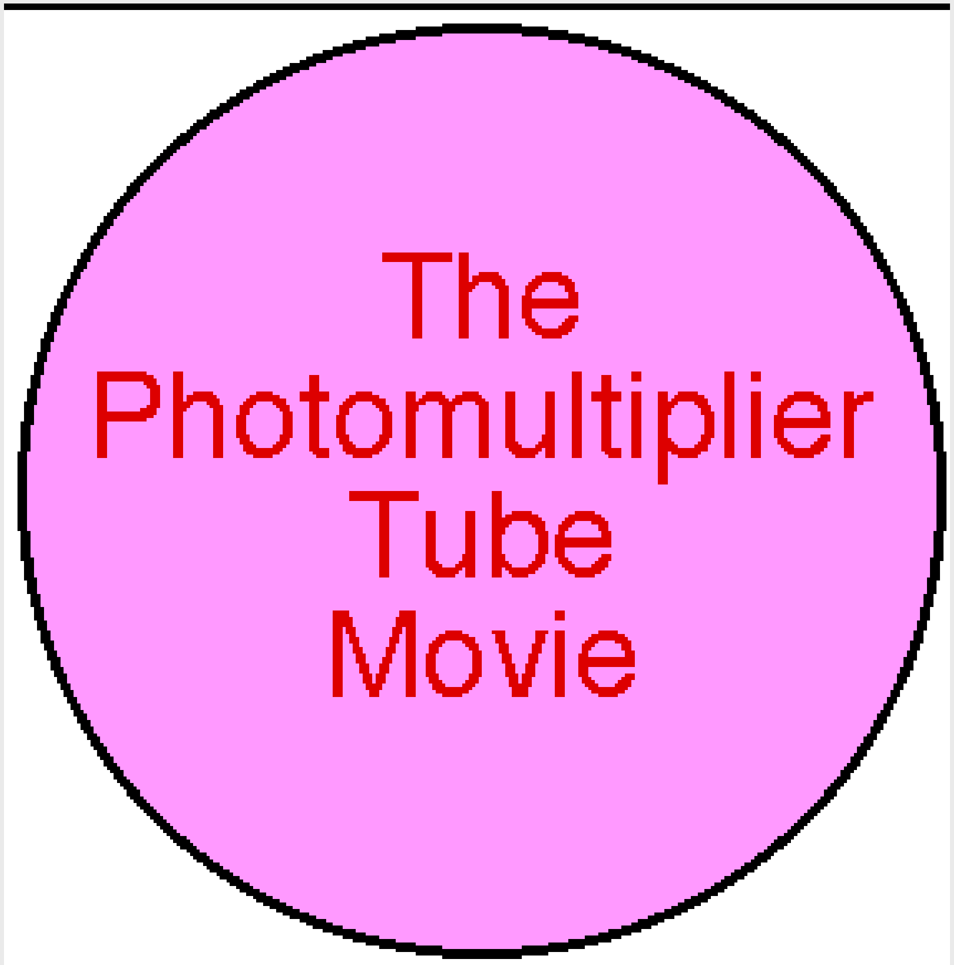


Fig.1.1 Elements of a photomultiplier based on the world's first fast PMT, the 56AVP, introduced by Philips (now Photonis) in 1956

Chemists Need a Cartoon to Understand This

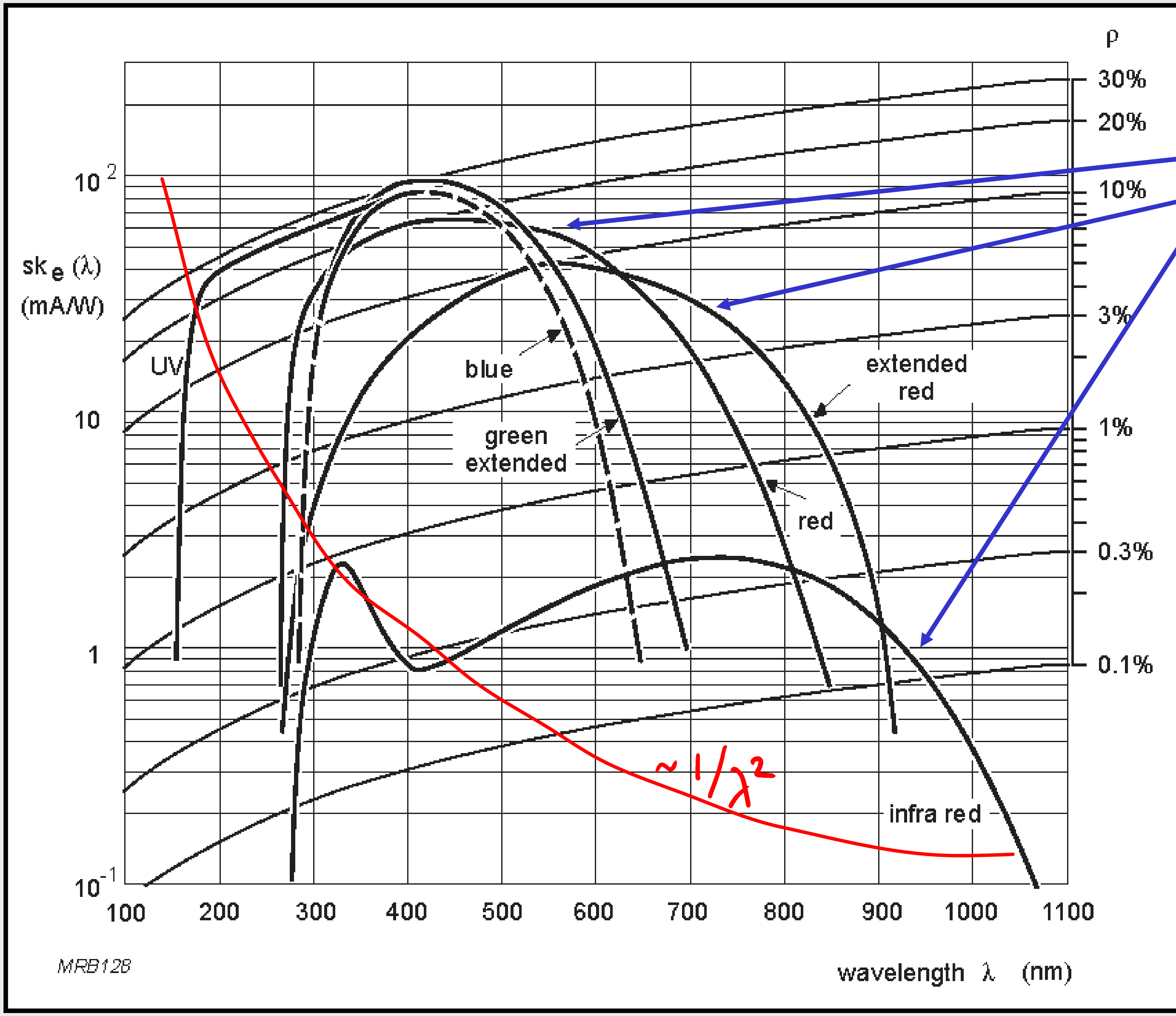


http://www.shsu.edu/~chm_tgc/sounds/sound.html

Photocathodes

- A variety of materials are used to convert photon flux into electron flux
- Important parameters
  - Spectral sensitivity
    - Want it to do a good job detecting photons emitted in the relevant wavelengths (UV and blue for Cherenkov light)
  - Quantum efficiency at λ_{max}
    - Q.E. = N(emitted e^-'s)/N(incident γ's)
    - Regrettably, Q.E.'s are generally not very high—lower than 30%.

Spectral Sensitivity & Quantum Eff.



Different photocathode materials

– Cherenkov Spectrum

Some Other Things that Matter

- Dark noise rate
  - Rate at which tube "sings" due to thermionic emission of electrons, leakage currents, decaying radioactive contaminants in PMT materials
- Gain
  - Ratio of anode current to cathode photocurrent
- Response time & time resolution
  - Time for output pulse to go from 10-90% of full value, given delta function light pulse at input
  - Time spread of (t_{in}-t_{out}); nanoseconds can matter
- Energy resolution
  - Spread of ($\Phi_{\gamma,in} - \int q dt_{out}$)
- Effect of external magnetic fields

PMTs can be Optimized

- E.g., by changing dynode configurations
- Can also change:
  - Materials
  - Voltages
  - Overall geometry
- The parameter space is huge…

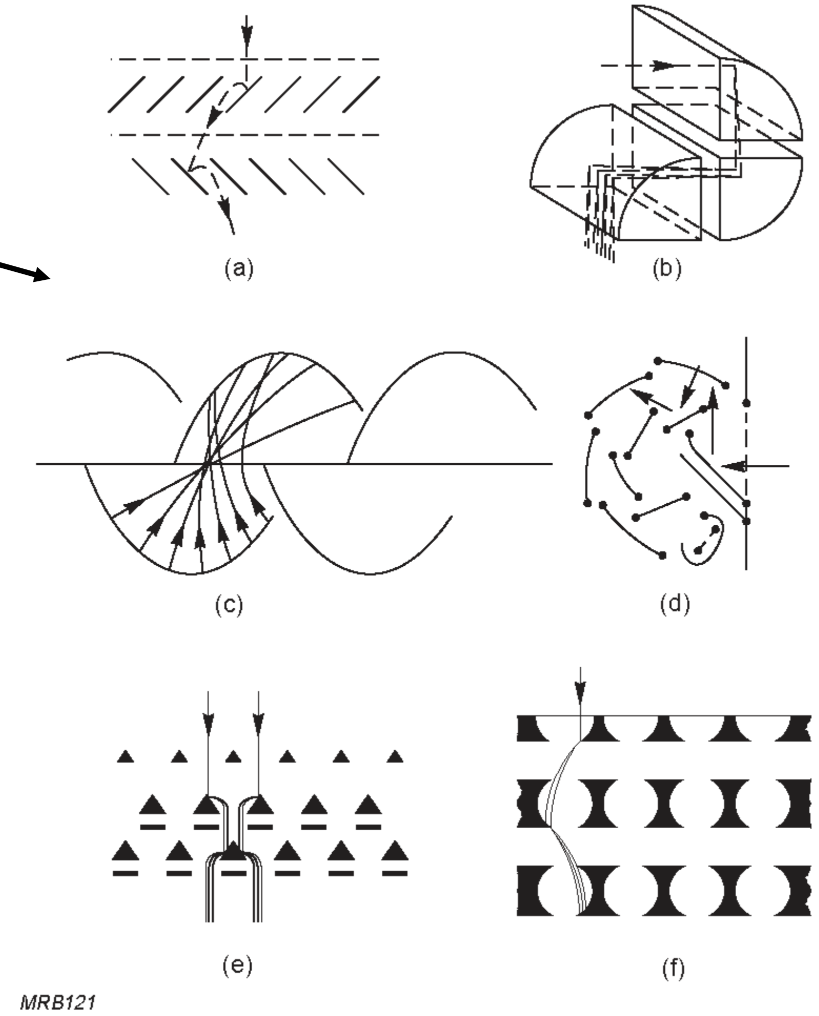


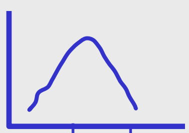
Fig.1.11 Dynode configurations: (a) venetian blind, (b) box, (c) linear focusing, (d) circular cage, (e) mesh and (f) foil

PMT Output Pulses

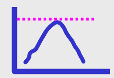
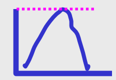
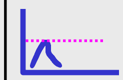
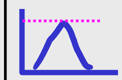
- Once powered, PMTs will produce an output signal as a result of
  - A single photon hitting the photocathode (…creating a free electron, which then gets multiplied in the dynode structure…)
    - Single photoelectron or SPE signal
  - Multiple photons hitting the photocathode over a short period of time
    - Multiple photoelectron or MPE signal
  - An electron getting freed by some other means in some other part of the PMT (e.g., on a dynode)
    - Noise, annoyance, aggravation,…

PMT SPE Response

- Due to statistical fluctuations and other effects, if you beam monochromatic photons, one at a time, at a photocathode, the output pulses will *not* be identical
  - Sample pulse might look like this



  - If you look at lots of pulses, you'll see a spectrum:

Input	γ_{400nm}	γ_{400nm}	proprio niente	...etc...	γ_{400nm}
Output				...	

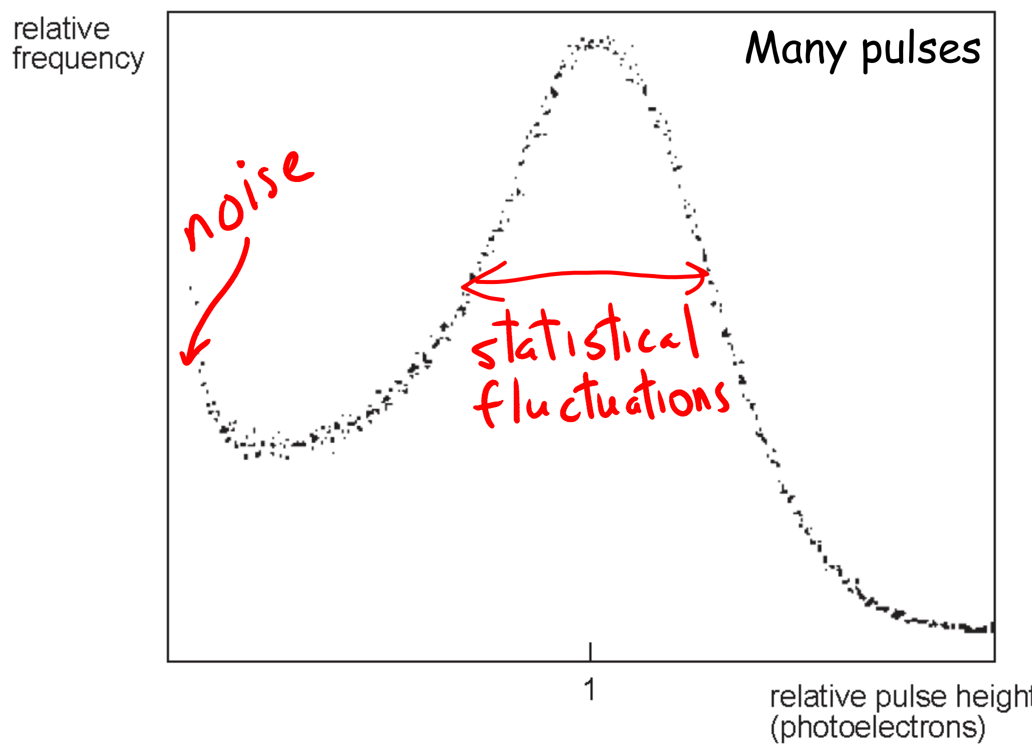


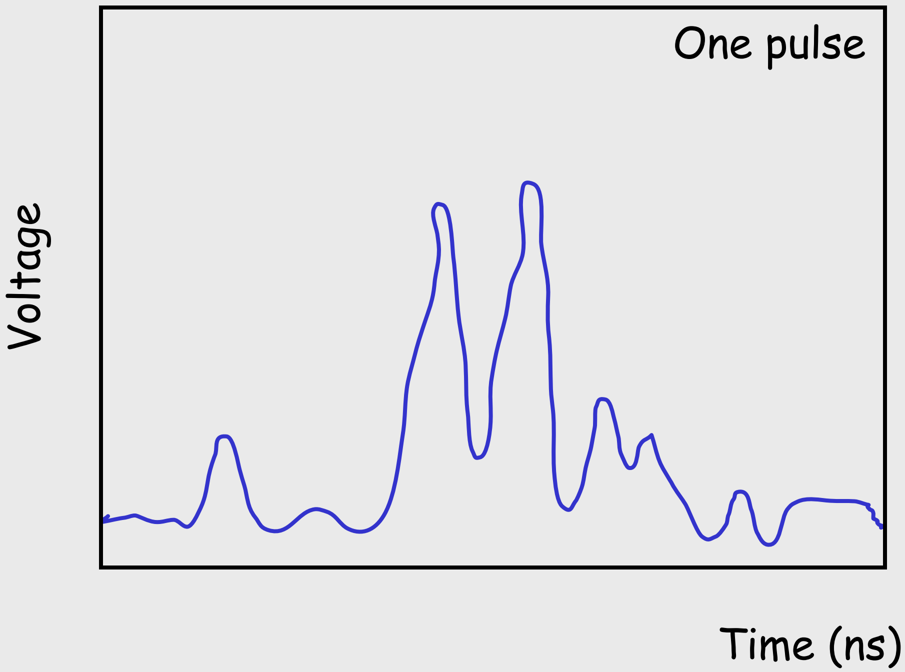
Fig.2.4 Typical single-electron spectrum. Resolution 67% FWHM. Peak-to-valley ratio 2.8:1

PMT MPE Response

- Basically just superpose SPE pulses
  - Output signals get substantially more complex
  - But: If too many photons hit the photocathode in a short δt, the PMT output will be saturated
- N.B.: If you expose a powered PMT to daylight, you will destroy it forever
  - From the "Photomultiplier Doctor" at http://www.electron-tubes.co.uk:
    - High interdynode currents are generated within a PMT when exposed to bright light. The electron bombardment of the dynode surfaces releases ions and if sufficient in number, breakdown will occur causing the PMT to glow. Removing the bright light leaves the PMT with an ion-damaged photocathode and filled with gas.

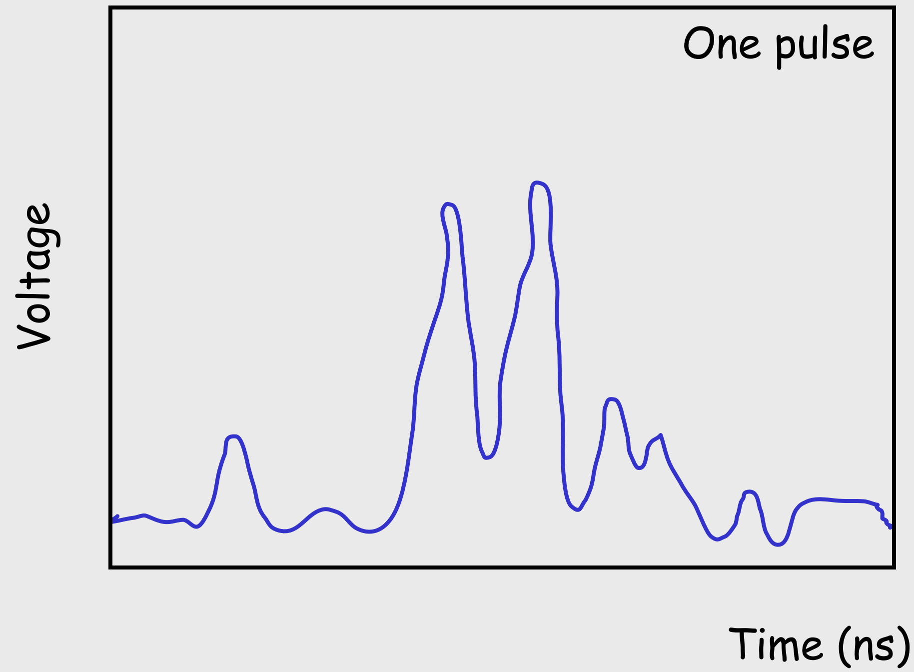
PMT MPE Response

- When many photons arrive within the time of interest, desire
  - separation between photons
  - resolution of number of photons in each group



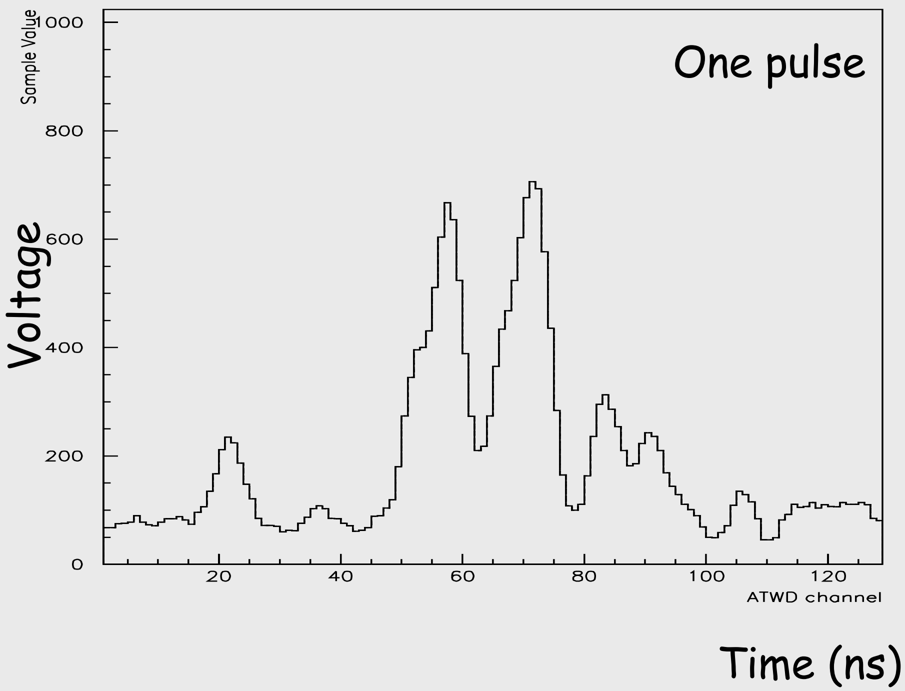
How Can We Decipher SPE and MPE Waveforms?

- Modern electronics allows us to digitize them
  - then we can use digital signal processing algorithms to extract the information we want



How Can We Decipher SPE and MPE Waveforms?

- Modern electronics allows us to digitize them
  - then we can use digital signal processing algorithms to extract the information we want



At regular time intervals (e.g., every few ns), use an analog-to-digital converter (ADC) to convert the voltage to a number. Repeat until the end or until run out of memory.

