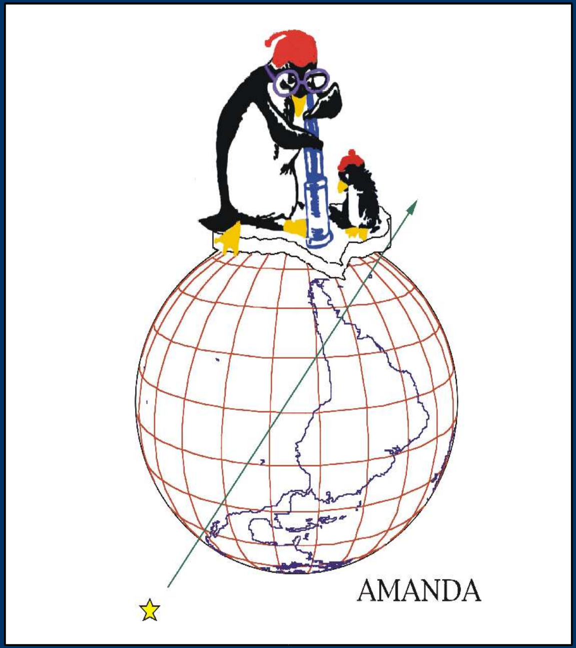
IceCube
the cubic kilometer neutrino telescope at the South Pole

The technology built on the Amanda detector concept & experience



Klaus Helbing

October 2004

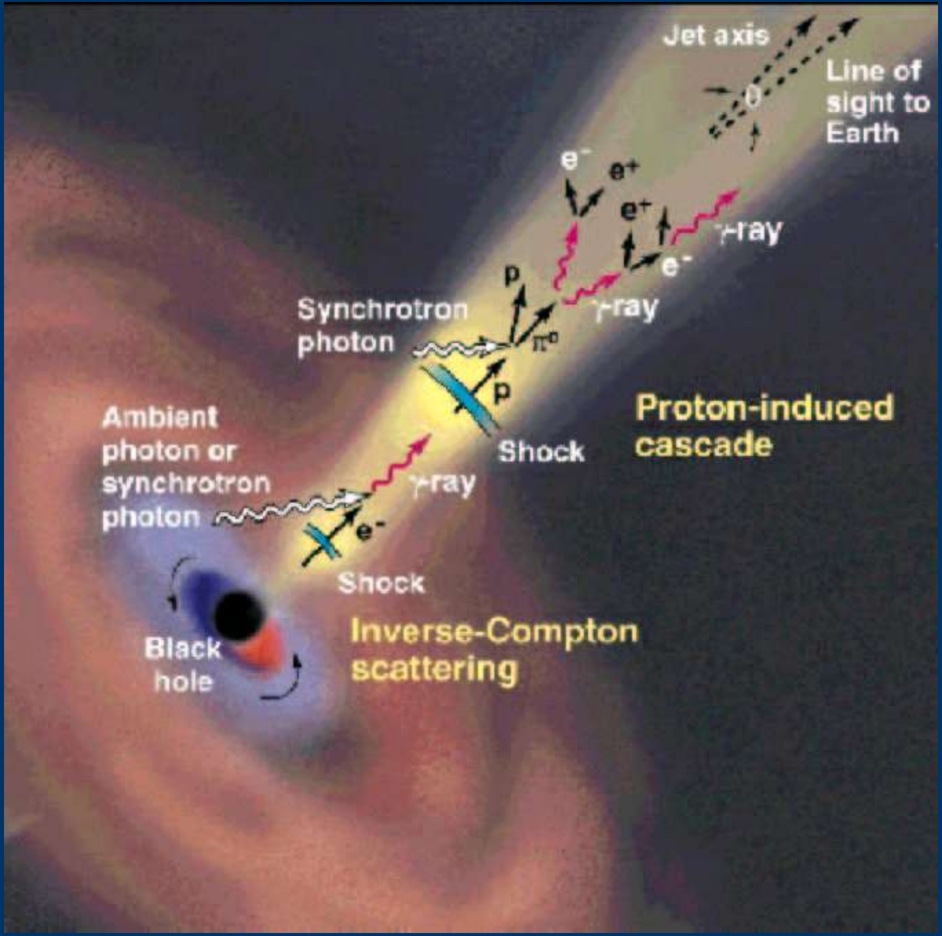
Outline

- Physics motivation: Astronomy, Cosmology
  - Origin of cosmic rays (→ K. Mannheim)
- High energy neutrino detection techniques
- Neutrino telescopes using Cerenkov light
- Amanda, IceCube: Particle detector
  - Layout
  - Expected performance
  - Technology
  - Waveform applications
    - Time synchronization with waveforms
    - PMT waveform compression
    - PMT waveform analysis
  - Single string reconstruction

- *Life(?) at the South Pole (→ Ch. Spiering)*

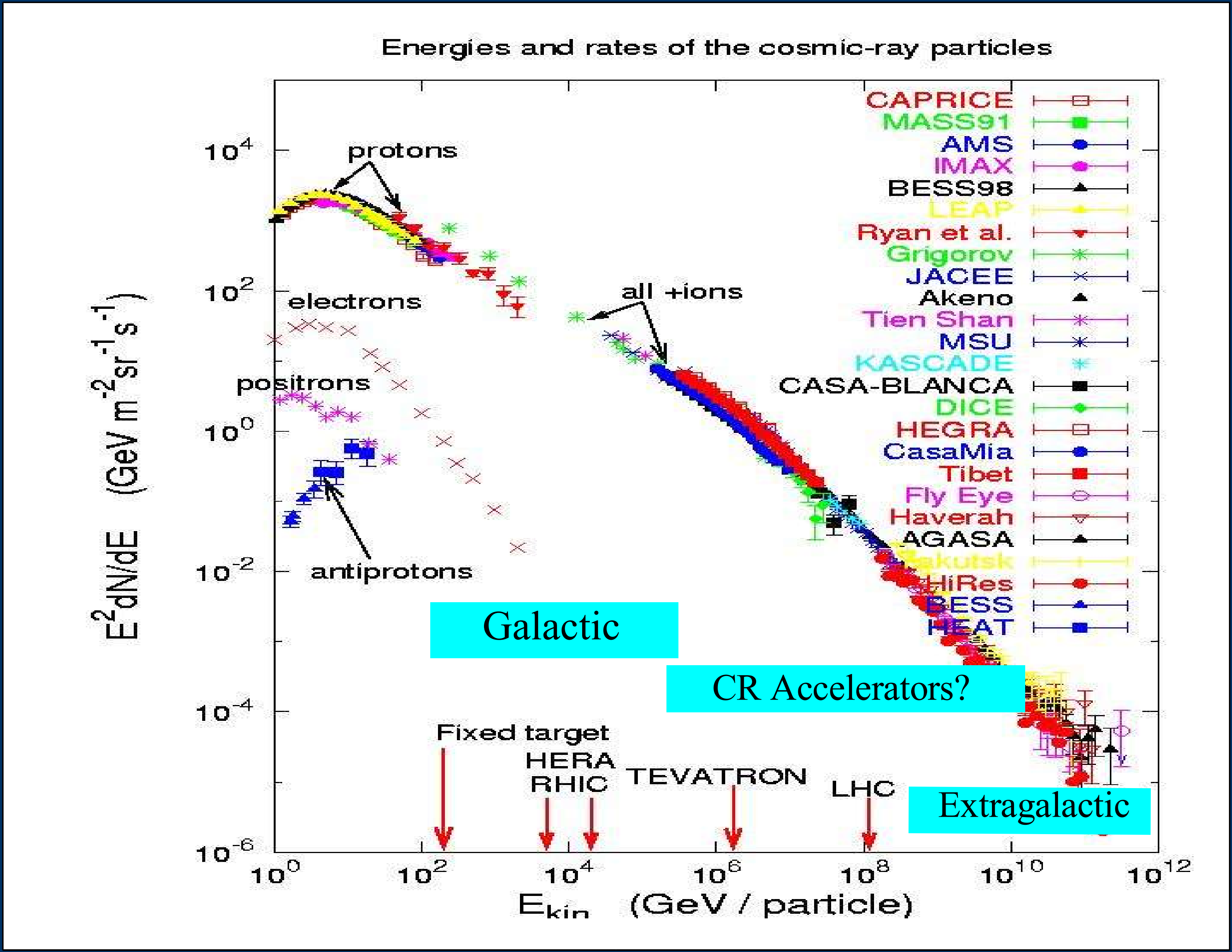
Objects of investigation

- **Origin and acceleration of cosmic rays**
- **Discovery of new cosmic objects**
- Neutrino properties
- Dark matter (WIMP annihilation)
- Search for big bang relics
- Test of relativity
- Effects of extra dimensions
- .....

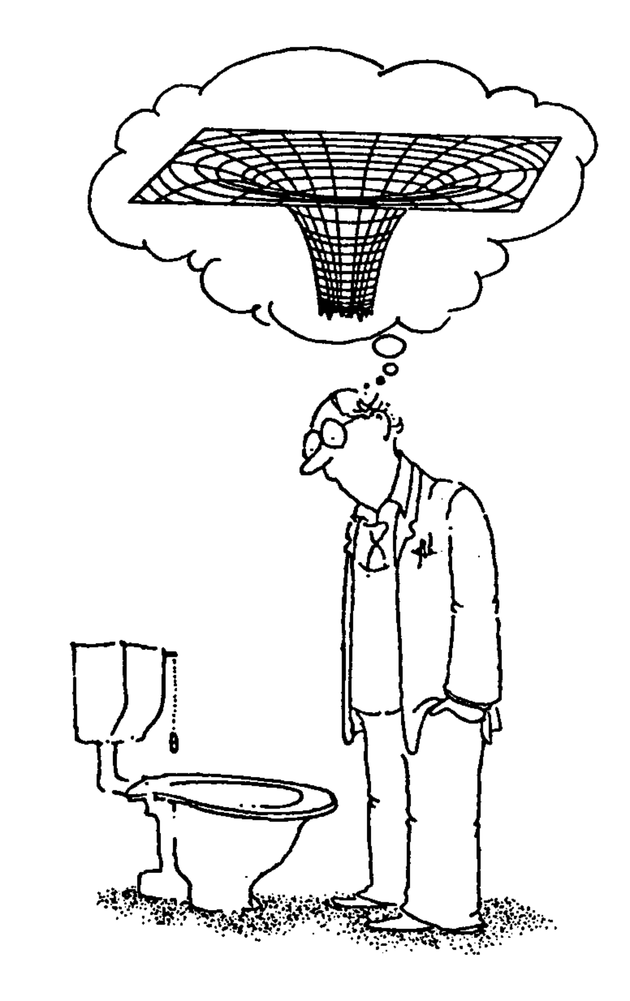


Promise of sheer size: Discovery of unexpected phenomena

Origin of Cosmic rays

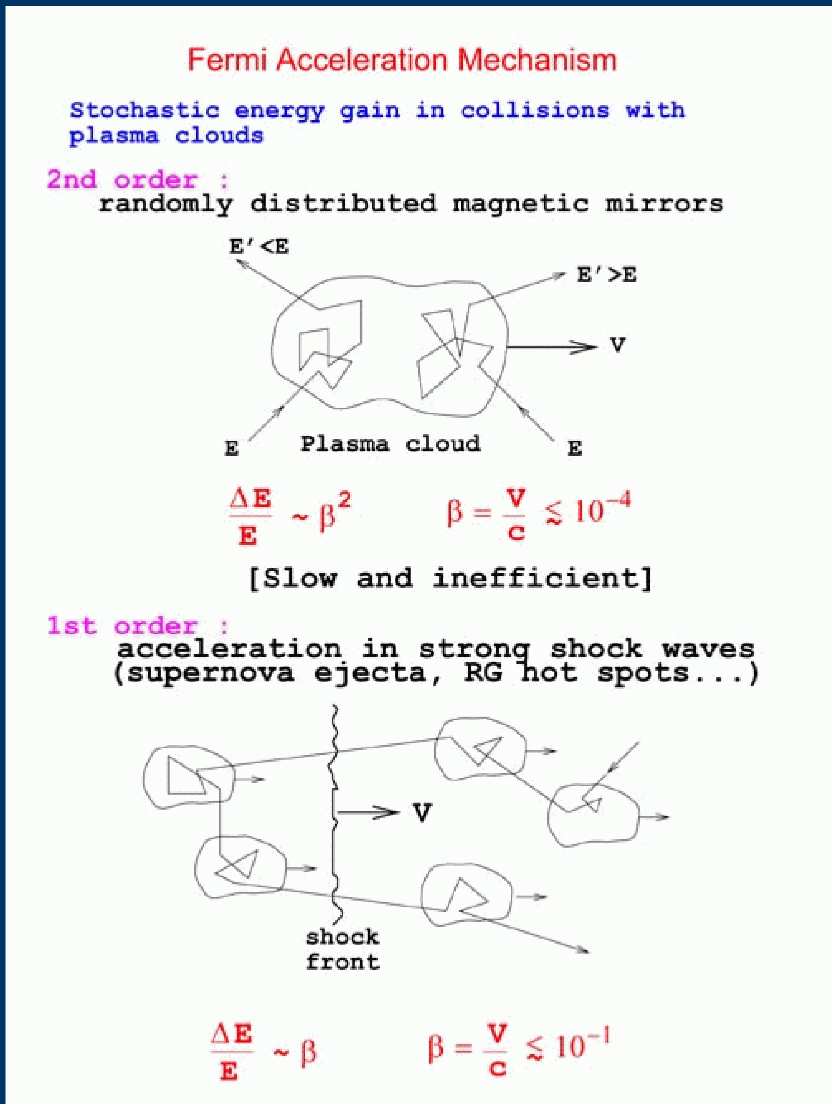


Acceleration to 10^{20} eV (100 EeV)?

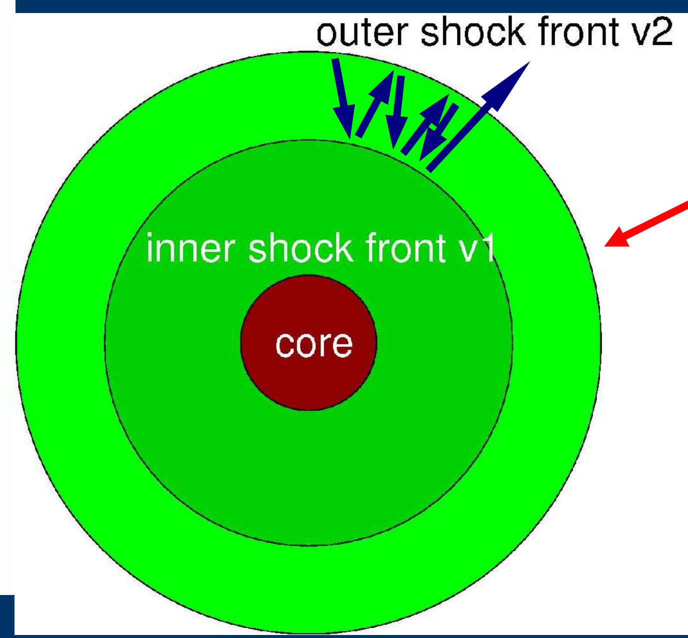


Single potential or single interaction hardly conceivable!

Fermi acceleration



- 2^{nd} order:
  - Need 2 clouds for net effect
  - $\Delta E/E \approx \Delta v^2/E$ (name)
- 1^{st} order:
  - 2 shock fronts
  - $\Delta E/E \approx 2\Delta v/v$



Supernova remnant:

$V1 \approx 20000$ km/s

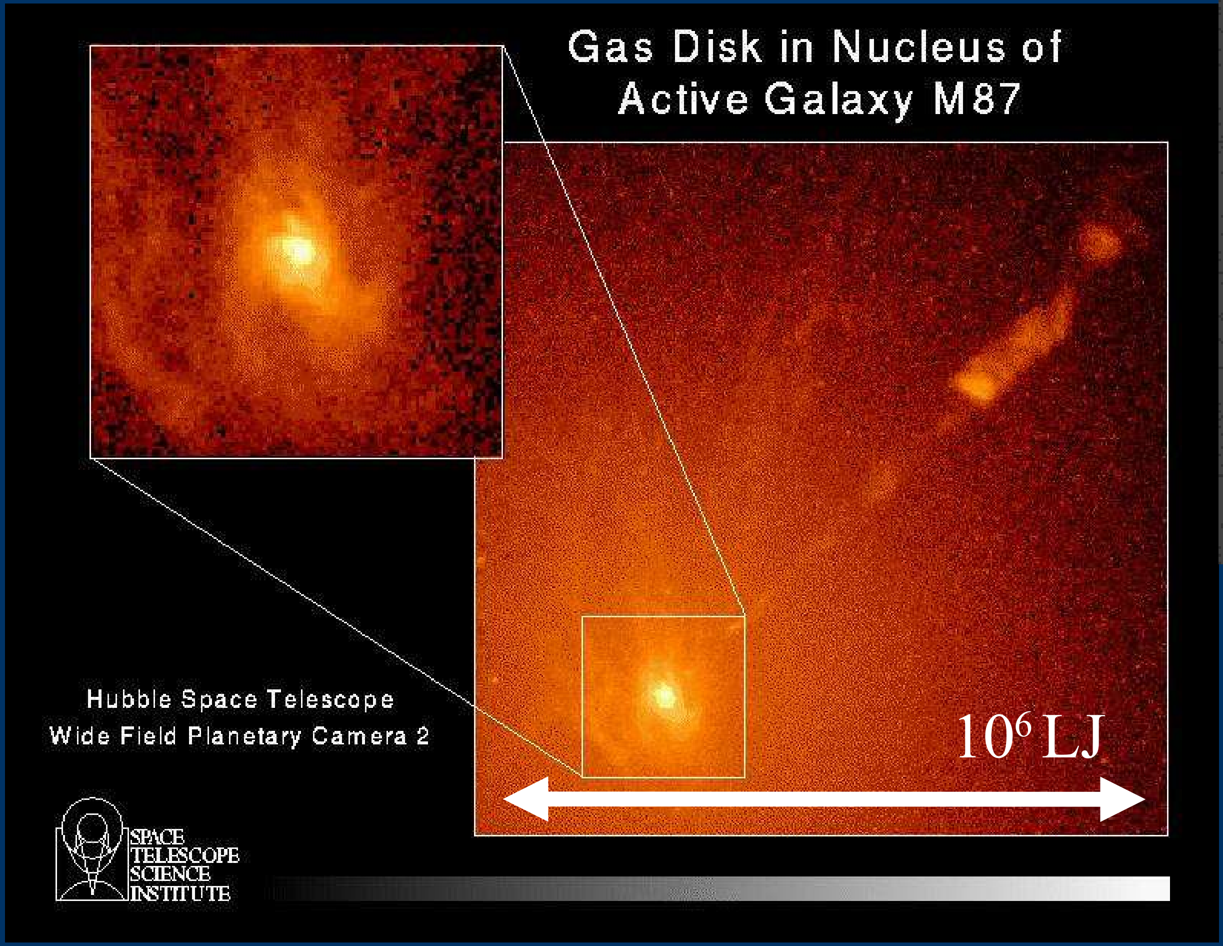
$V2 \approx 200$ km/s

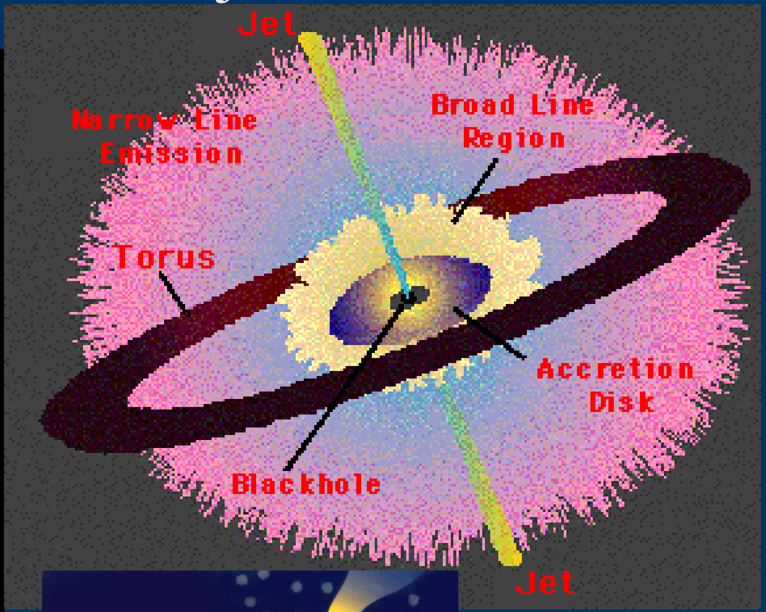
K. Helbing, LBNL/Erlangen, 10/2004

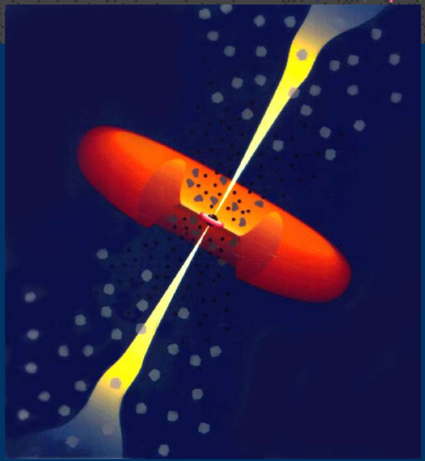
Source candidates: AGNs

Accretion flow into black hole of $10^8\ M_\odot$ with jets pointing outward

Acceleration in accretion disks and jets?







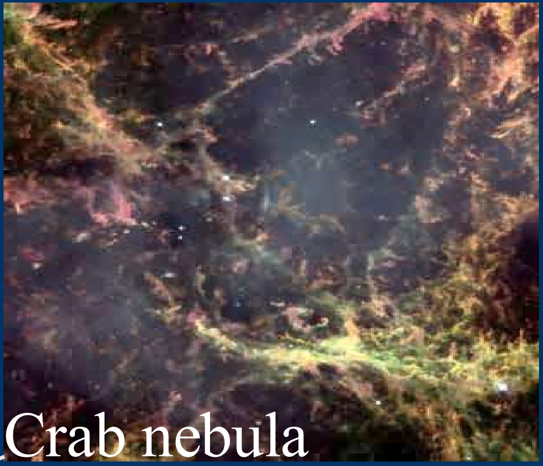
Sources: Gamma Ray Bursters

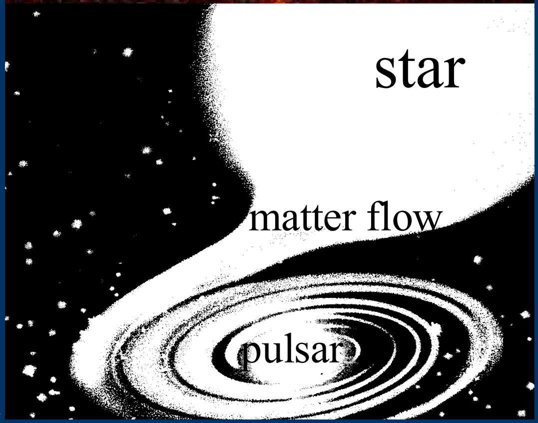
- Intense bursts of keV-MeV photons
  - Duration: up to 100 s
  - Variability: 1ms
- At cosmological distances

- Fireball model:
  - Diameter: ~100,000 km
  - Expansion: highly relativistic $\Gamma \sim 100$
  - Within model proton energies of 10^{20} eV attainable
  - Progenitors: Supernovae, Hypernova (?)

