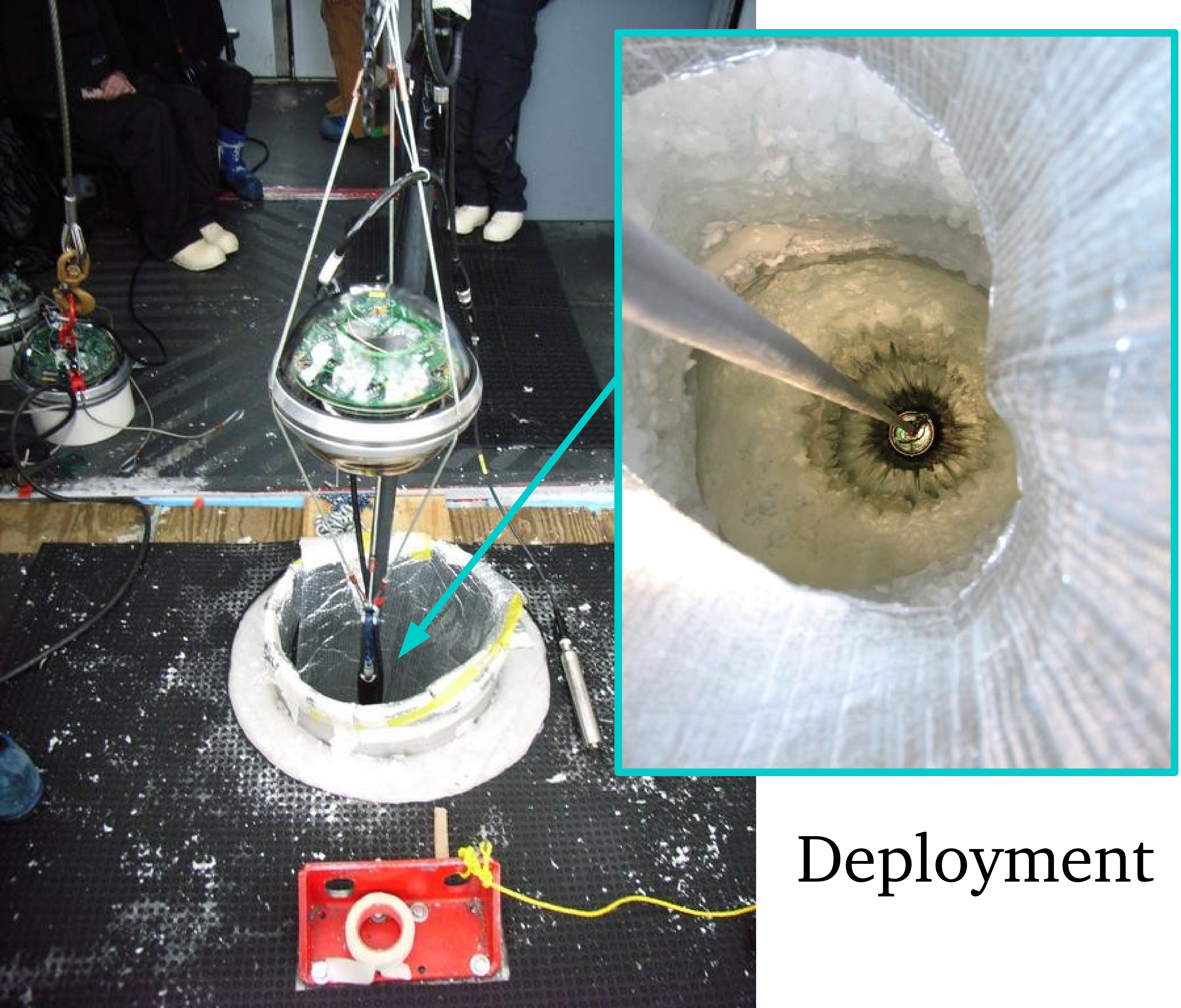
IceCube Hardware

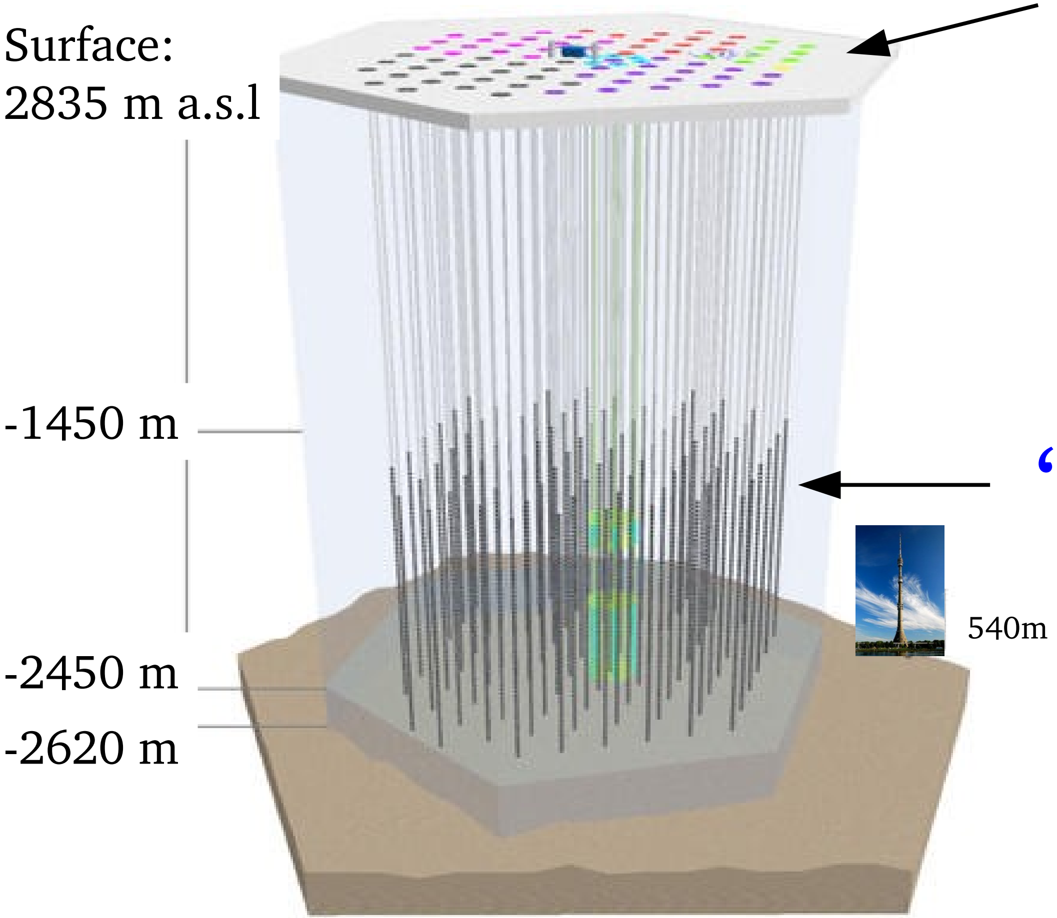
II: Data Acquisition and Calibration

Seminar
October 29nd, 2015



Deployment

IceCube Detector



IceTop Surface Array