"Modern Electronics": Custom ASICs

- You cannot buy digitizers "off the shelf" to do this task (at least, not for a reasonable amount of money)
  - There are no high-volume commercial applications (yet)
- Need to do it yourself
  - This type of task is well-suited to being placed on an integrated circuit
    - These are called custom application-specific integrated circuits, or "custom ASICs"
    - $\Rightarrow$Design your own integrated circuit

Custom ASICs

- Older experiments, like the solar and atmospheric neutrino telescopes SNO and SuperK, use custom ASICs, not to digitize waveforms, but to extract key pieces of information from them, like time and charge. Reasons:
  - technology for digitizing not readily available
  - didn't really need more than good I.D. of SPEs
- Newer experiments, like the cosmological neutrino experiments ANTARES, NESTOR and IceCube, have a physics need for waveforms and so take advantage of newer technology by designing and using custom ASIC waveform digitizers
- These custom chips are often the heart of the data acquisition (DAQ) systems of these experiments

Data Acquisition Systems

- The job of DAQ systems is to move the data from the detector sub-elements to computer disk so that they can be analyzed for physics content
  - PMTs are a popular sub-element
  - Custom ASICs acquire PMT waveforms
  - An electronic "discriminator" decides if the waveform is big enough to be interesting
  - "Trigger" formation is attempted
    - Signals from many PMTs are examined to see if, say, more than N PMTs fired in T ns ("majority" trigger)
    - In general, to reduce dataflow, triggers can implemented at several "levels" as data moves "downstream" from sub-element to computer disk
  - On a positive trigger, all the relevant data is "built" into an event
  - The event is shipped off to computers for further analysis

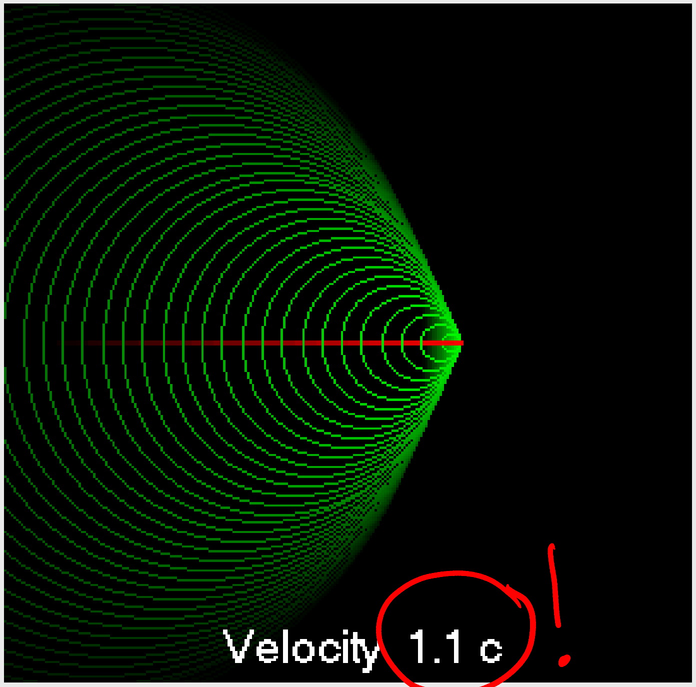
PMTs are Well-Suited to Detection of *Cherenkov Light*

When an object moves faster than waves in the medium, a shock wave results:

Cherenkov, getting inspiration

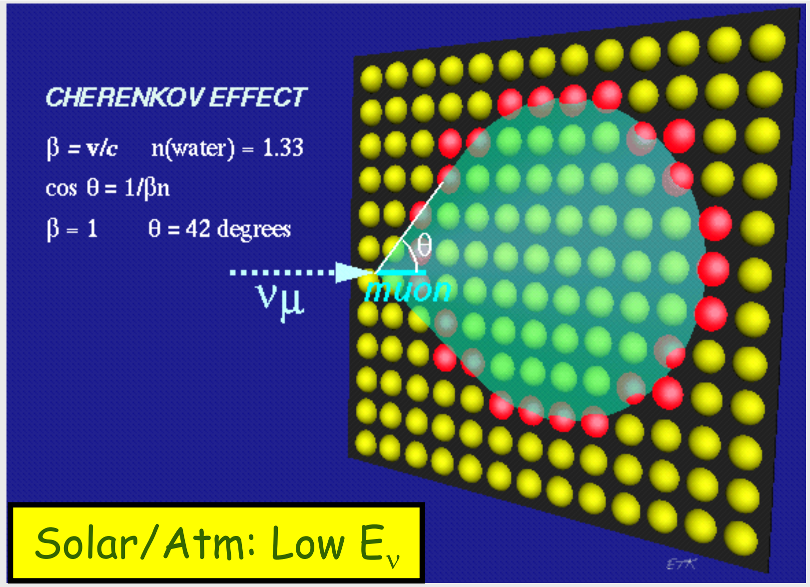
Cherenkov Light

- A charged particle can have a velocity of $c/n < v < c$, in which case it will emit EM radiation in a shock wave with characteristic angle $\cos\Theta = 1/\beta n$:

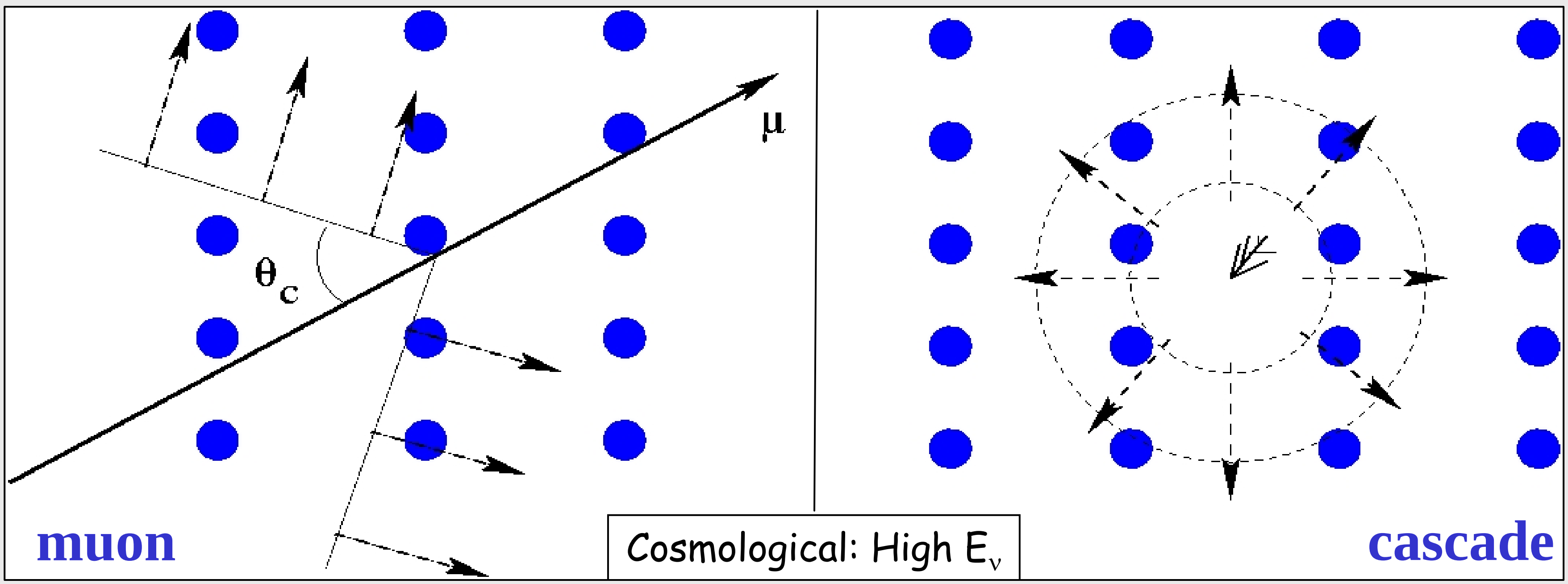


- From the same web page:
  - "How can the particles travel faster than light? Suppose that they are travelling at 0.9 of the speed that light has in a vacuum, usually denoted by c. If they pass into a refractive medium where the speed of light is 0.75 of its vacuum speed c, the particles now have 0.9 / 0.75 of the local speed of light, that is <u>1.2 of the vacuum speed of light.."</u> (you cannot believe everything you read on the web…)

Cherenkov Light can be Imaged by PMT arrays!



From SuperK website



This is the fundamental detection principle of many particle astrophysics neutrino experiments.

Other Similarities

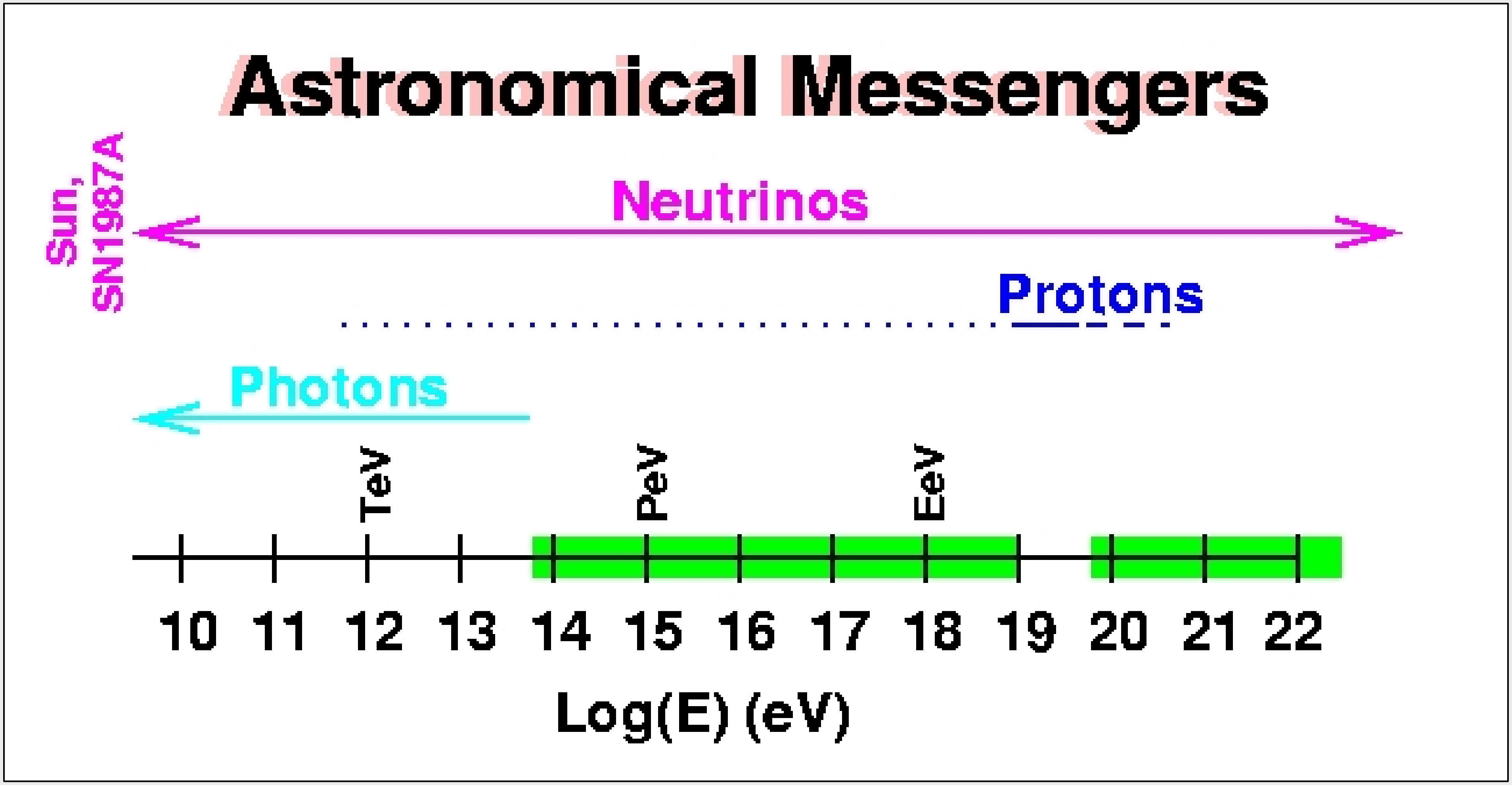
- Low data rates
  - Especially true of neutrino detectors, which expect to see O(1-100) neutrinos daily, and which take data (mostly backgrounds) at O(100Hz)
    - By contrast, LHC beam crossings are at O(GHz)
- Background sensitivity
  - Especially true of detectors sensitive to lower energy signals, such as solar neutrinos or WIMPs: natural radioactivity can mimic signal
  - Everything must be kept extraordinarily clean

Other Similarities

- Large fiducial (i.e., active) volumes
  - Especially true of ultrahigh energy neutrino detectors, for which large volume means higher likelihood of
    - seeing a neutrino interact
      - a neutrino at solar neutrino energies (10^{6-7} eV) has an interaction length in lead of about a light-year
      - at higher energies, neutrinos get more social, but only at about 10^{15} eV does the interaction length equal the earth's diameter
    - containing most or all of its interaction products when it *does* interact
      - an event at 10^{15} eV has an "SPE radius" of about 250m

Other Similarities

- Many use neutrinos:



The Differences

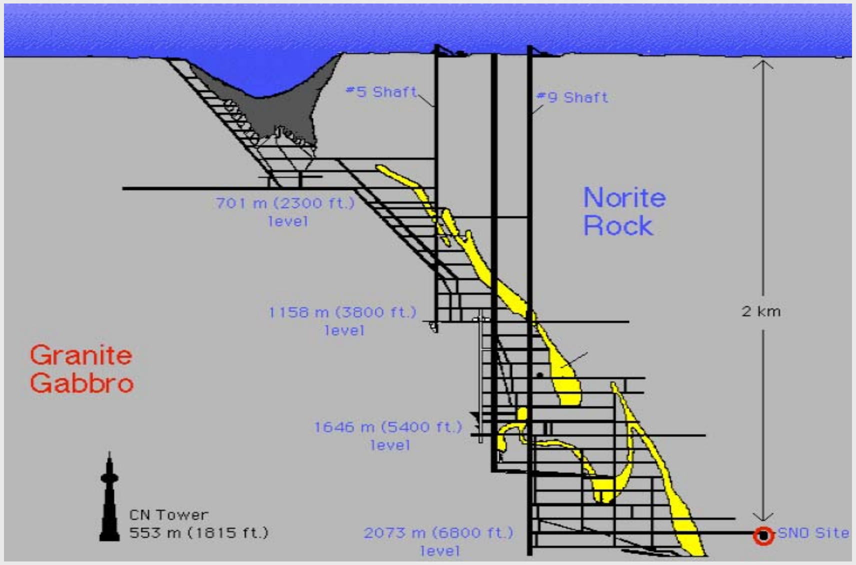
- To give you a feeling for the differences, we'll look in some detail at the following detectors and describe how they work:
  - Sudbury Neutrino Observatory (SNO) and KamLAND
    - Low energy solar and reactor neutrinos
  - AMANDA/IceCube*
    - Ultrahigh energy neutrinos
  - ANITA
    - super-duper-ultrahigh energy neutrinos
  - Pierre Auger
    - really high energy cosmic-ray protons
  - CDMS-II
    - low energy WIMPs
  - LIGO
    - gravity waves

*John Carr will cover sea-based UHE neutrino detectors such as ANTARES

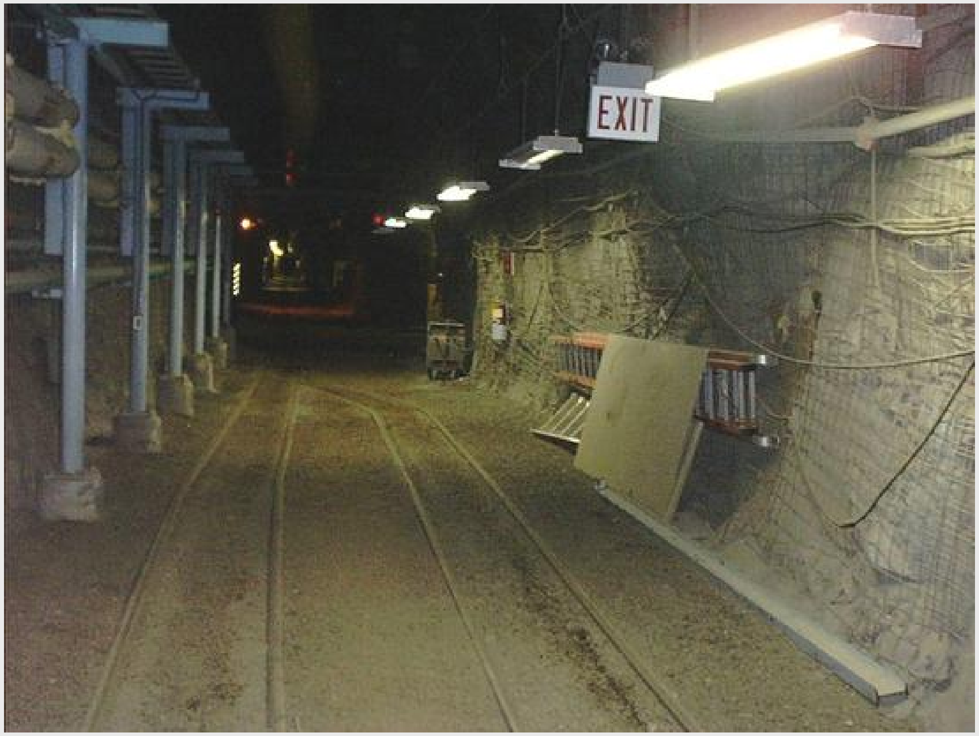
SNO and KamLAND

- SNO and KamLAND study low-energy neutrinos from the sun and from nuclear reactors
  - Background reduction is absolutely critical
- Each have 1000s of PMTs looking at kiloton-size active volumes
  - For SNO, one *gram* of dust in its one *kiloton* of heavy water would have caused a 10%-level background
- SNO solved the 30-year-old "solar neutrino problem" and KamLAND confirmed and fine-tuned that result

SNO

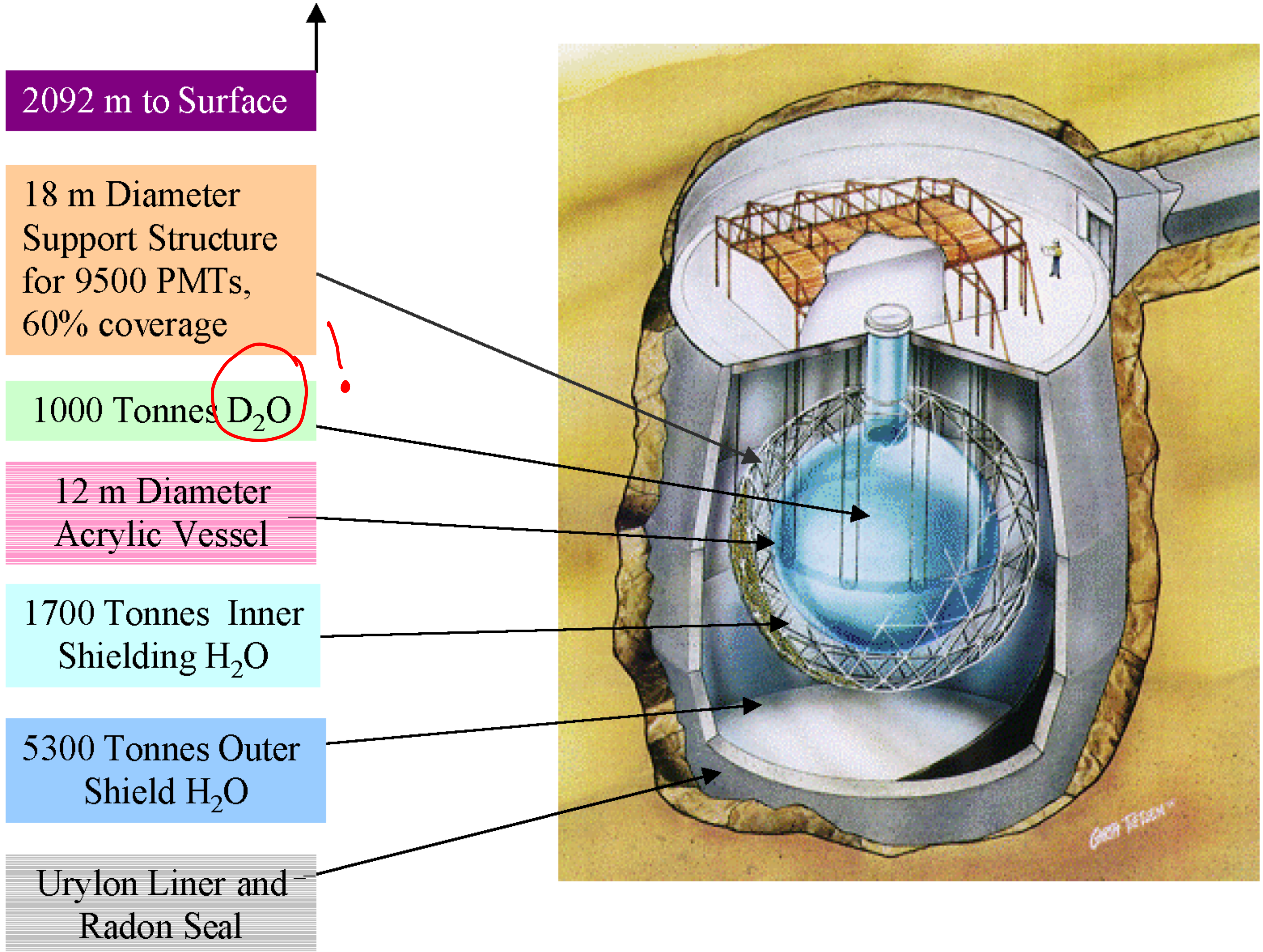


Deep underground in an active nickel mine, to reduce cosmic-ray muon backgrounds.



The disadvantage was that it was an extremely dirty environment

Sudbury Neutrino Observatory

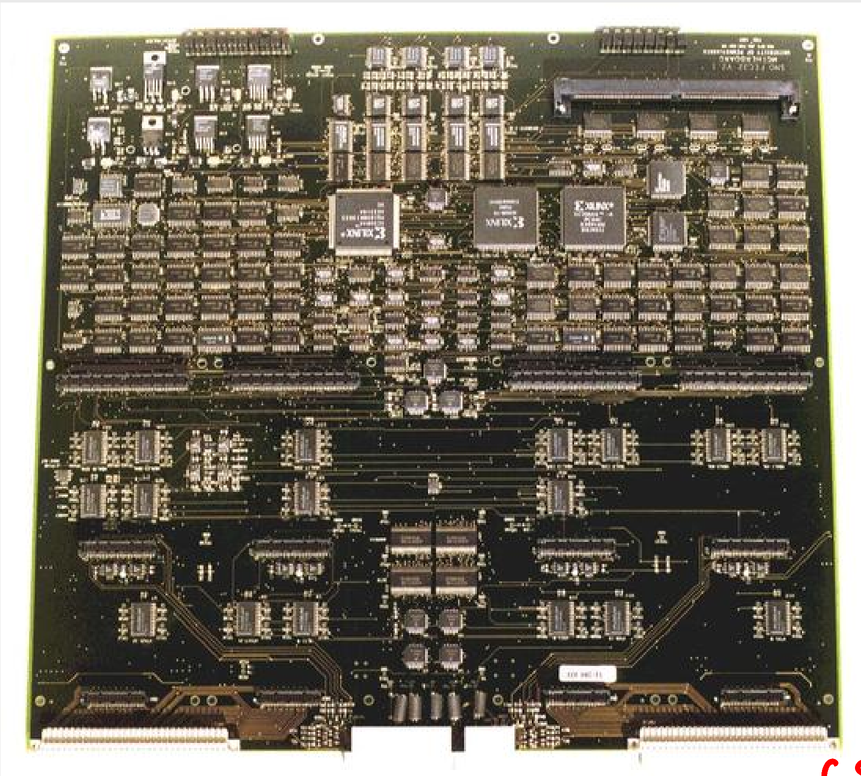


Slide courtesy S.Oser

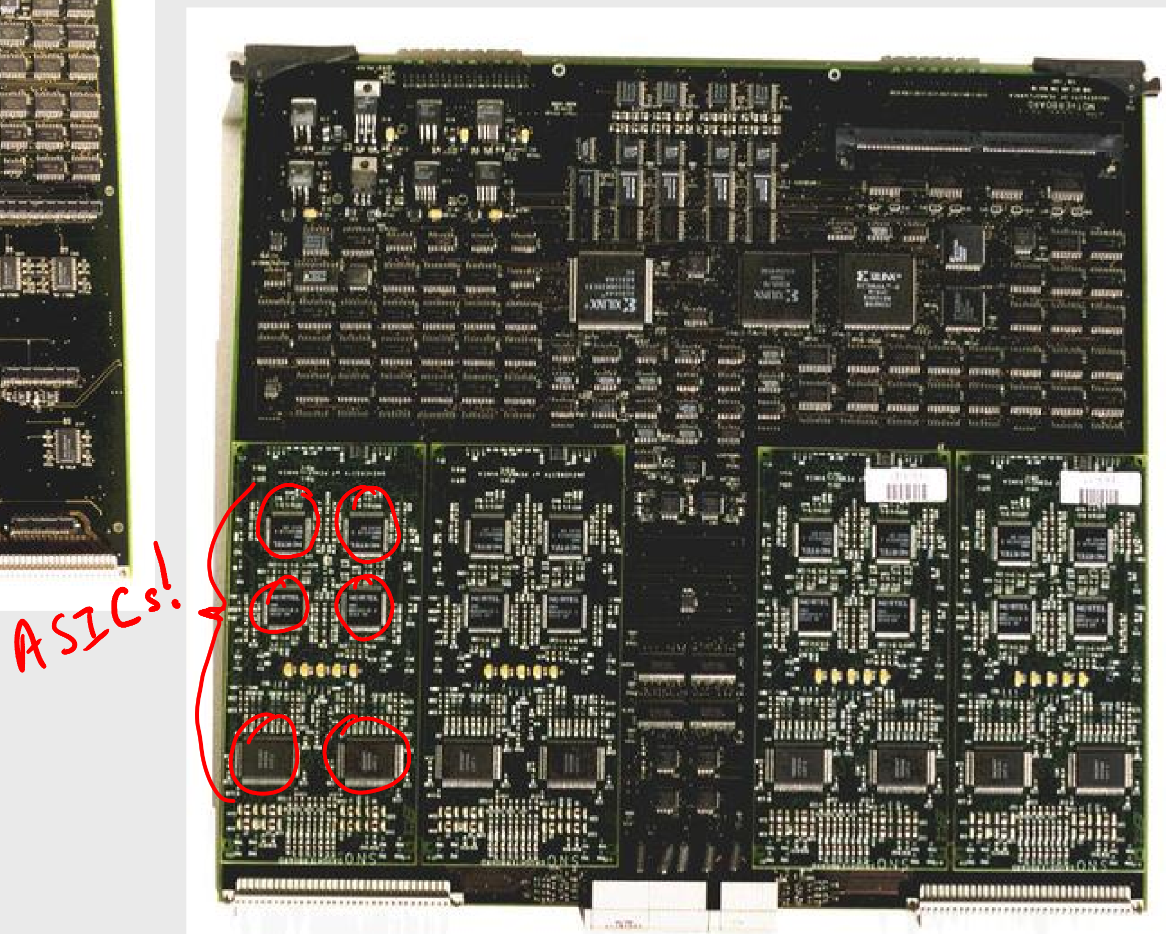
How SNO Works

- An incoming solar neutrino can interact with an electron or a deuteron in the D_2O
  - One or more electrons get accelerated to $v > c/n$ and emit Cherenkov light
  - The surrounding ~10,000 PMTs detect this light, the DAQ system converts the light pulses into arrival times and integrated charge (i.e., number of photons), and then this information is used to reconstruct events