Other sources: galactic

- Supernova Remnants:
  - Blast waves into interstellar medium by core collapse
  - Leading candidate for galactic CRs (< 10^{15} eV)
- Microquasars: galactic x-ray binaries
  - Accreting black holes, pulsars
- Magnetars: pulsars with extreme magnetic fields
  - Accel.: B field and rotation

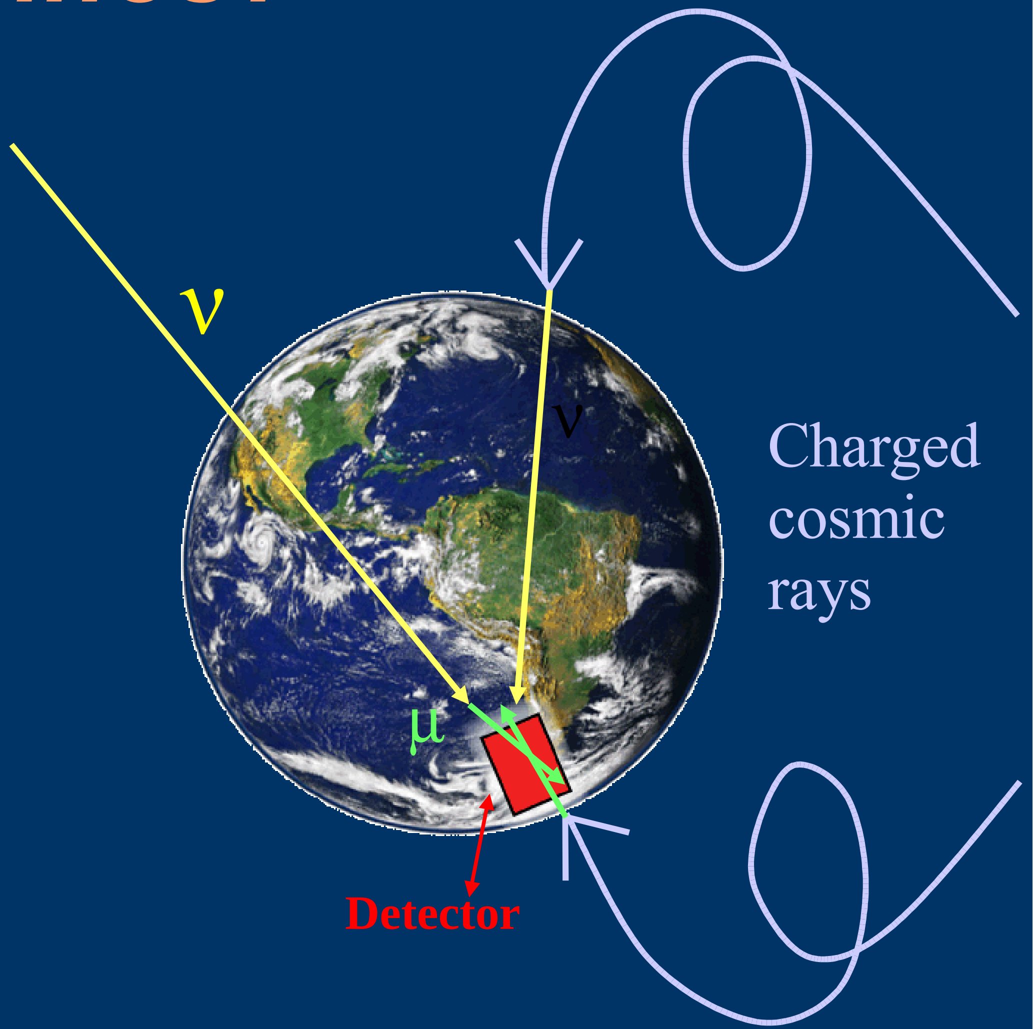




Why look for neutrinos?

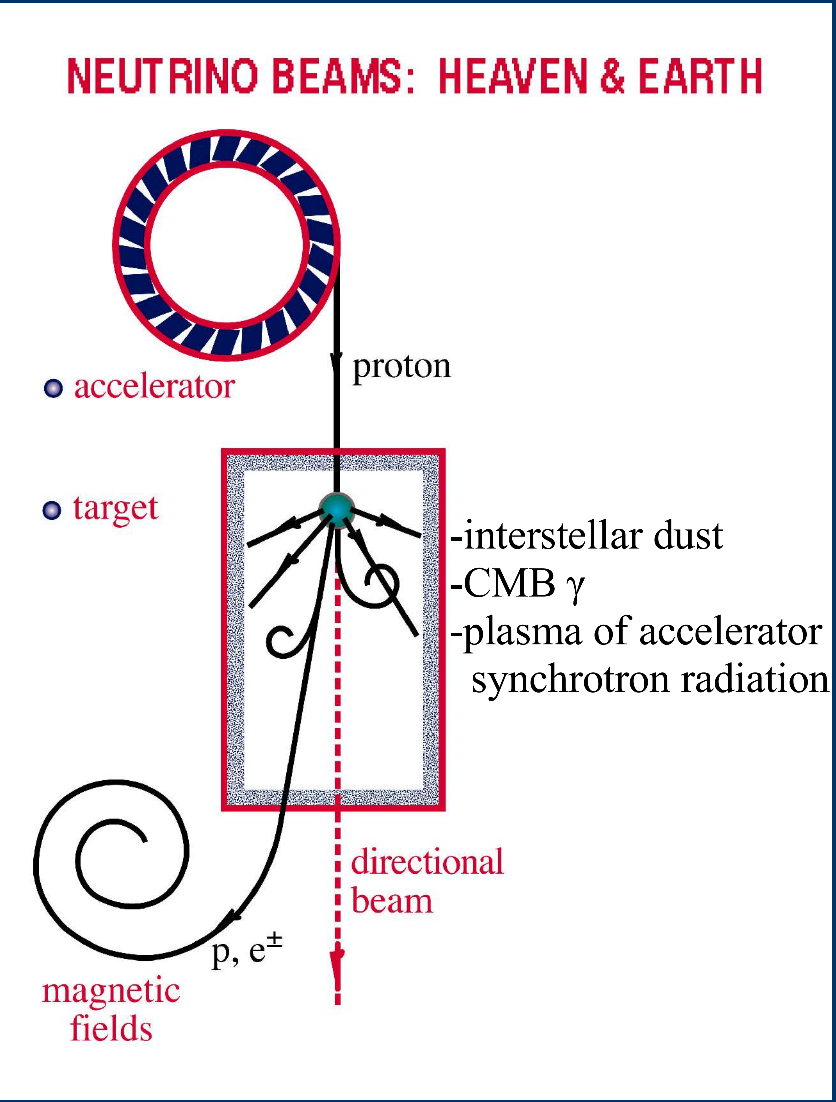
- No electric charge
  → point back to source
- Escape dense objects
  → "look" at accel. site
- "No" absorption or scattering by interstellar matter

- High energies:
  - $\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$ (>1PeV)
  - $\sigma_{\nu N} \sim E$, μ range ~ E



Why should there be neutrinos?

- **Interactions** of CRs with **interstellar matter** or intra-cluster gas:
  - Guaranteed to exist
  - intensity known within factor 2, $E < 10^{17}$ eV
  - Doesn't point back to origin of CR, acceleration
- **Meson photoproduction** via Δ-resonance on site:
  - at acceleration site (points back!)
  - UHCR with CMB:
  - $\gamma N \rightarrow \Delta \rightarrow N\pi^- \rightarrow N\mu^- \bar{\nu}_\mu$
    $\rightarrow Ne^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu$ **($E_\nu \approx 5\%\ E_N$)**



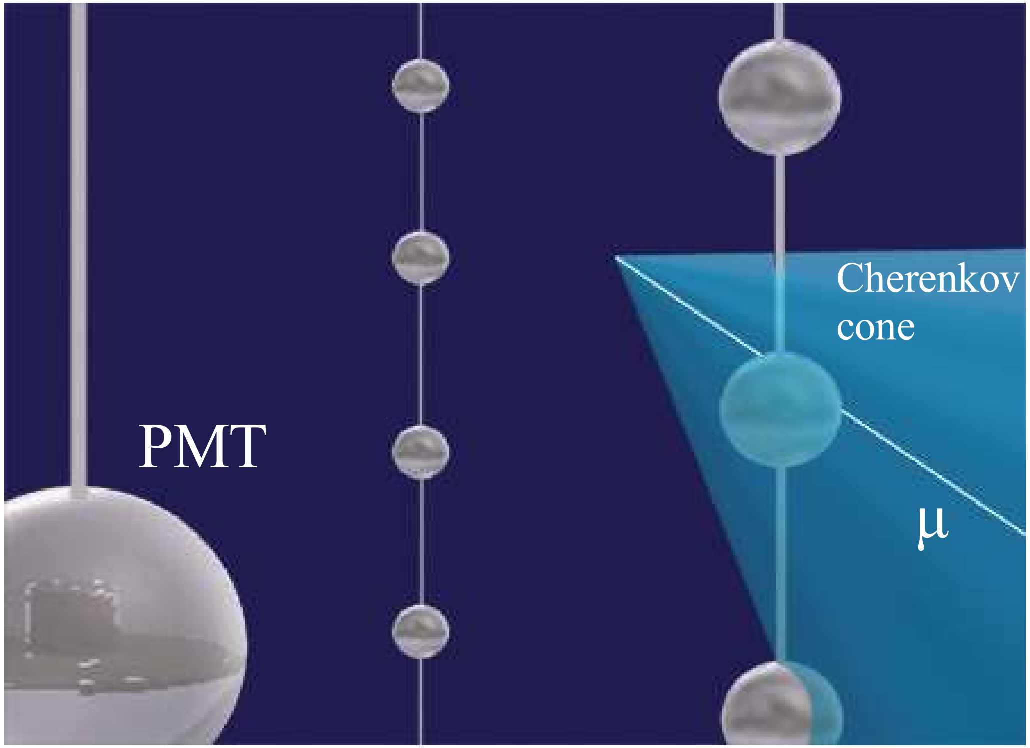
Detection of HE ν: Cerenkov light

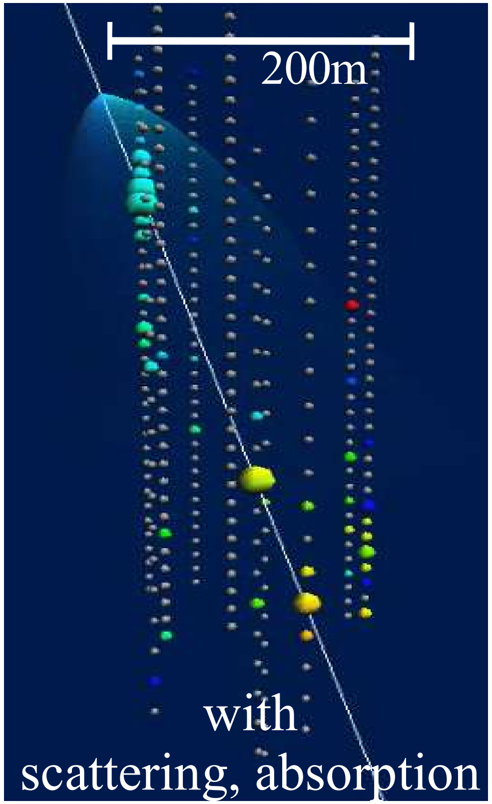
Cerenkov light in ice or water:

$\nu_\mu + N \rightarrow \mu + X$, μ range: kilometers

Dumand, Baikal, Amanda, Nestor, Antares, Nemo,

IceCube

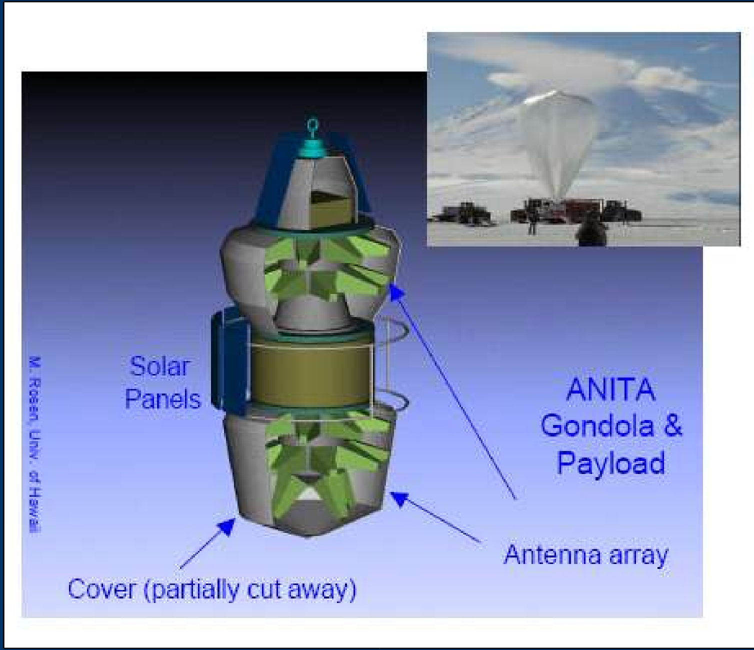




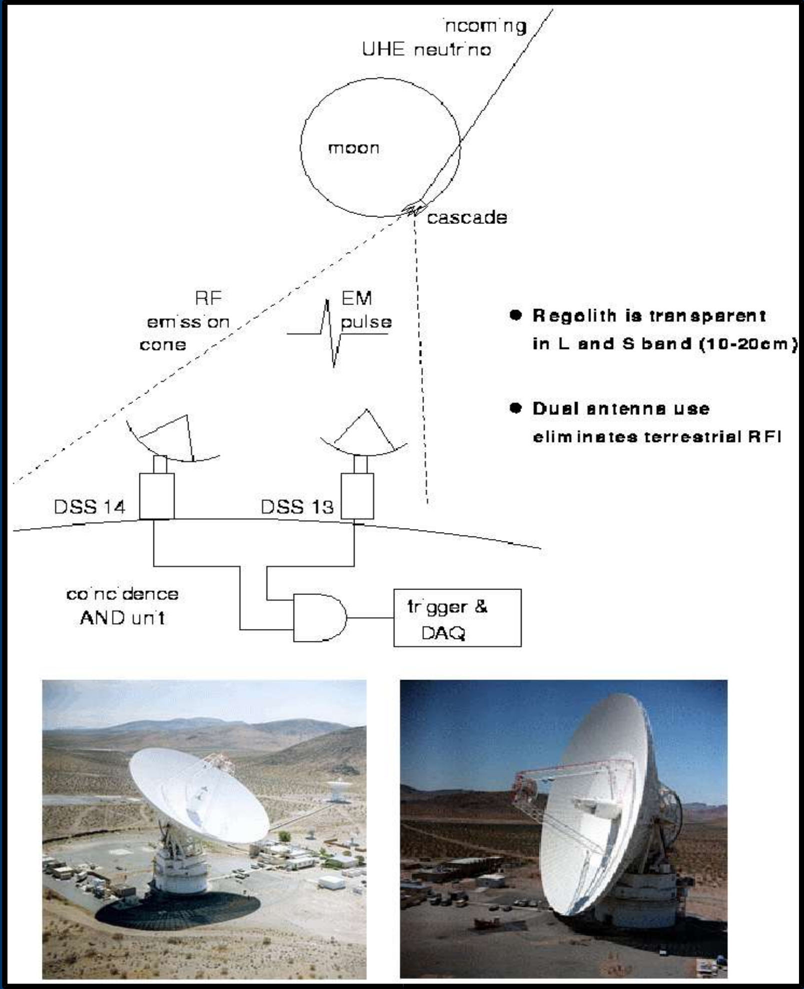
Detection of HE ν: Cerenkov radio

Cerenkov radio (showers) in ice, atmosphere, Moon:
Rice, Glue, Forte, Anita

e$^{\pm}$ cascade, positrons annihilate
$\Rightarrow$~20% e^{-} excess
for wavelength >> cascade size:
coherent Cerenkov radio emission



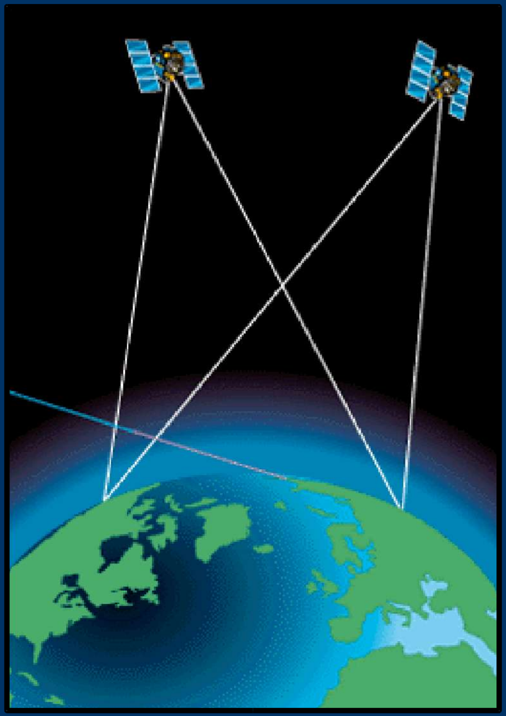
From: Gorham et al.



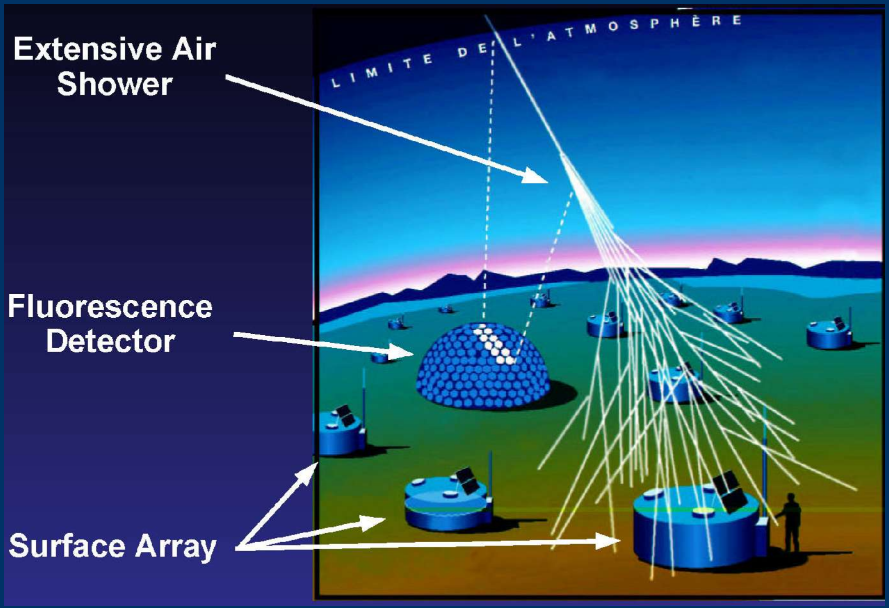
Detection of HE ν: fluorescence

Extensive showers in air
→Nitrogen fluorescence

Fly's Eye, Auger Observatory, EUSO, AGASA

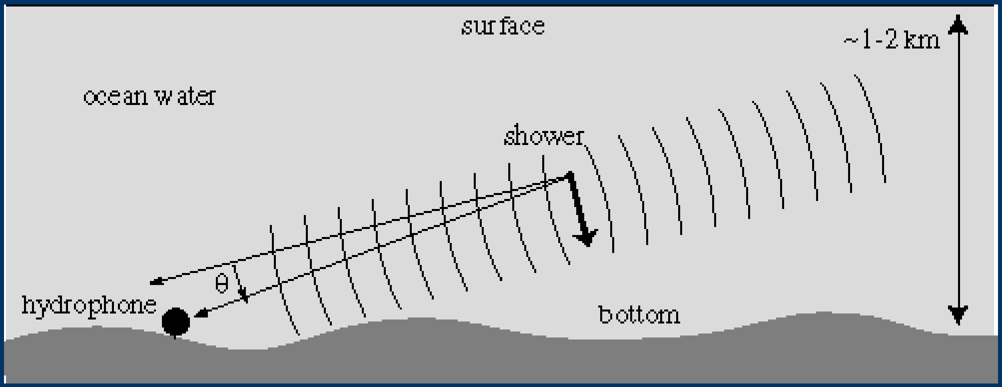


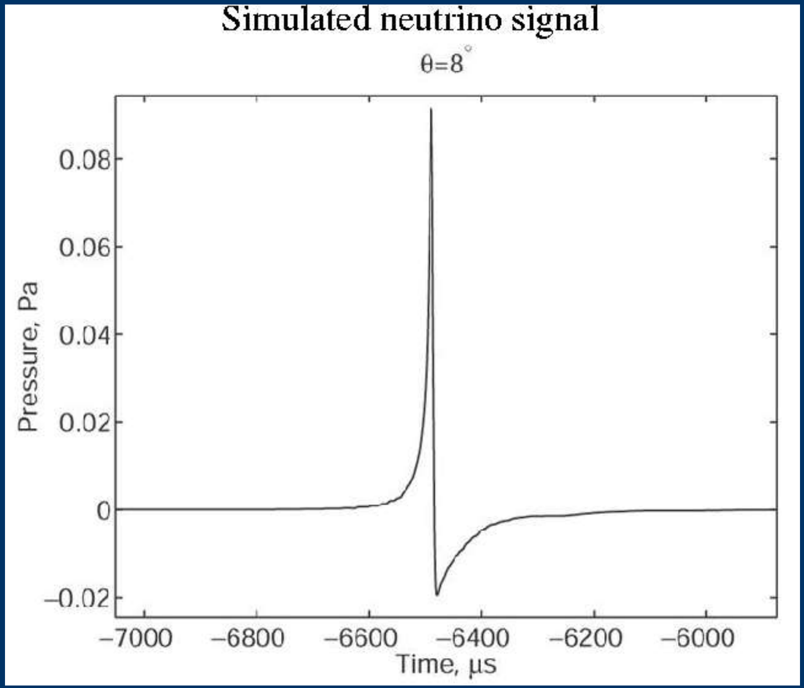
From: Bottai, Les Houches 2002



Neutrino ID:
horizontal showers,
shower starts lower in athmosphere

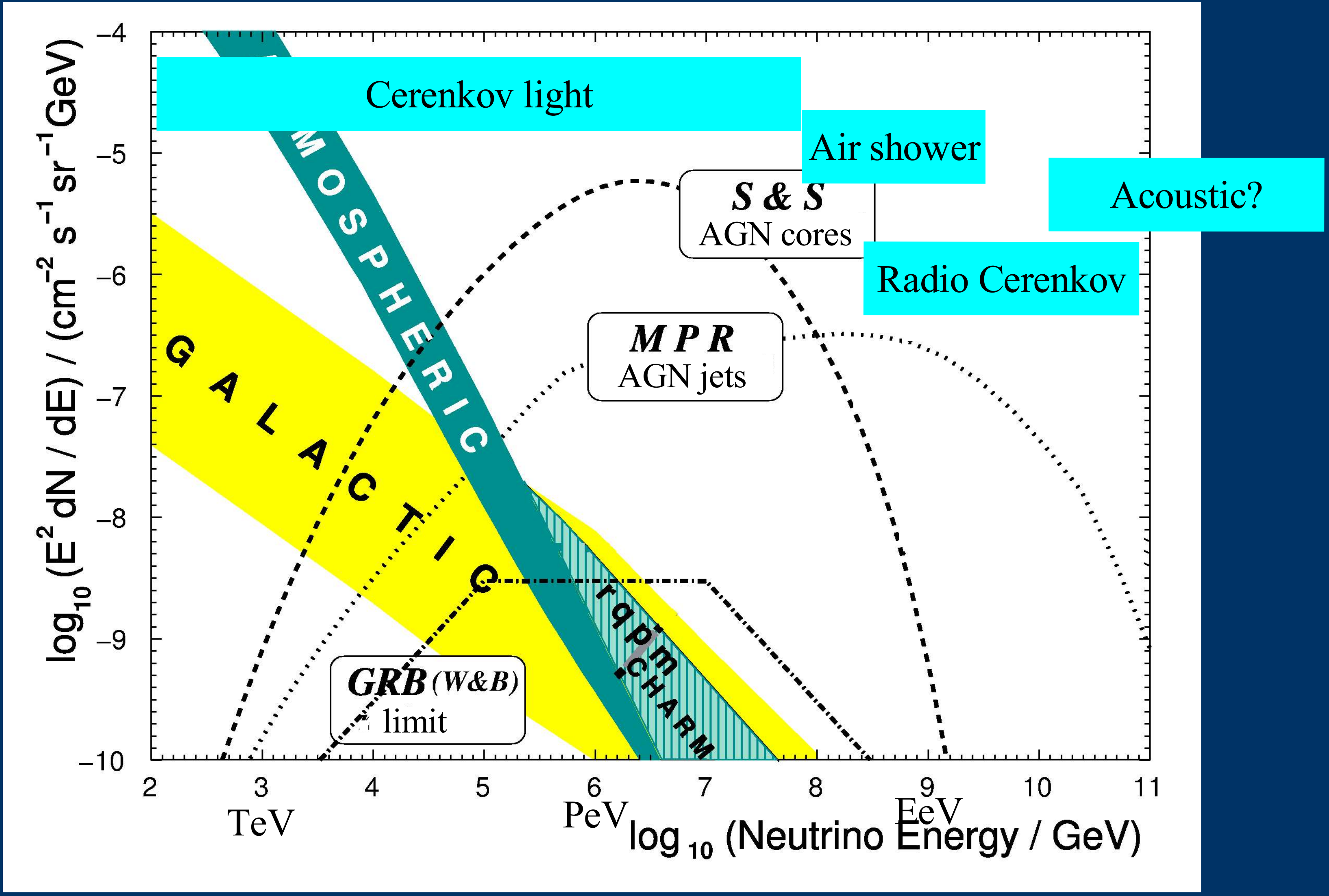
Detection of HE ν: acoustic





- Revived after 25 years
- Advantages:
  - Potentially >> km^3 effective volumes
  - Well developed sonar technology
- Disadvantages:
  - Deep ocean and ice impulsive backgrounds still not yet well known
  - Ice and Salt properties not yet known (soon?)
  - Small Signals, Threshold >> PeV
- Prospects:
  - Modest activity under way
  - Few years from dedicated experiment