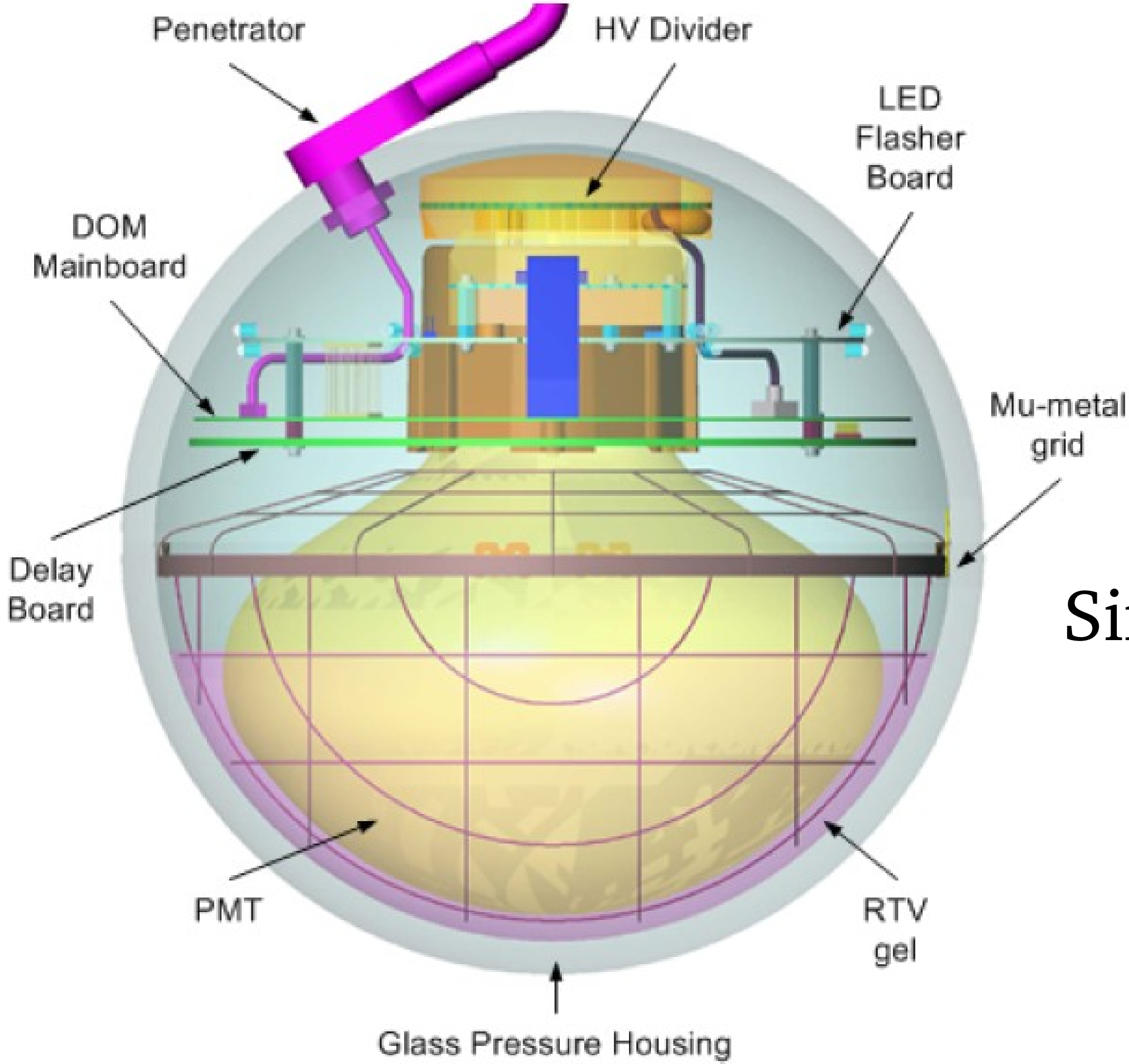
81 Stations
x 2 Tanks
x 2 DOMs
= **324 DOMs**

"InIce" Volume Detector

86 Strings
x 60 DOMs
= **5160 DOMs**

DOM

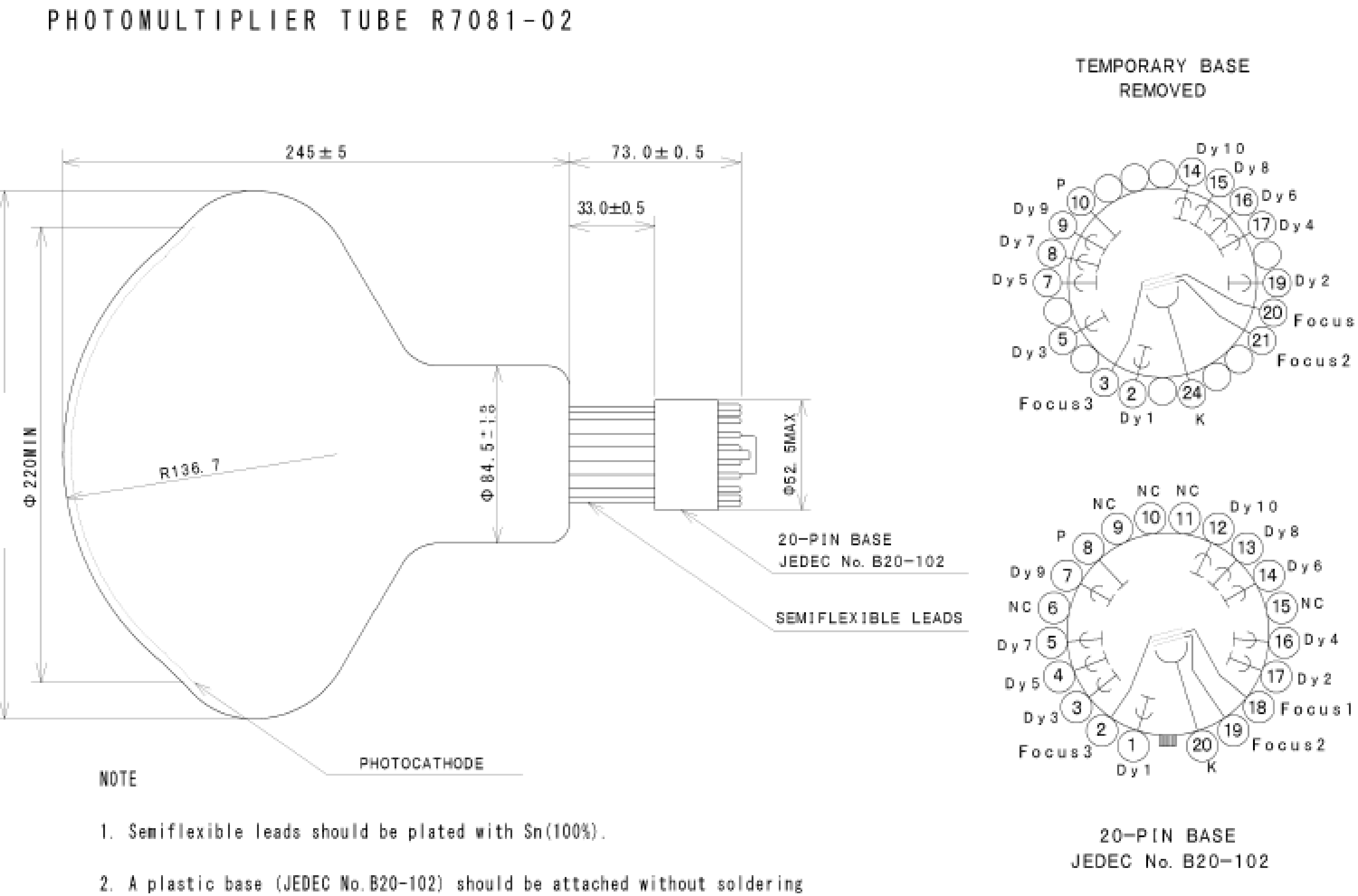
(Digital Optical Module)