SNO DAQ

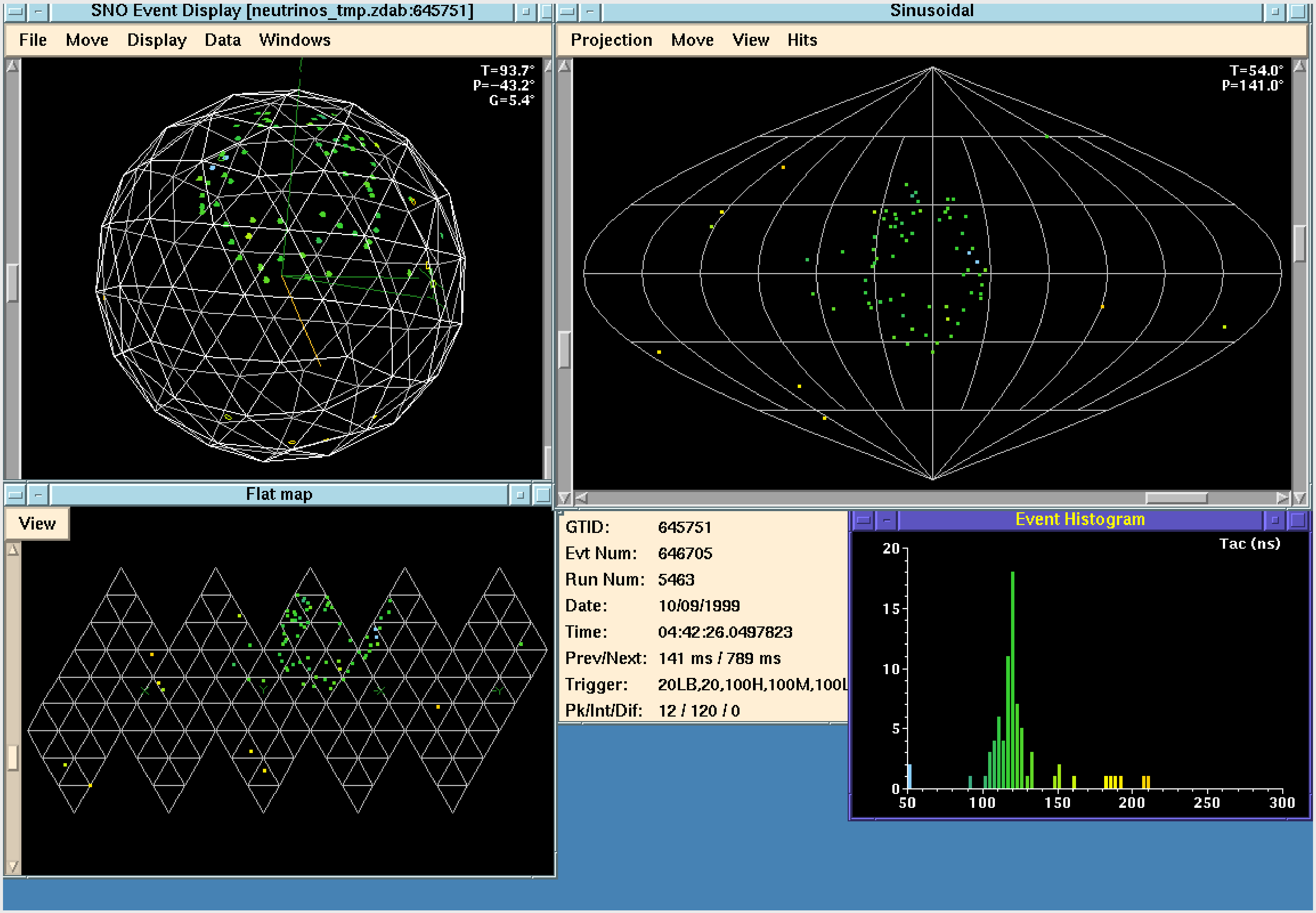


One of ~300 SNO "mother boards"

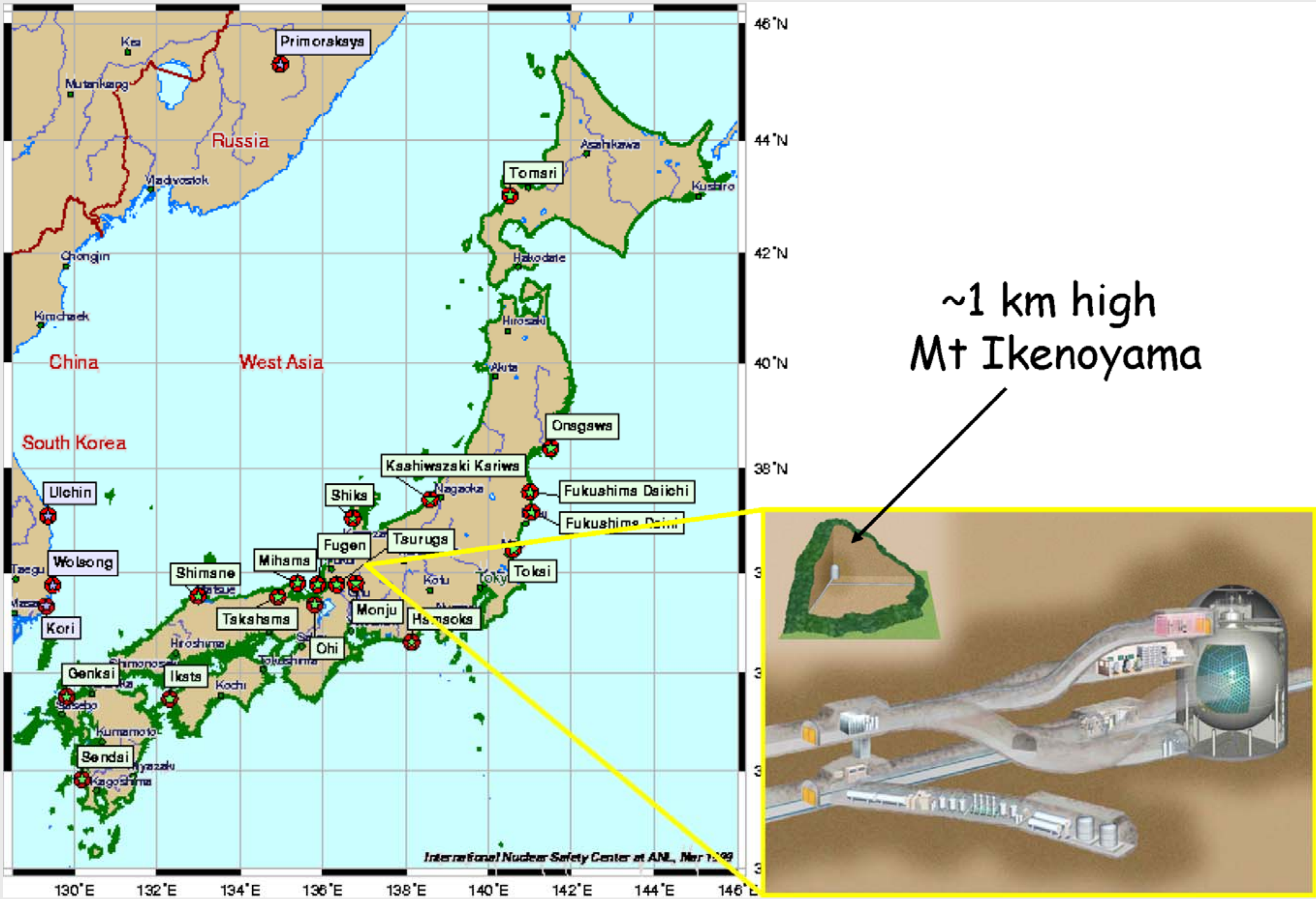


SNO mother board with four "daughter boards"

SNO Event


SNO Event Display [neutrinos_tmp.zdab:645751]
File Move Display Data Windows
T=93.7°
P=-43.2°
G=5.4°
Sinusoidal
Projection Move View Hits
T=54.0°
P=141.0°
Flat map
View
GTID: 645751
Evt Num: 646705
Run Num: 5463
Date: 10/09/1999
Time: 04:42:26.0497823
Prev/Next: 141 ms / 789 ms
Trigger: 20LB,20,100H,100M,100L
Pk/Int/Dif: 12 / 120 / 0
Event Histogram
Tac (ns)
20
15
10
5
0
50
100
150
200
250
300

KamLAND

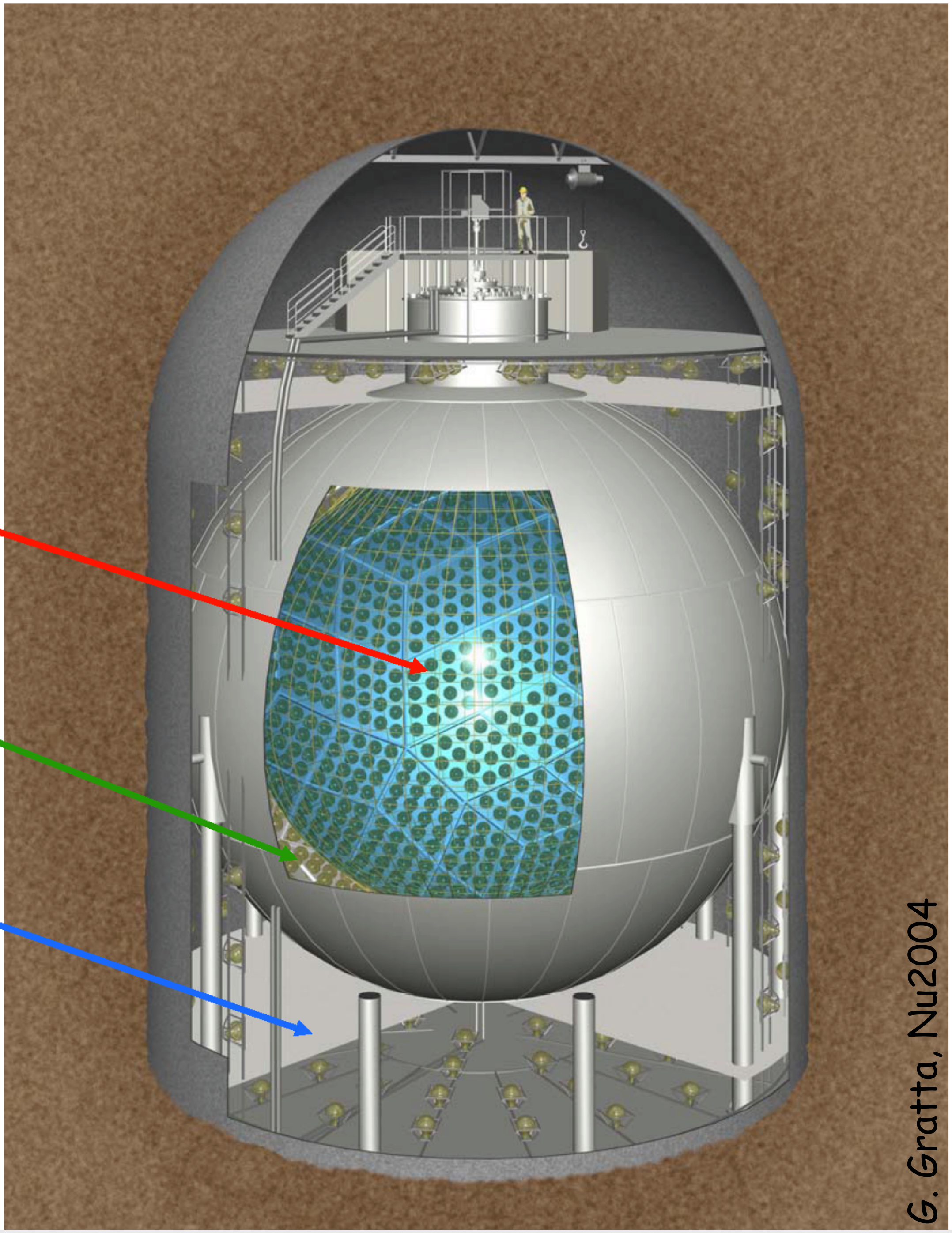


~1 km high
Mt Ikenoyama

Gratta, Nu2004

KamLAND:
Kamioka Liquid scintillator AntiNeutrino Detector

- 1 kton liq. Scint. Detector in the Kamiokande cavern
- 1325 17" fast PMTs
- 554 20" large area PMTs
- 34% photocathode coverage
- H_2O Cerenkov veto counter



How KamLAND Works

- The Kamioka Liquid Scintillator Anti-Neutrino Detector uses, instead of D_2O, liquid scintillator
  - Advantage: lower energy threshold
  - Advantage: clear signal

$$\bar{\nu}_e + p \rightarrow e^+ + n \;\searrow^{\tau \approx 200\ \mu s}\; p + n \rightarrow d + \gamma(2.2\ MeV)$$

  - Challenge: make it clean. Succeeded:
    - ^{238}U: 3×10^{-18}g/g; ^{232}Th: 5×10^{-17}g/g; ^{40}K: 2×10^{-16}g/g

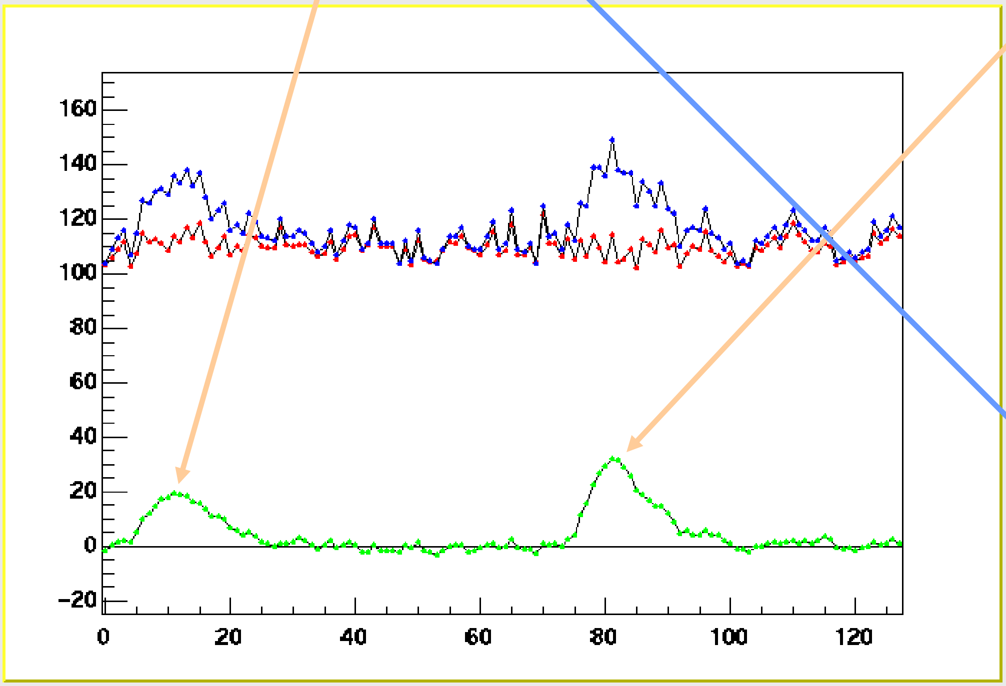
How KamLAND Works

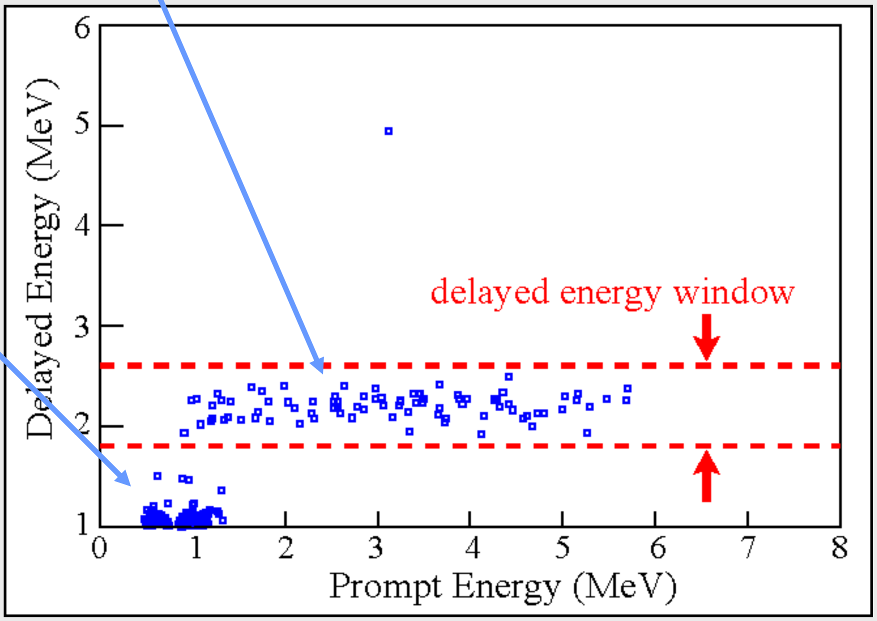
- Clear signal:

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

$$\tau \approx 200\ \mu s$$

$$p + n \rightarrow d + \gamma(2.2\ MeV)$$



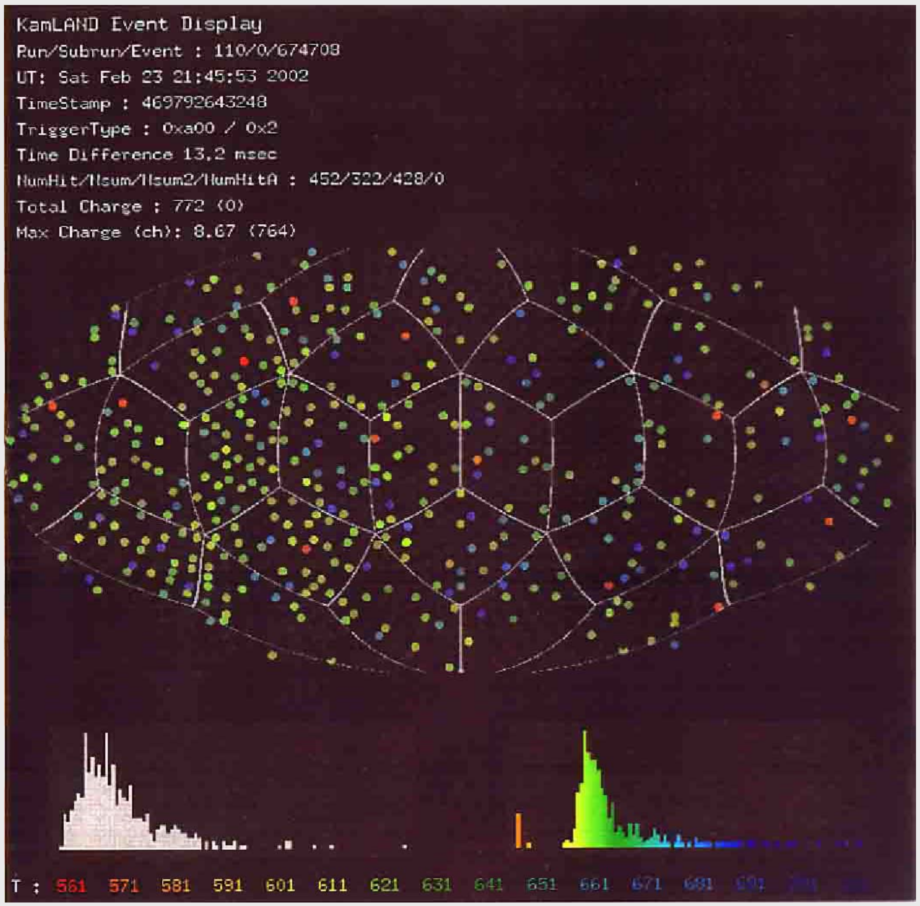


N.B. Not real signal data, but real KamLAND electronics (1.5 ns bins)