Reach of detection techniques



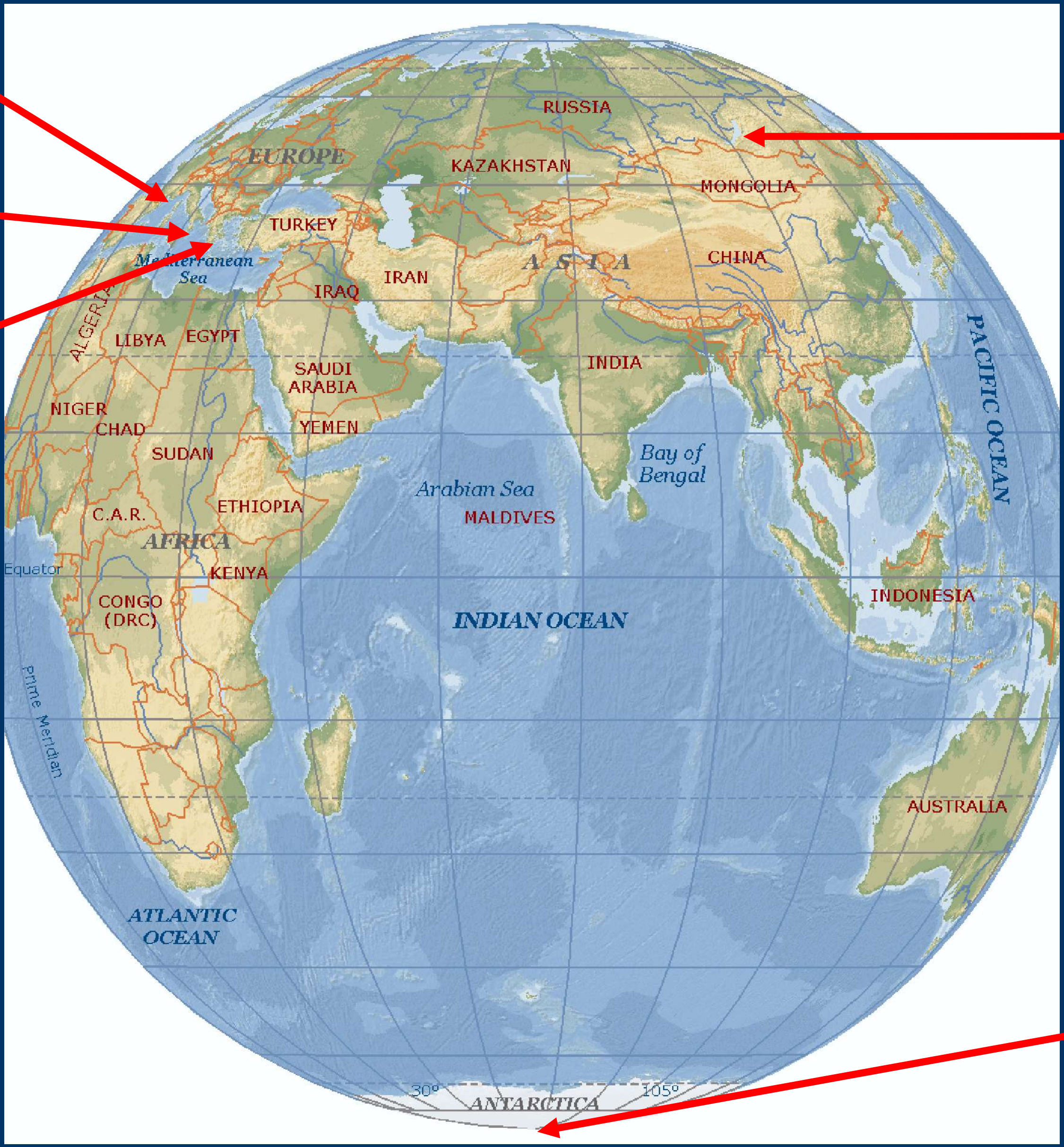
K. Helbing, LBNL/Erlangen, 10/2004

Cerenkov light neutrino telescopes

Antares
France

Nemo
Italy

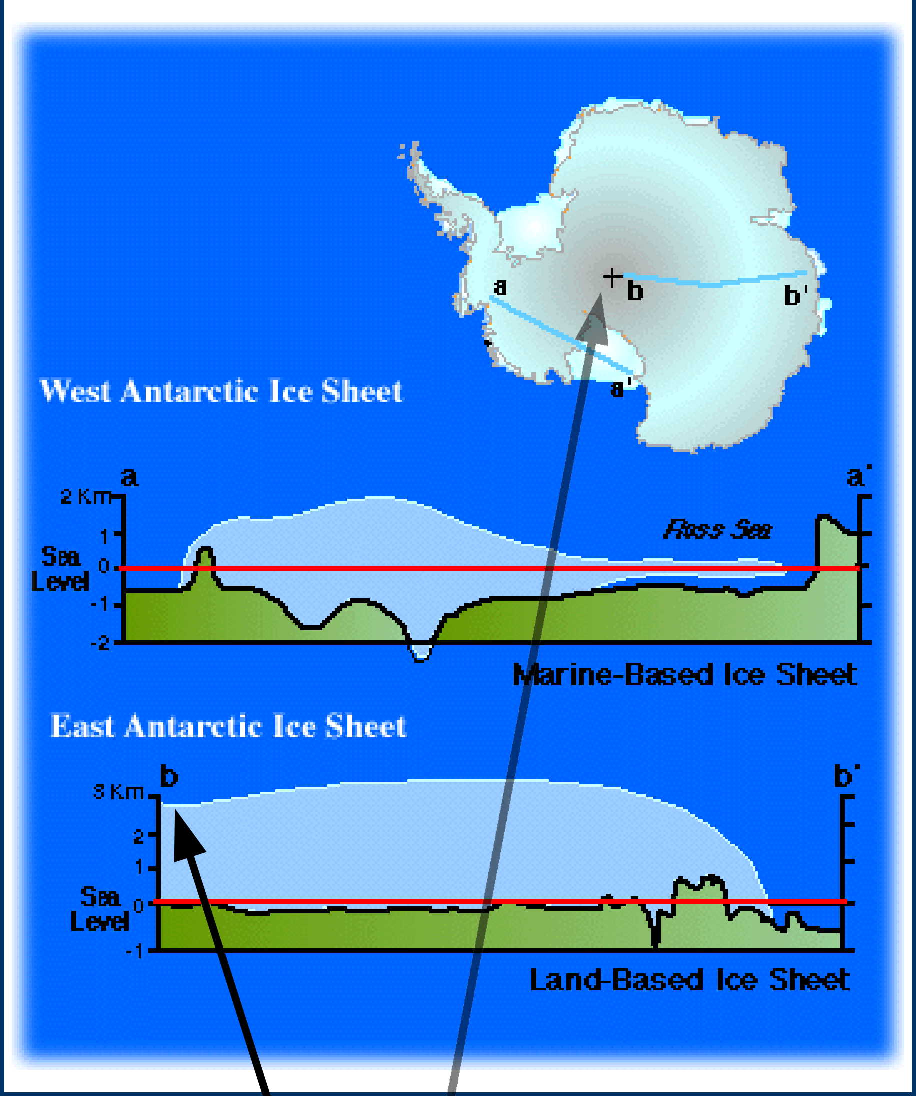
Nestor
Greece



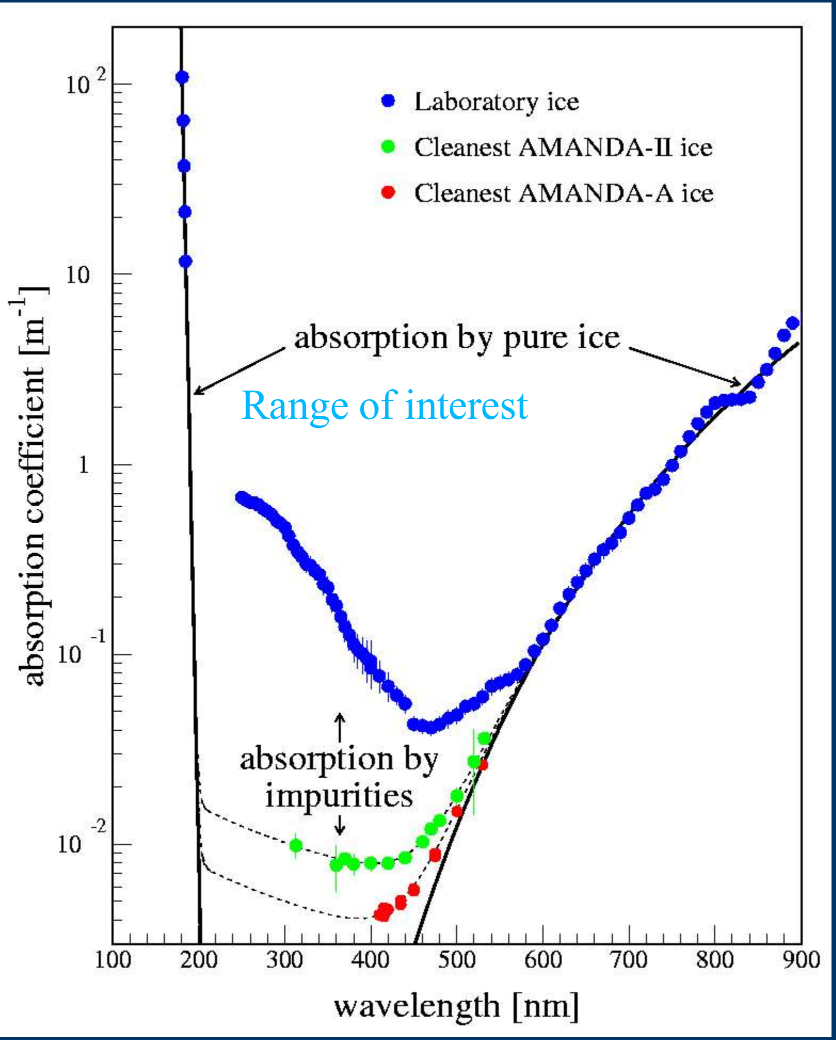
Lake Baikal
Russia

Amanda
IceCube
USA ☺

South Pole ice



South Pole



Cleaner than man made ice!

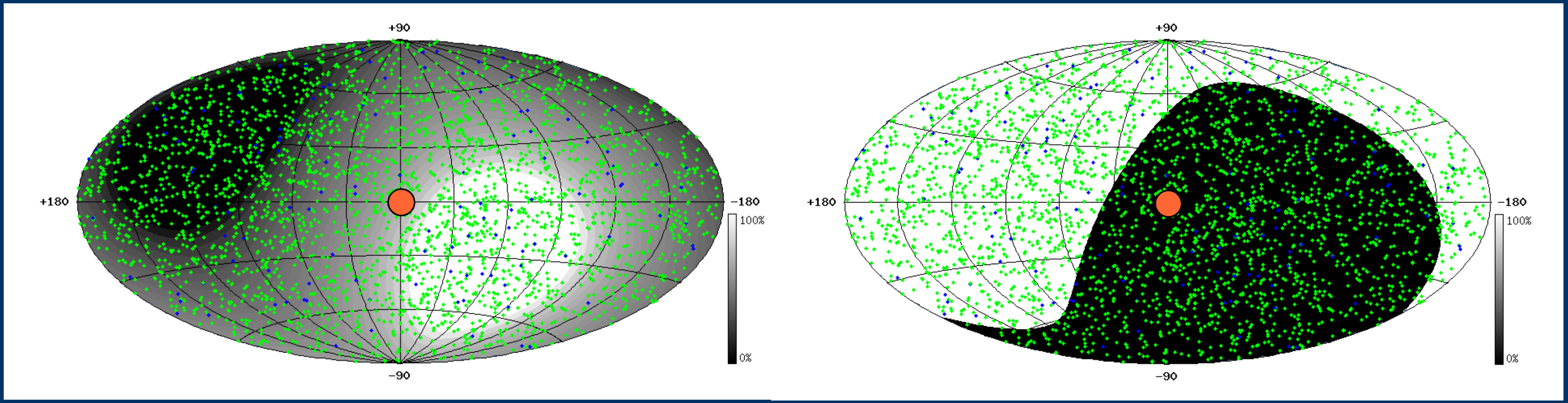
K. Helbing, LBNL/Erlangen, 10/2004

Complemetary sky coverage

Approximation for E < 100 TeV

Mediterranean (sea)
Antares, Nestor, km3net ...

South Pole (ice)
Amanda, IceCube



● Galactic center

dots: distribution of gamma ray bursts (GRBs)

Remark: IceCube will cover galactic center for E > 100 TeV

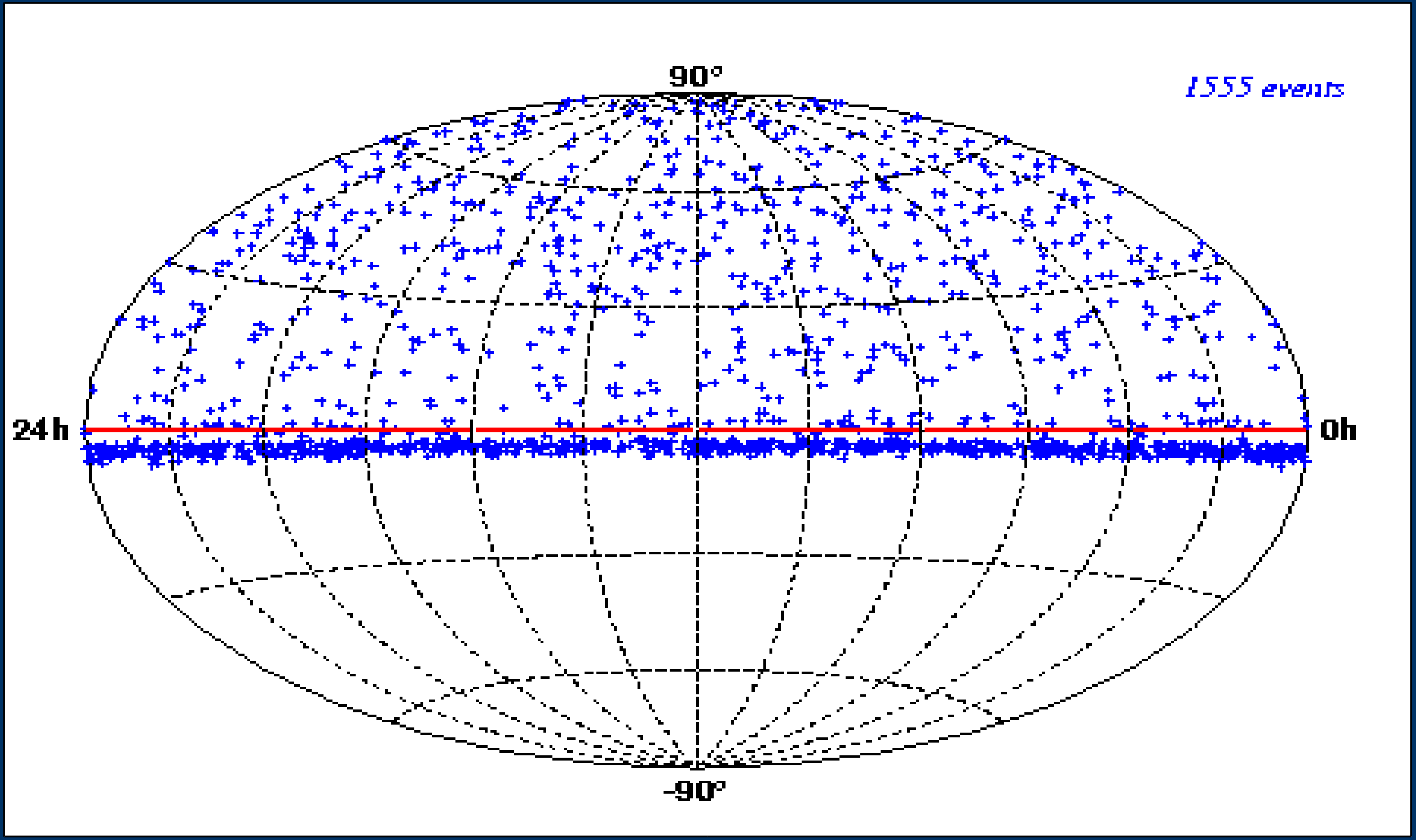
Complementary deployment environments ☺

- Accessible year round
- Reachable within few hours of travel

- No distraction due to beach beauties
- No sea sickness

→ **Unobscured work flow**

Amanda: Point Source Search



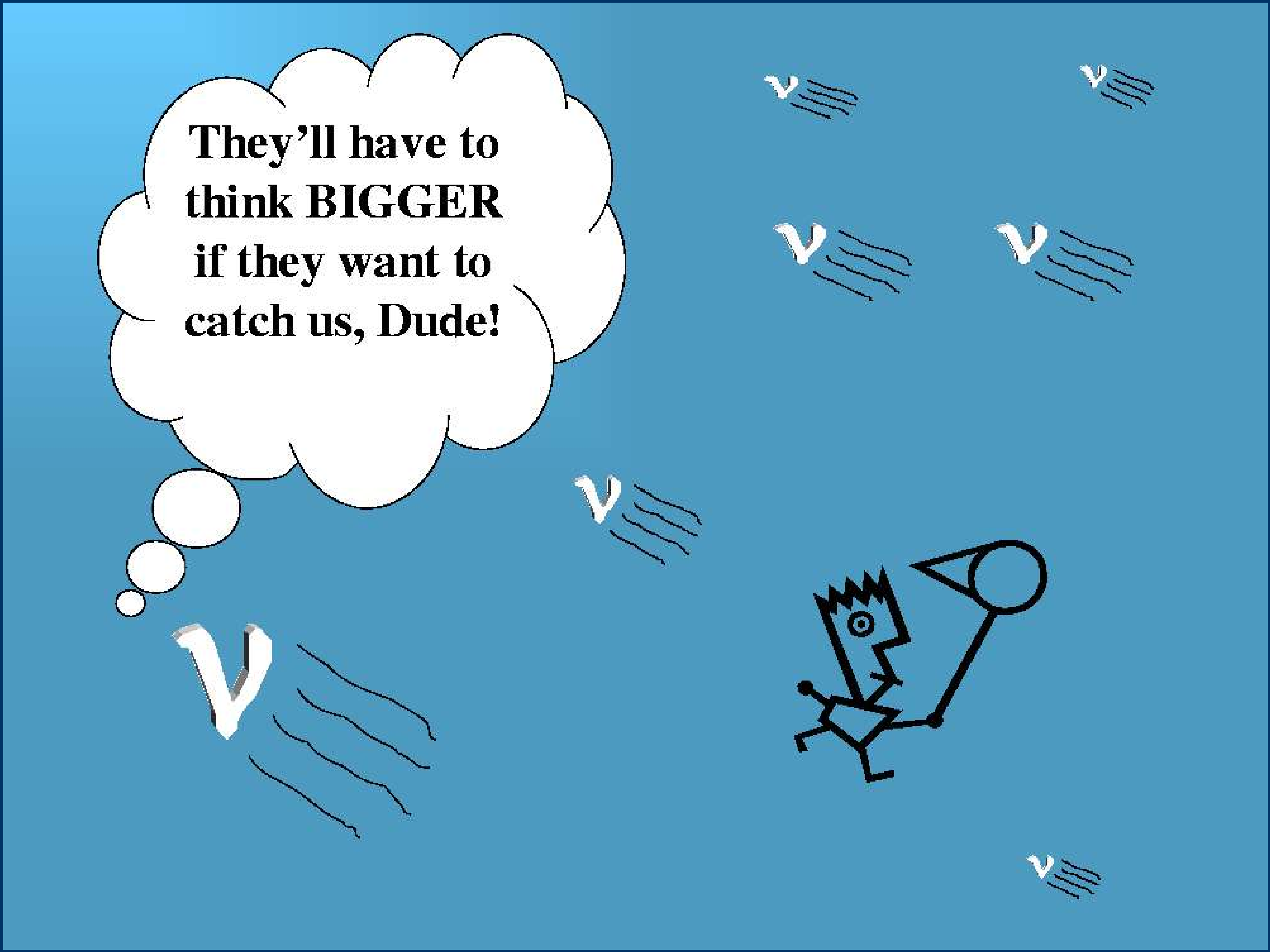
NO statistically significant clustering found so far
→ Events consistent with atmospheric neutrinos

Amanda results, general

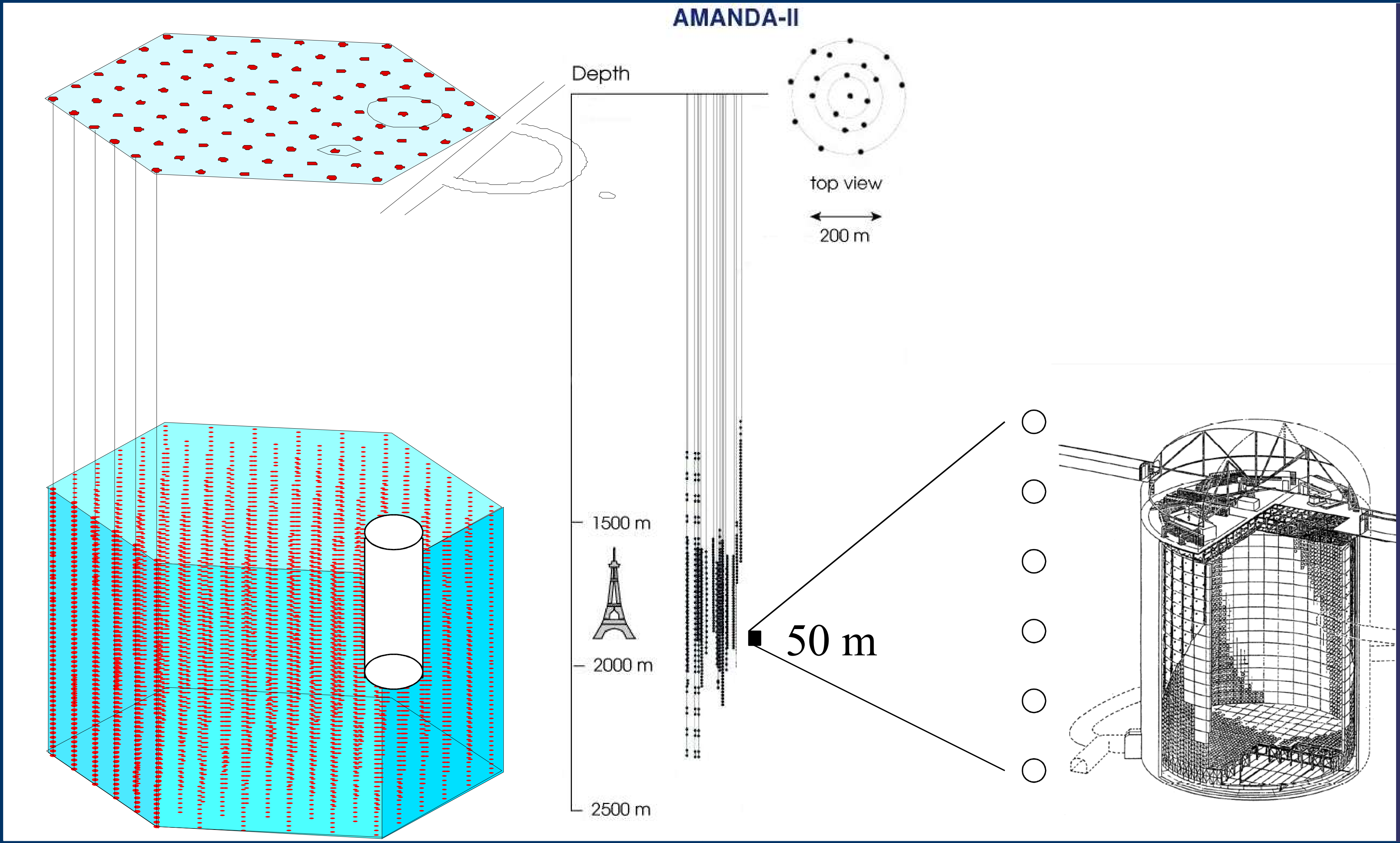
- **Supernovae**: Astropart.Phys.16:345-359, 2002
- **Point Sources**:Astrophys.J.583:1040-1057, 2003, Phys.Rev.Lett.92:071102,2004
- **Diffuse Cascades**:Phys.Rev.D67:012003, 2003
- **Atmospheric Neutrinos**:Phys.Rev.D66:012005, 2002
- **WIMPS**: Phys.Rev.D66:032006, 2002

So far no statistically significant excess of any neutrino flux
Limits constrain models

Neutrino physics is largely an art of learning a great deal
by observing nothing.
Haim Harari


They'll have to think BIGGER if they want to catch us, Dude!