Connection:
Single twisted-pair cable
Power:
3.75 W
Bandwidth:
1Mbit/s

HAMAMATSU
DATA SHEET
Nov.12. 2003

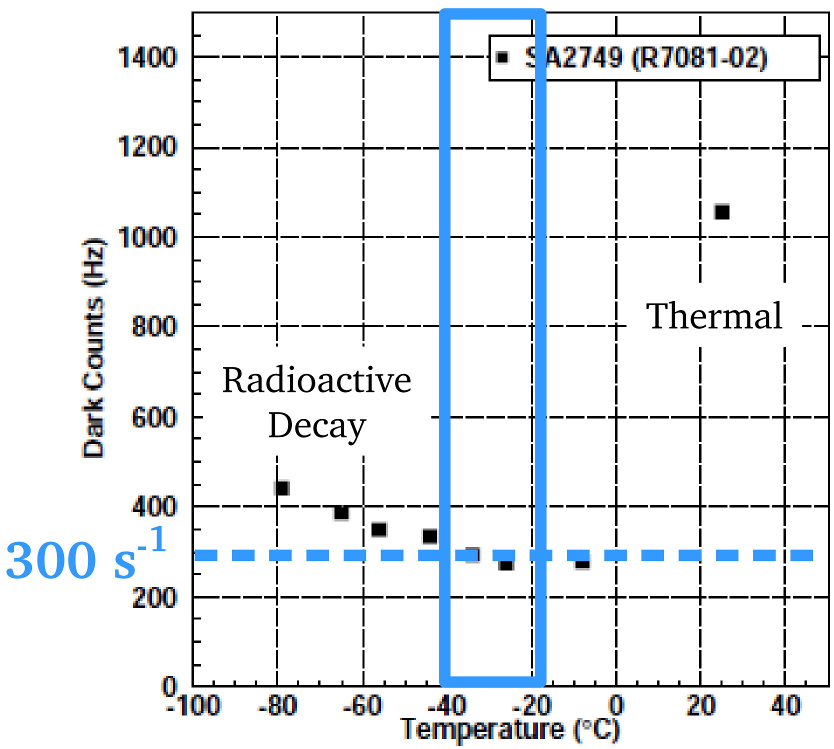
PHOTOMULTIPLIER TUBE
R7081-02
for ICECUBE Experiment



10 inches
(253±5 mm)

Dark Noise

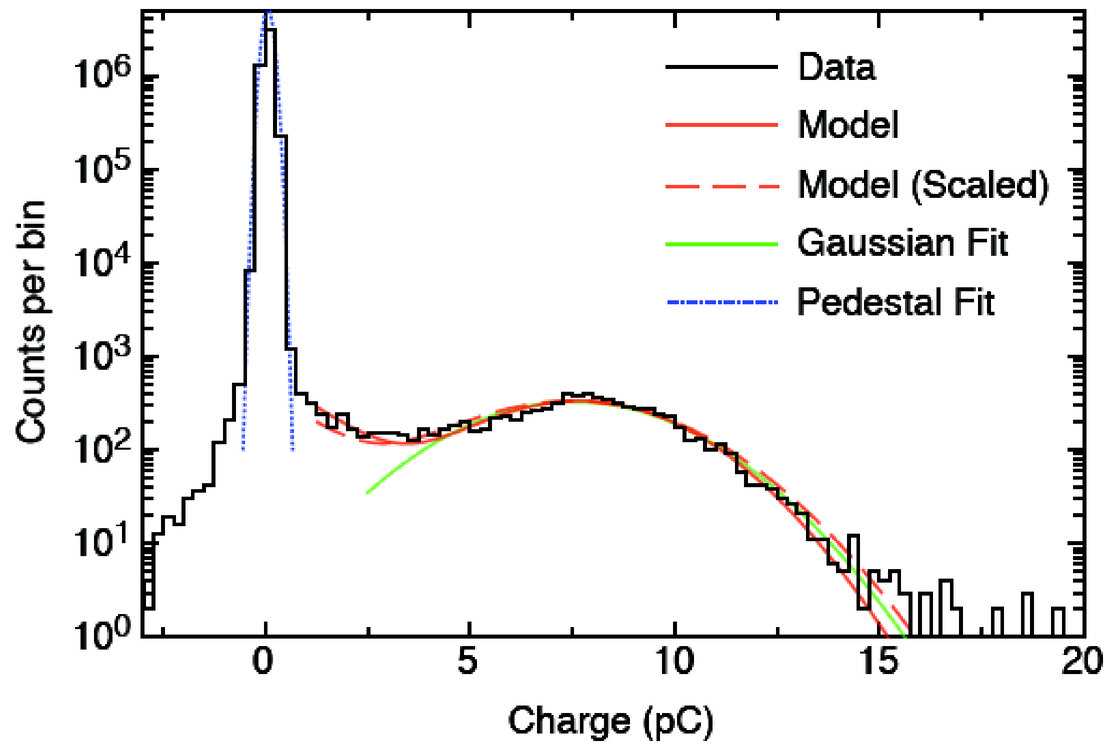
Gain: $1 \cdot 10^7$
Threshold 0.25 p.e.
6 µs time window