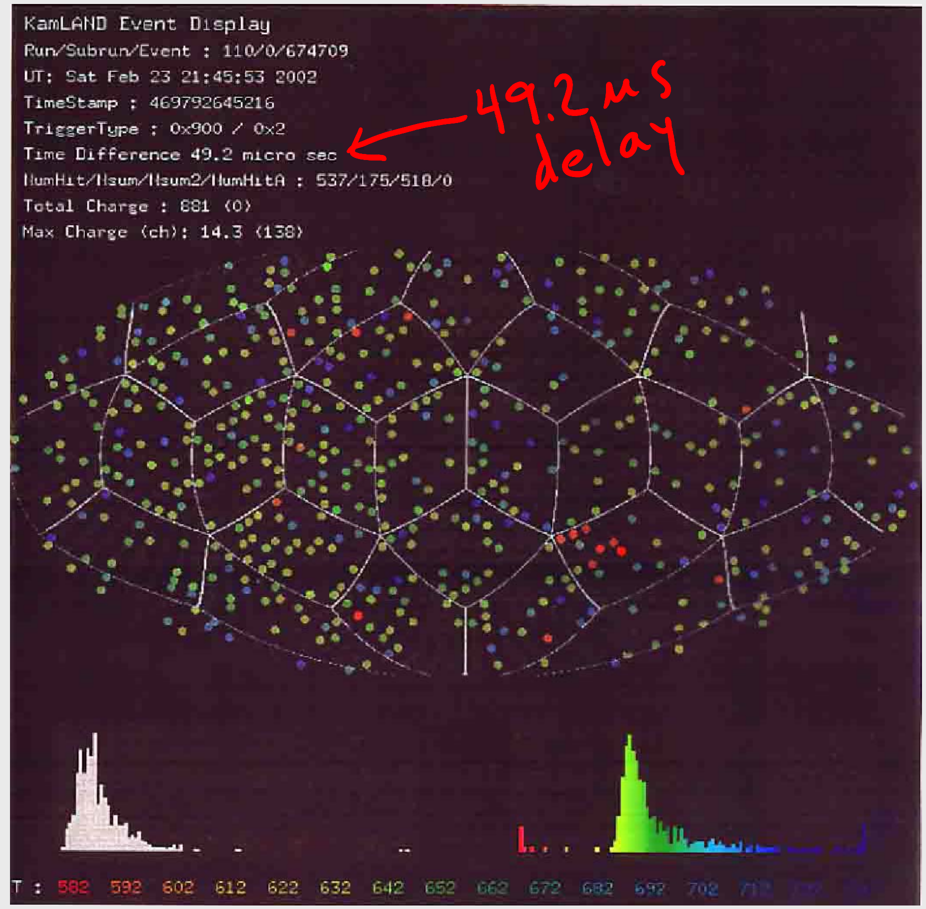
KamLAND DAQ

* Similar to IceCube's ASIC

First Candidate KamLAND $\bar{\nu}_e$ Event



Prompt event

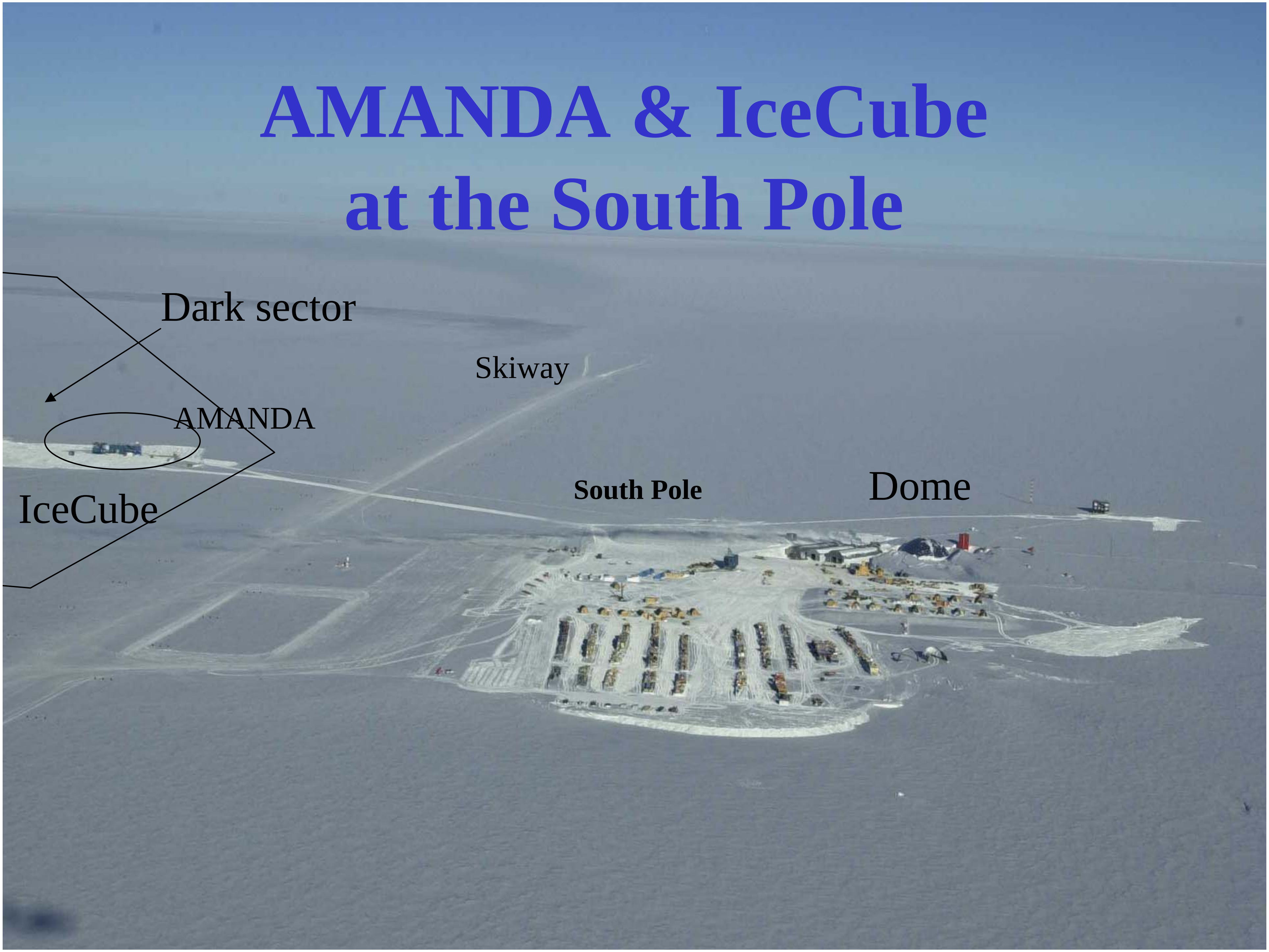


Delayed event

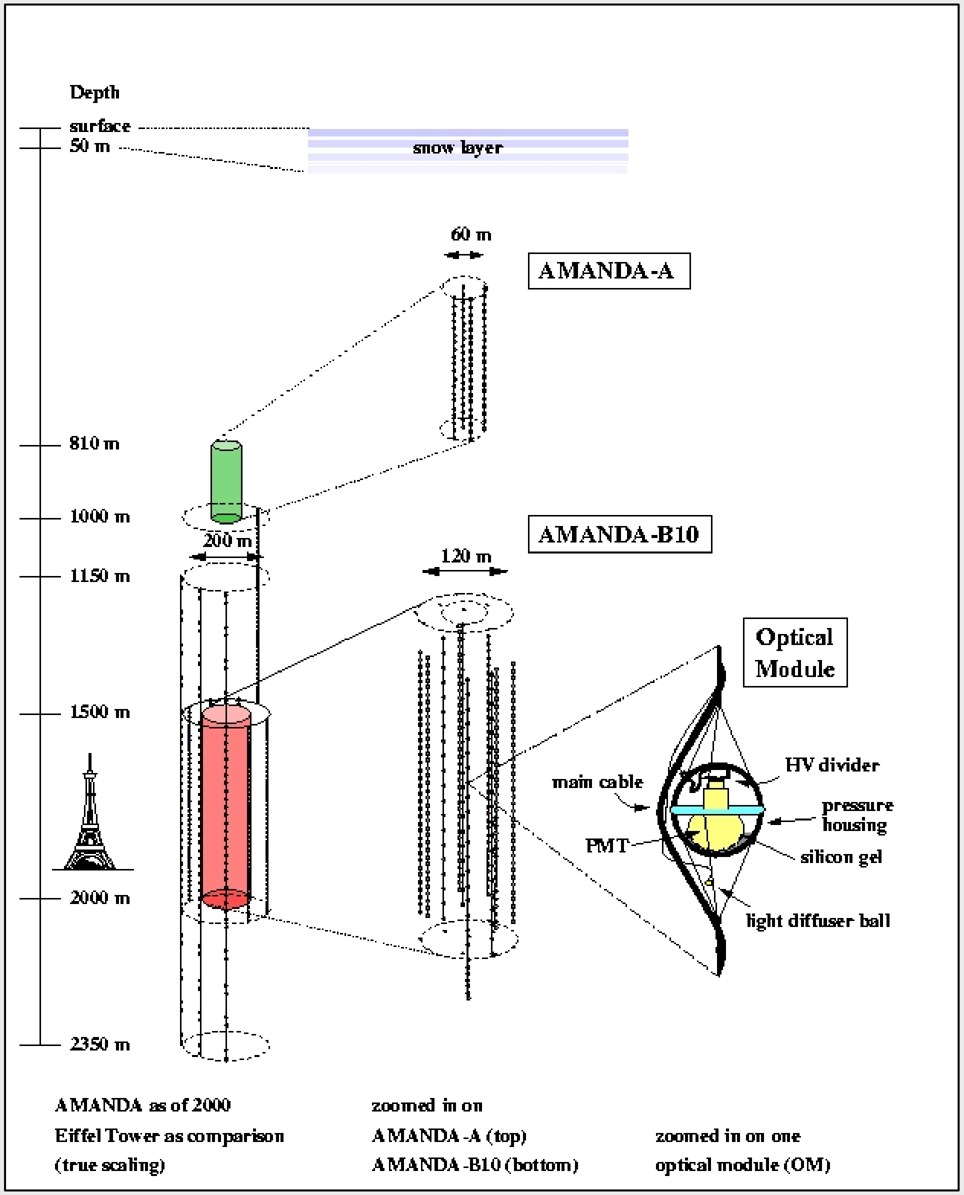
Detectors for Ultrahigh Energy ν's

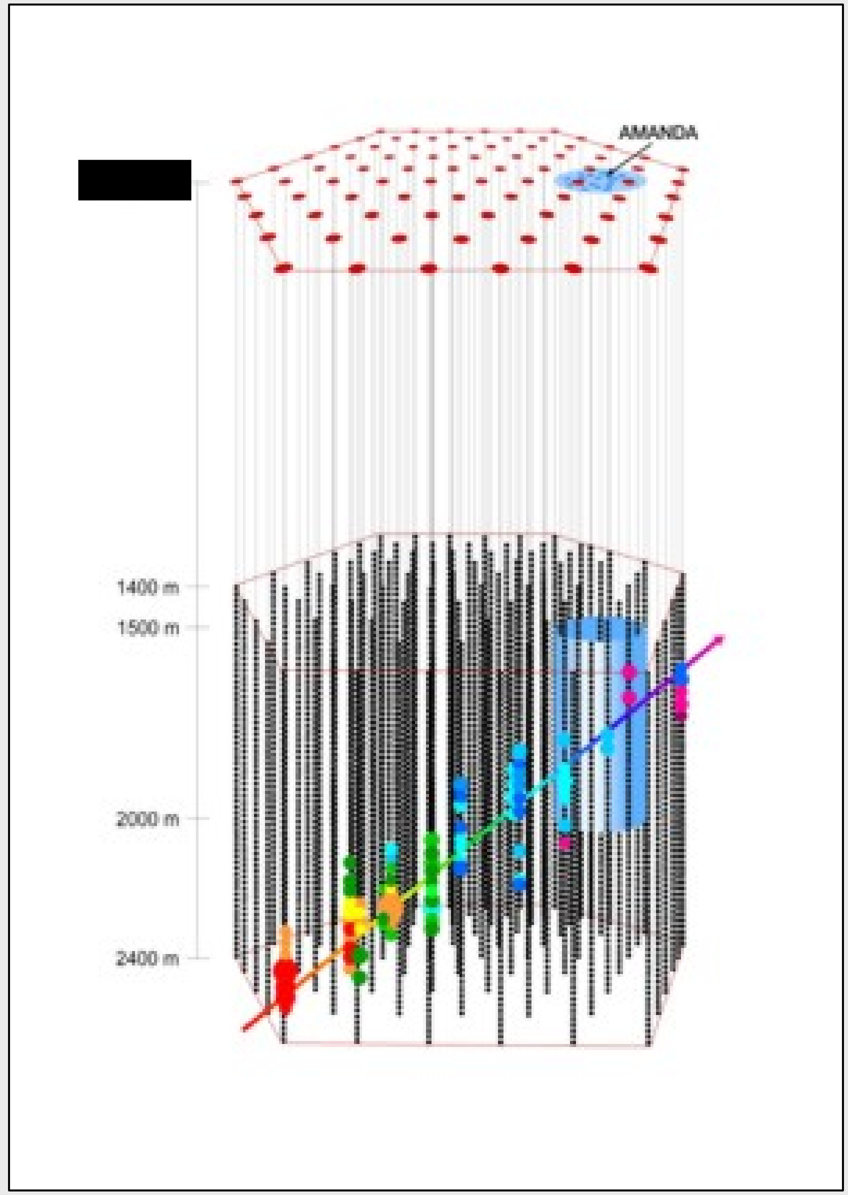
- Need a large, clear, "pre-fabricated" volume. Reasons:
  - affordable
    - can instrument at low pixelization density
    - but insuring precise relative timing is a challenge
  - well-suited to rare events w/PeV energies
    - more likely to have interaction
    - more likely to contain event when interaction occurs
- At least two locales satisfy this requirement:
  - deep water sites in various places, especially the Mediditteranean (see talks by John Carr)
  - deep ice at the South Pole

AMANDA & IceCube at the South Pole



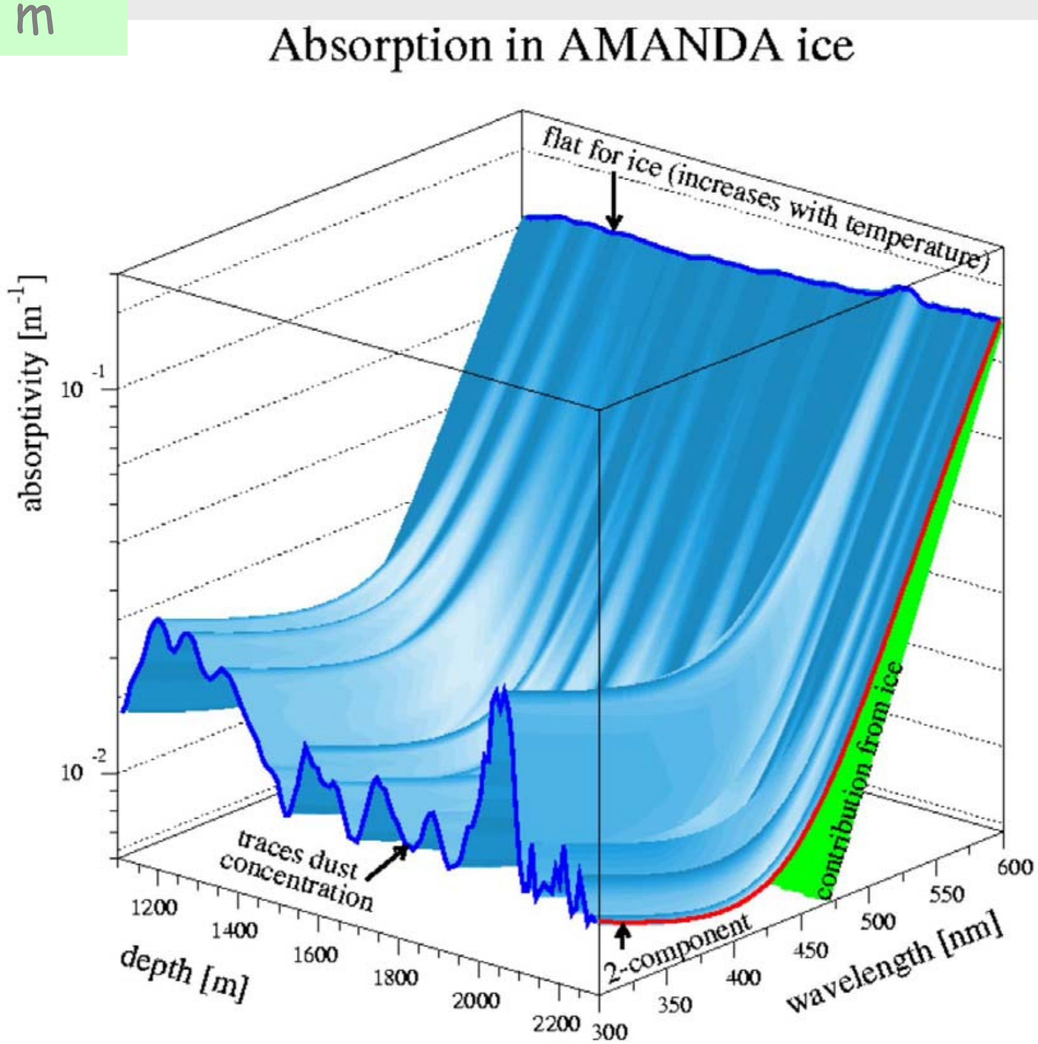
AMANDA and IceCube





Arctic ice - most transparent natural solid
available in large quantity

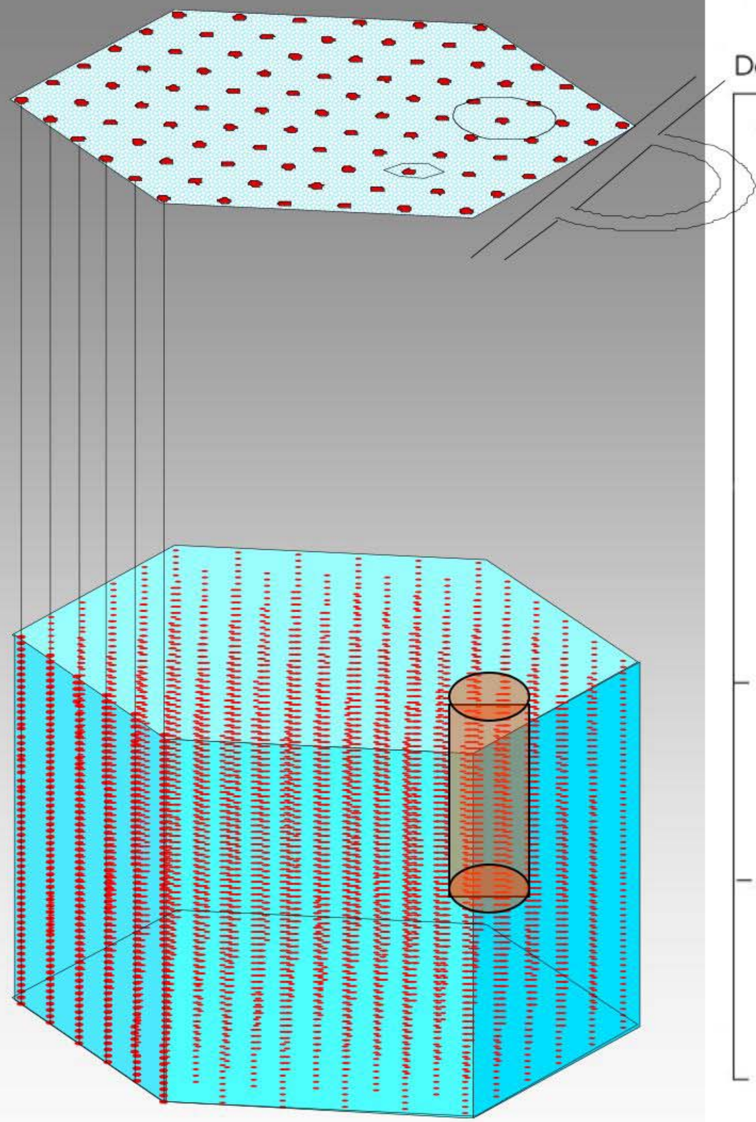
@ 400 nm and 1700m depth
- absorption length ~120 m
- scattering length ~30 m

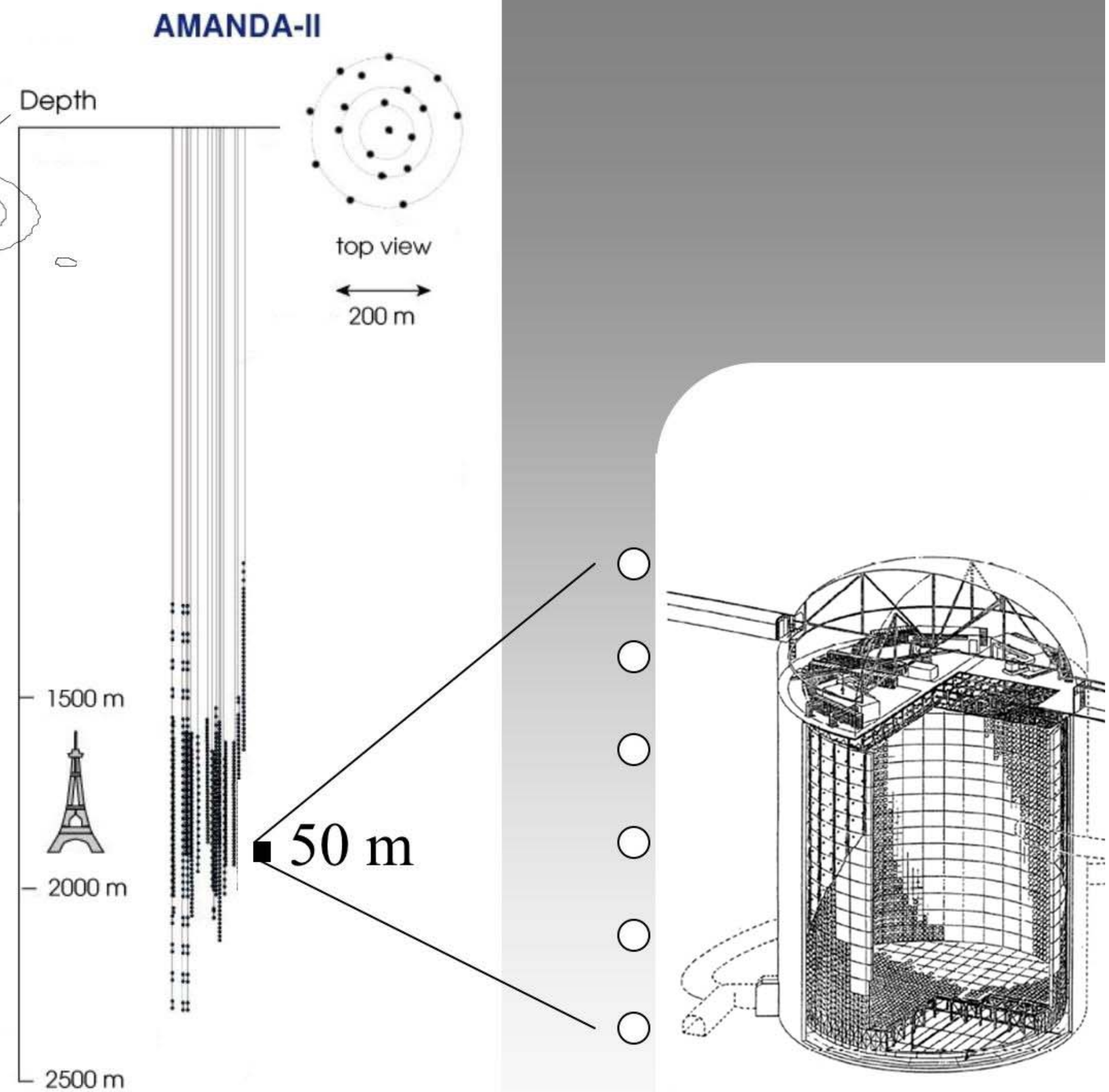


⇒ Complex data
⇒ Extended in time

Waveform capture important

Scattering is worst above ~1.4 km due to air bubbles





Size Perspective

How AMANDA and IceCube Work

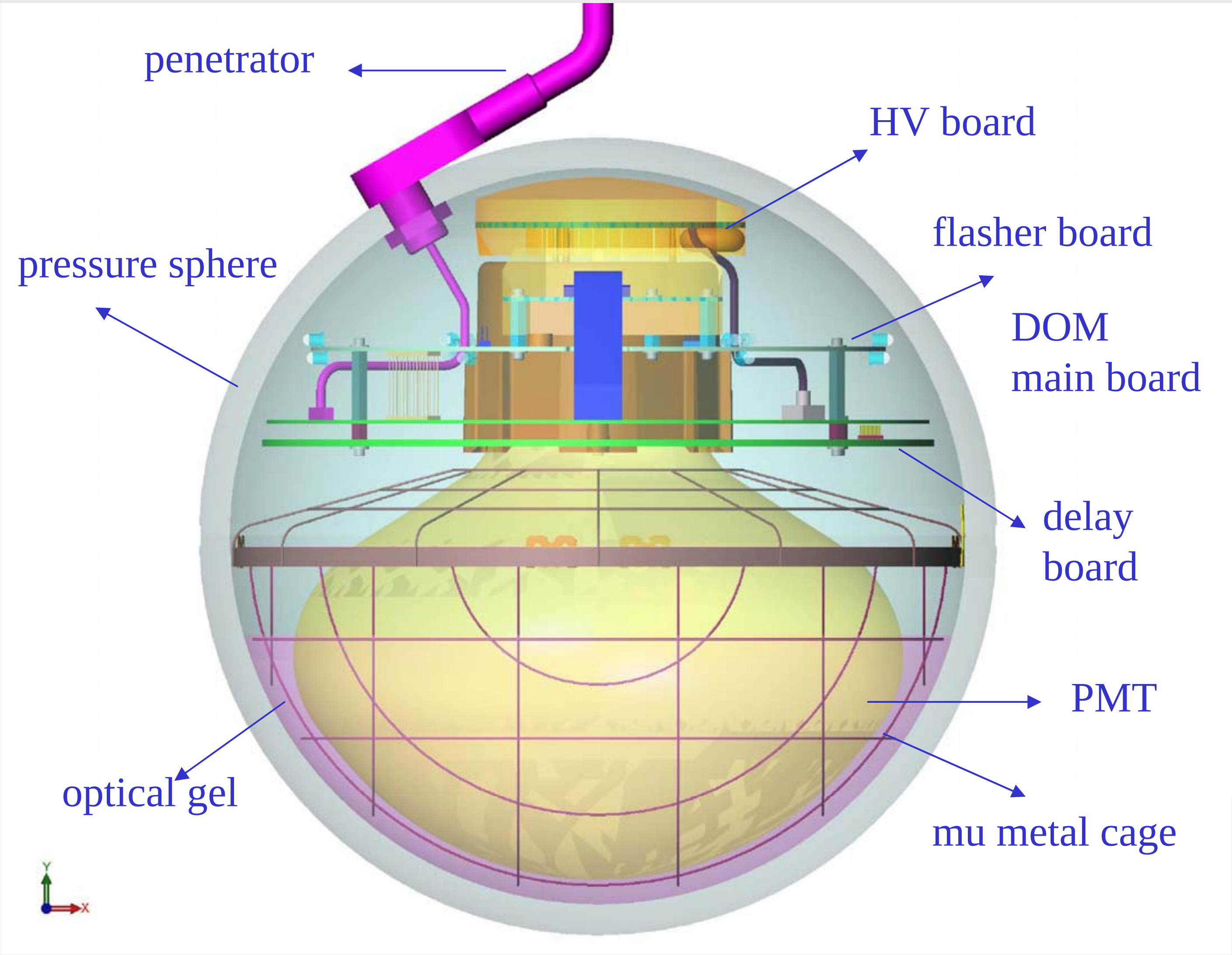
- A neutrino interacting in or near the buried array of PMTs produces particles that emit Cherenkov light
  - a muon neutrino can make a charged muon, resulting in a track crossing the detector volume
  - an electron neutrino can make an electron, resulting in a "cascade" manifested as an expanding sphere of light fully or partially contained in the detector volume
    - A cascade in particular can produce complex MPE waveforms in PMTs that contain loads of useful information for reconstructing the cascade vertex, direction and energy—so digitization is a very useful thing to be able to do