Size perspective



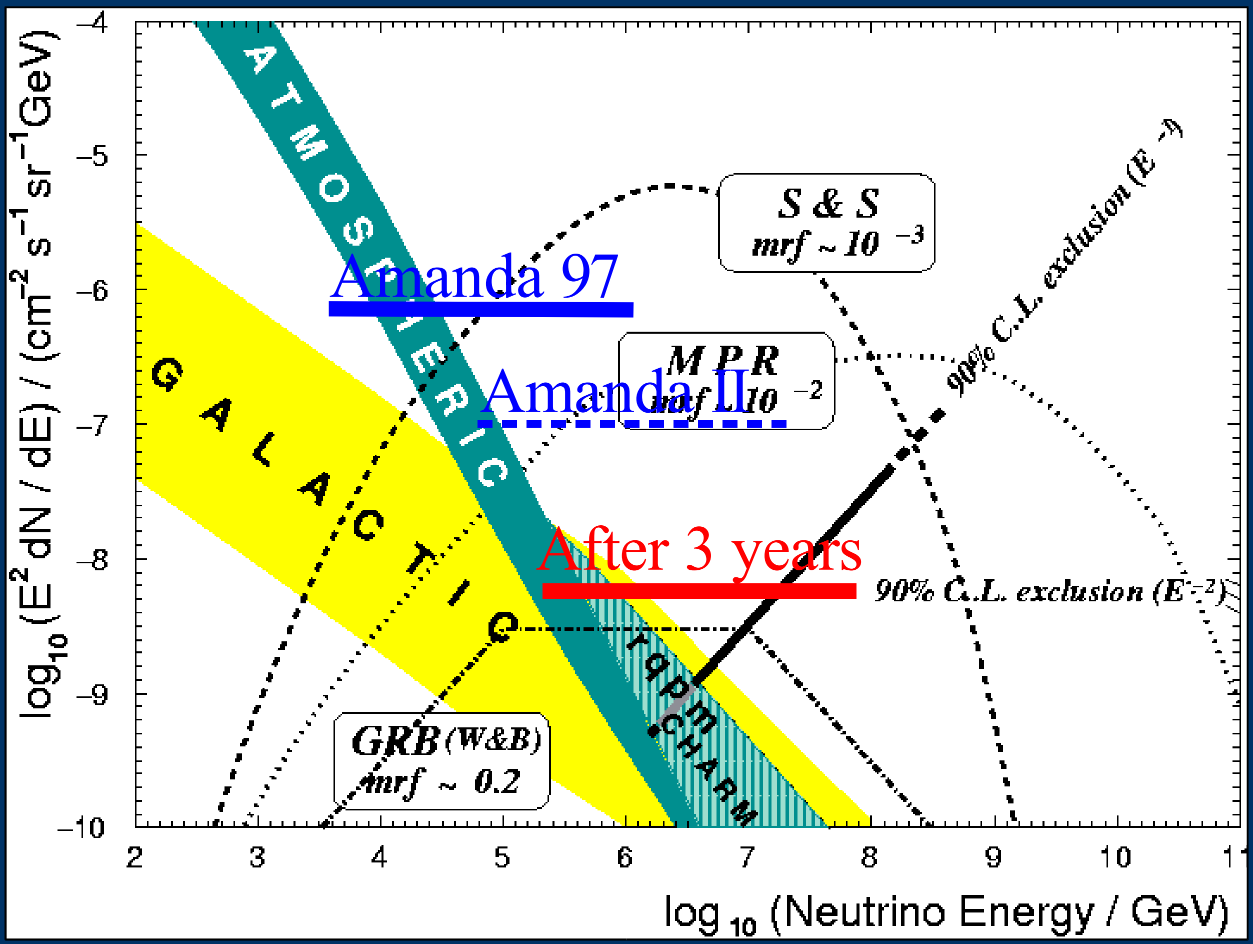
Amanda ⟶ IceCube

- 19 Strings ⟹ **80 Strings**
- 677 OMs ⟹ **4800 OMs**
- Instrumented volume: 0.02 km^3 ⟹**1 km^3, 1 Gton**

- Analog optical modules ⟹ **digital** modules
  - Signal (waveform) digitization down in the ice
  - Digital data transfer to surface
  - Trigger logic in software
  - Time calibration and synchronization: automatically scheduled task every ~ 10s

IceCube Sensitivity

Diffuse fluxes

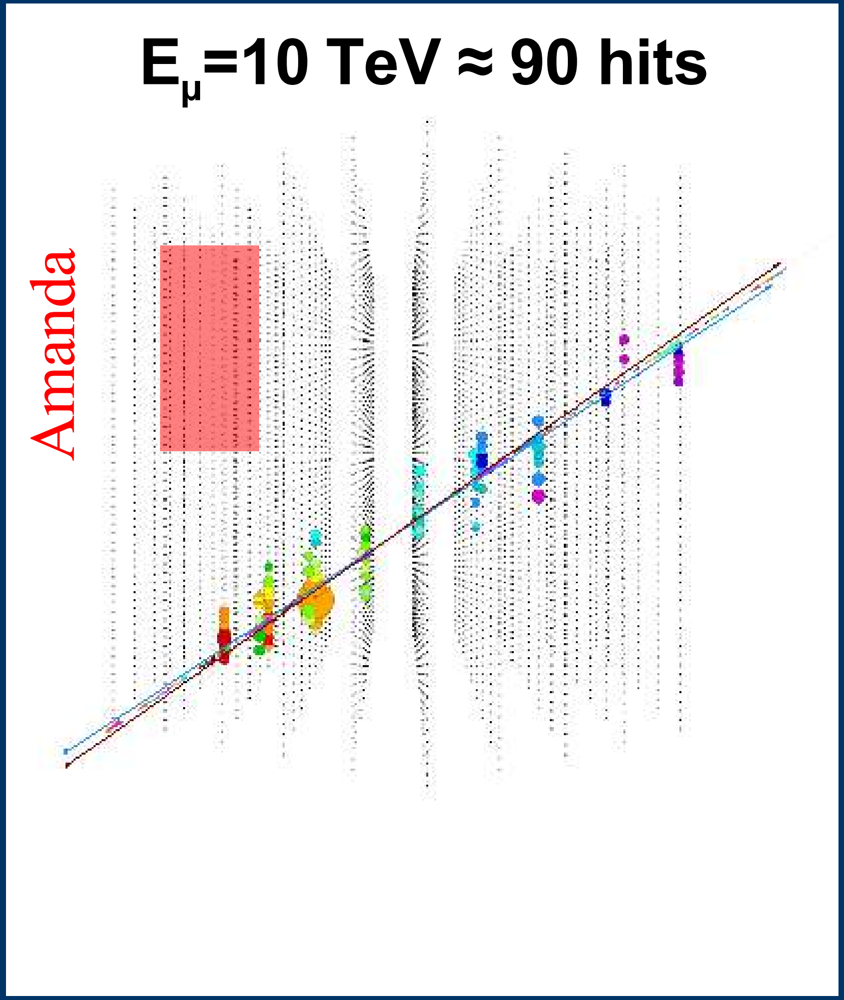


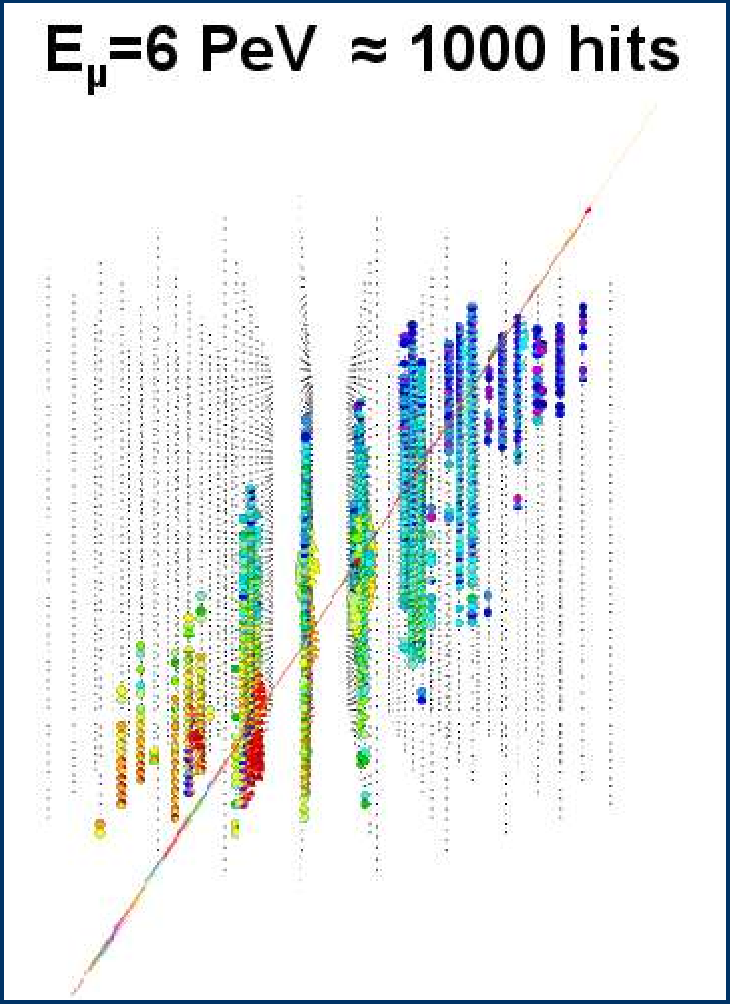
GRBs

- Background is dramatically reduced by time and direction coincidence with satellite γ ray burst observation.
- Could get 5σ signal after 200 bursts (500/yr/hemisphere)
- IceCube sensitive to GRB ν flux of 1/5 the Fireball model
- If ν's not seen, can rule out model after 100 bursts

Size: Improved energy resolution

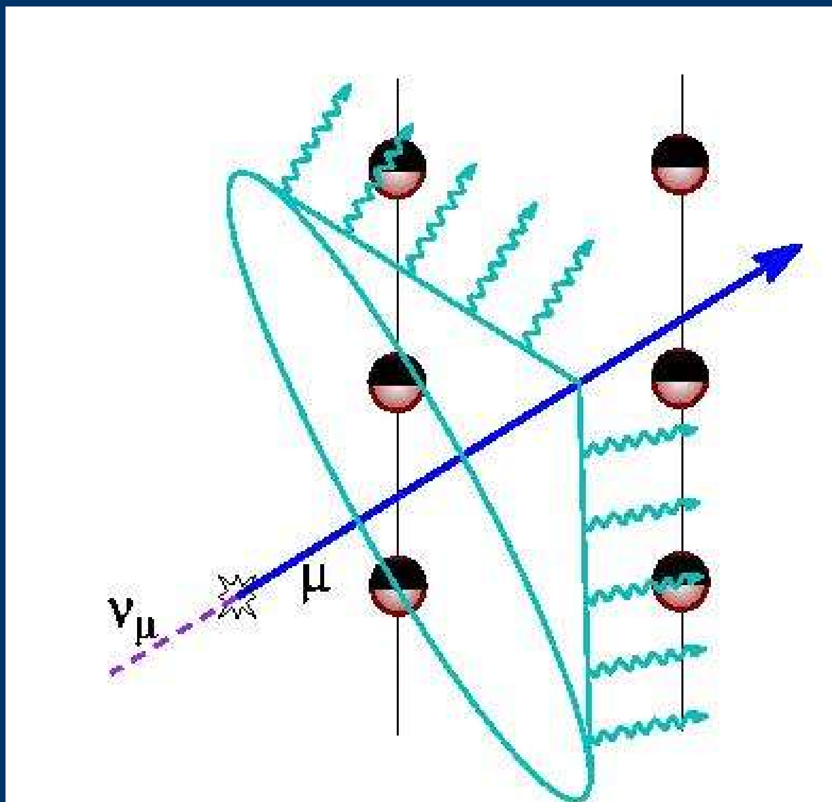
Small detectors: Muon energy is difficult to measure because of fluctuations in dE/dx
IceCube: Integrating sampling and scattering of light reduces the fluctuations.
$\longrightarrow$ Requires large dynamic range in amplitude.





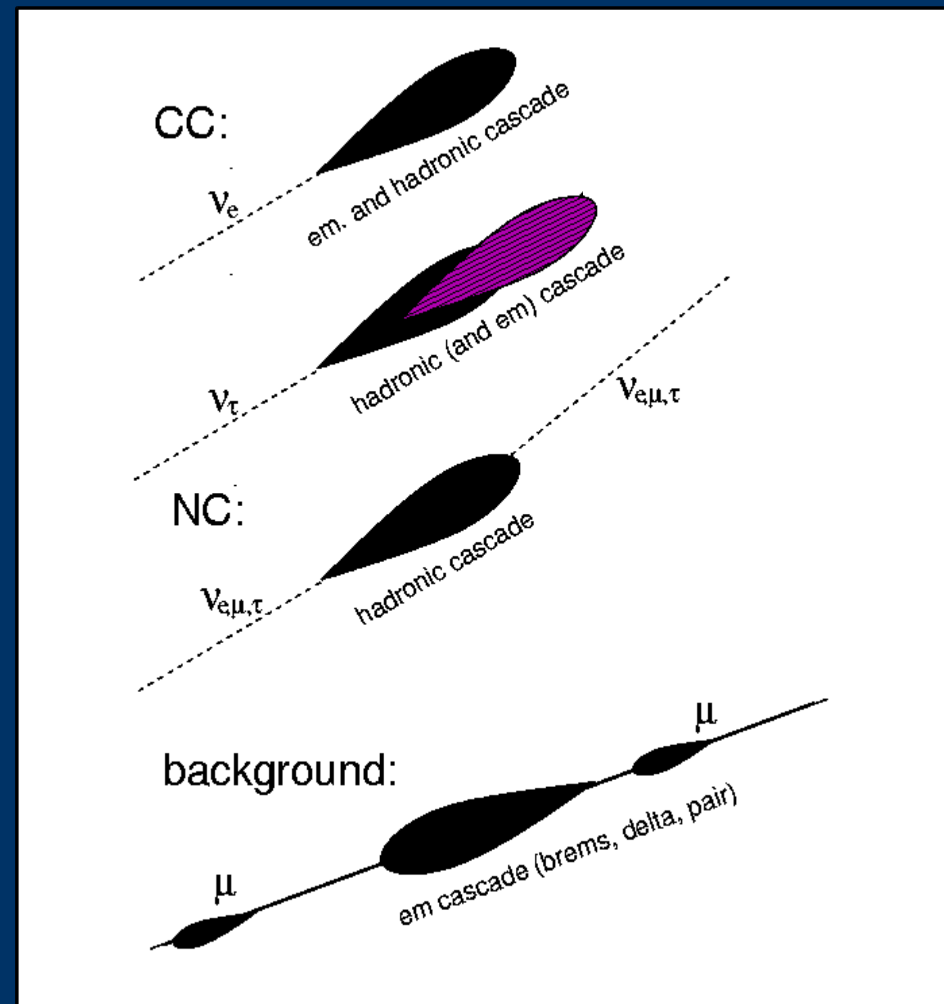
Goal: Flavor separation

O(km) long muon tracks



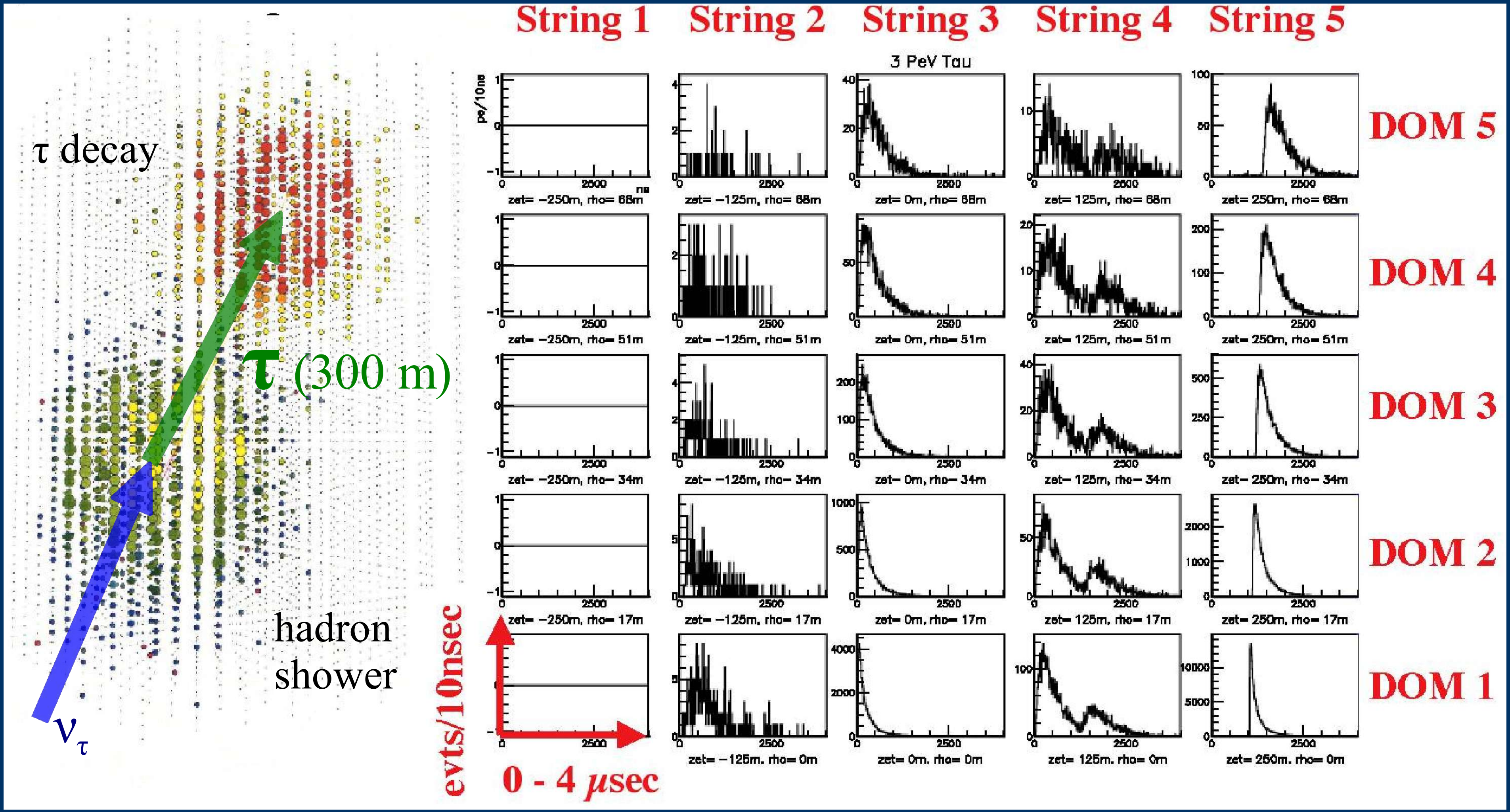
direction determination
by Cerenkov light timing

Electromg and hadronic cascades



$\Longrightarrow$ Requires time resolved charge determination.

"Double bangs"



Flavor oscillation: ν_τ expected; Signature: two cascades

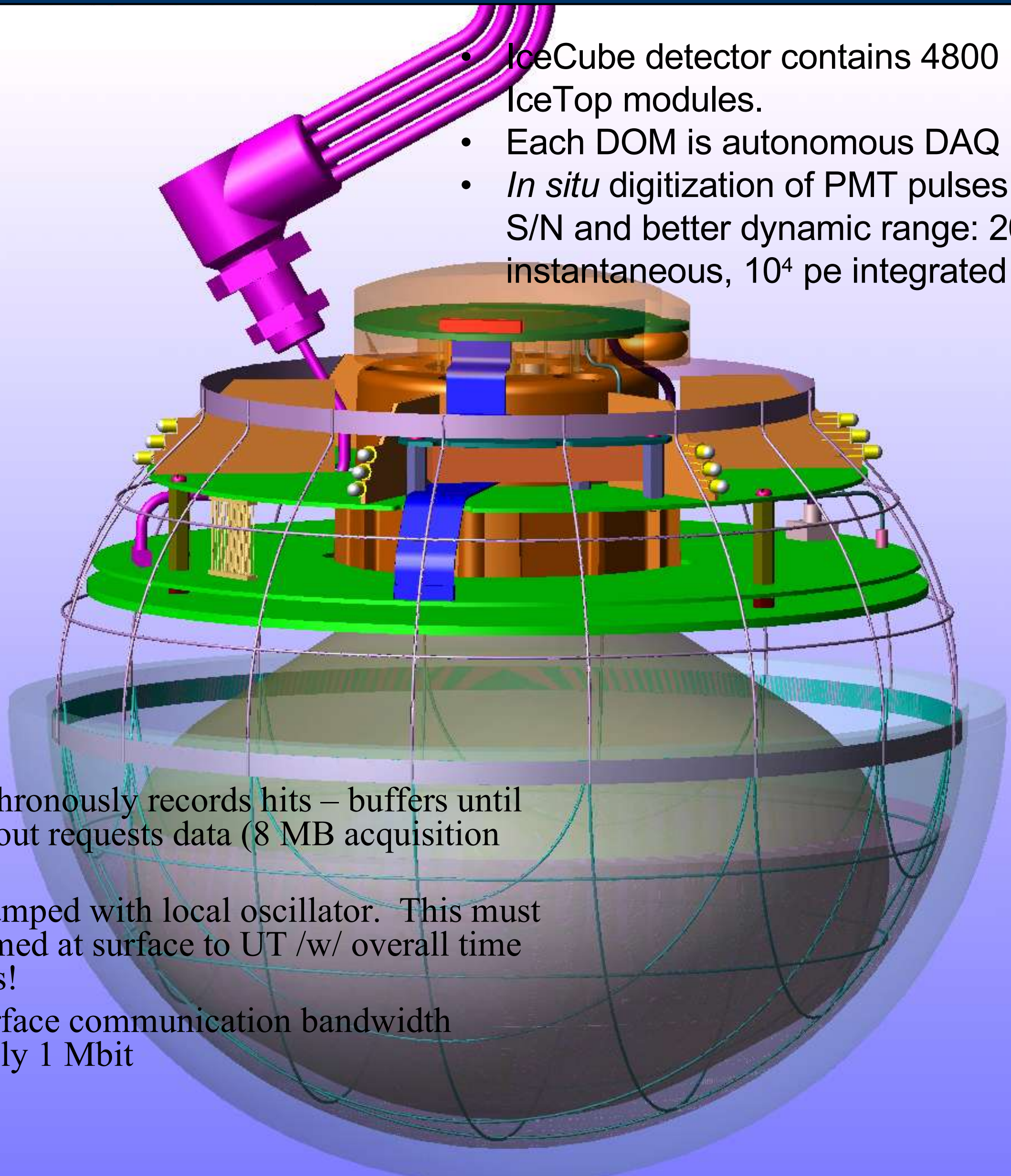
Requires full pulse shape (waveform) capture, high dynamic range

Requirements and functionality of Digital Optical Modules (DOMs)

- High optical sensitivity
- Time resolution: 7 ns
- Dynamic range: 200 p.e/15 nsec
- Waveform capture up to 4 μsec
  - 300 MHz up to 300 nsec
  - 40 MHz up to 4 μsec
- Compatibility with deployment in ice.

- Operate PMT and set HV.
- Trigger, capture and digitize all PMT pulses.
- Attach a time stamp derived from the local clock.
- Synchronize local clock to system masterclock (GPS linked).
- Store several minutes of data (8MB).
- Upon request send data to surface via 3 km copper cables.