arxiv:1002.2442

SPE Peak

Gain: $5 \cdot 10^7$

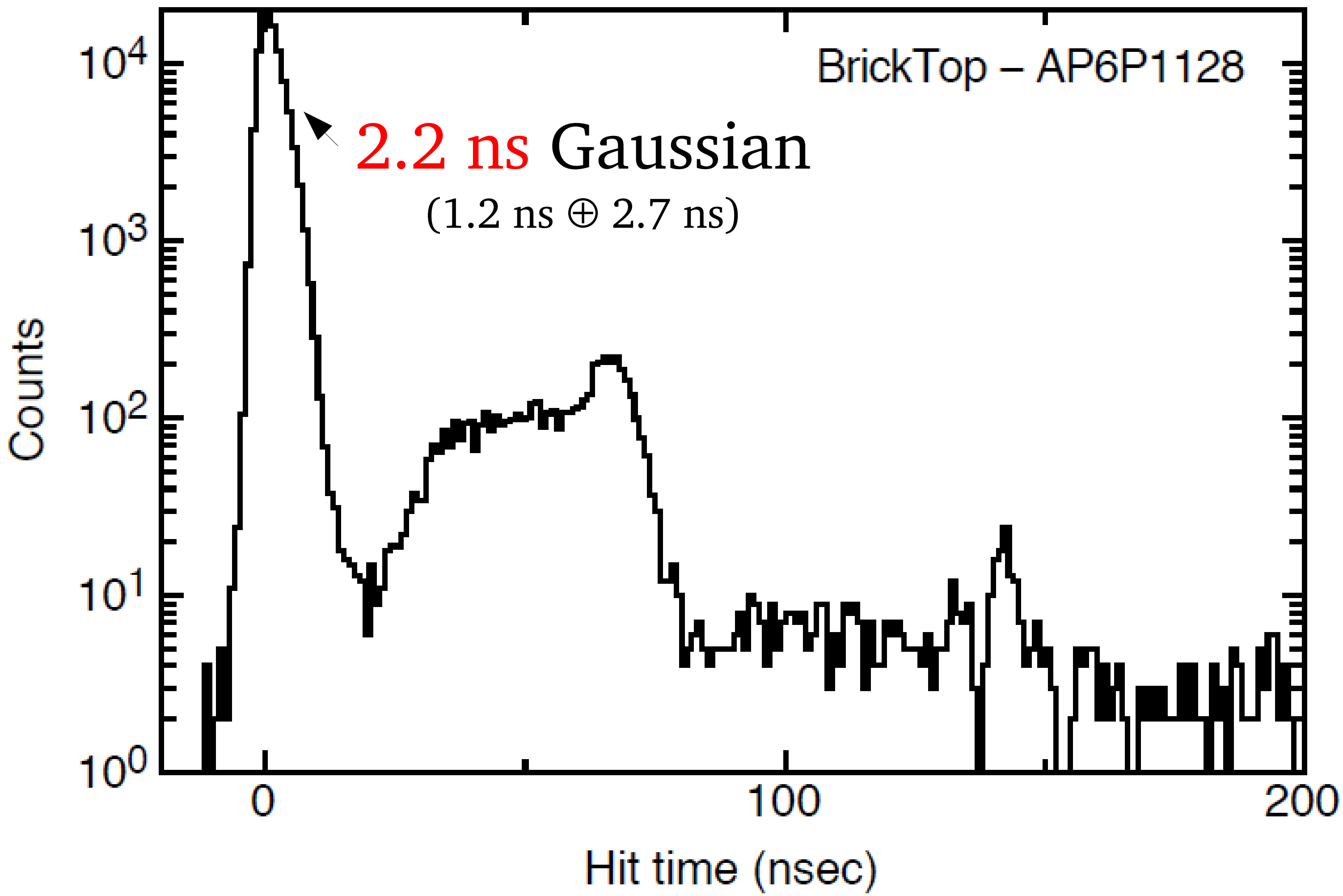


$$f(q) = \frac{P_e}{q_\tau} \exp\left[-\frac{q}{q_\tau}\right] + (1-P_e)\frac{1}{\sqrt{2\pi}\sigma_q} \exp\left[-\frac{(q-q_0)^2}{2\sigma_q^2}\right]$$

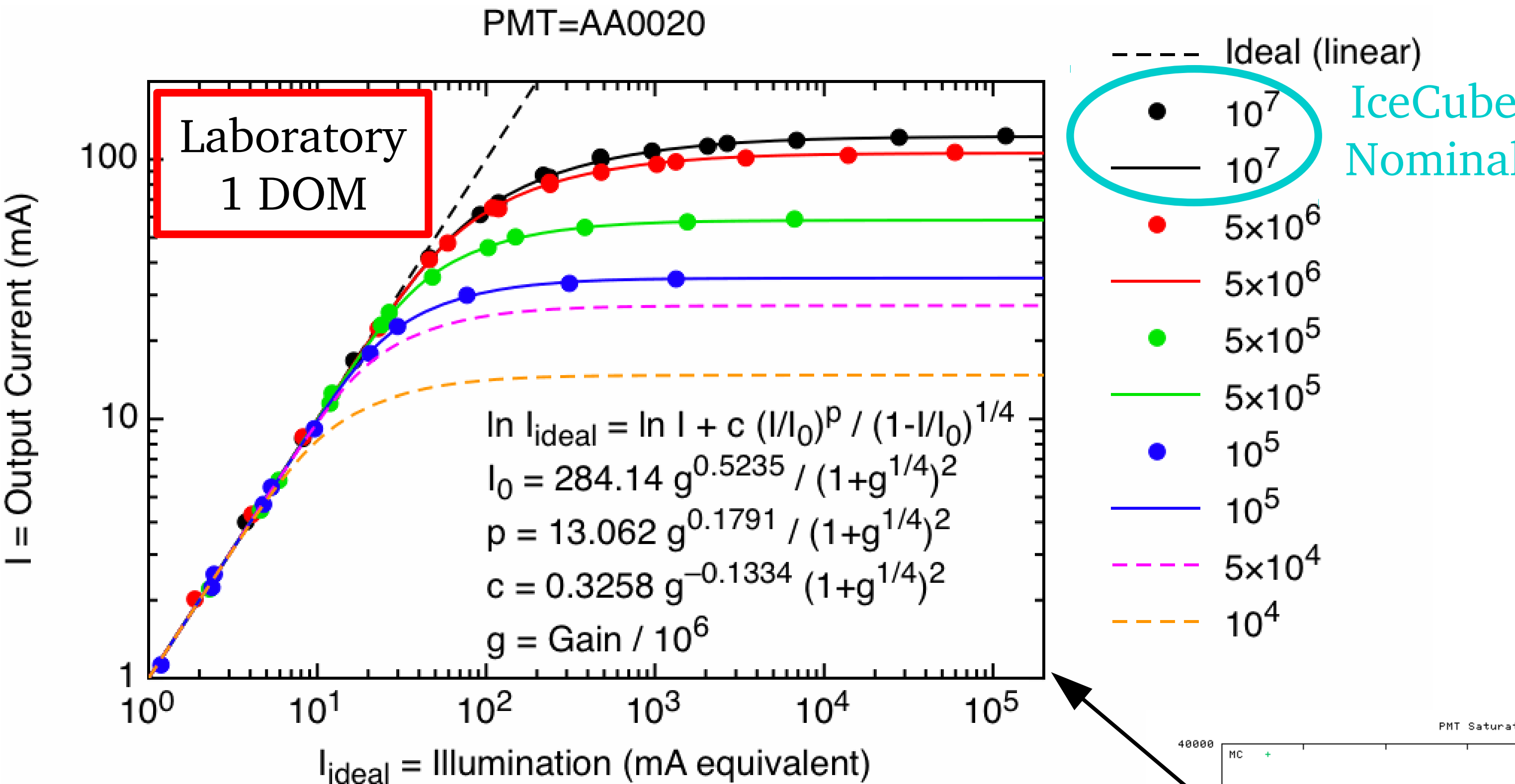
P_e is the fraction of events in the low-charge exponential part, q_0 is the charge at the SPE peak which defines the PMT gain, σ_q is the width of the Gaussian fit around the SPE peak, and q_τ is the decay constant in the exponential component.