AMANDA Events

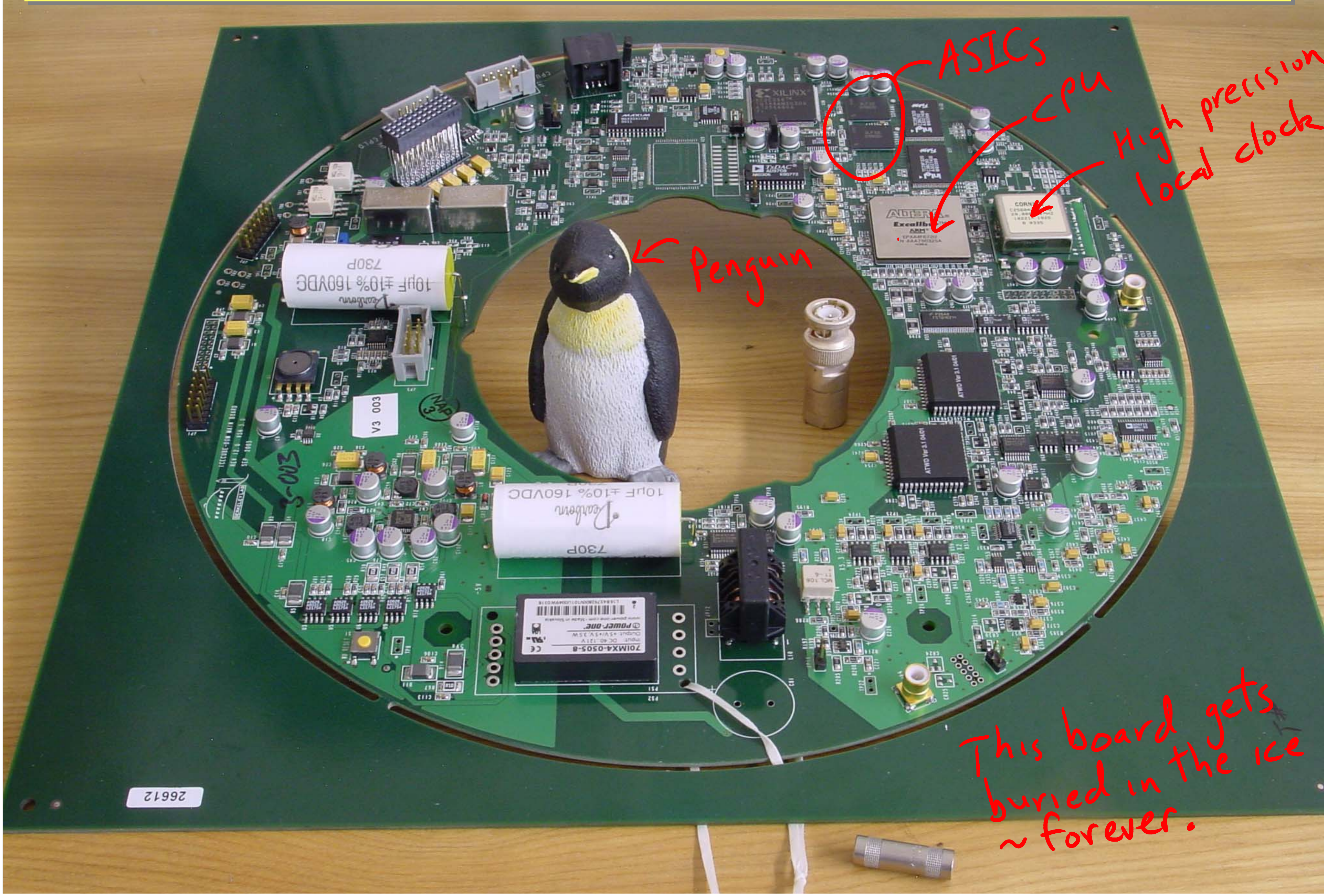
IceCube DAQ

- Very similar to those of other UHE neutrino experiments
- Remarkably, IceCube (and NESTOR, a UHE neutrino experiment off the Greek coast) use the *same* custom ASIC (the "ATWD" or Analog Transient Waveform Digitizer) as the much lower energy experiment, KamLAND
  - DAQ systems—and the people who know them—are often very portable across experiments
- The ANTARES experiment, off the coast of France, has a similar ASIC called the "ARS1"
  - I am told this is pronounced "A-R-S one" and not any other way

IceCube Digital Optical Module (DOM)

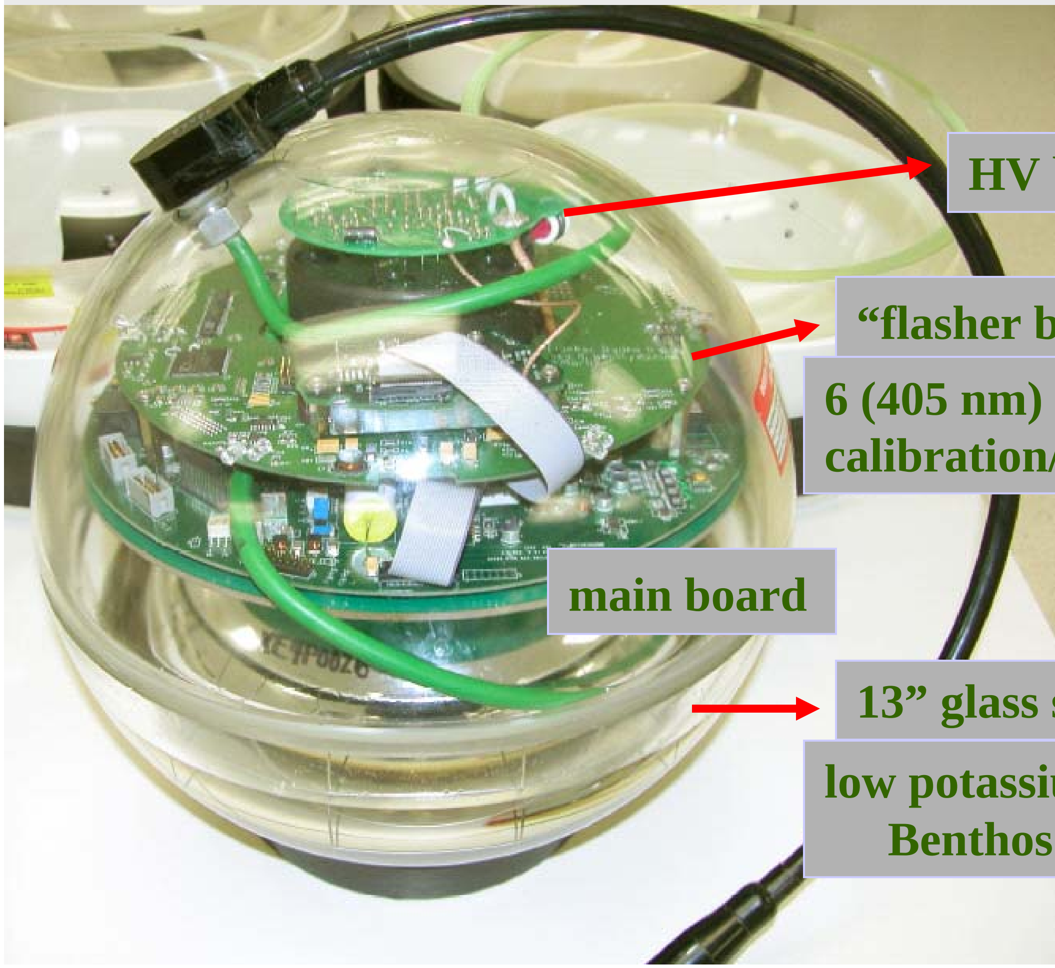


Digital Optical Module Main Board



DOM components

10” PMT



HV base

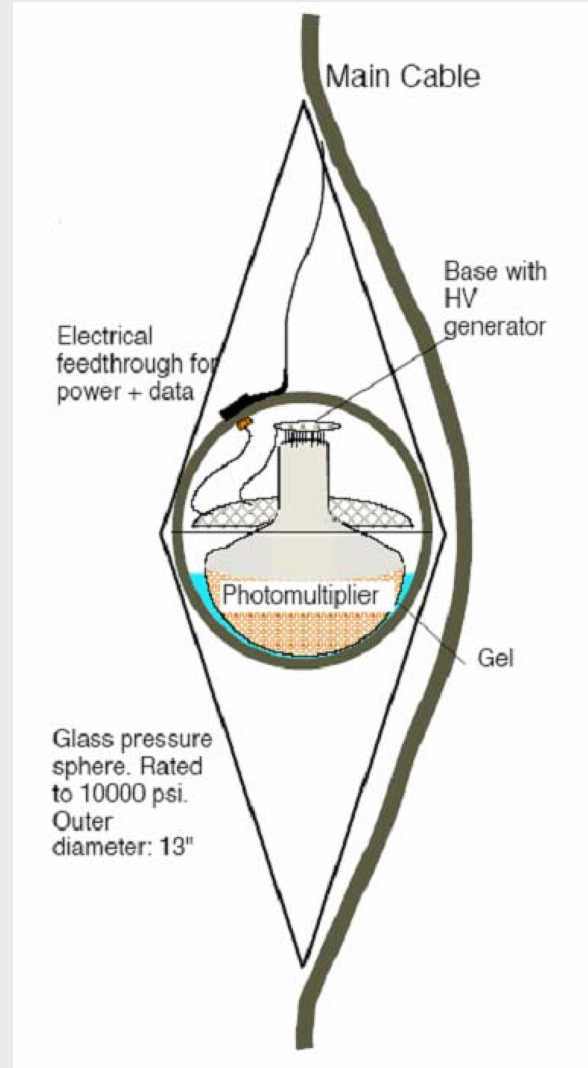
“flasher board”

6 (405 nm) LEDs ⇒ calibration/geometry

main board

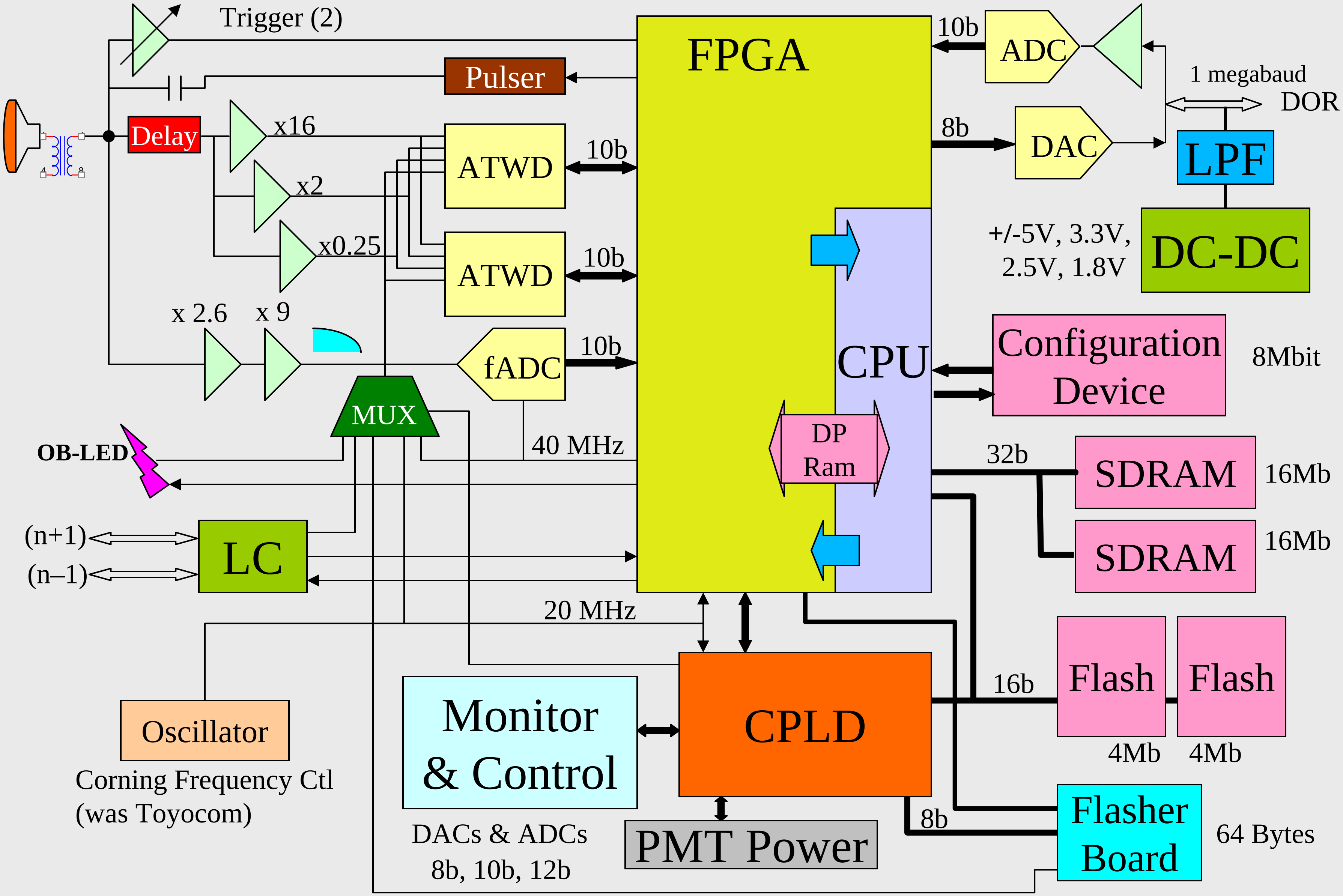
13” glass sphere

low potassium Benthos



schematics of OM prepared for deployment

DOM MB Block diagram: a mini-DAQ!



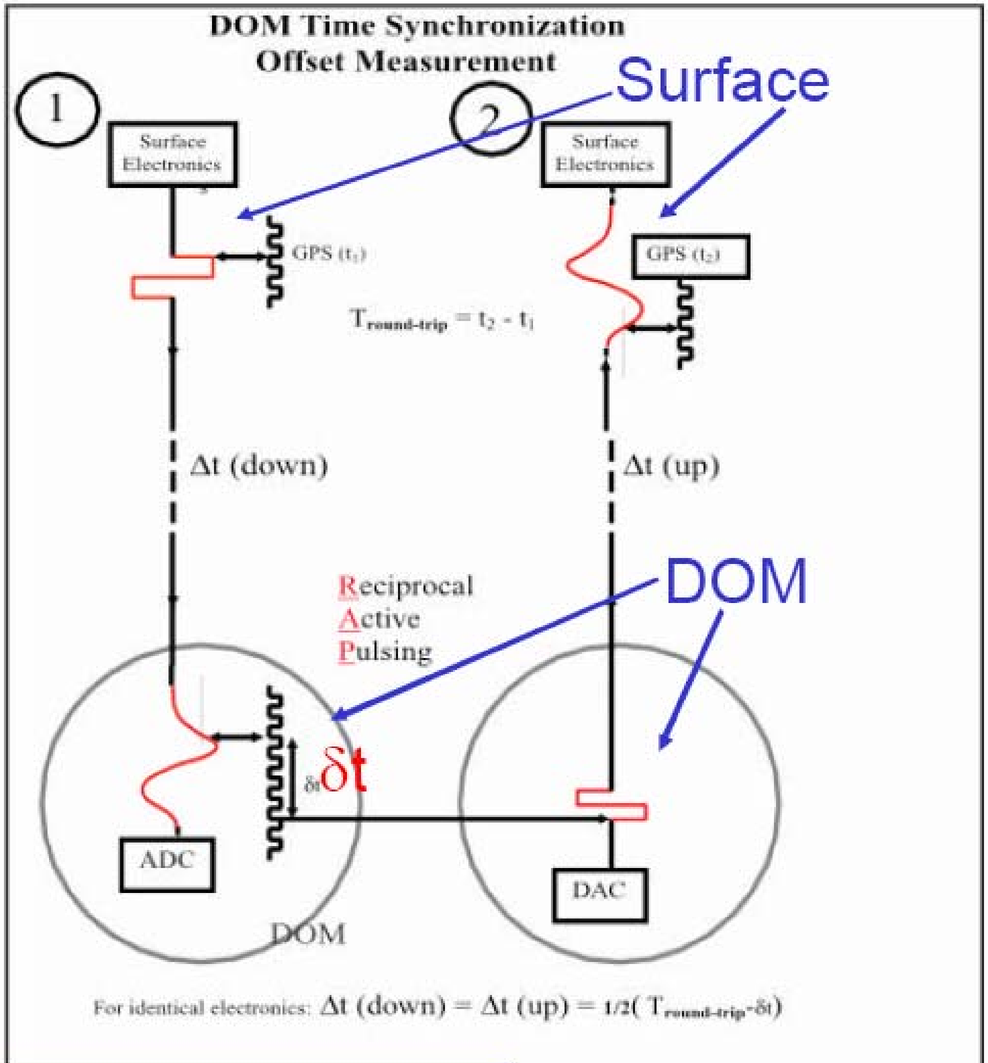
Major IceCube Challenge: Relative Timing

Time Synchronization

relative to the master clock

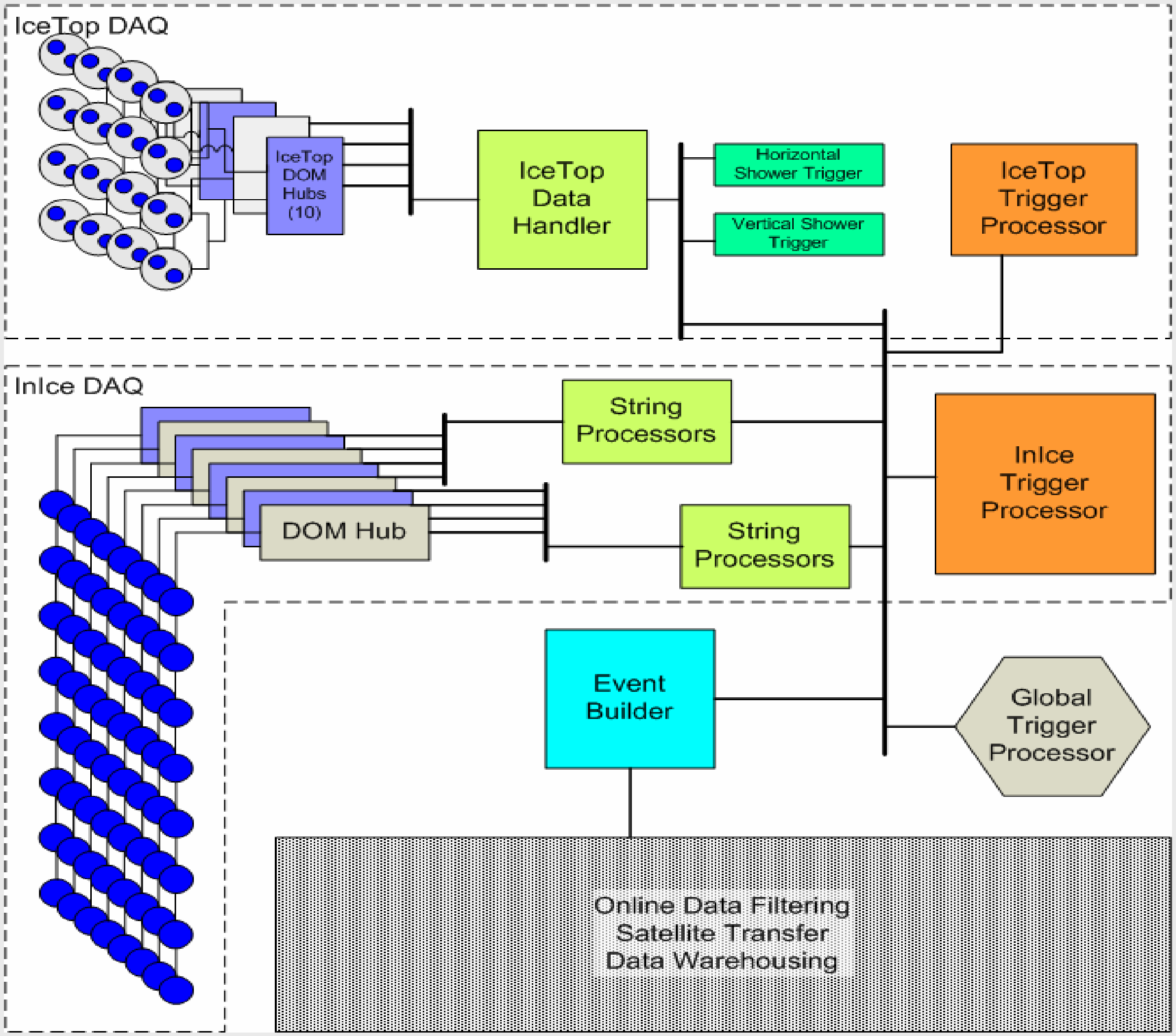
❖ Time calibration of individual DOMs achieved sending timing pulses synchronized to the master clock at known time intervals