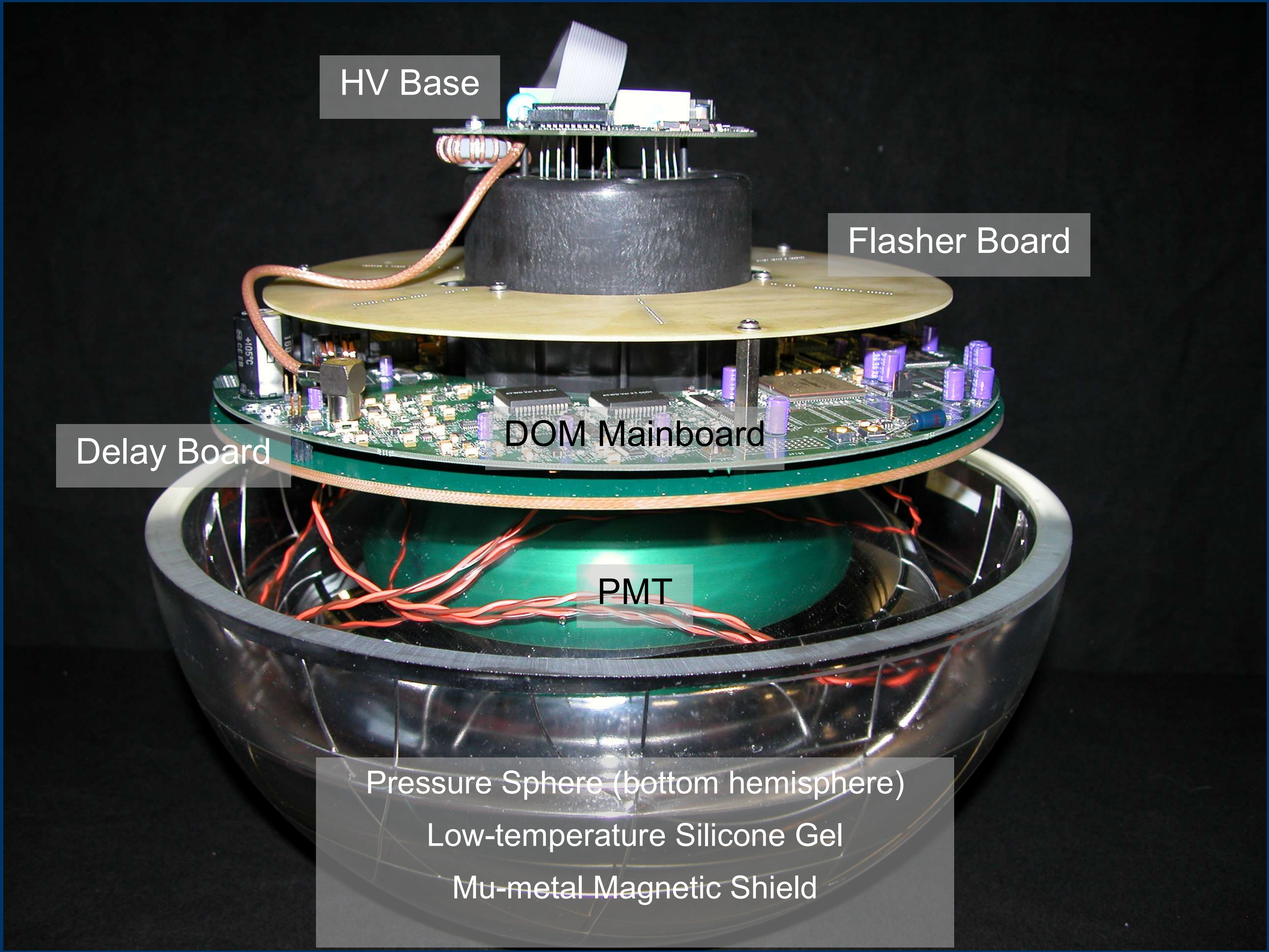
Digital Optical Module (schematic)



- IceCube detector contains 4800 InIce and 360 IceTop modules.
- Each DOM is autonomous DAQ platform
- *In situ* digitization of PMT pulses for increased S/N and better dynamic range: 200 pe instantaneous, 10^4 pe integrated

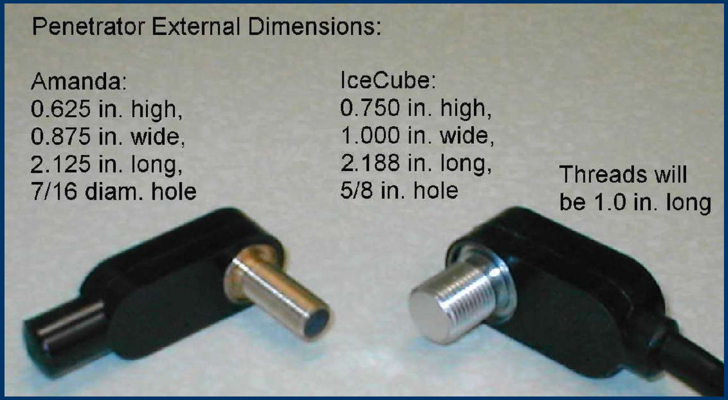
- DOM asynchronously records hits – buffers until surface readout requests data (8 MB acquisition memory)
- Hits time stamped with local oscillator. This must be trans-formed at surface to UT /w/ overall time res. of < 5 ns!
- DOM-to-surface communication bandwidth approximately 1 Mbit

Digital Optical Module



Pressure Sphere

- Vendor – many decades of experience with deep sea applications + AMANDA OMs
- 13” O.D., 0.5” thick borosilicate glass hemispheres joined under negative pressure
- Single 5/8” penetrator brings in power, signals.
- Low noise (require < 300 Hz induced spe rate in PMT)
- UV transparency: $T_{50} \sim 350$ nm or less and residual sensitivity down to 315 nm: λ^{-2} Cherenkov γ.

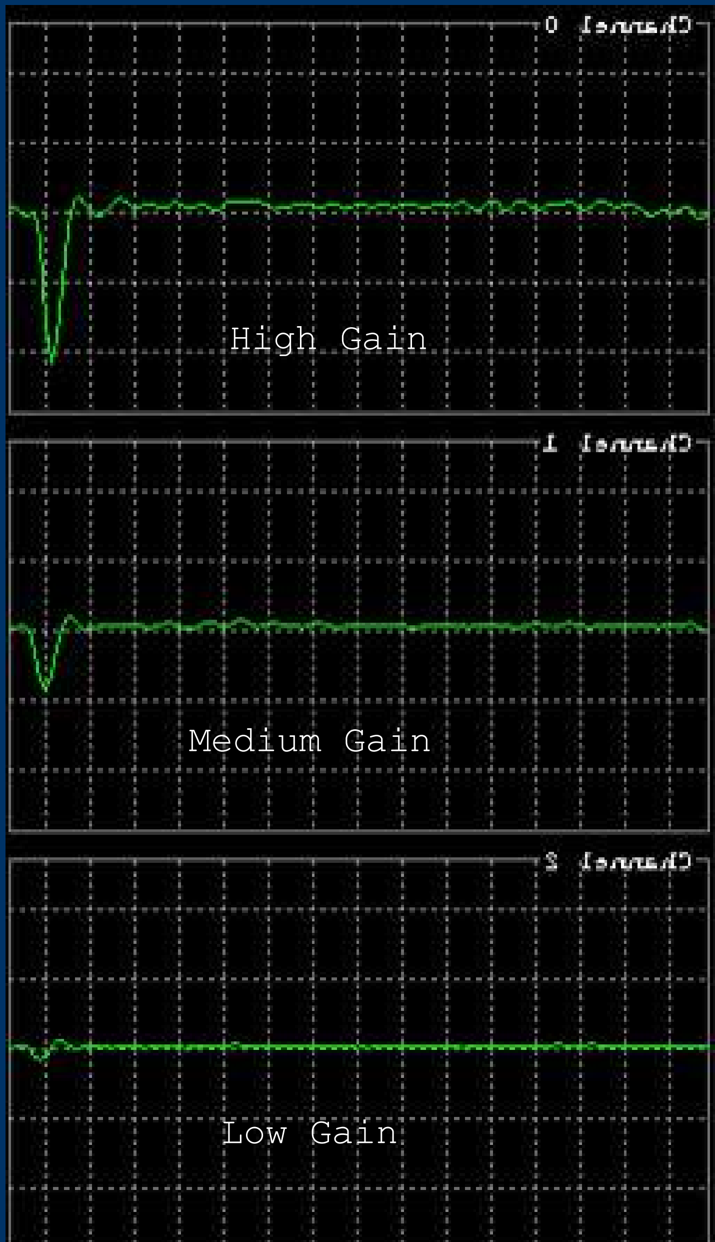


IceCube PMTs

Hamamatsu R7081-02

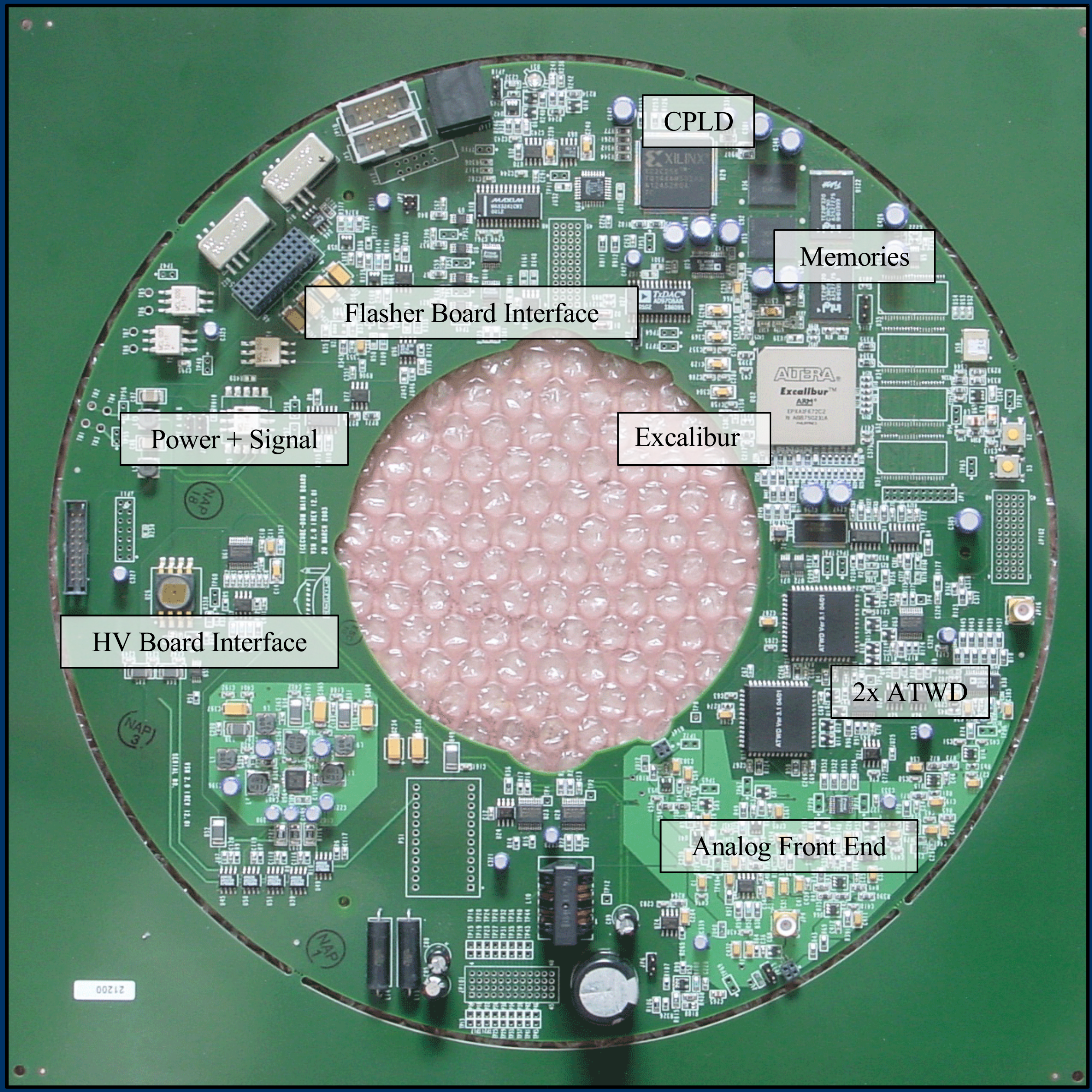
- Large area (10” dia.) bi-alkali photocathode deposited on borosilicate glass envelope.
- 10 dynode stages in box-and-line configuration
- Fast pulse (6.5 ns width; < 3 ns risetime; < 3 ns FWHM TTS)
- *Very low noise (250 cps typ. @ -40 ºC and ¼ pe counting threshold)!*
- High gain: 10^8 @ 1500 V typ.
- IceCube operating range ~ 10^7 with modified bleeder

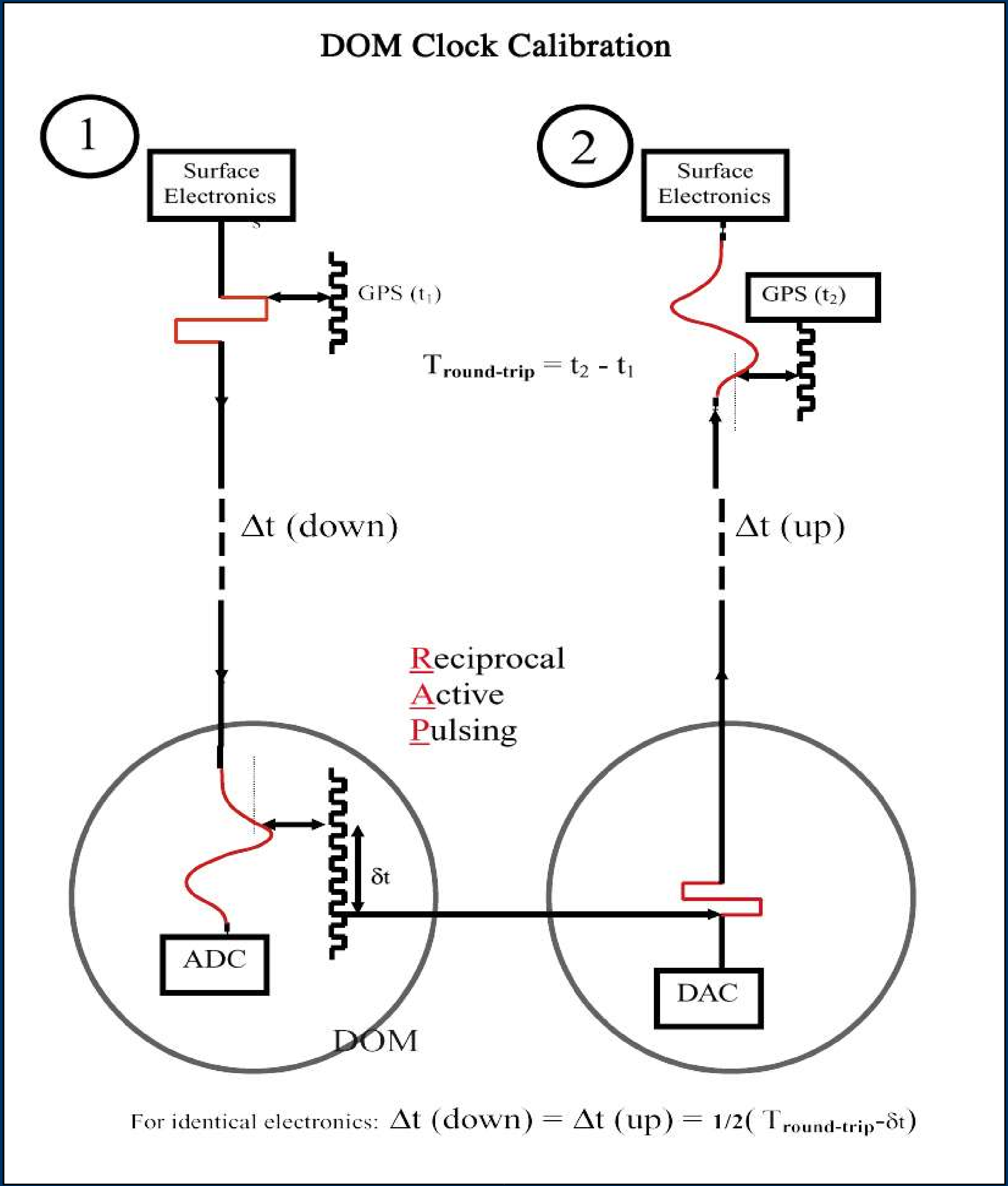
DOM waveform capture



- Altera Excalibur ARM922t µP+ 400k gate FPGA on a single chip
  - CPU runs data acquisition, testing facility, and diagnostic utilities
  - FPGA controls communications interface, time critical control of DAQ hardware, fast feature extraction of waveforms
- 2× ATWD – each with 4 channels capable of digitizing 128 samples at rates from 0.25 – 1.0 GHz. 2 of them for ‘ping-pong’ mode.
- 3 gain channels in ATWD for complete coverage of PMT linear region
- 10-bit, 40 MHz FADC for capture of extended photon showers in the ice.

DOM Mainboard





RAPCal

Relating the local DOM oscillator to GPS time.

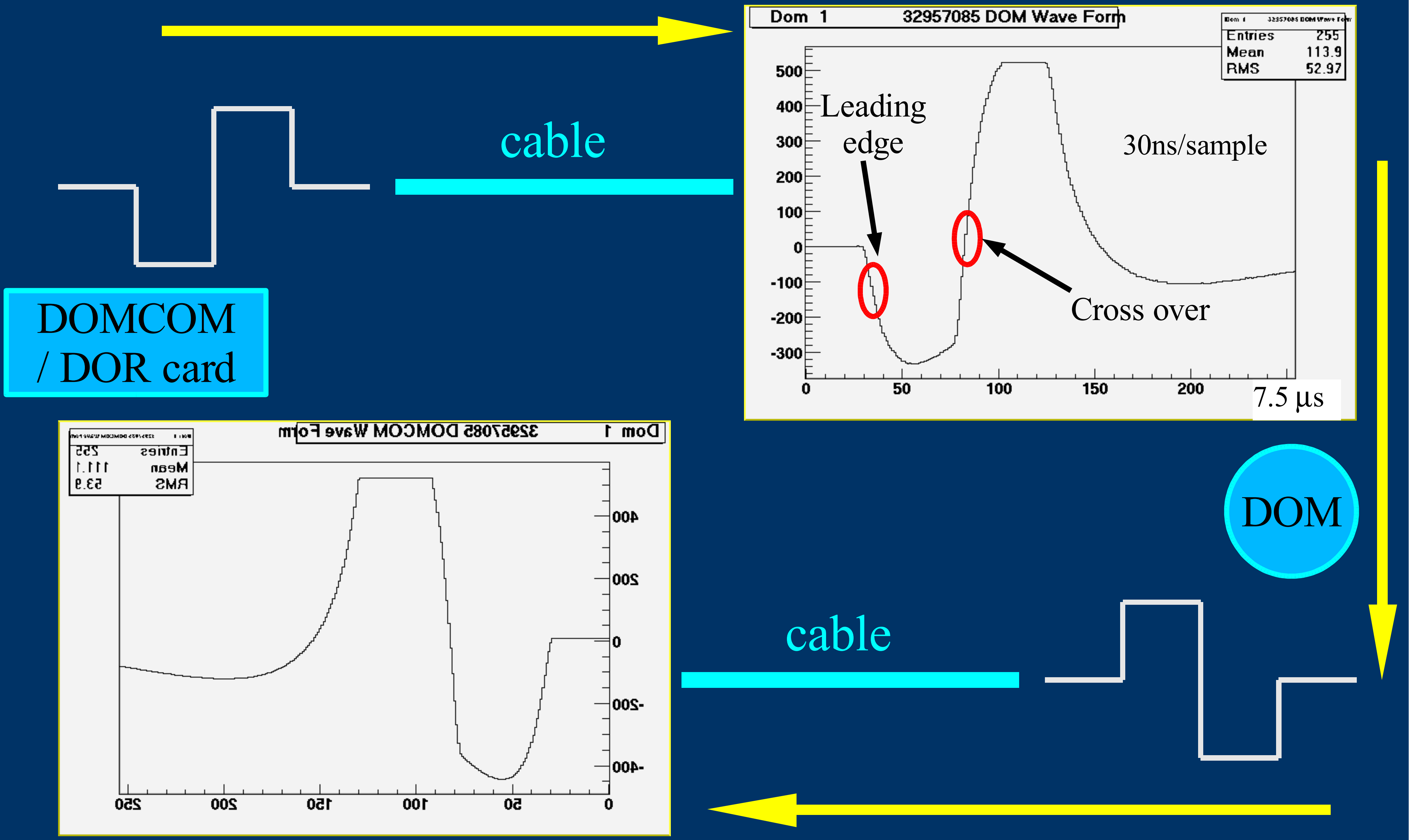
Golden Rule of Time Calibration:

One-way time =
1/2 round trip time

ONLY IF

Symmetry in pulse generation, processing and transmission at both ends

RAPCal waveforms



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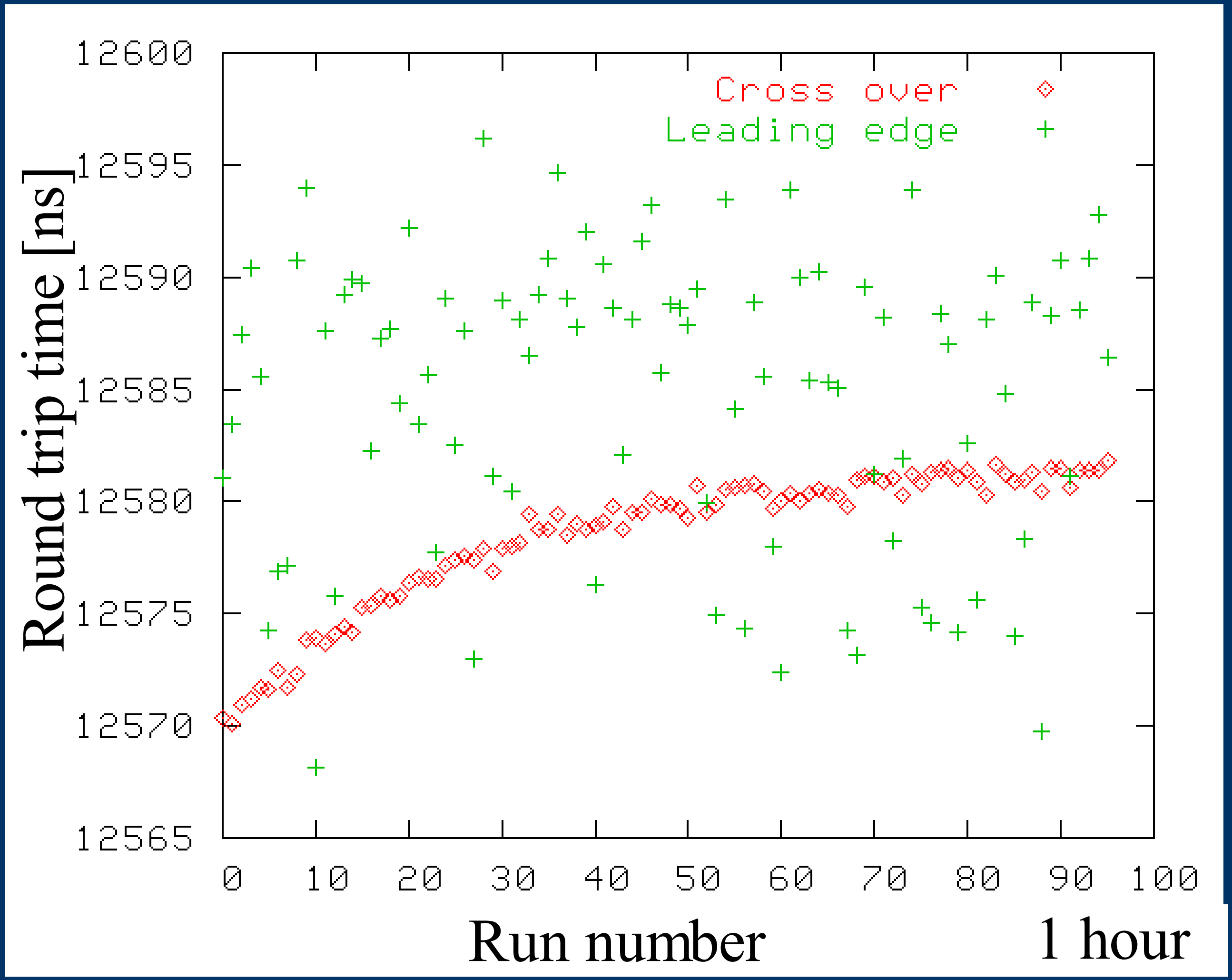
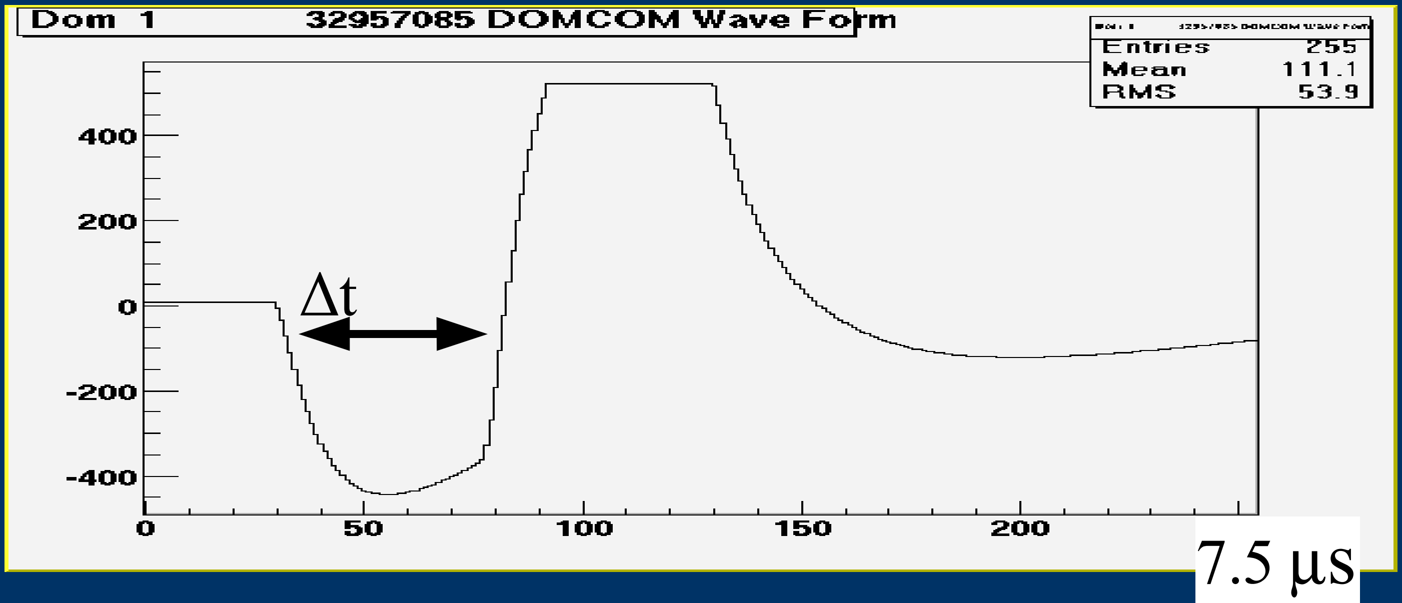
Temperature dependence of leading edge vs cross over



Leading edge ok with temperature but
has about 10 times higher RMS (~10ns) than cross over!