PMT Time Resolution

laboratory measurement using laser

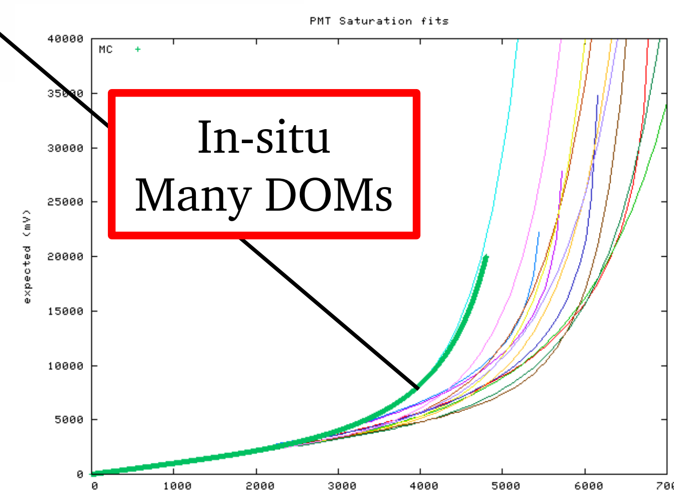


PMT Saturation



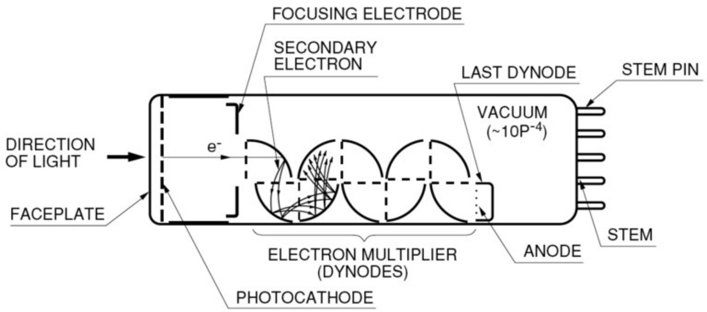
Translation from I to U:

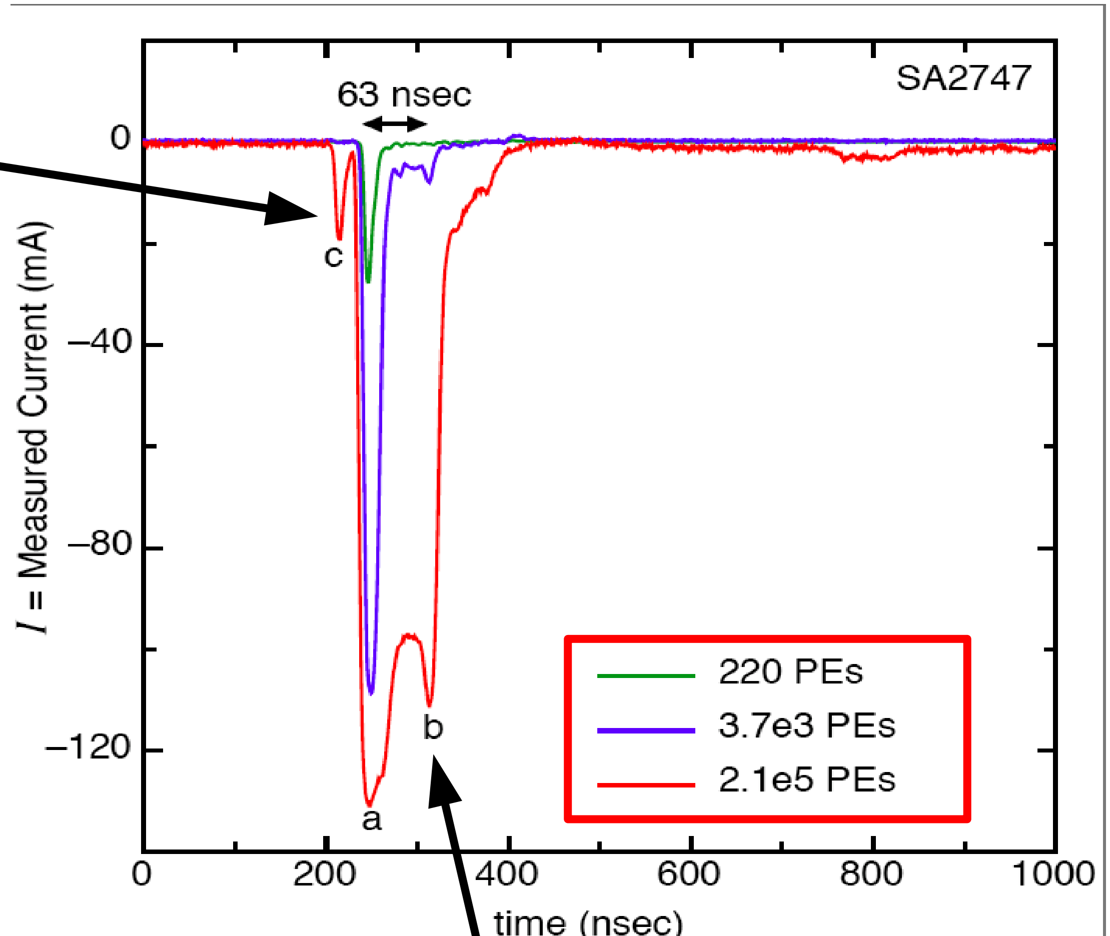
50 Ω



Prepulses, Afterpulses

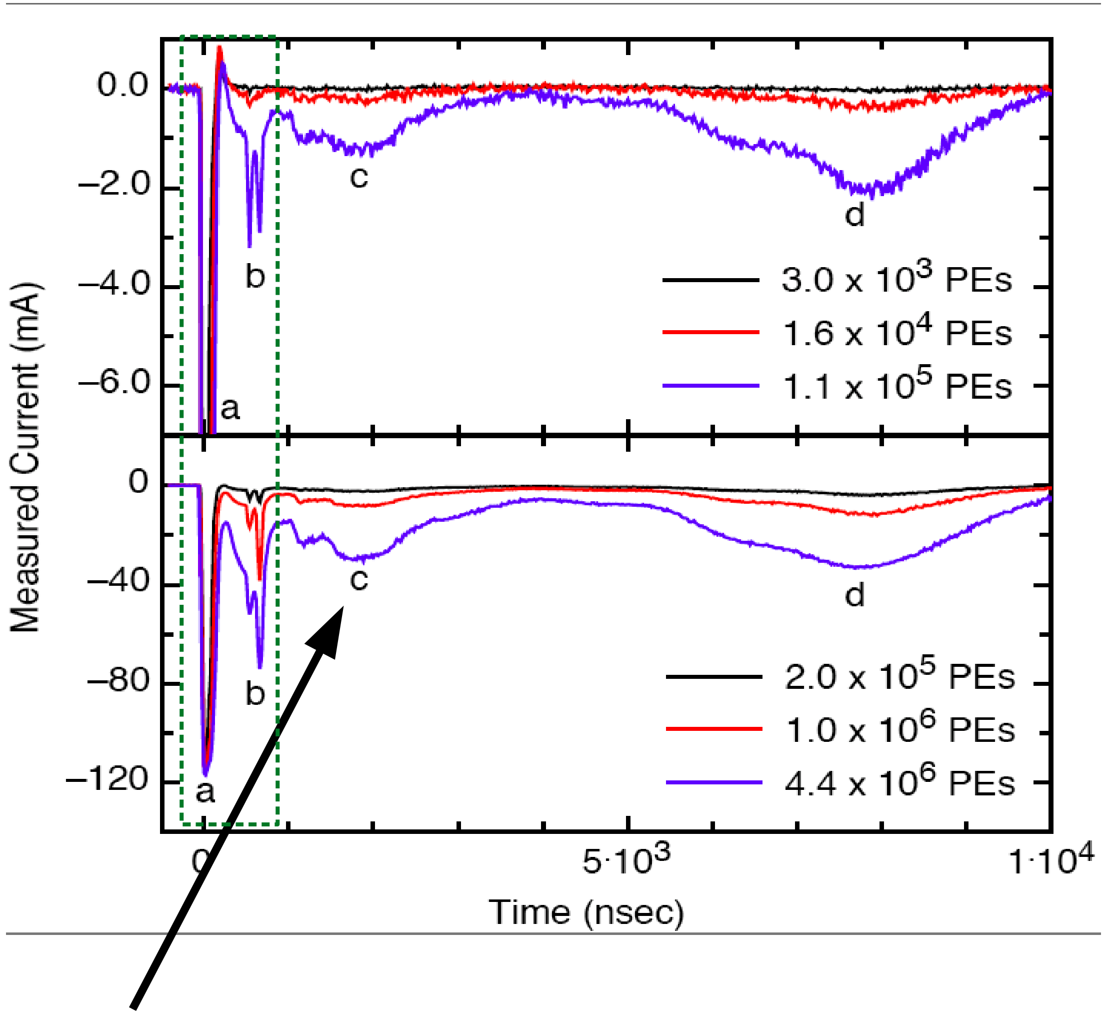
Prepulse:
Electrons skipping dynode





Afterpulse:
Ionization of residual gas

Prepulses, Afterpulses



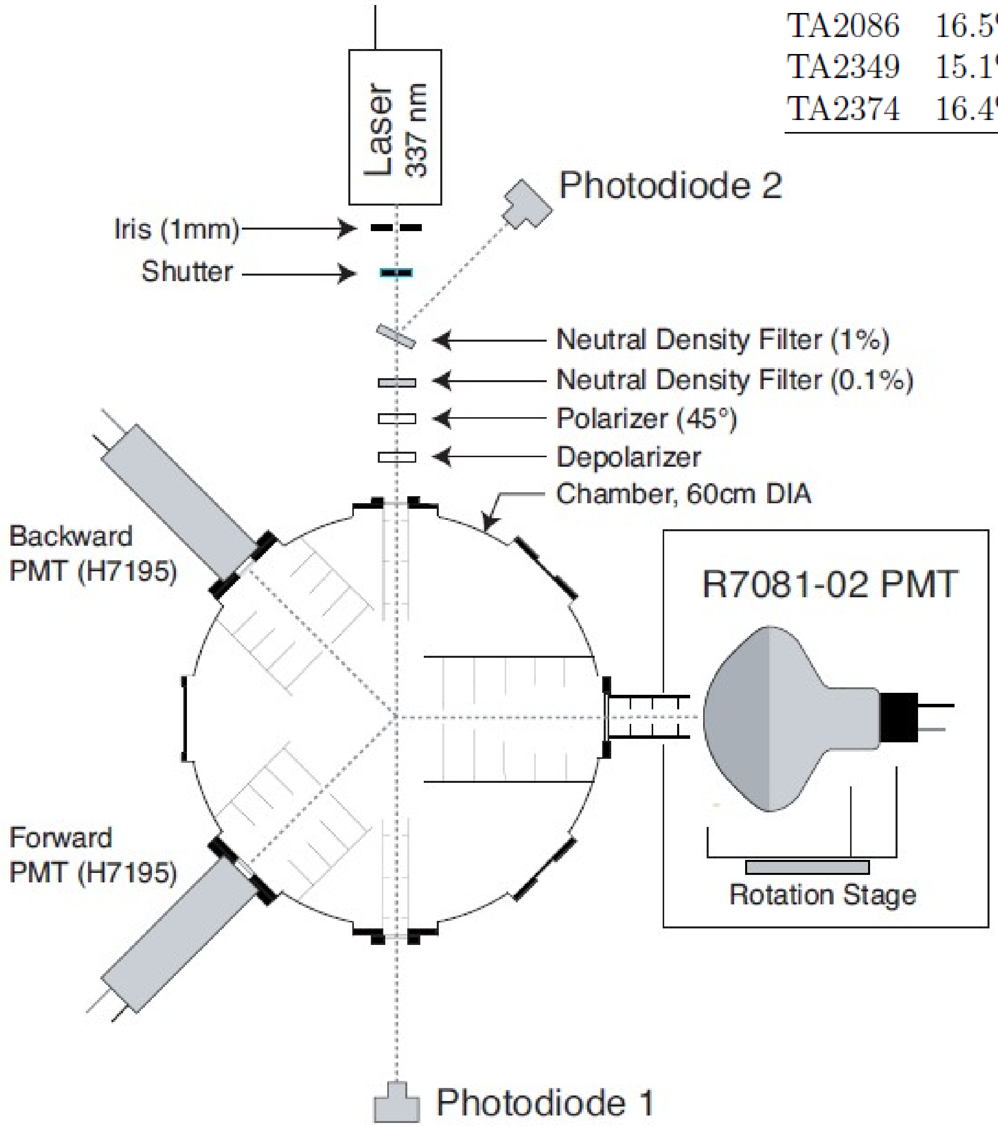
Afterpulses:

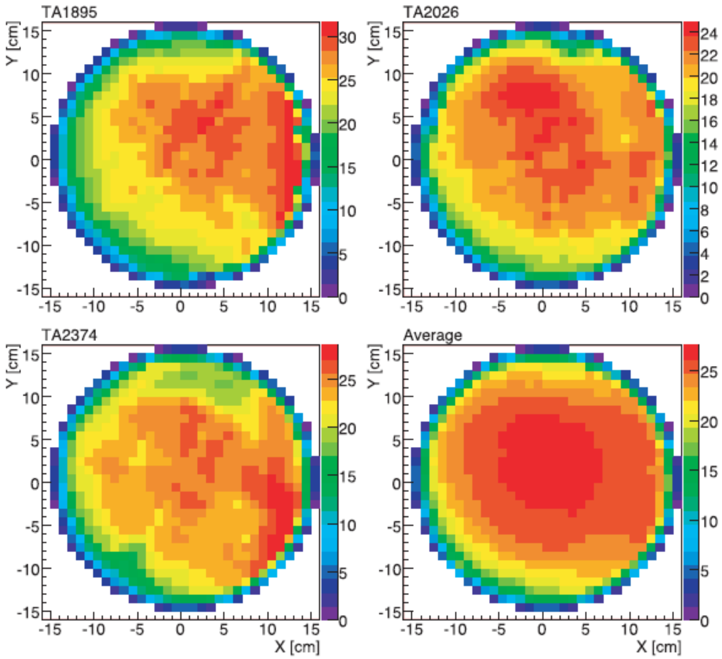
Ions of different masses(?)

Absolute Calibration

Table 2: Measured photon detection efficiency (η) and photon effective area (A_{eff}) at 25 °C for four different PMTs at wavelength 337 nm and gain 10^8. Values for $q_{\text{th}} = 0$ were extrapolated using Eq. 1, where model parameters were fit independently for each PMT.