❖ The time offset of each DOM determined from the round trip time of pulses (RAP)



$$\Delta t_{down} = \Delta t_{up} = 1/2(T_{round\text{-}trip} - \delta t)$$

IceCube DAQ diagram

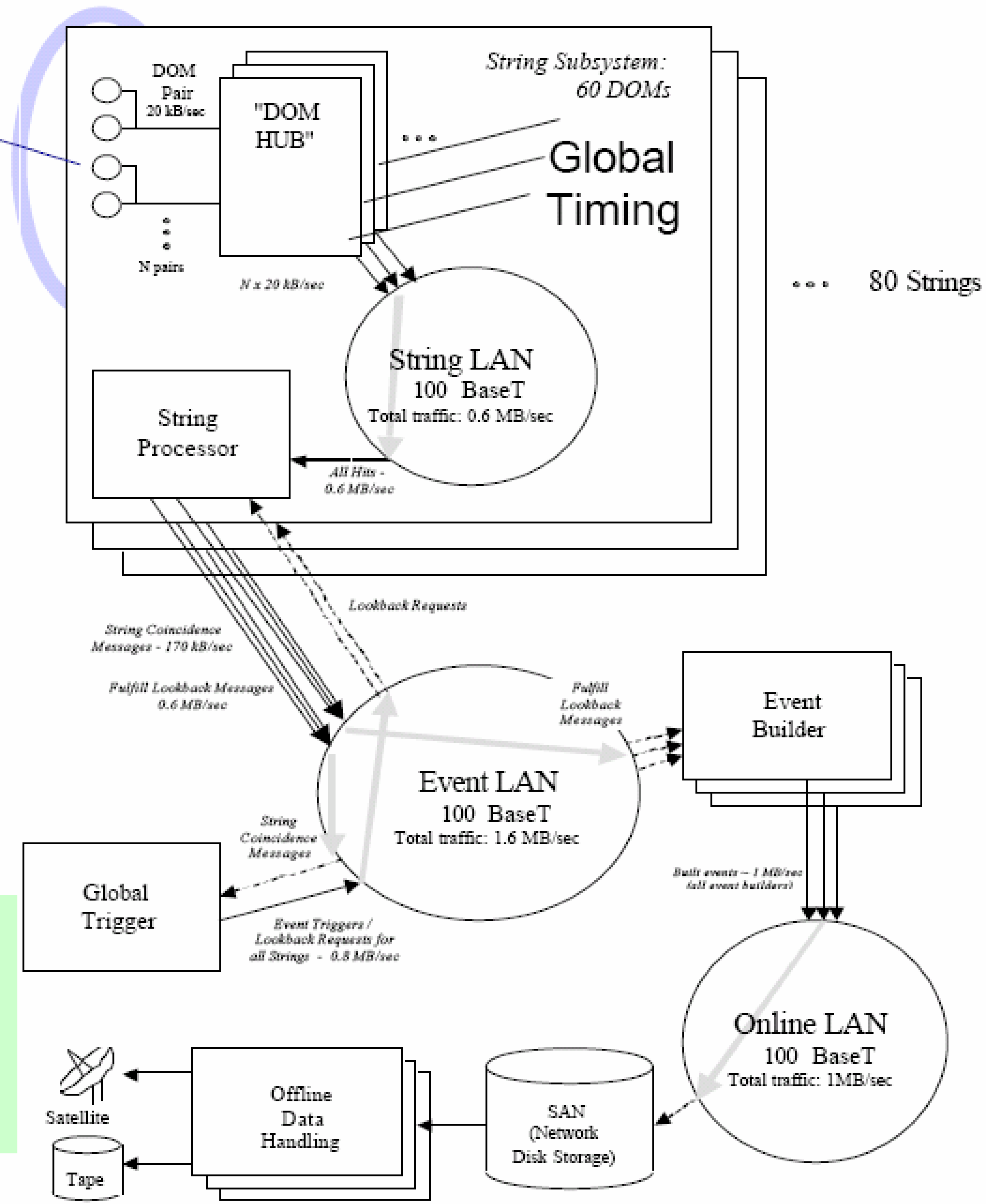


Requirements
- robustness
- long life
- insensitivity to EMI
- reasonable cost

Concept
- modularity
- network based implementation
- communication along twisted pair copper cables

String -
Electronics in the ice

DAQ Network Architecture



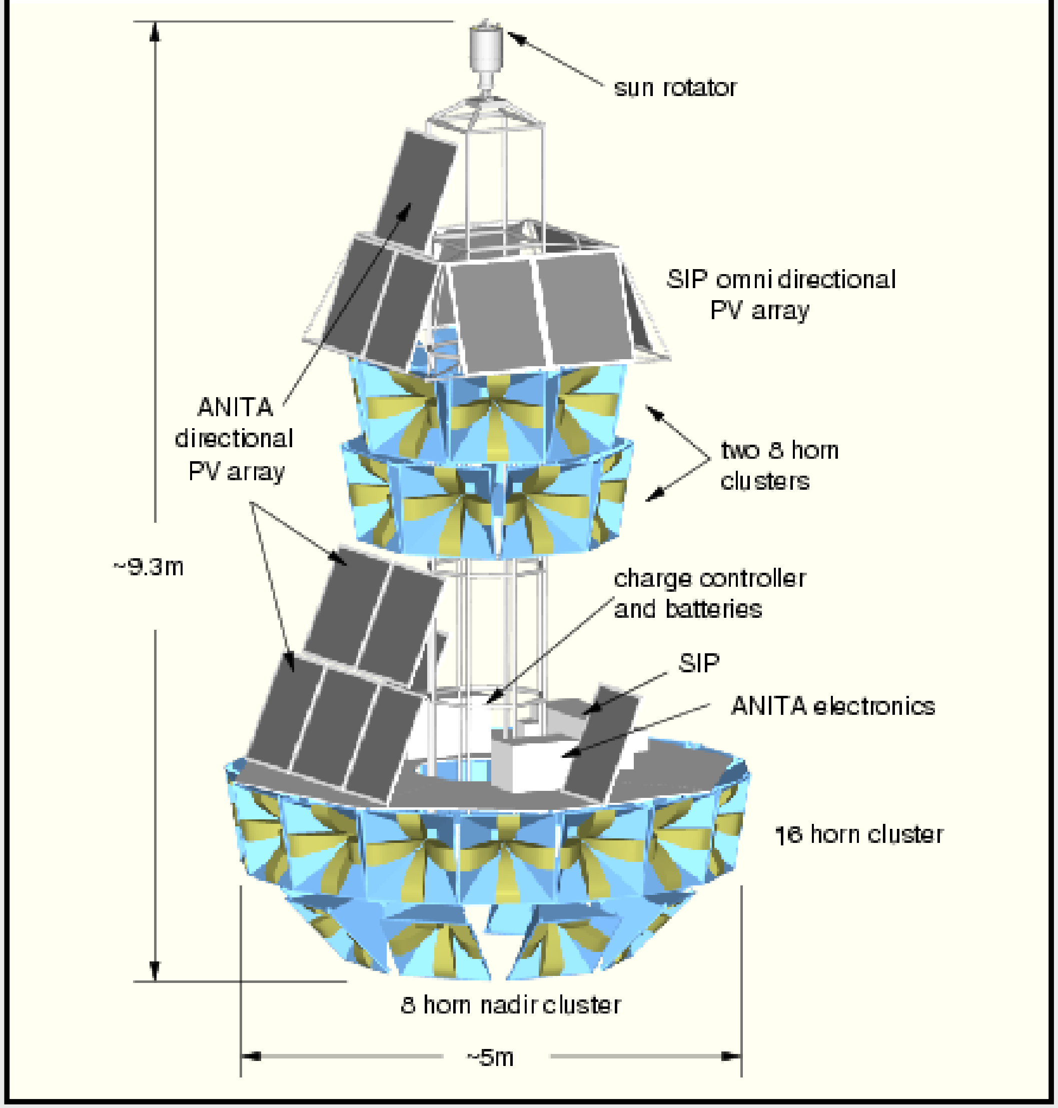
Expected data volume for full array after trigger
- 150 GB/day
- 28 GB/day after filtering

ANITA

- The ANtarctic Impulsive Transient Array is also looking for UHE neutrinos, but in a rather different way
- Interacting neutrinos can produce showers (cascades) which emit light
  - But the same cascades will also produce radio emissions, and will do so coherently
    - the size of the shower is comparable to the wavelength at 300MHz or so
    - This means LOTS of energy is dumped into the radio, and it goes as E^2, so the bigger the E_ν, the more radio energy
- ANITA aims to detect these radio emissions, produced by "GZK" neutrinos

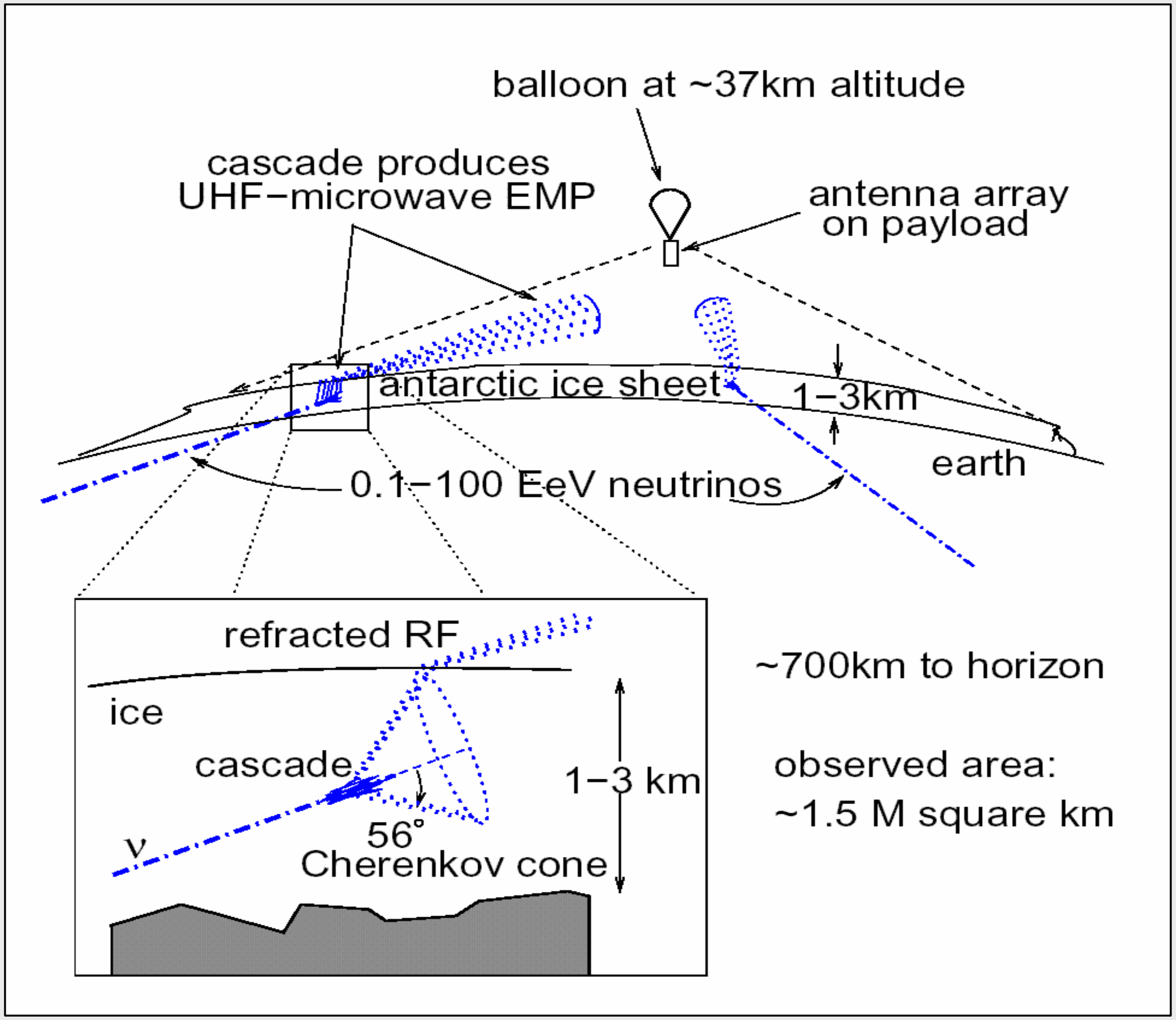
ANITA

South Atlantic Ocean
Cutaway View of Ice Sheet
Weddell Sea
Queen Maud Land
Flight Path
Enderby Land
Indian Ocean
South Pole
West
Antarctica
Marie Byrd Land
Ross Ice Shelf
East
Antarctica
Ross Sea
Victoria Land
Wilkes Land
South Pacific Ocean
McMurdo Station



sun rotator
SIP omni directional PV array
ANITA directional PV array
two 8 horn clusters
~9.3m
charge controller and batteries
SIP
ANITA electronics
16 horn cluster
8 horn nadir cluster
~5m

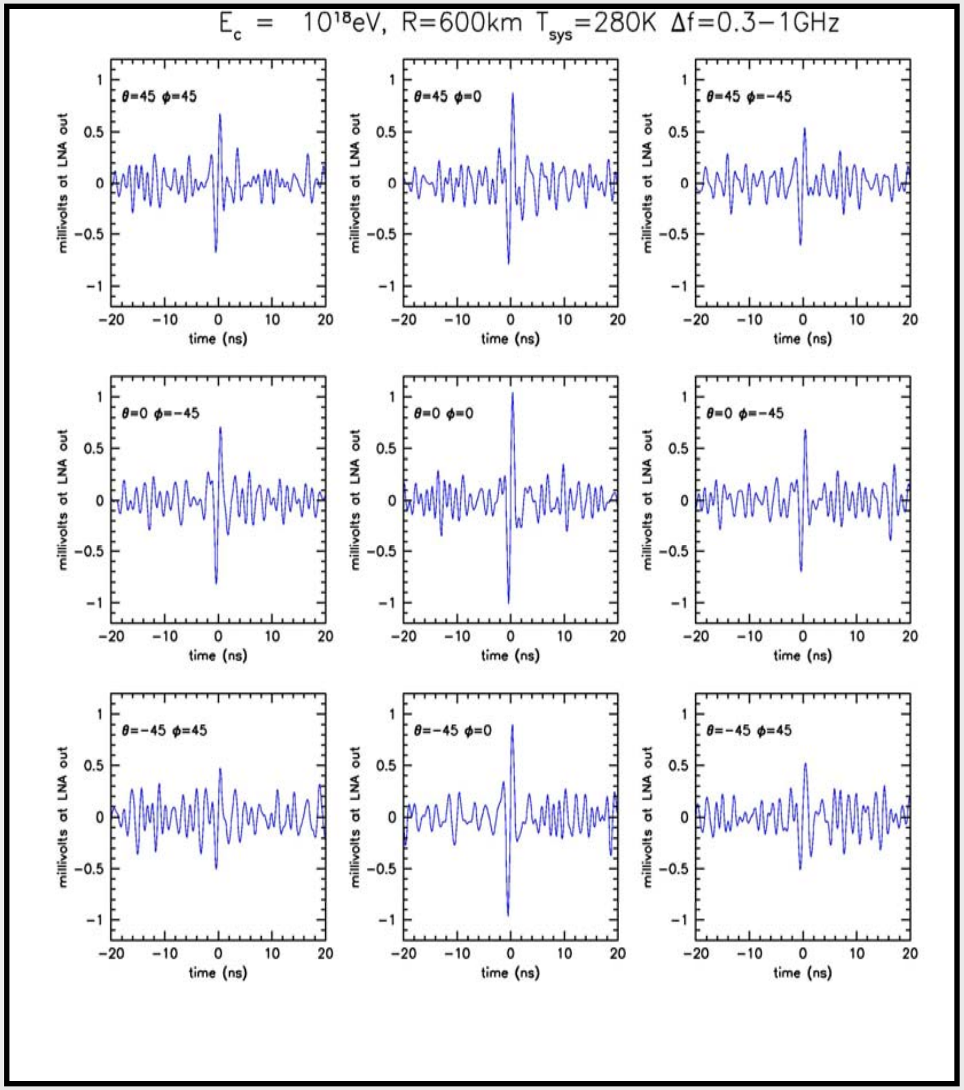
How ANITA Will Work



- Look for coincident radio pulses in several of ~40 antennae
  - signal pulses will be very short duration compared to expected backgrounds
  - can play tricks with polarizations too
- Loop around Antarctica; instrumenting *gigatons* of ice
  - but energy threshold is rather high: $10^{17\text{-}18}$ev

ANITA Signal (simulated)

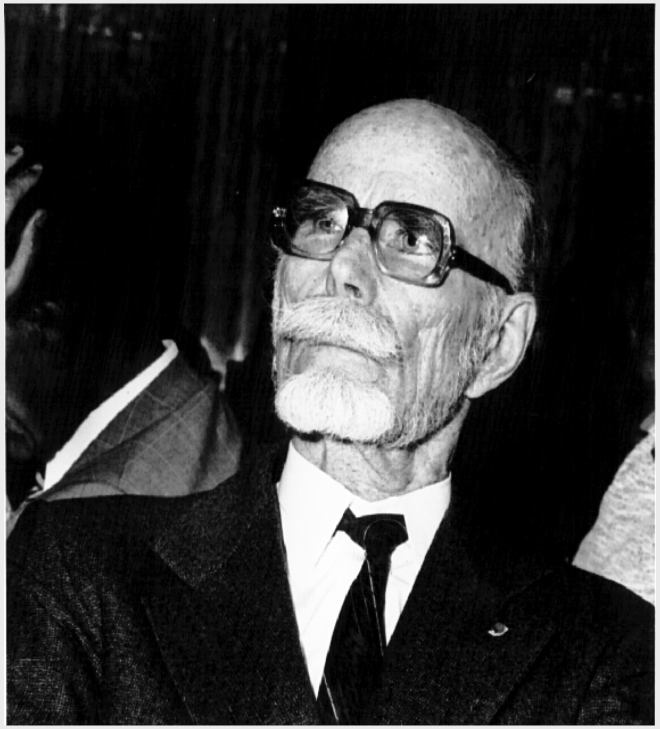
- Radio pulse seen in multiple antennae
  - excellent tool for beating down backgrounds
- On-board DAQ electronics includes
  - a waveform digitizer (a fast one)
  - stripped-down Linux system to process, store all interesting data and selectively ship especially interesting subset via slow satellite link to base station
  - All data is written to disk on the payload and recovered after the balloon gently drifts back to the ground



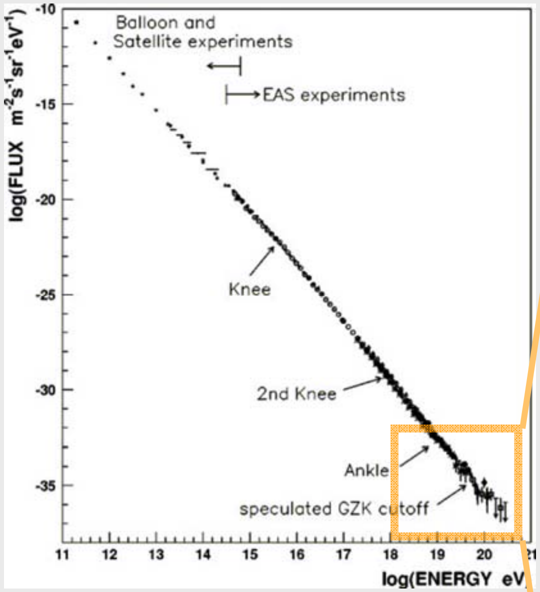
"Recovery" of ANITA-Lite

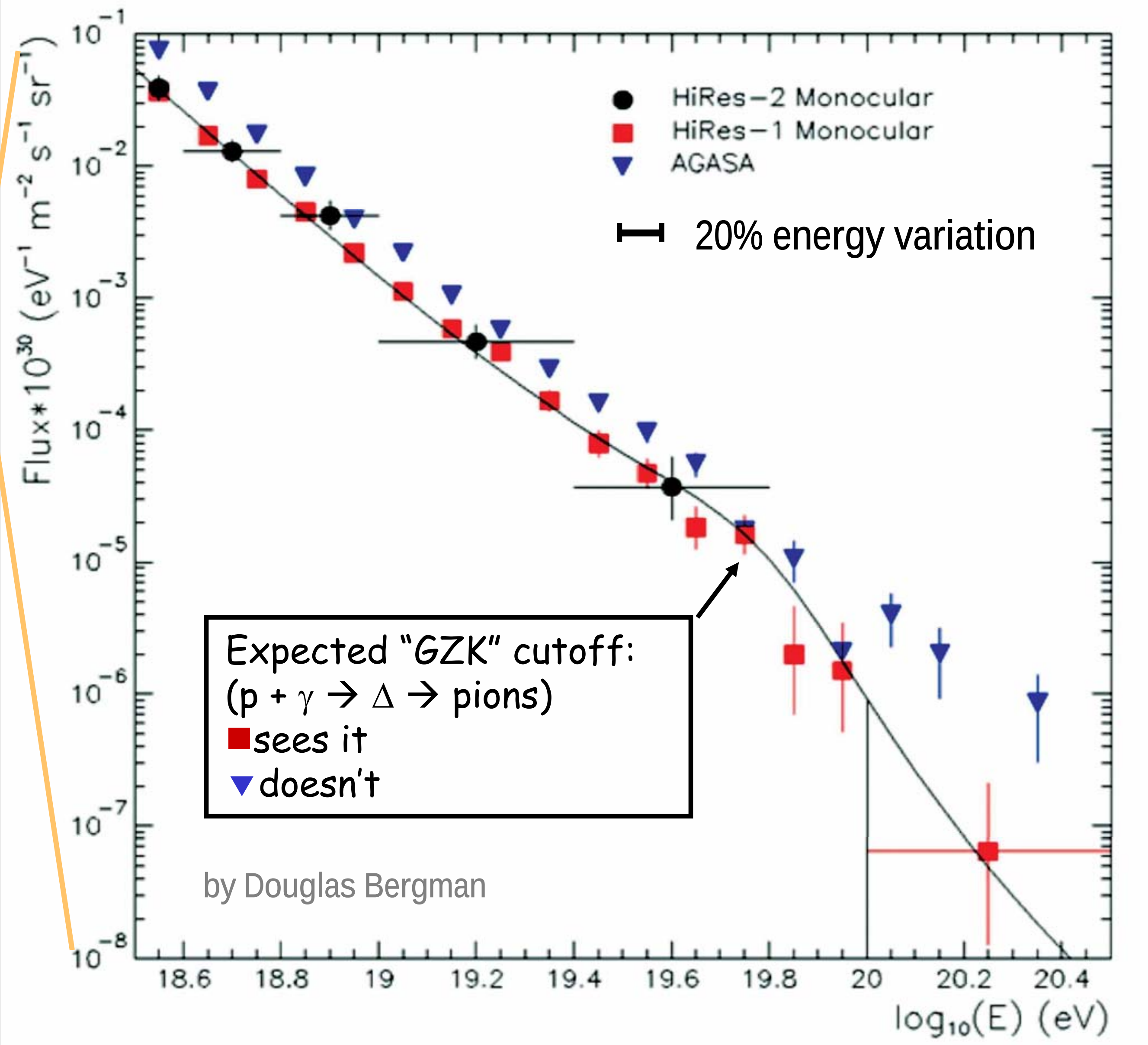
Pierre Auger

- Named after Pierre Auger, the discoverer in 1938 of extended air showers, the Auger experiment aims to study the enigmatic ultrahigh energy cosmic-rays (UHECR) at $E \geq 10^{18}$eV
  - Note: this is a *HUGE* amount of energy for a single particle to have...
- Other air shower arrays have done this using one of two main techniques
  - surface based particle detectors
  - fluorescence telescopes