K. Helbing, LBNL/Erlangen, 10/2004

Sytematics of LE vs CO

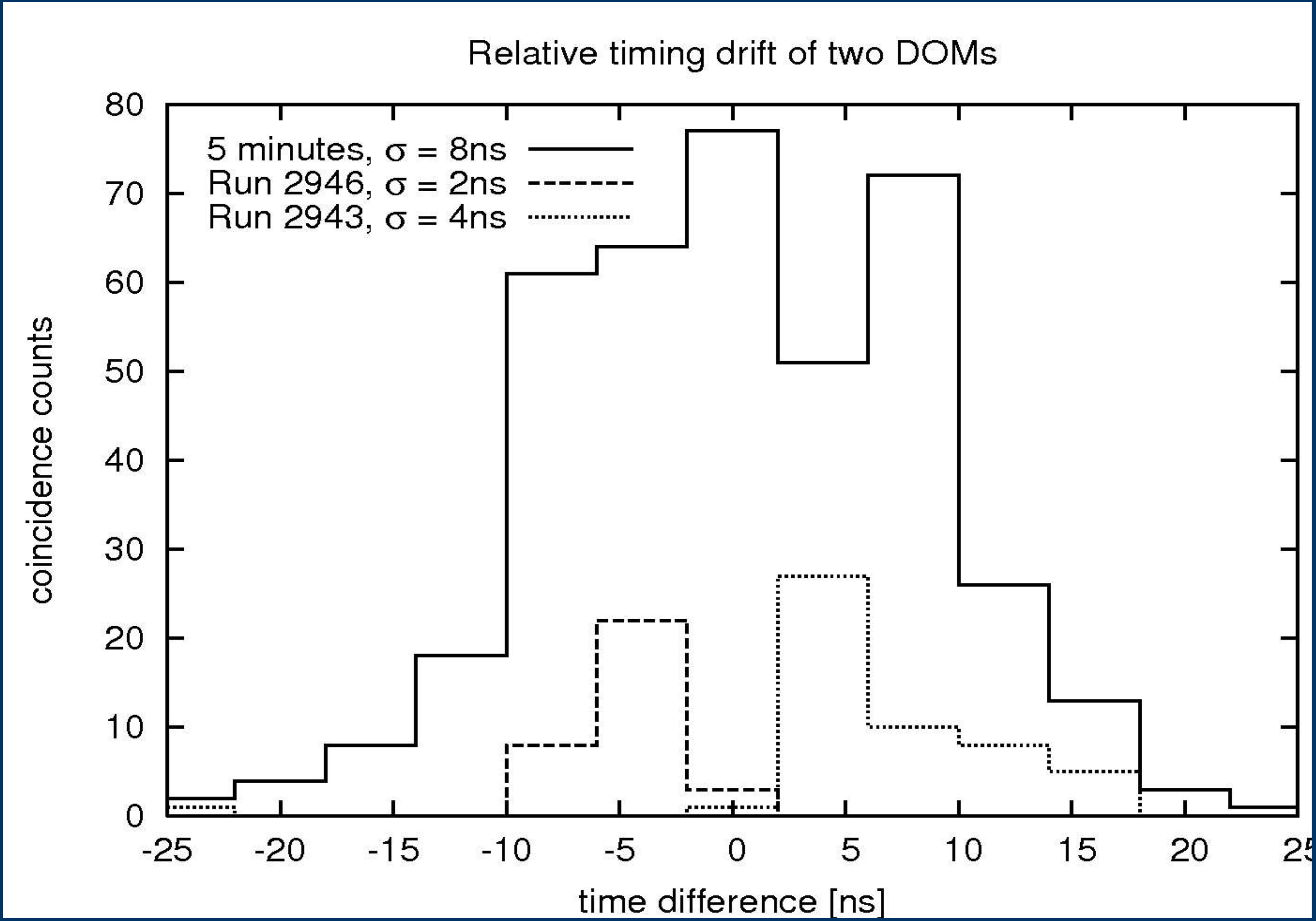


- Δt spreads out with rising temperature.
- Effect is the same for down going and up going RAPCal pulses.
- Differences between individual DOMs show up symmetrically on both ends.

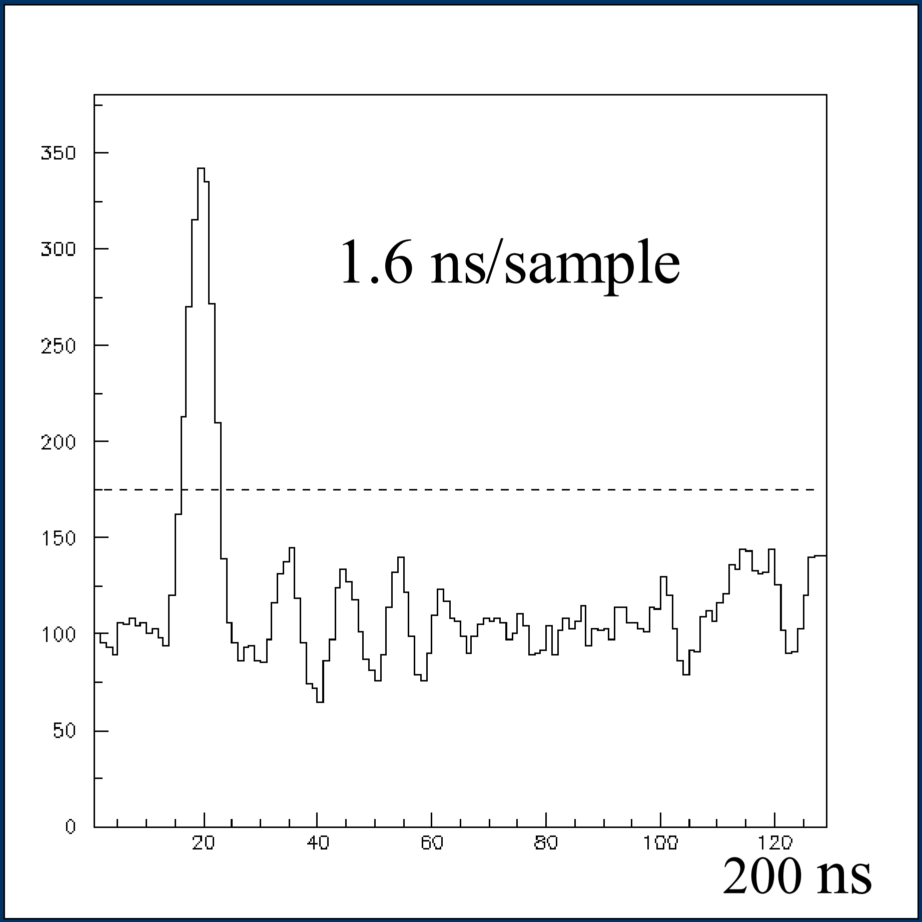
Use of cross over ok → Benefit from 1 ns RMS

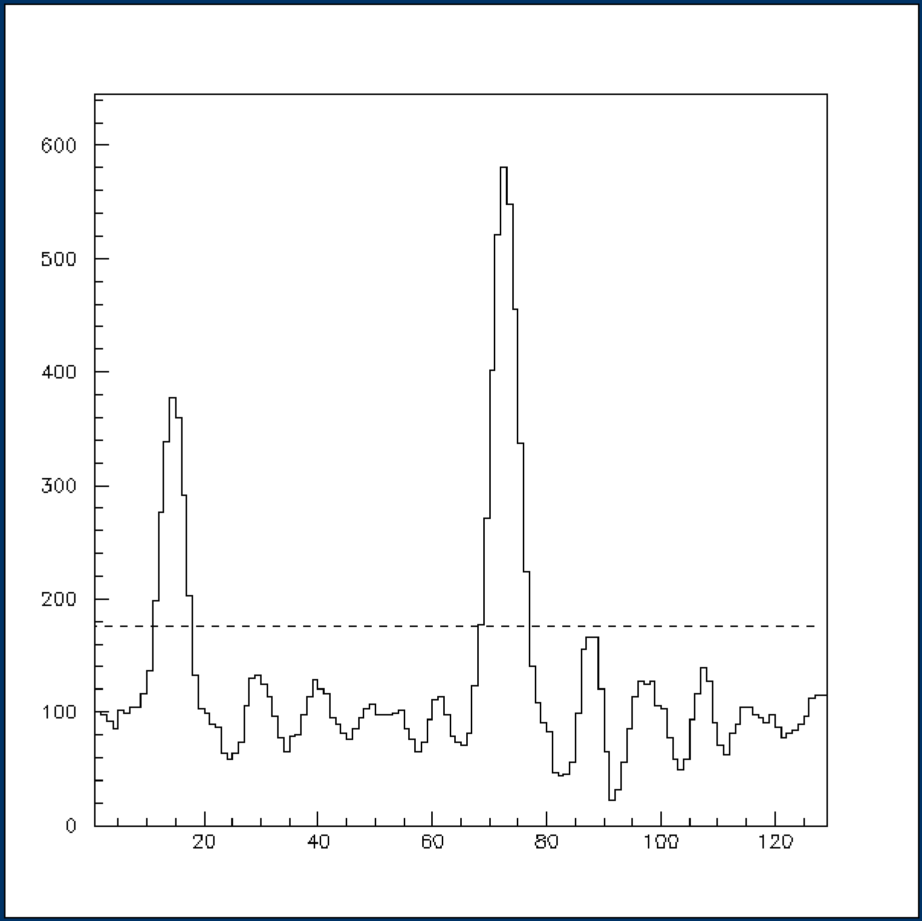
Timing accuracy

Comparison of LED flasher hit times converted to global times of 2 DOMs

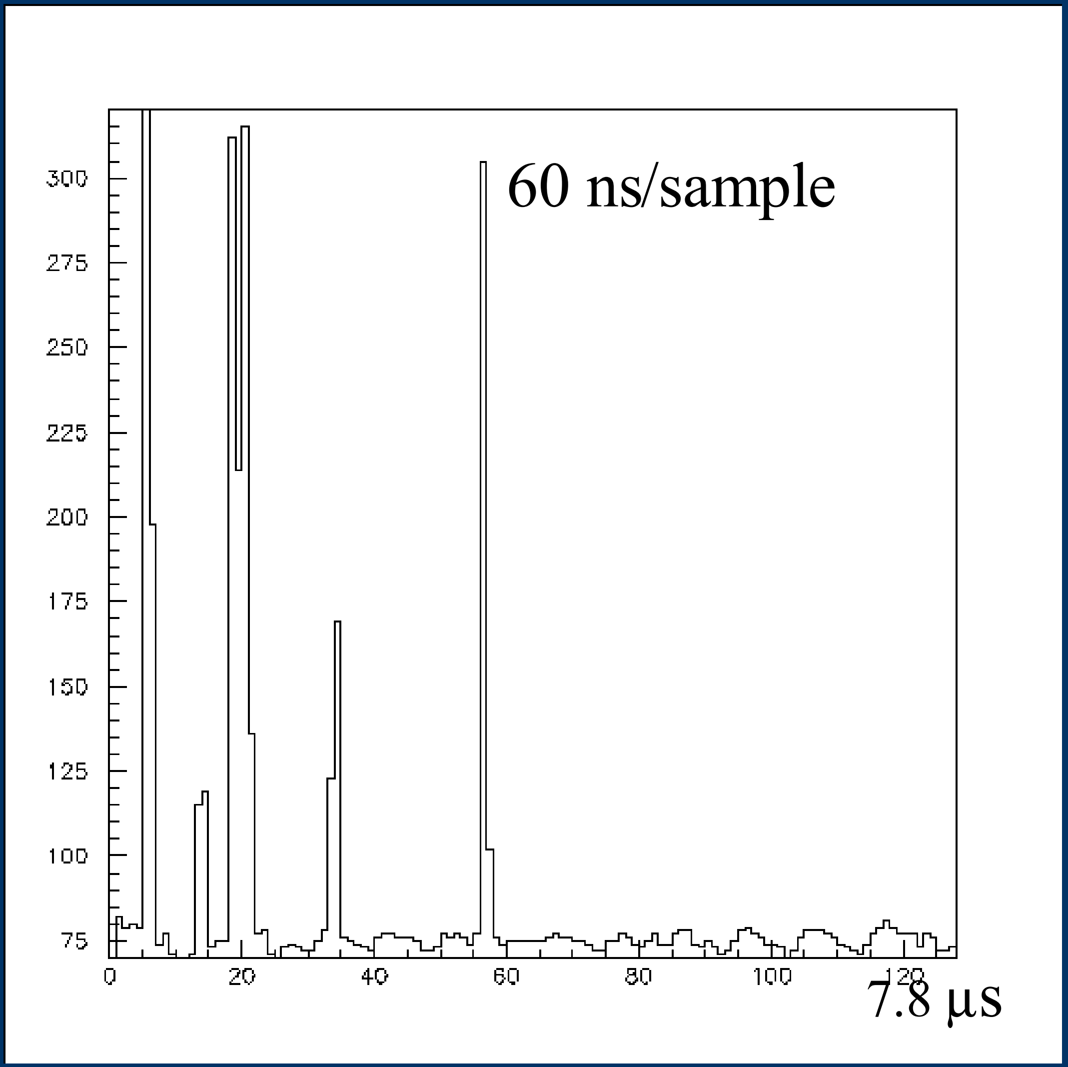


PMT waveforms: Examples from ATWD





PMT waveforms: Busy example from fADC



Constraints on compression

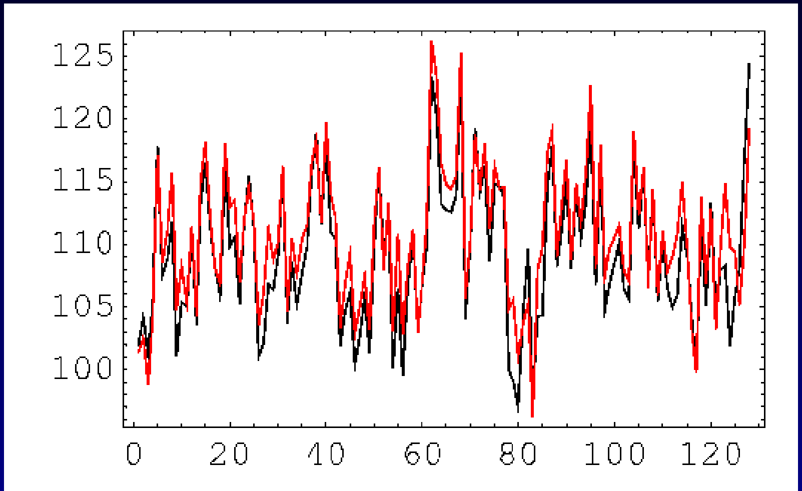
- Bandwidth: 1 Mbaud per 2 DOMs $\rightarrow$ Karl-Heinz Sulanke
- Computing resources:
  - CPU: 40 MHz ARM (16.8 MHz in String-18)
  - FPGA: $\sim$ 16,000 Logic elements ($\sim$ 3000 in String-18, no room left for compression)
- Noise rate: 500 Hz (required; 1kHz in String-18)
- Correlation of noise:
  $\Rightarrow$ feature extract SPEs and send MPEs uncompressed doesn't work.

Too much data for available bandwidth
Too few resources to do standard compression like gzip

Principle idea

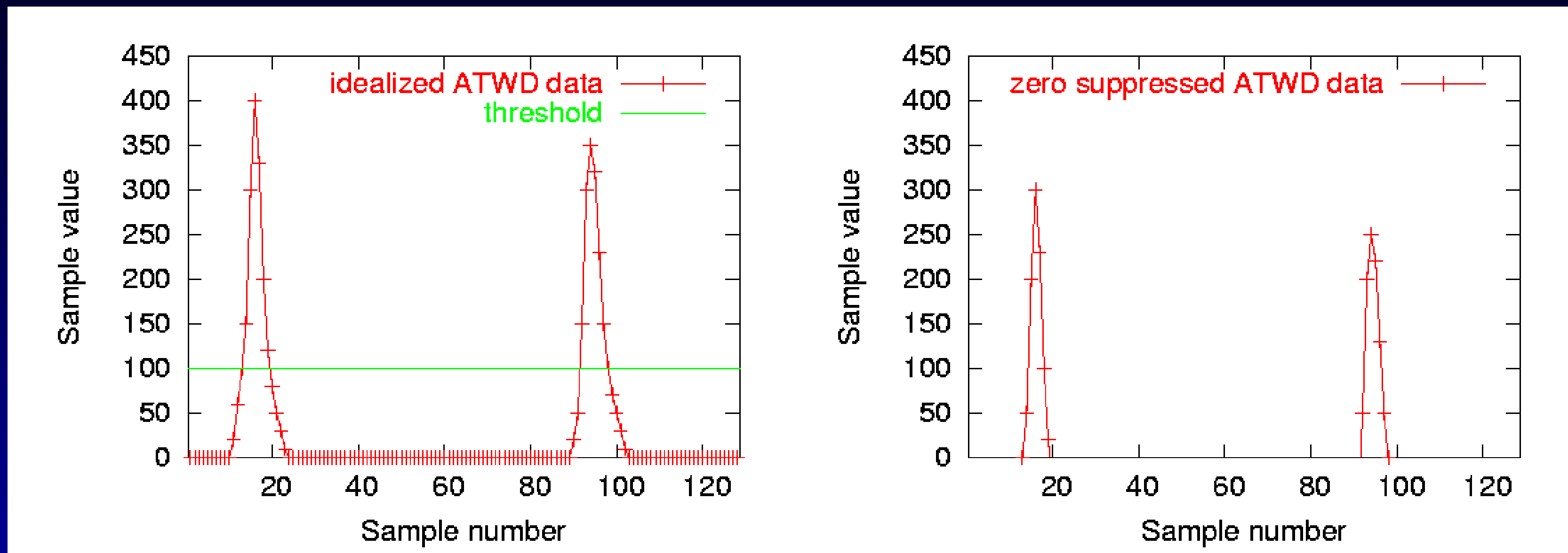
- Waveform of 1 ATWD channel or fADC similar to a facsimile scan line.
- Waveform corresponds to gray-scale representation of FAX line.
- Original FAX encoding: run-length encoding followed by Huffman encoding.
- Group 3 CCITT facsimile standard: fixed, immutable, Huffman code, optimized for a set of eight standard documents.
- Do Huffman encoding of waveforms with static table (to be generated as a calibration task).
- Further simplify this to “Huffman-lite”

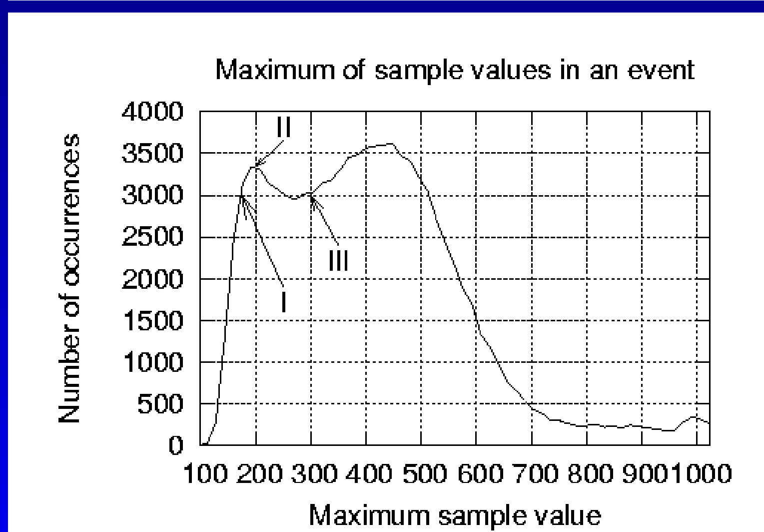
Step I: Pedestal etc



- Pedestal investigated by David Seckel: not perfectly constant in String-18, integrated IceCube DOM should deliver constant fingerprint (ATWD tester, STF, TestDAQ)
- Ringing should not occur in IceCube DOMs!
- Baseline: Low frequency noise on different ground levels.
- Pick ATWD channel with highest gain that doesn't saturate.

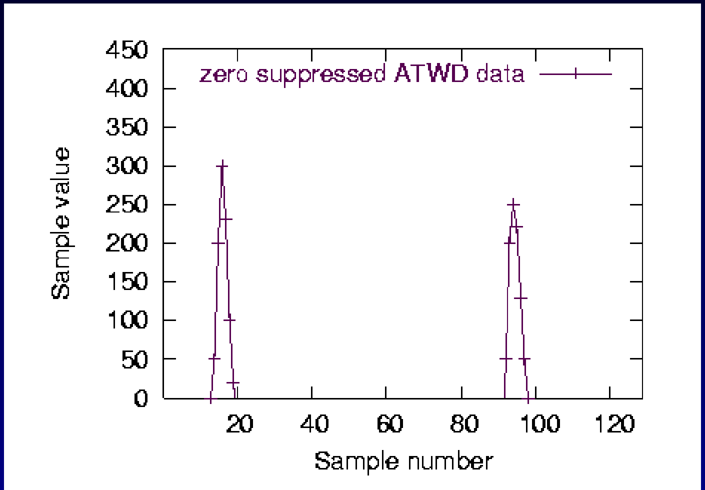
Step II: Zero suppression





Typical setting of threshold of discriminator and zero suppression: 25% - 33% of average SPE pulse hight over baseline.

Step III: Run-length encoding



0 . . . 0 50 200 300 230 100 20 0 . . . 0 50 200 250 220 130 50 0 . . . 0: **128 Bytes**

$\Downarrow \quad \Downarrow \quad \Downarrow \quad \Downarrow$

12 0, 0 50, 0 200, 0 300, 0 230, 0 100, 0 20, 71 0, 0 50, 0 200, 0 250, 0 220, 0 130, 0 50, 30 0: **30 Bytes**

Meaning of pair here: Number of consecutive *repetitions*, Value.

Standard RL: Number of consecutive *occurencies*, Value.

tweak of standard $\Rightarrow \sim 50\%$ of numbers are zeros (less entropy).

Step IV: Huffman-lite

Huffman encoding:

- Minimal variable-length "character" encoding based on the frequency of each "character".
- more frequent "characters" are encoded with few bits, and rare "characters" are encoded with many bits.