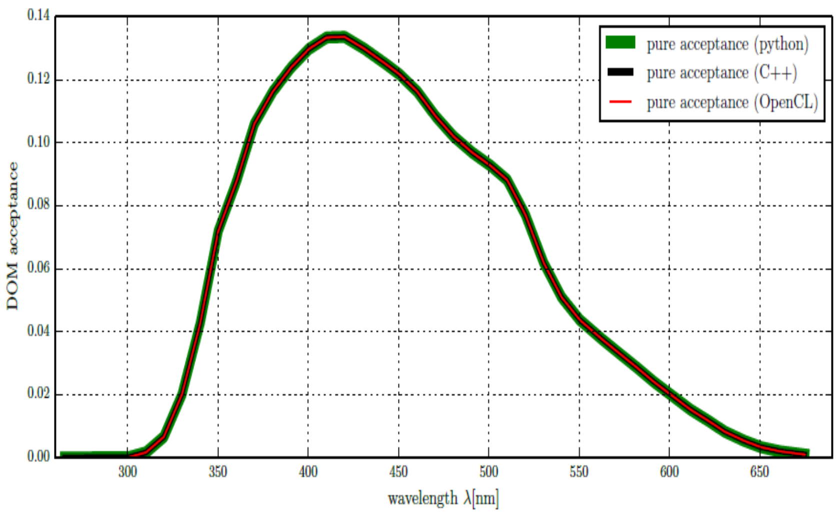
PMT	η_{center} ($q_{\text{th}} = 0.5q_0$)	η_{whole} ($q_{\text{th}} = 0.5q_0$)	η_{whole} ($q_{\text{th}} = 0$)	A_{eff} (cm^2) ($q_{\text{th}} = 0.5q_0$)	A_{eff} (cm^2) ($q_{\text{th}} = 0$)
TA1895	16.4%	13.2%	18.6%	84	119
TA2086	16.5%	13.6%	18.8%	87	120
TA2349	15.1%	12.1%	17.6%	77	112
TA2374	16.4%	13.0%	17.8%	83	114