The UHECR "Problem"



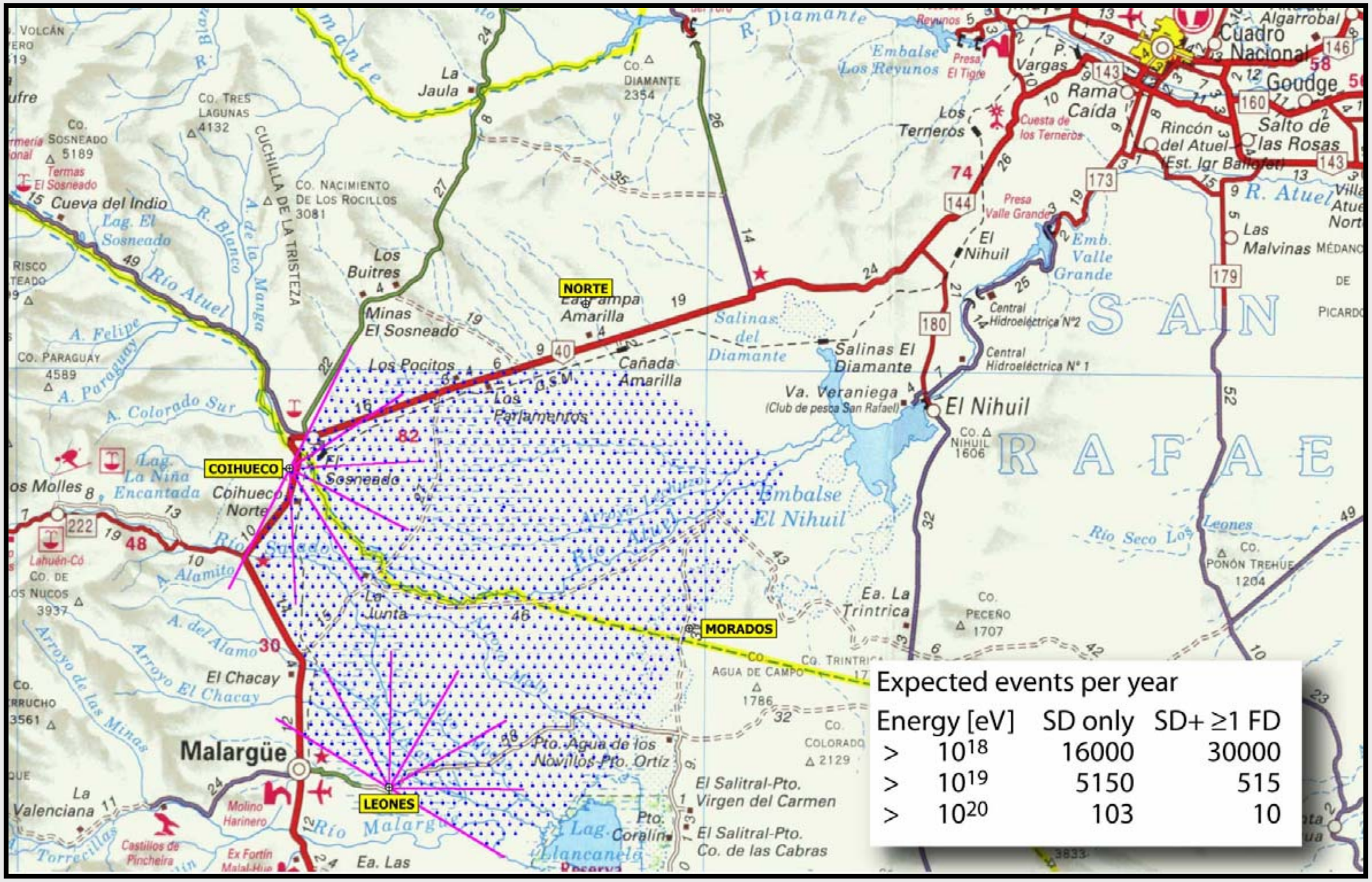


Auger Will Look at UHECR Both Ways, Simultaneously

- 1600 water Cherenkov detectors (SDs)
  - 1.5 km spacing
  - 3000 km^2 coverage

Plus…

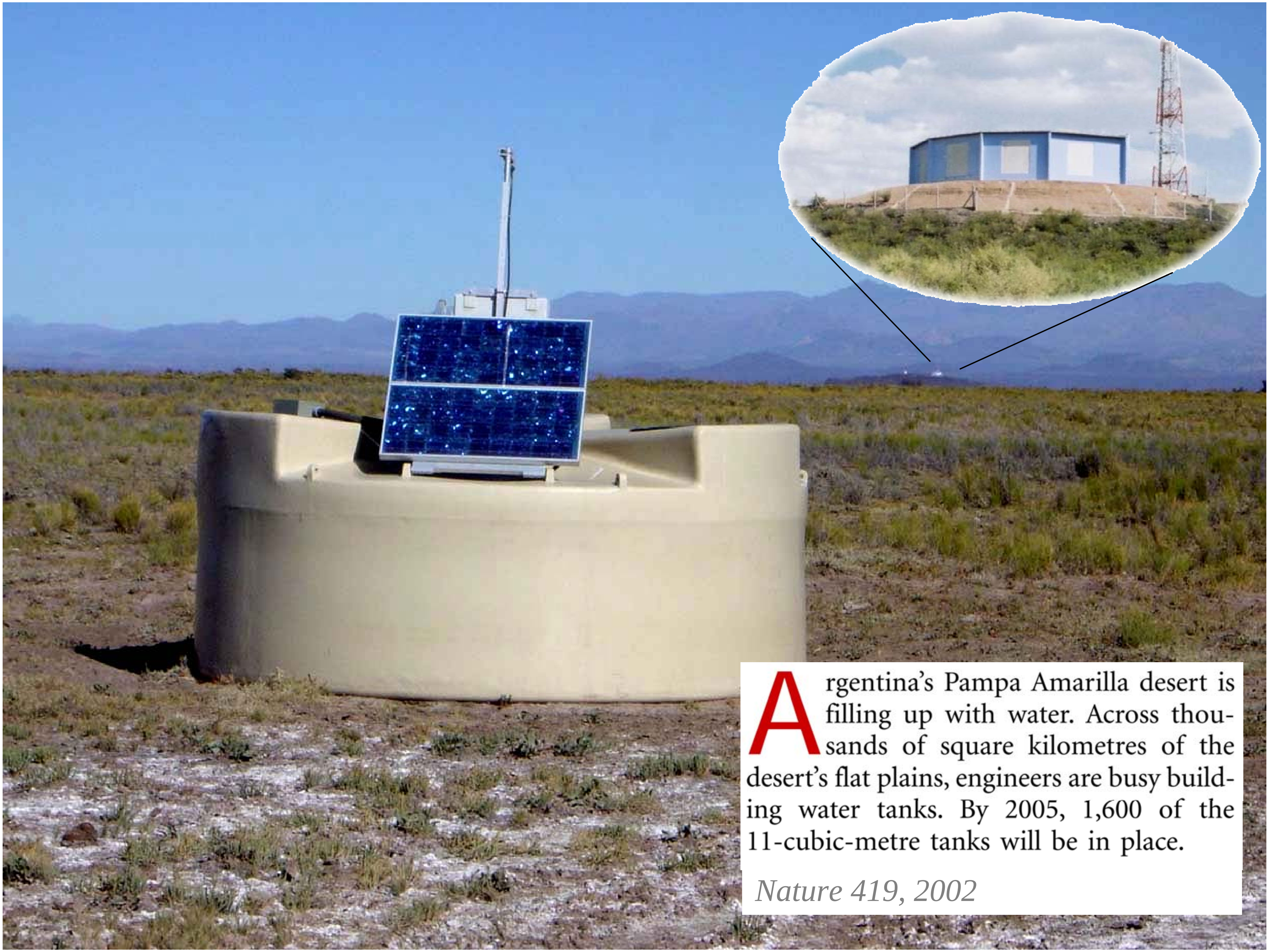
- 4 stations with 24 fluorescence detectors (FDs)
- Having it both ways will reduce systematical uncertainty in energy measurement

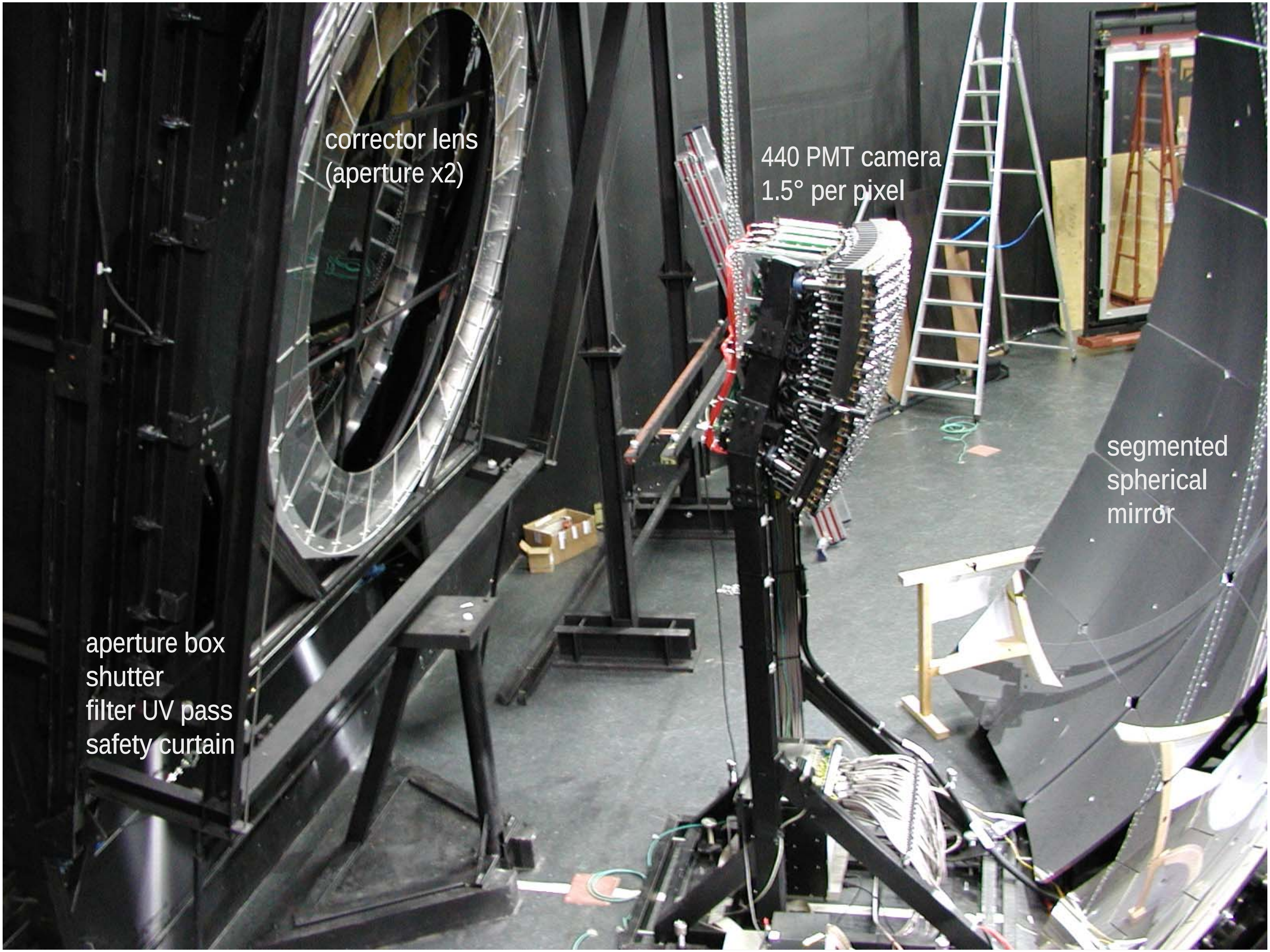


Expected events per year

Energy [eV]	SD only	SD+ ≥1 FD
> 10^{18}	16000	30000
> 10^{19}	5150	515
> 10^{20}	103	10

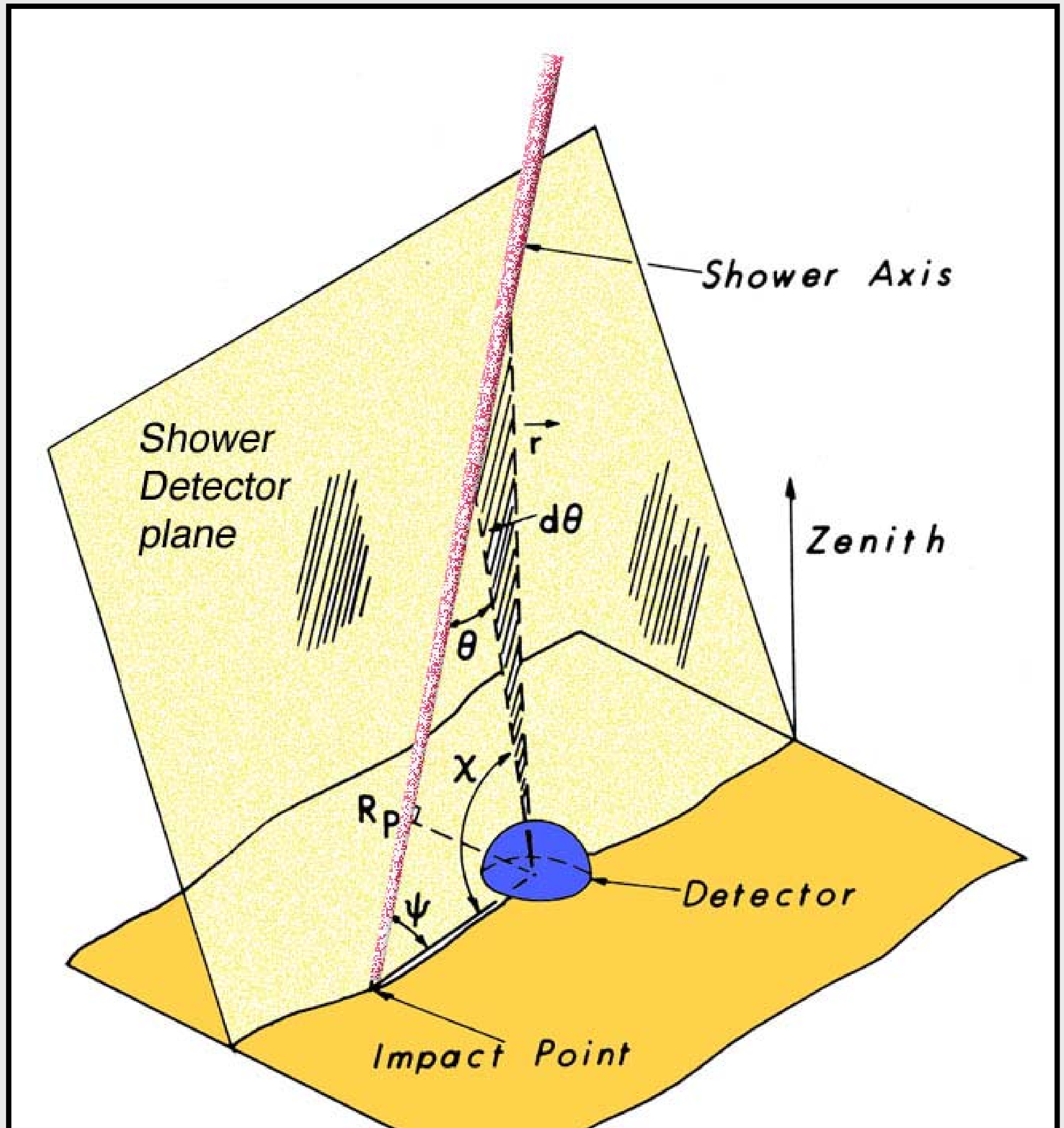
Argentina (on the Pampas)


Argentina's Pampa Amarilla desert is filling up with water. Across thousands of square kilometres of the desert's flat plains, engineers are busy building water tanks. By 2005, 1,600 of the 11-cubic-metre tanks will be in place.
Nature 419, 2002


corrector lens
(aperture x2)
440 PMT camera
1.5° per pixel
segmented
spherical
mirror
aperture box
shutter
filter UV pass
safety curtain

How Auger Will Work

PIERRE AUGER OBSERVATORY

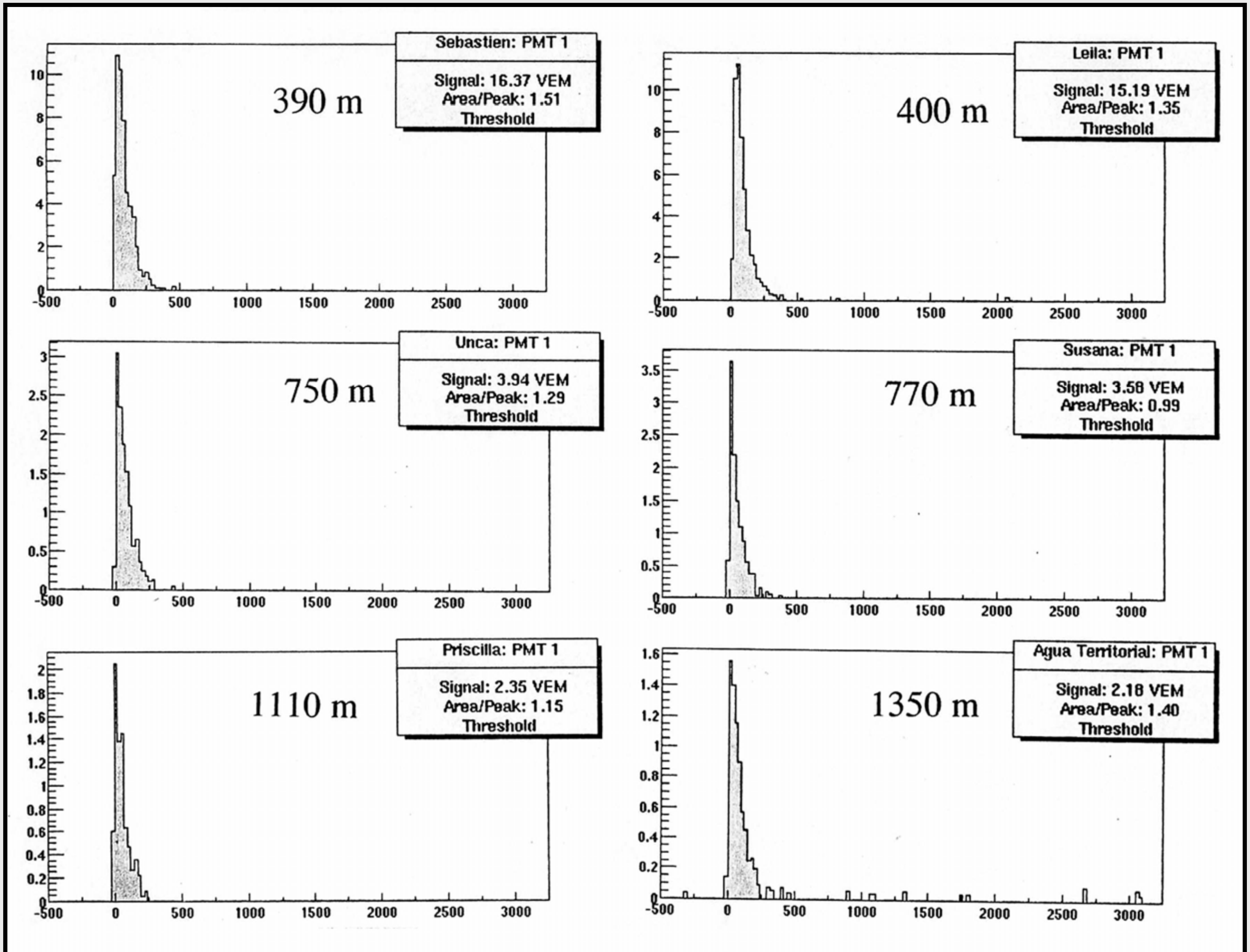


from Fly's Eye 1985

How Auger Will Work

- Using energy measurements and relative timing in the tanks, it can determine the vertex, direction, and energy of the shower
- Part of the time (dark moonless nights) it can also compare these measurements to those obtained with the fluorescence telescopes on a *shower-by-shower* basis
- This combined measurement will give a more reliable measure of the shower energy

Auger Signals: Digitized PMT Pulses!