Huffman-lite:

- $\sim$ 50% of numbers ("characters") are zeros.
- Minimize bits used for zeros, don't work on finite values.
- Convert "0" (8 bits) $\rightarrow$ '0' (1 bit)

  Convert "N" (8 bits) $\rightarrow$ '1',"N" (9 bits)

  12 0, 0 50, . . . $\rightarrow$ '1000011000100110010 . . . '

Compression efficiency

[Bytes/event]	STRING-18			ICECUBE (estimate)		
Method	ATWD	fADC	header	ATWD	fADC	header
RAW	128	128	6	128	128	6
run-length	19	6	6	11 [a]+3 [b]	6	6
"gzip –fast"	15		6			6
"bzip2 -9"	10		6			6
"Huffman-lite"	15		6	12		6

Total: "run-length + Huffman lite" **21** **18**

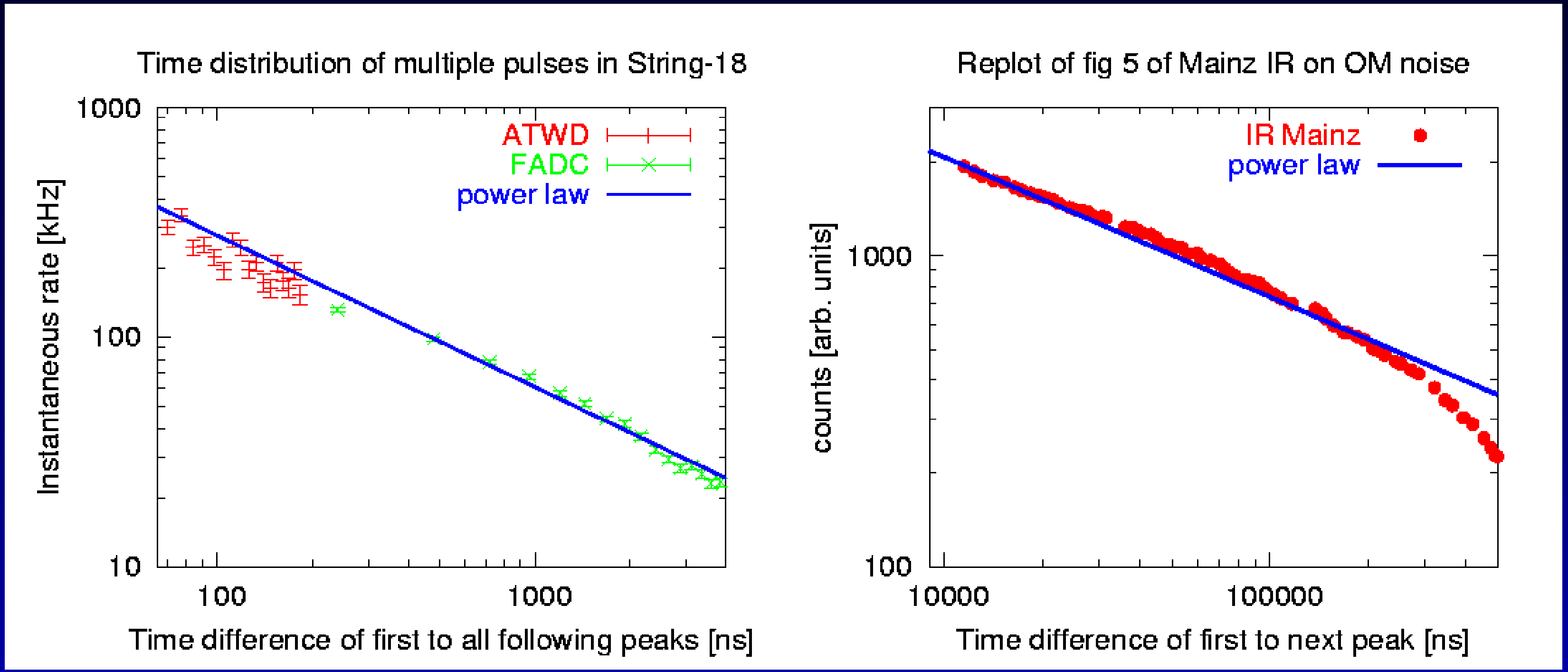
- **STRING-18:** 1 kHz PMT noise, 1 DOM/cable → 21 kB/s
- **ICECUBE (estimate):** 0.5 kHz, 2 DOM/cable → **18 kB/s**
- **Available bandwidth (IceCube): 100 kB/s/cable**

[a] 11: Half the sampling speed of ATWD.

[b] 3: Estimate for longer ATWD time window in ICECUBE.

Problem: Noise shows correlation!

Parameterization of time dist



- Log-Log plot shows data lie on straight line
- Resulting power law: $\dot{N} \simeq 6\ \mathrm{MHz} \cdot (\Delta t/\mathrm{ns})^{-2/3}$
- Data in Mainz IR (20010301-noise2) show same behavior up to $\sim 200\ \mu$s.

Radioactive sources

Nuclide	particle	energy [MeV]	range	activity† [Bq]
^{109}Cd	x-rays	0.020	$e^{-l/1.8\text{ mm}}$	$9 \cdot 10^5$
^{90}Sr$\rightarrow^{90}$Y	β^-	< 2.3; Ø:0.3	< 5 mm	$4 \cdot 10^4$
^{40}K	90% β^-	< 1.3; Ø:0.3	< 3 mm	$\sim 10^3$ ‡
	10% γ	1.5	$e^{-l/9\text{ cm}}$	§

Rough estimate of Čerenkov photons from ^{40}K β's:

- Č-threshold: 0.7 MeV $\Rightarrow$ less than 20% of β's produce Č-light at all.
- Above thres: $E_ø \sim 0.9$ MeV; track length < 1 mm; < 8 photons/mm.
- β emission isotropic, vast multiple scatt. $\Rightarrow \sim 1$ traveling to cathode

Efficiency for ^{40}K decay via Č-light $< 4\%$ $\Rightarrow$ **another mechanism exists!**

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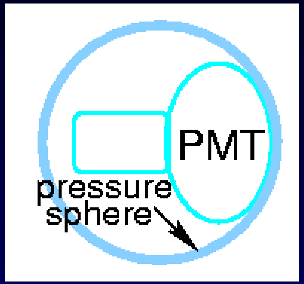
†: activity within observing reach of photo tube (collimated towards or facing).

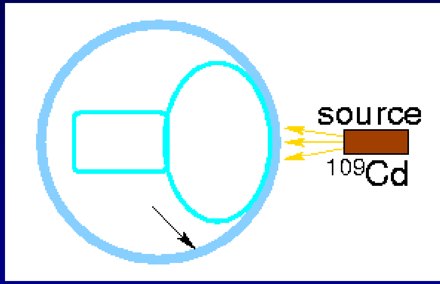
‡: Based on 1‰ potassium content, 1.2 cm thick pressure sphere, 450 cm^2 effective cathode area.

§: Contribution can be neglected due to low conversion probability.

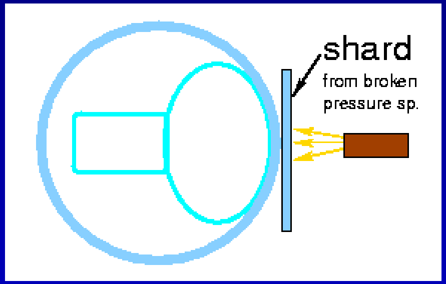
Irradiation of pressure spheres



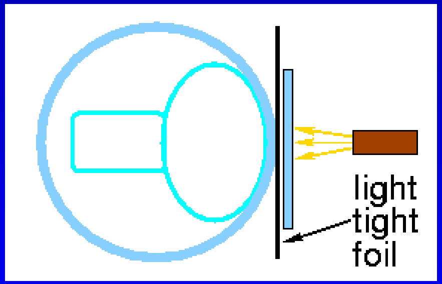
6 kHz dark count rate (increased level of thermal noise)



20 kHz with direct exposure to 20 keV x-ray source; 2 mm range of x-rays ⇒ light produced in glass.

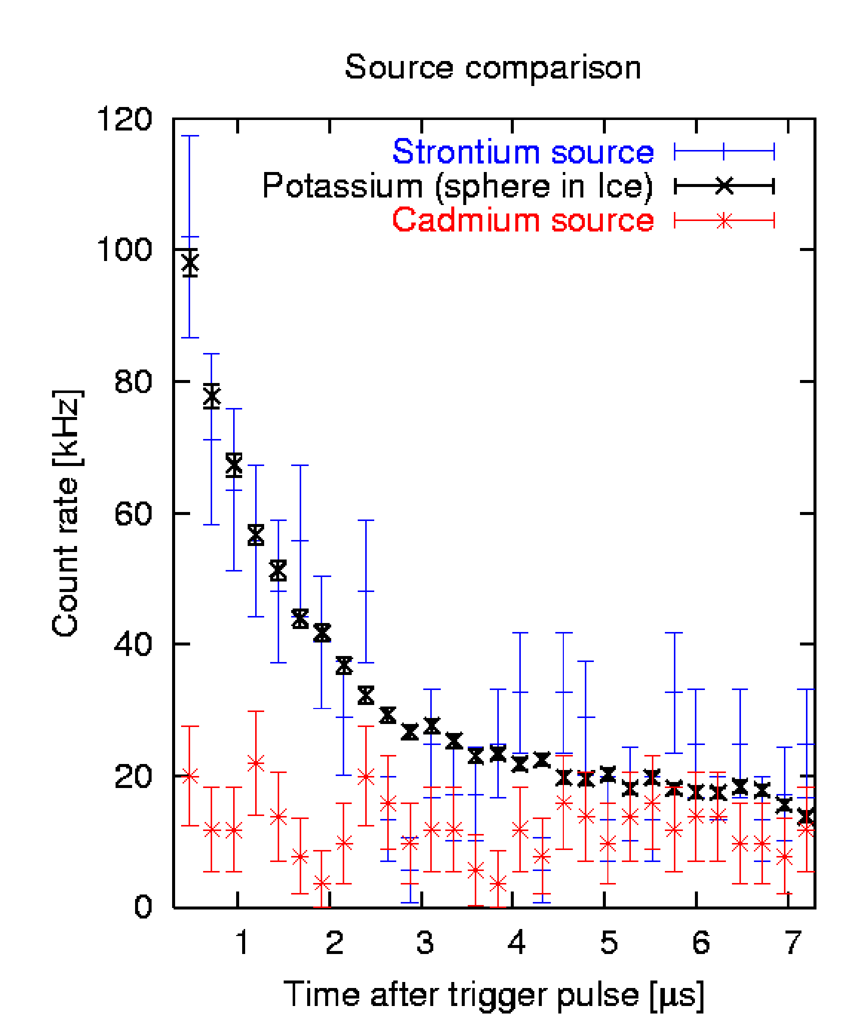


19 kHz with x-rays absorbed in extra glass shard ⇒ about the same amount of light still reaches photo cathode.



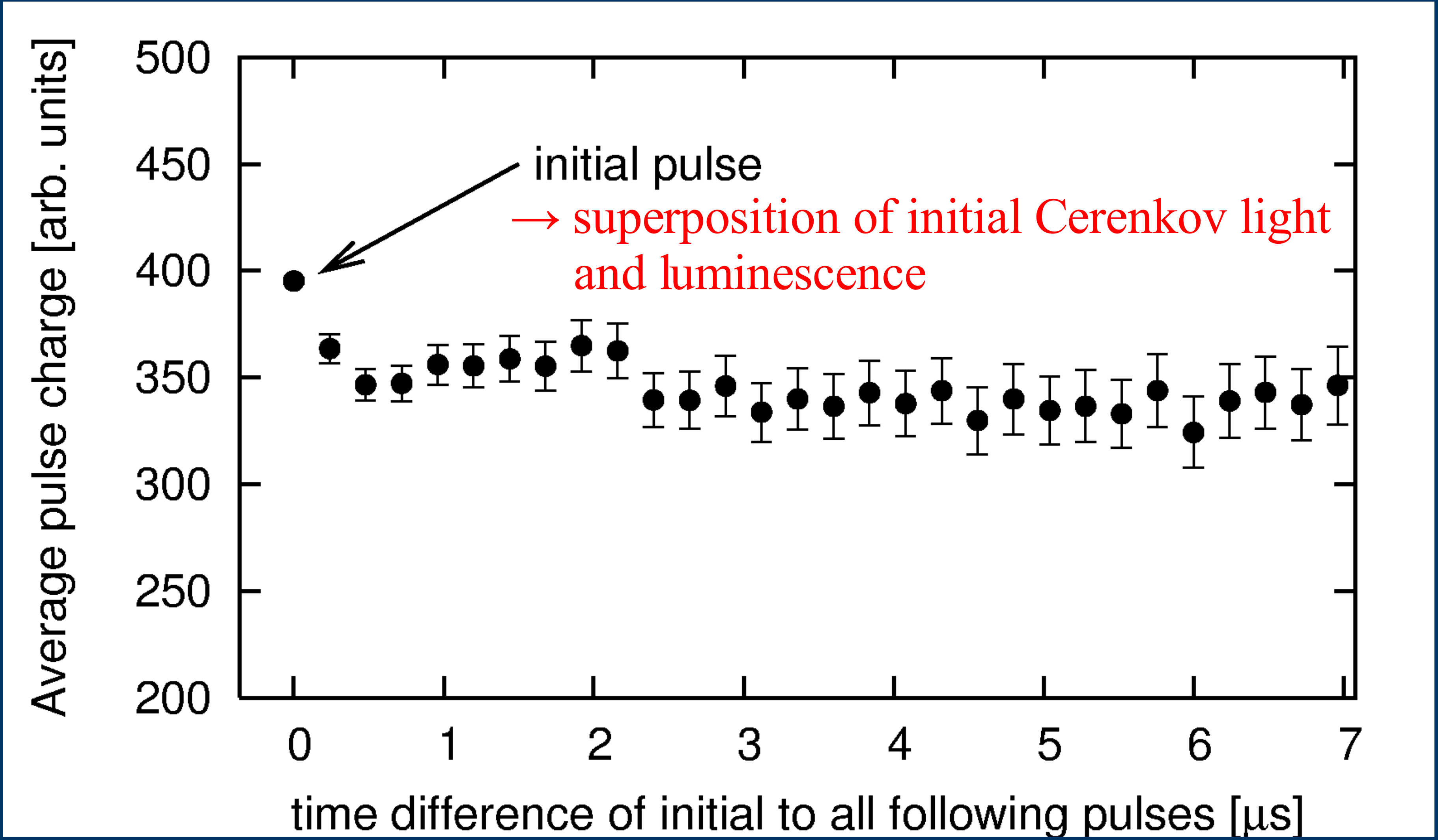
6.5 kHz with extra glass shielded: back to dark current ⇒ **It's not the x-rays directly but the energy deposit exciting light emission in the glass!**

Time distribution due to sources

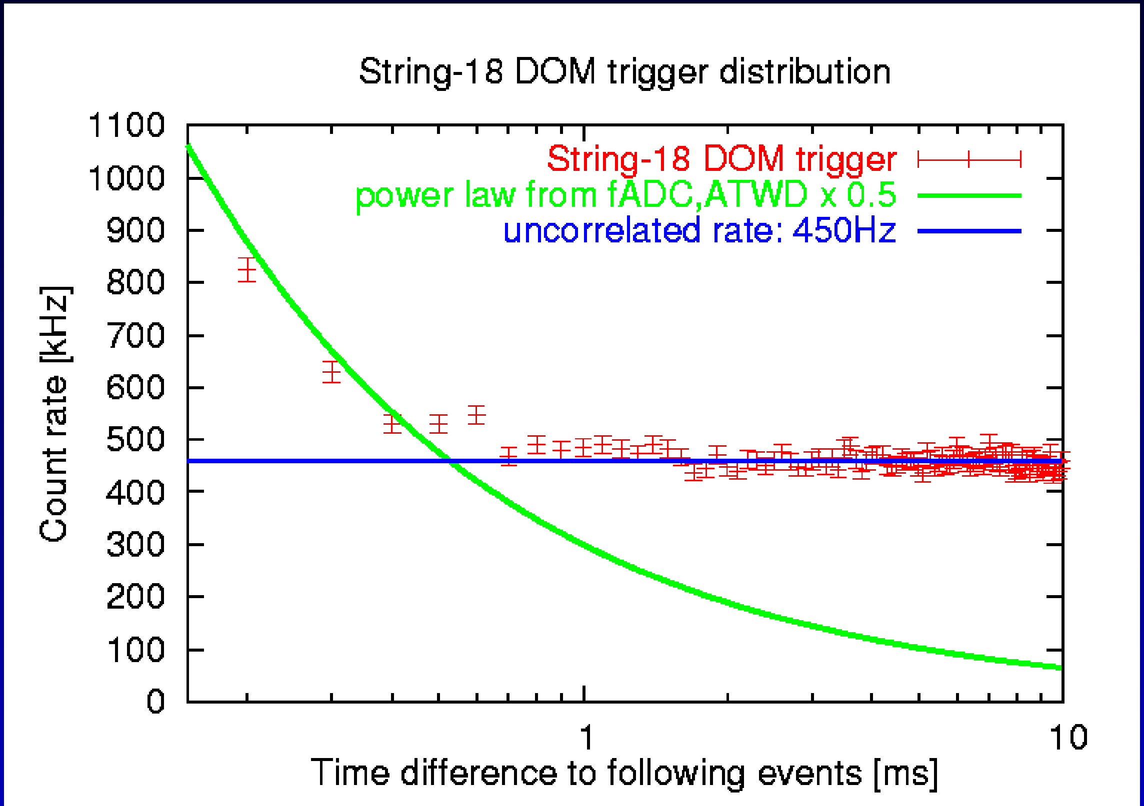


- ^{40}K and ^{90}Sr show similar behavior: correlation!
- Both excite luminescence in glass due to avg energy deposit of $\simeq 0.3$ MeV
- ^{109}Cd deposits only 20keV $\Rightarrow$ low probability for multiple PEs $\Rightarrow$ pulses uncorrelated.

Amplitude analysis of individual PMT pulses



Parameterization (cont.)



- Extrapolation of power law parameterization by 3 orders of magnitude still correct! (factor of 2 due to different trigger thresholds)
- Uncorrelated noise starts dominating at $\Delta t > 300 - 800\ \mu s$

Comparison: efficiency for ^{40}K

Material	photons/E [keV^{-1}]	efficiency
Benthos sphere	0.02	70 %
Scintillating glass (4% Ce_2O_3)	1.50	100 %
Plastic scintillator	10.00	100 %

- Benthos sphere only slightly less efficient for ^{40}K than dedicated scintillators!
- βs from ^{40}K hardly produce any Čerenkov light.

Not the amount of ^{40}K is the problem but seeing it via scintillation!

. . . power law was seen before

C. Angelini *et al.*, NIM A281 (1989) 50

Decay time of light emission from cerium-doped scintillating glass:

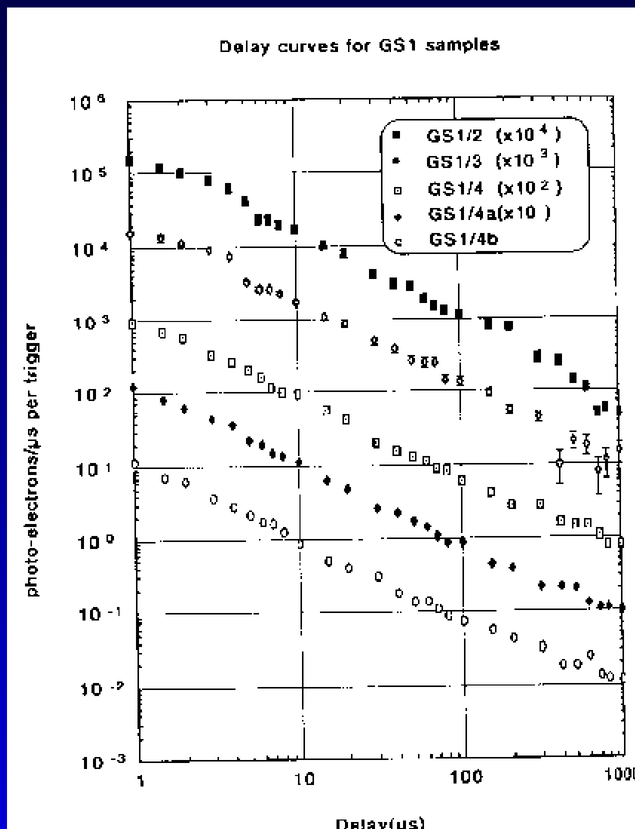


Fig. 6. Comparison of the slow component in the emission of several GS1 samples. (1) GS1/2, GS1/3, GS1/4 contain 2, 3, 4% Ce_2O_3 by weight; (2) GS1/4a, GS1/4b were annealed to 600 ° C and 650 ° C.

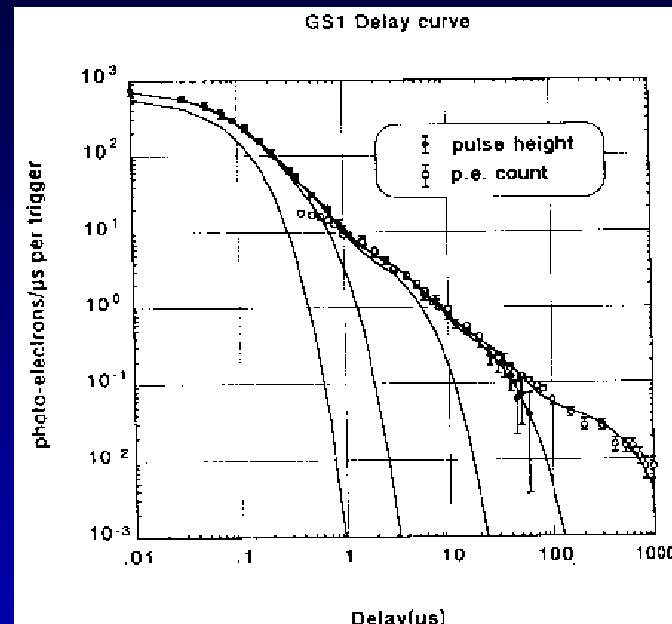
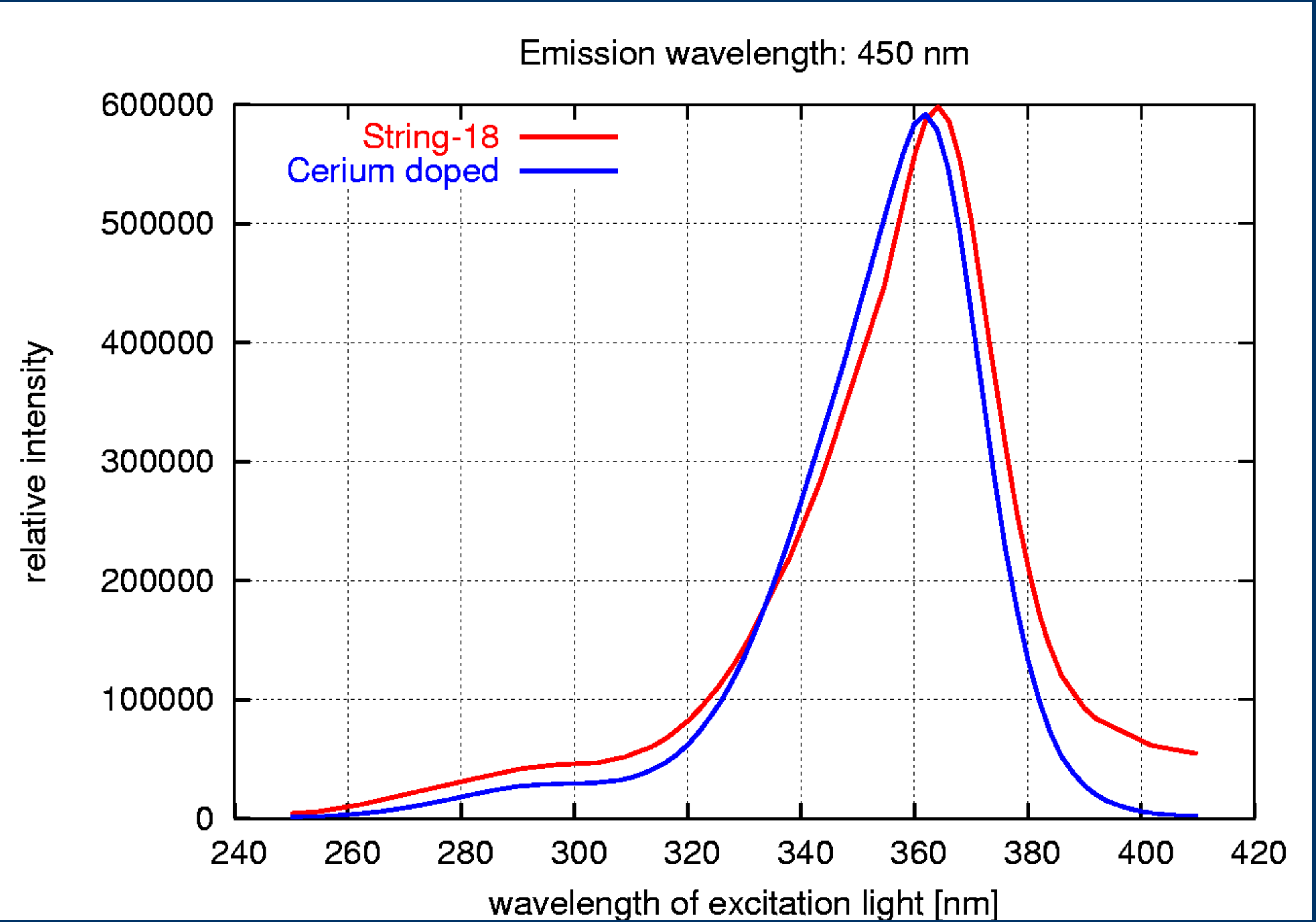


Fig. 5. Emission time data from GS1 comparing pulse height and counting methods. Curves corresponding to terms in the overall fit are indicated.

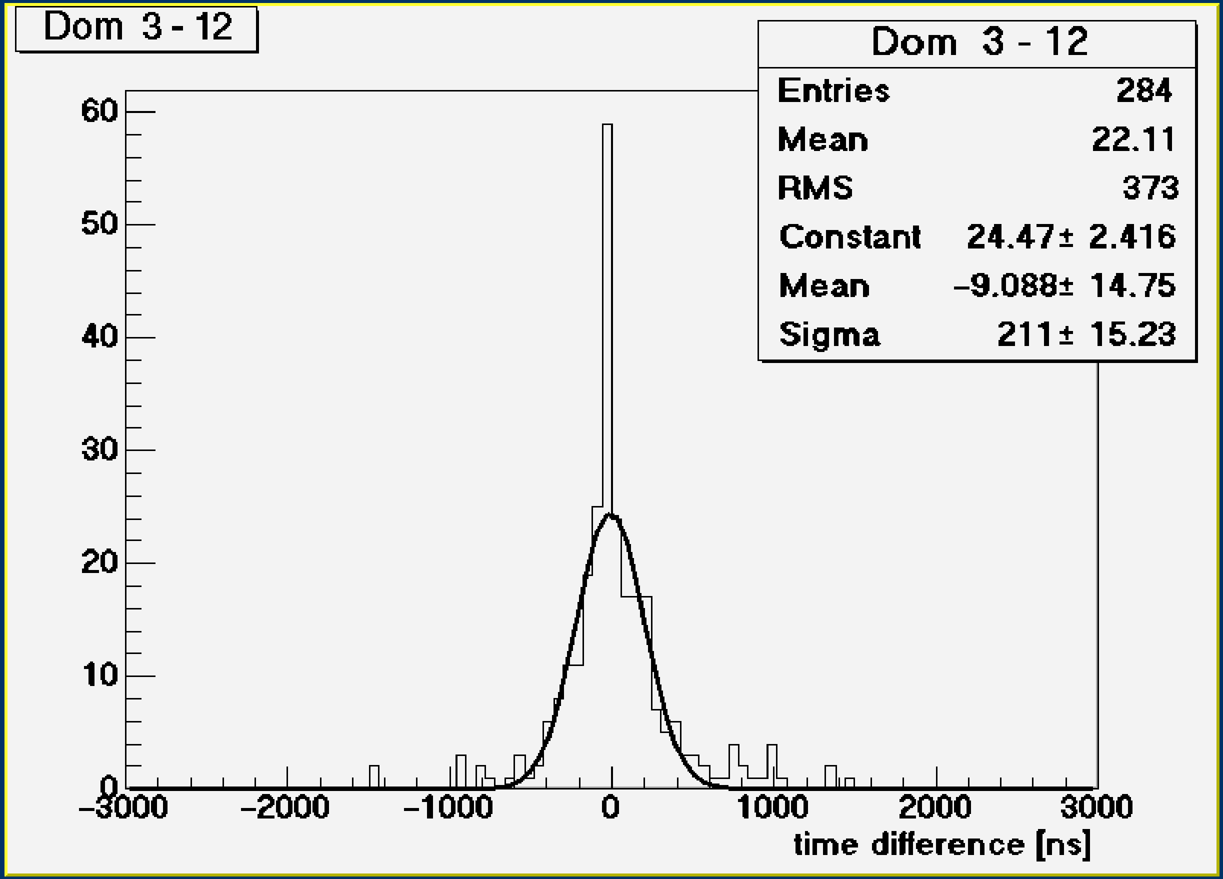
“Power law” could be superposition of several exponential decays with amplitudes obeying power law

. . . strange enough!

Excitation spectrum of Cerium doped glass vs pressure sphere glass



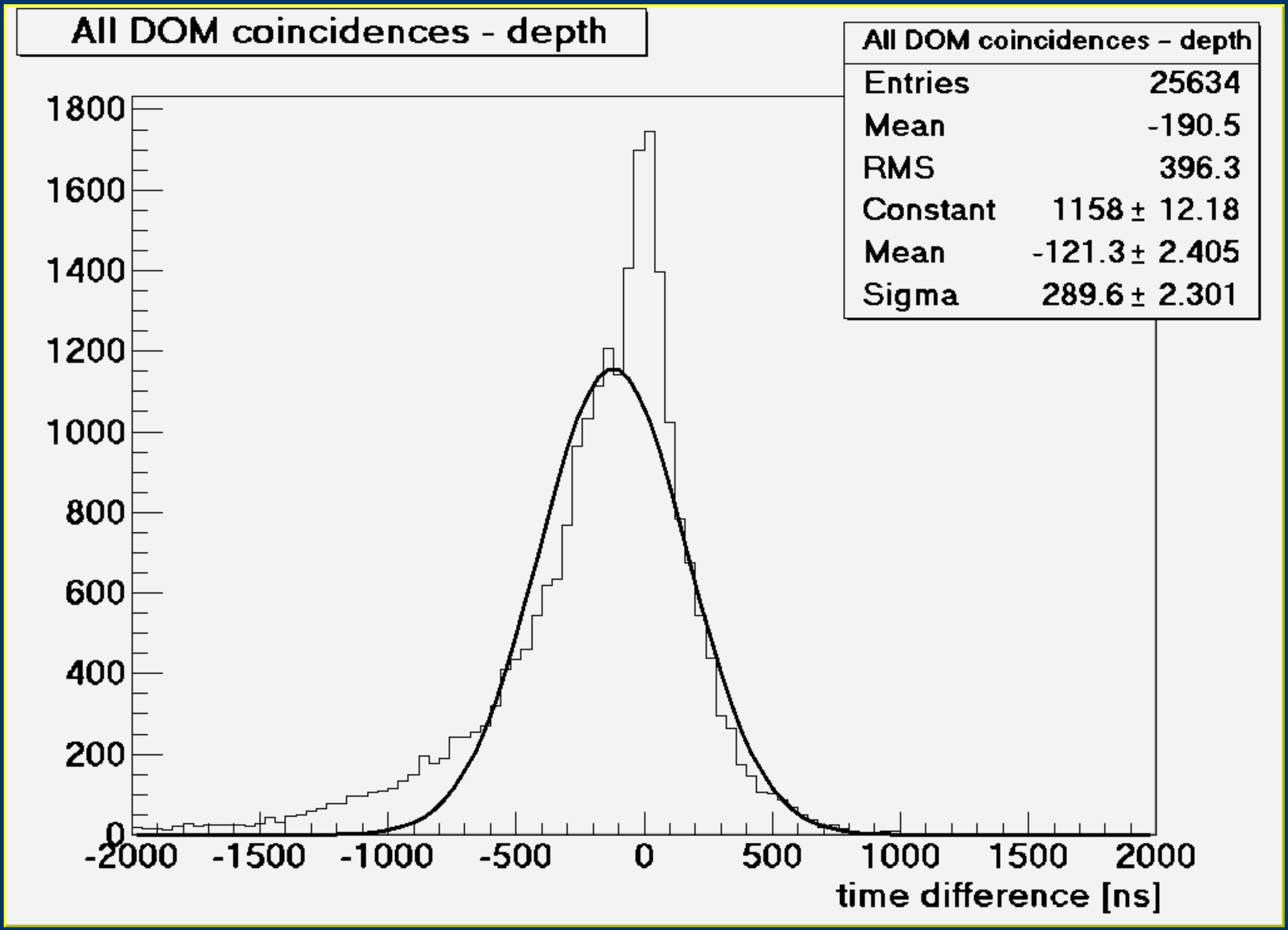
Down-going muon analysis: Coincidences between DOMs



DOM separation: 36m

Times shifted wrt hypothesis of down going muons

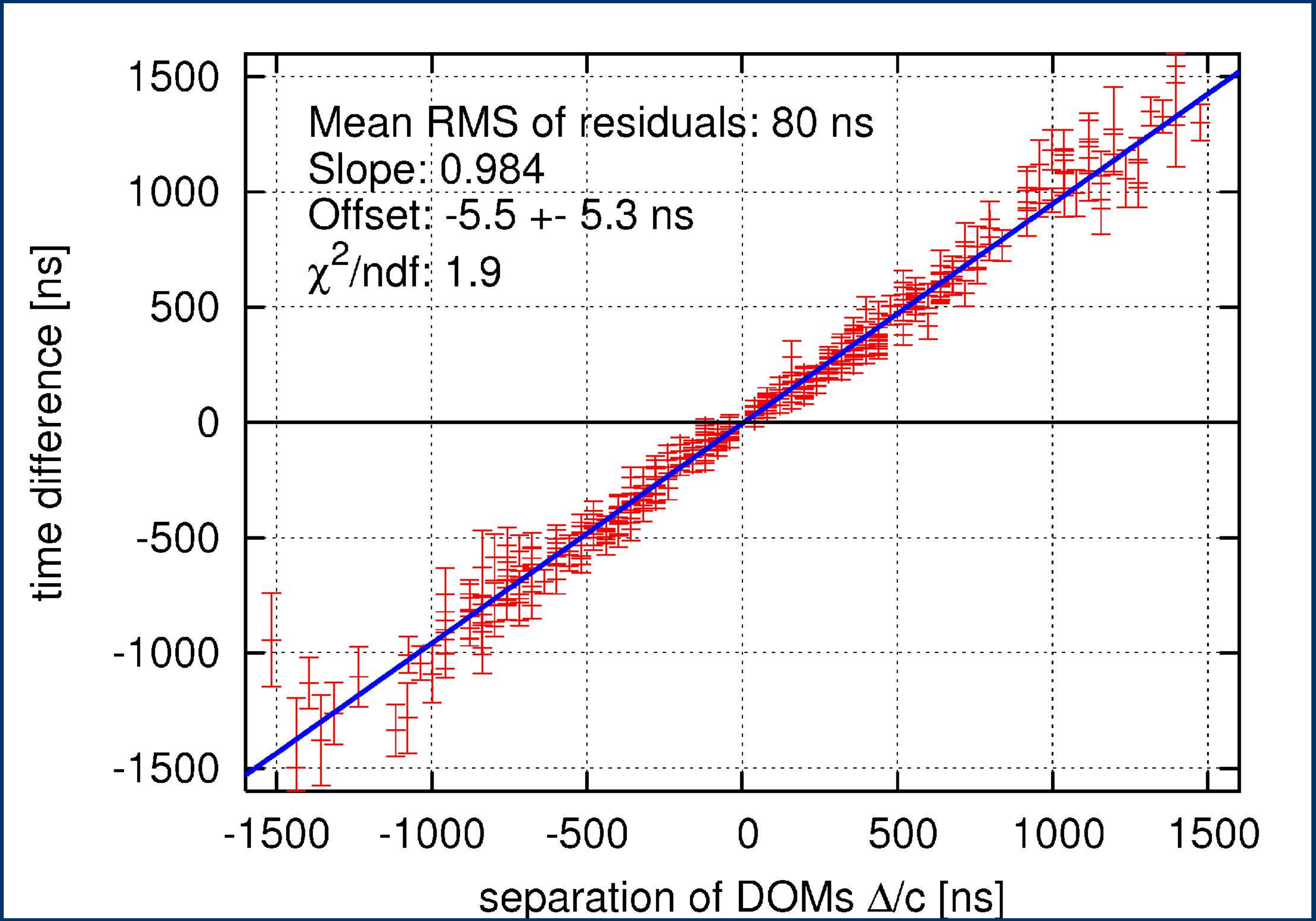
All DOM coincidences piled up



Asymmetry due to angular distribution of muons

Distribution is consistent with down going muon hypothesis

DOM combinations vs separation



Multiplicity => 8

! Clearly down going muons !

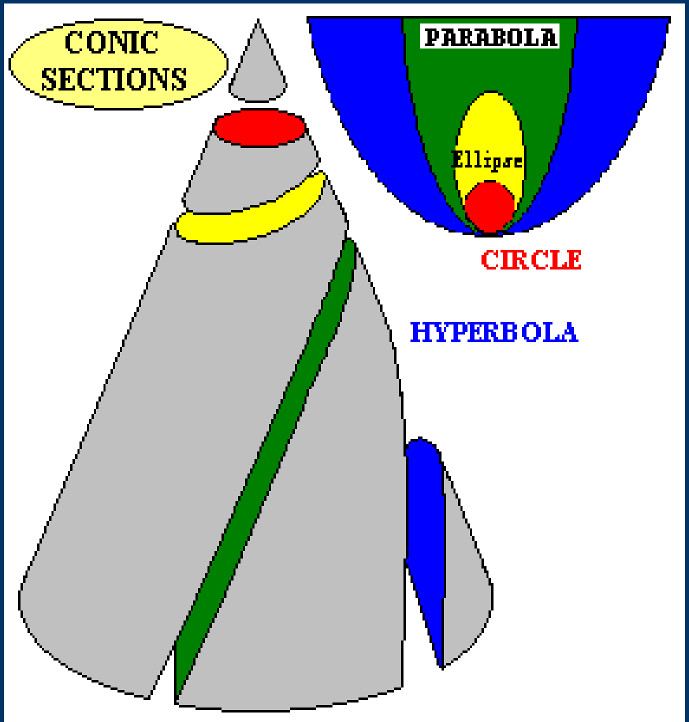
Independent cross check of Amanda geometry calibration

K. Helbing, LBNL/Erlangen, 10/2004

Muon reconstruction with a single string

Hyperbola:

$$t = t_0 + \frac{1}{c}\left[(z - z_0)\cos\theta + \sqrt{n^2 - 1}\sqrt{d^2 + (z - z_0)^2 \sin^2\theta}\right]$$



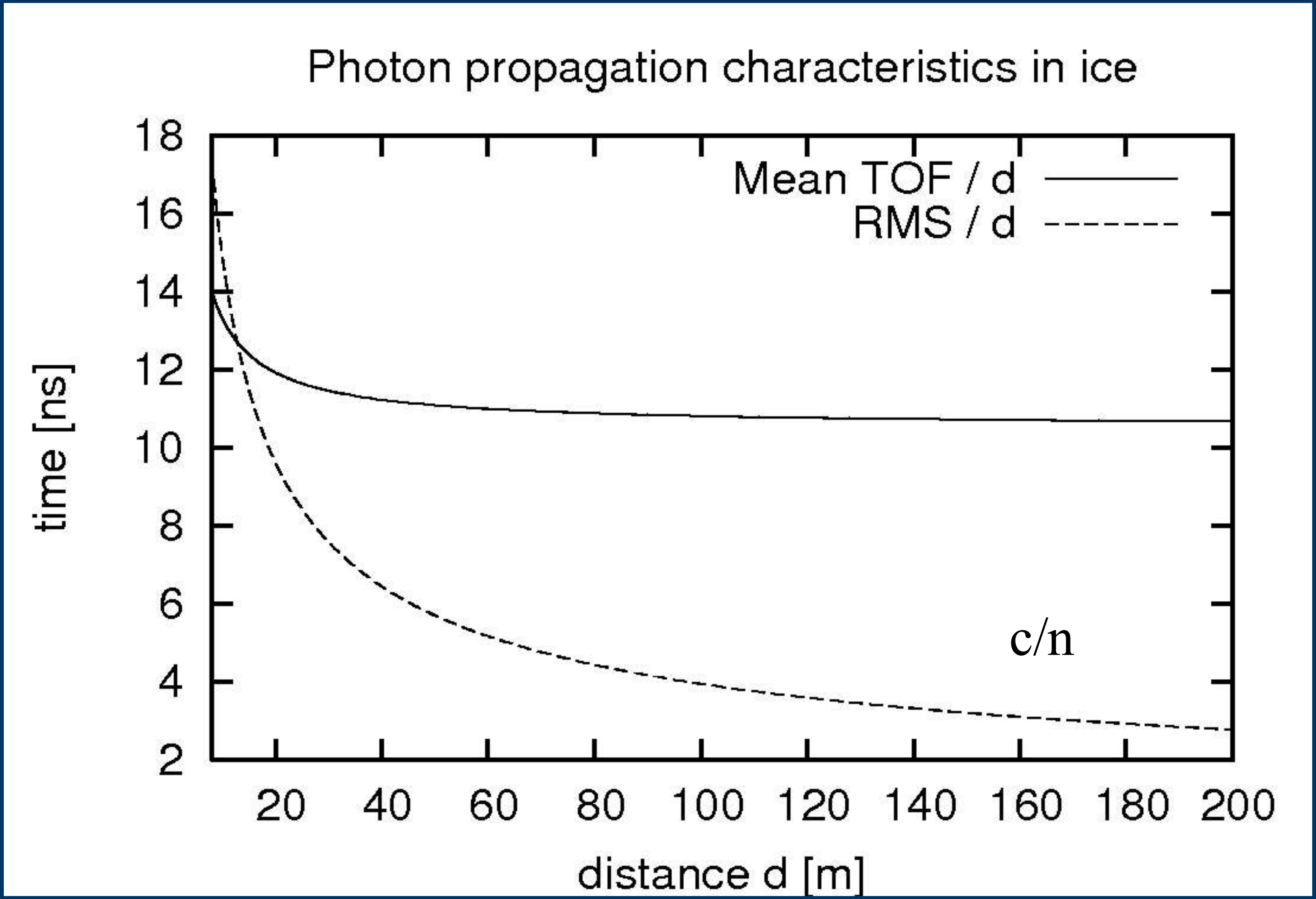
Special case of hyperbola:
section is parallel to symmetry axis:

$$z = \frac{1}{a}\sqrt{d^2 + y^2},\ a = 1/\sqrt{n^2 - 1}$$

$$z \Rightarrow (t - t_0)c - (z - z_0)\cos\theta$$

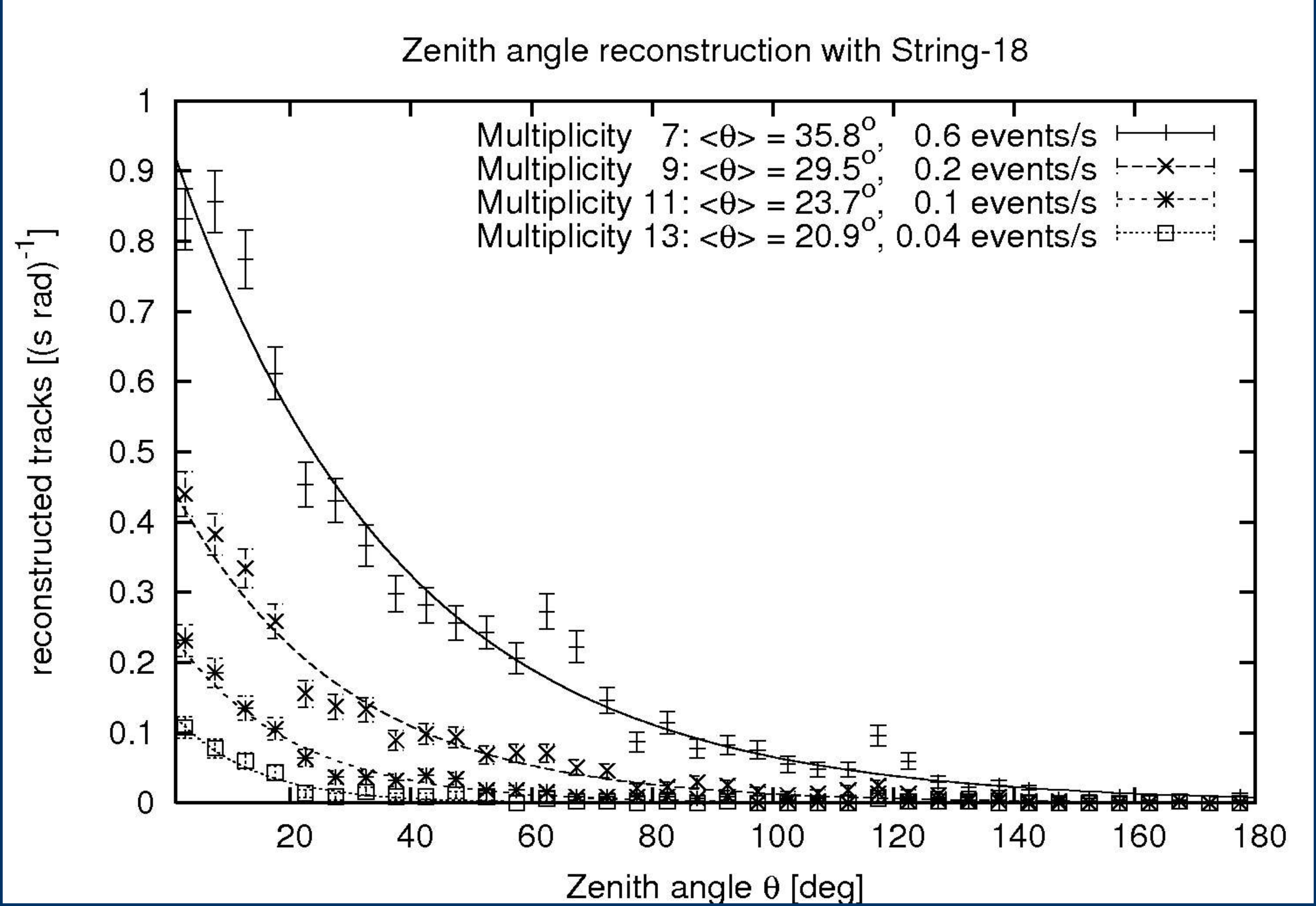
$$y \Rightarrow (z - z_0)\sin\theta$$

The effective speed of light in ice

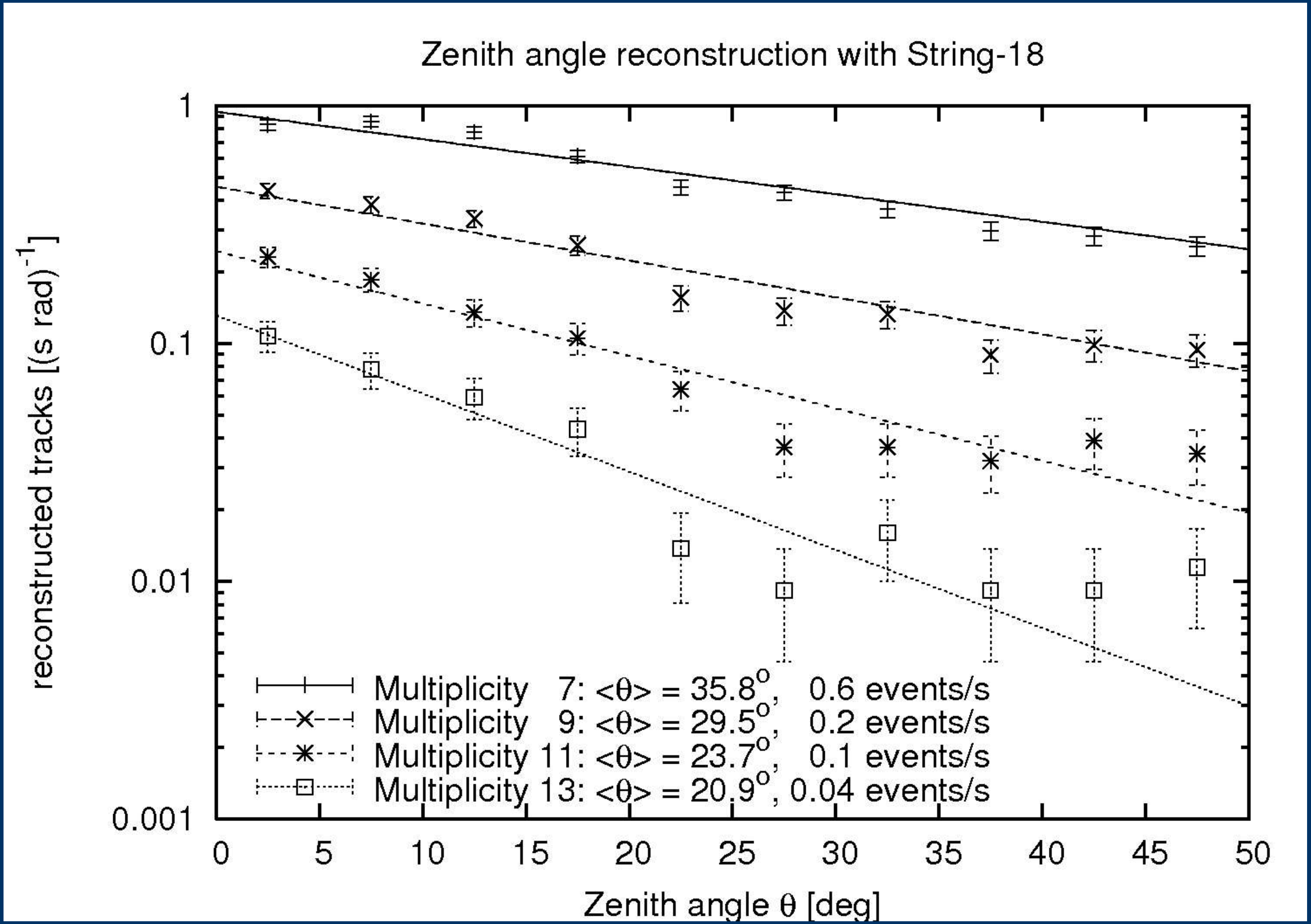


Replace n = 1.32 with n = 3.16 to mimic mean progress

Applied to String-18 data



Effect of multipliciy



IceCube status

- Large-scale production and testing of digital optical modules under way
- Drill equipment built and shipped
- First deployment DAQ system under construction
- First 4 strings will be deployed 2004/05 season
- ***1 km^2·yr will be achieved in 2007***
- Construction scheduled to be completed in 2010.