Auger DAQ

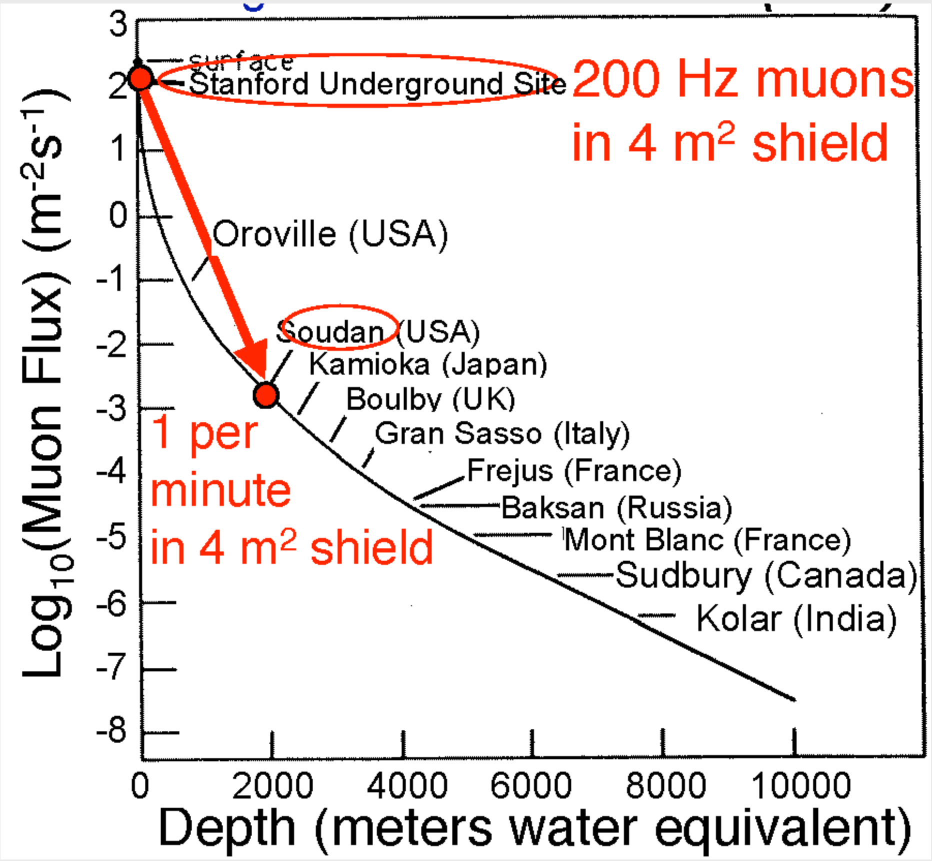
- One of the biggest challenges for Auger was how to provide power to each tank, and then how to gather up all the signals from all the tanks
  - running cables between them all was out of the question—the distances were too great! Would have been too expensive, and cows would have wreaked havoc, not to mention jeeps, tractors…
- Clever solution: use solar power and cell-phone technology!
  - each tank is equipped with a bank of solar panels for power
  - each tank has electronics to convert its signals to cell phone frequencies for transmission to a central location for further processing

CDMS-II

- The Cryogenic Dark Matter Search II is one of a number of experiments trying to perform *direct* detection of dark matter
  - "direct" implies a design in which dark matter interacts in, and is detected by, the experiment
    - In CDMS-II, a WIMP dark matter particle would
      - rattle the crystal lattice, creating a detectable phonon
      - create detectable ionization
    - Paramount to reduce backgrounds by any means possible
  - ("indirect" by contrast means one aims to detect the *by-products* of dark matter interactions and thereby infer its existence and its properties)
- CDMS-II is presently at the forefront of this field of experiments

CDMS-II Location

- CDMS-II is a "table top" sized expt.
- It is very sensitive to backgrounds, especially neutron backgrounds
  - neutrons are due largely to cosmic-ray activity
  - Solution: Go Deep

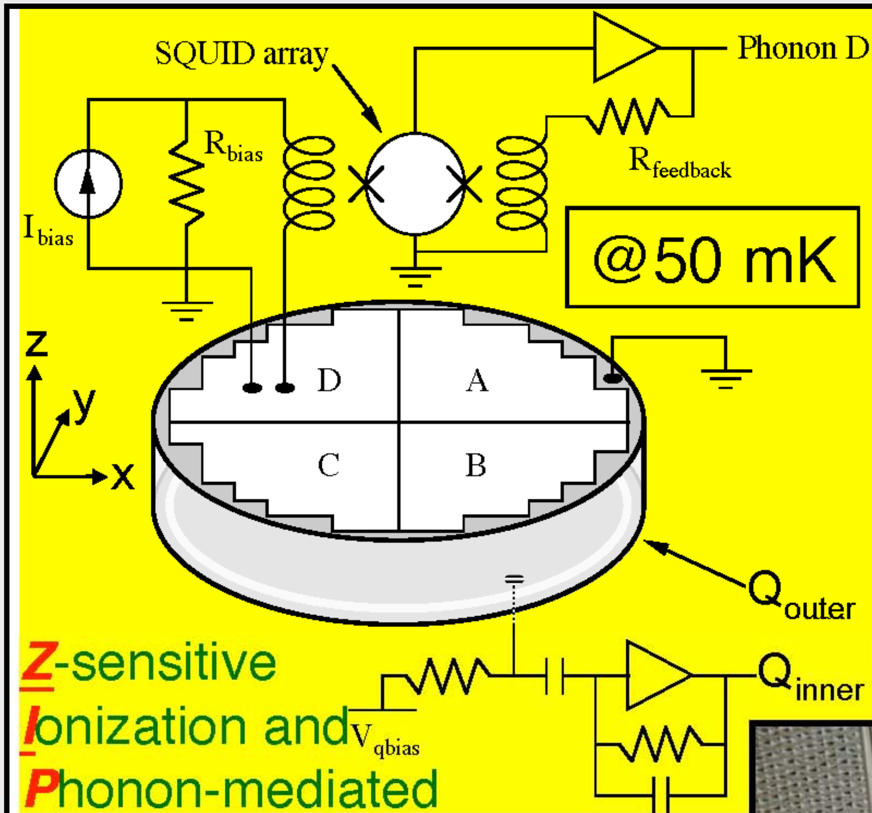


CDMS-II Sacrifice in the Name of Science

Sunny, warm Stanford, California

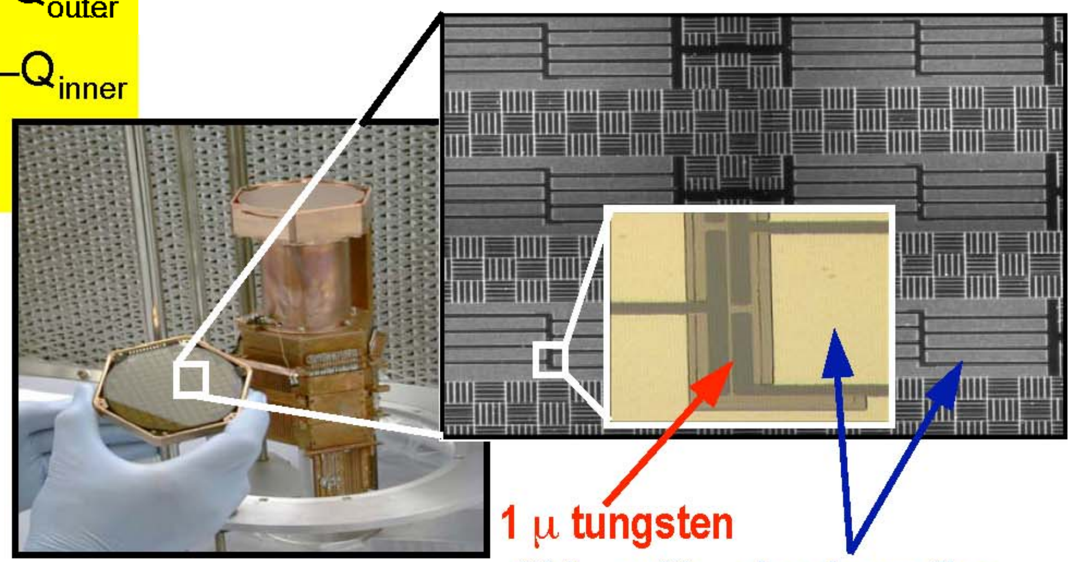
Soudan Mine, Minnesota

How CDMS-II Works



- 250 g Ge or 100 g Si crystal
- 1 cm thick x 7.5 cm diameter
- Photolithographic patterning
- Collect athermal phonons
  - Phonons propagate, some reach surface
  - At surface, phonon energy converted into quasi-particles (e^- pairs)
  - These e^- pairs migrate to Tungsten, which is held at the brink of a SC→Normal transition; e^- pair pushes it over brink

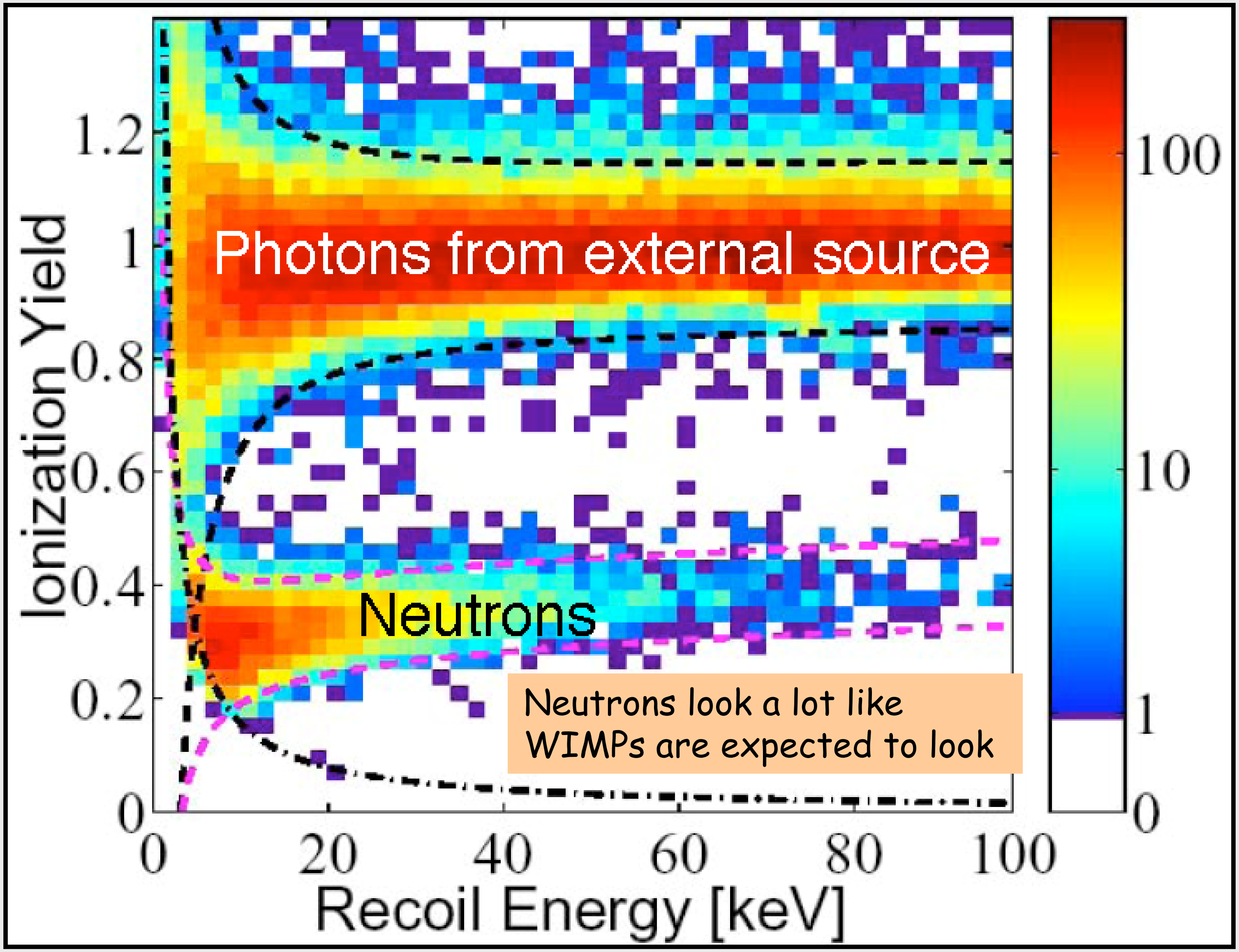
Measure ionization in low-field (~volts/cm) with segmented contacts to allow rejection of events near outer edge



CDMS - Neutrino 2004

Richard Schnee

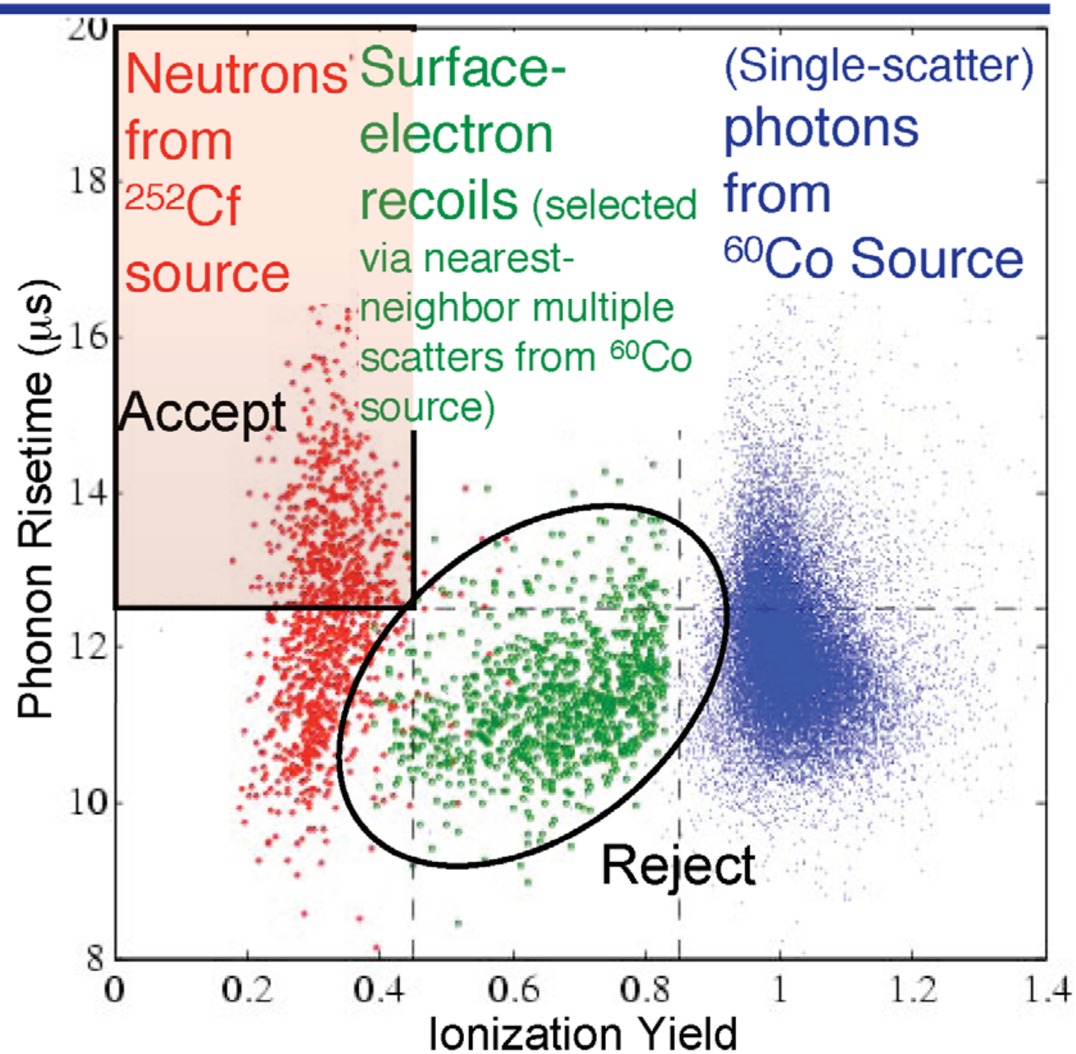
CDMS-II Signals: Calibration Sources



CDMS-II Signals: Calibration Sources

ZIP Z-Position Sensitivity Rejects Electrons

- Events near crystal surfaces produce different frequency spectrum of phonons
- These phonons travel faster, result in a shorter risetime of the phonon pulse
- Risetime cut eliminates the otherwise troublesome background surface events
- >99% above 10 keV



CDMS - Neutrino 2004 Richard Schnee

CDMS-II DAQ

- This is a very low rate experiment, so the DAQ requirements are not very stringent
- Commercial off-the-shelf (COTS) products are used, from hardware (commercial ADCs) to software (LabView)
- Main challenge: making the whole thing remotely controllable, so people did not have to live in a mine in Soudan, Minnesota
  - accomplished using modern software techniques (Java with RMI, etc.)

LIGO

- The Laser Interferometer Gravitational-Wave Observatory is the first of a new generation of gravitational-wave detectors
  - LIGO is one of several such instruments now operating
    - TAMA (Japan), Virgo (Italy), GEO (Germany), AIGO (Australia)
- LIGO works using interferometric techniques which give it astounding sensitivity to motion
  - Whether this sensitivity will be sufficient to detect gravitational-waves is another question!

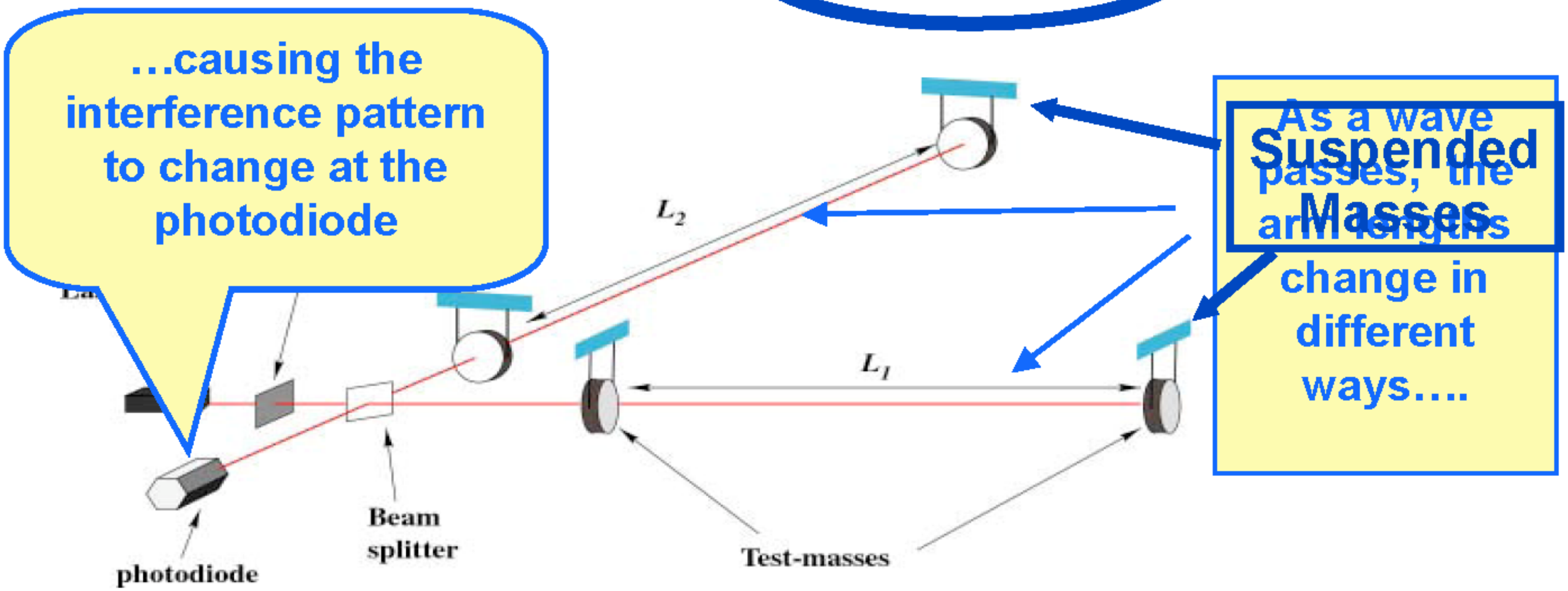
LIGO Locations

- Louisiana and Washington, USA
  - Far removed from most human activity to avoid vibrational noise
  - two sites used to attain important redundancy in measurement

Louisiana site
(another a sacrifice in the name of science)

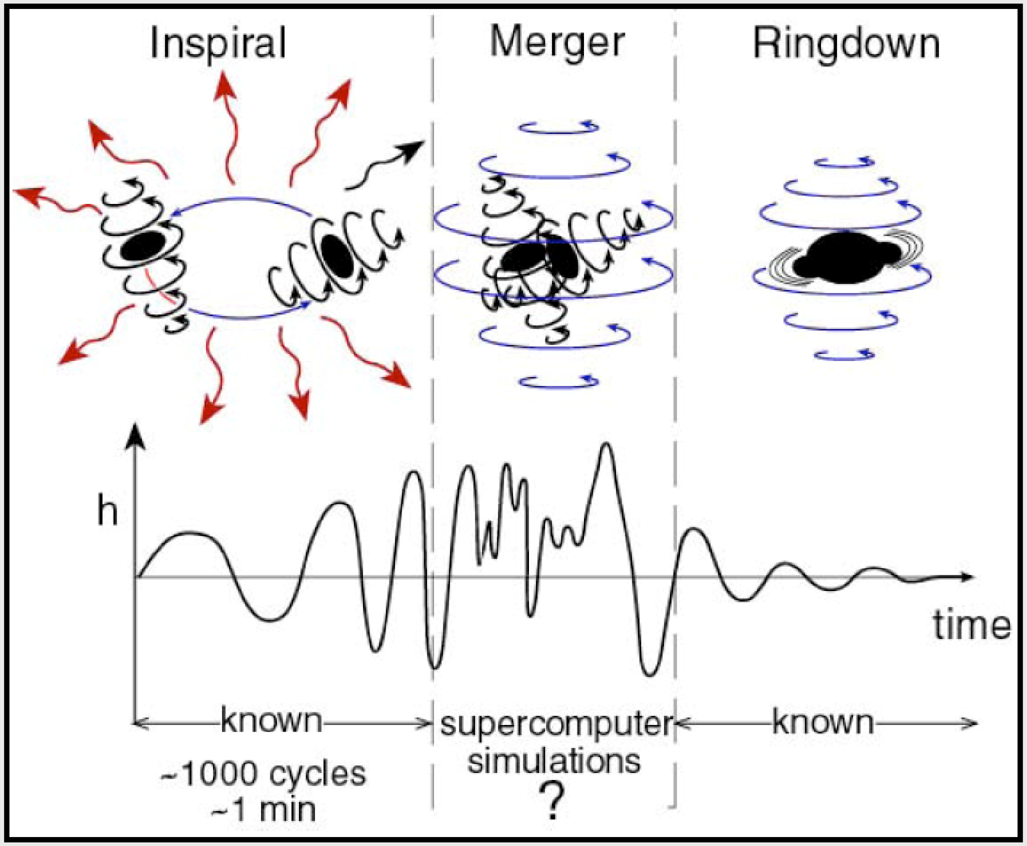
How LIGO Works

- Laser used to measure relative lengths of two orthogonal arms
- Arms in LIGO are 4km
- Measure *difference in length to one part in 10^{21} or 10^{-18} meters*



Possible LIGO Signals

- Chirps
  - Compact binary inspiral
- Bursts
  - Supernova/GRBs
- Periodic
  - Galactic pulsars
- Stochastic
  - Cosmological signals from early universe



Compare data to templates, like this one, to search for possible signals.

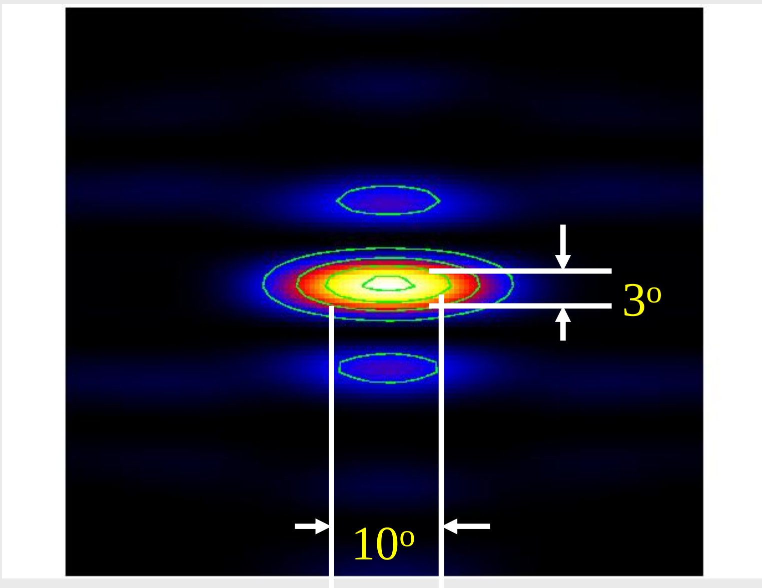
LIGO DAQ

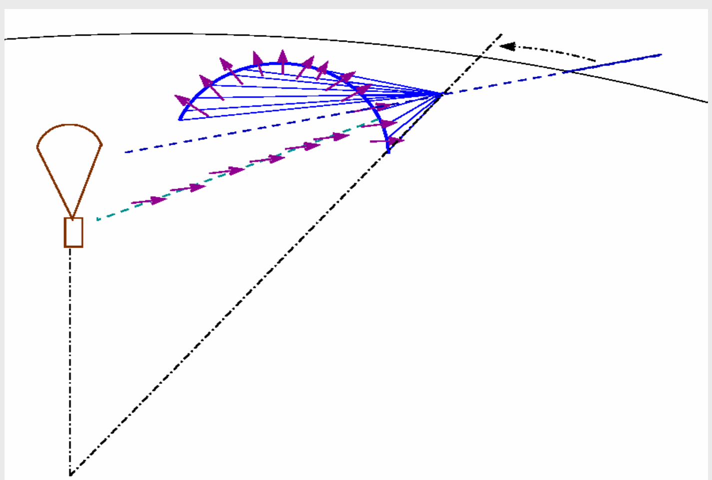
- Digitize signals with commercial ADCs
- Collect data at 1.6TB/day
- As with other detectors, run 24/7

Detectors and DAQ: Conclusions

- Particle astrophysics detectors exhibit striking variety
  - Indeed, this pair of lectures has only covered a representative subset of these detectors
- However, there are salient similarities
  - underlying technology in DAQ is very similar
  - many detectors use PMTs as their fundamental detector sub-element
- The field is clearly building on the previous detector-building experience of its scientists, while at the same time being extremely innovative
- Experimental particle astrophysicists are rising to the challenge, and having fun doing it!

ANITA as a neutrino telescope





- Pulse-phase interferometer (6 antennas assumed) gives intrinsic beamsize of ~3° elevation by ~10° azimuth for arrival direction of radio pulse