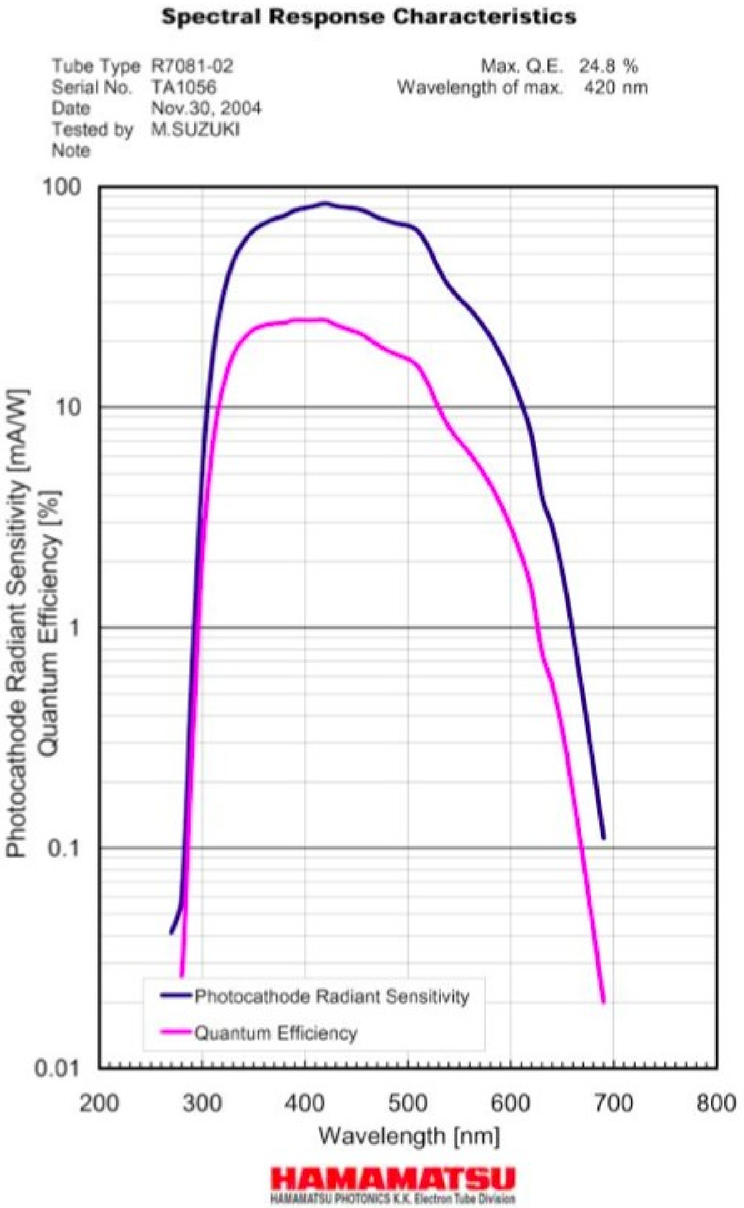




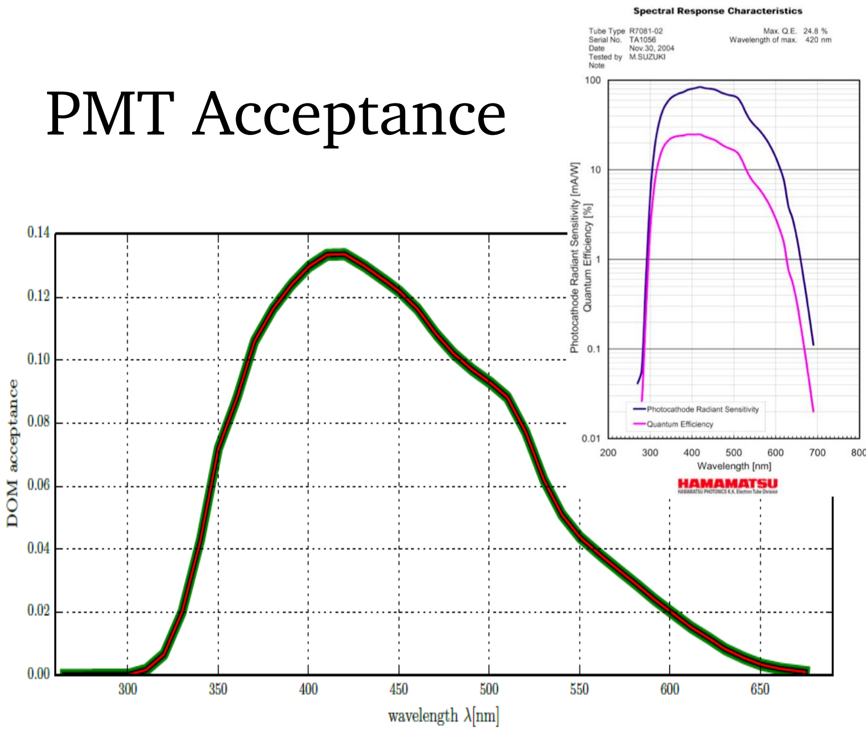
2-d scan

PMT Acceptance



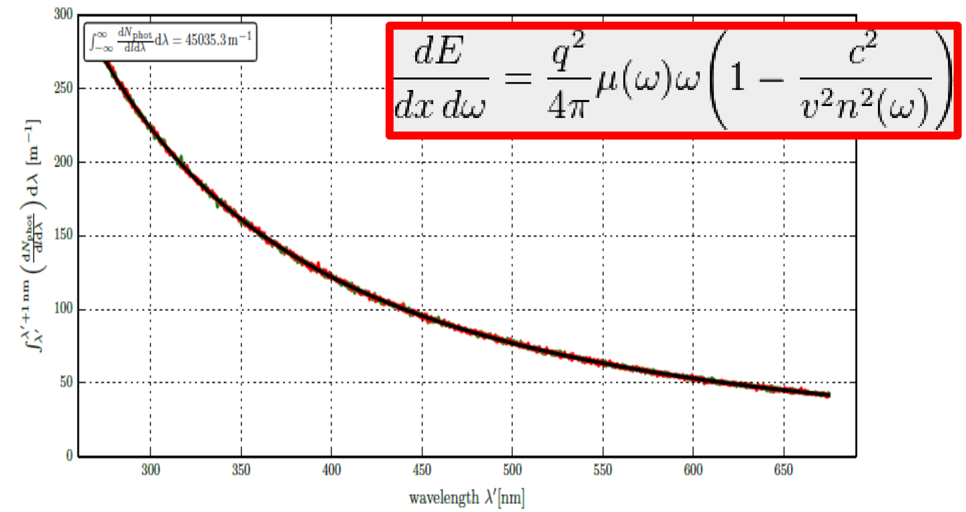


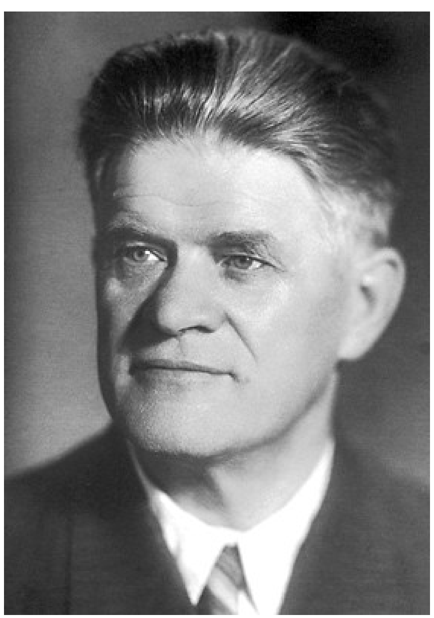
PMT Acceptance



"Frank-Tamm" Formula

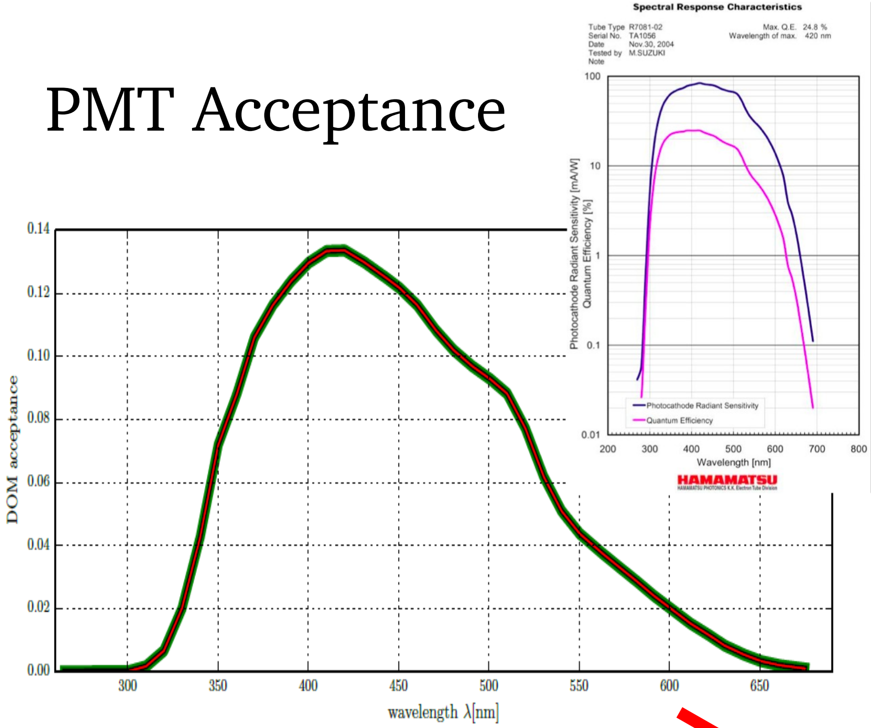
(Cherenkov Light Emission)





1958

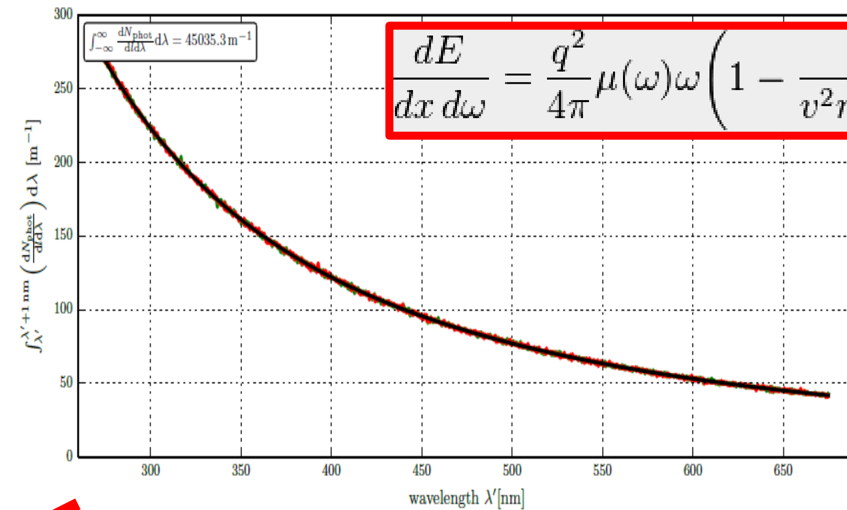
PMT Acceptance

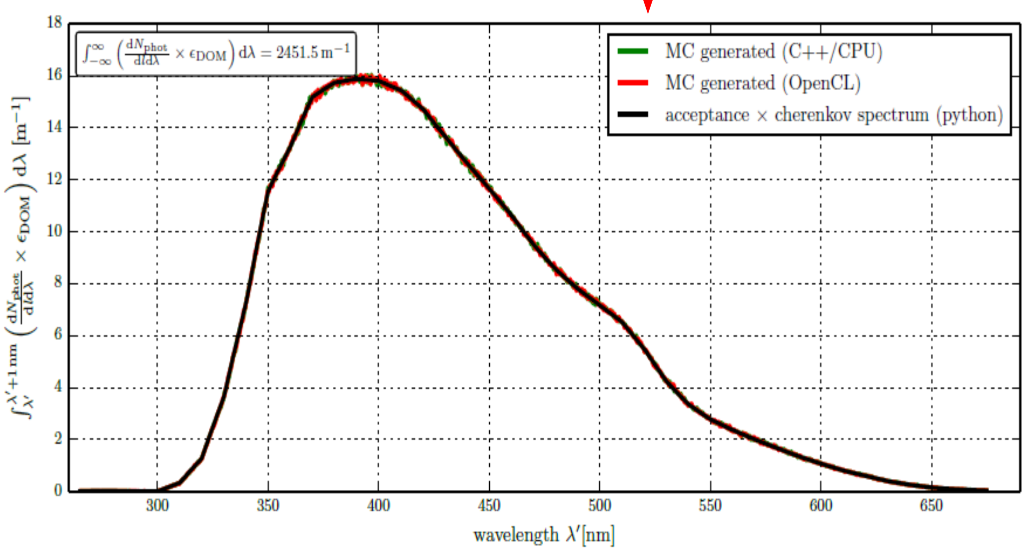


"Frank-Tamm" Formula

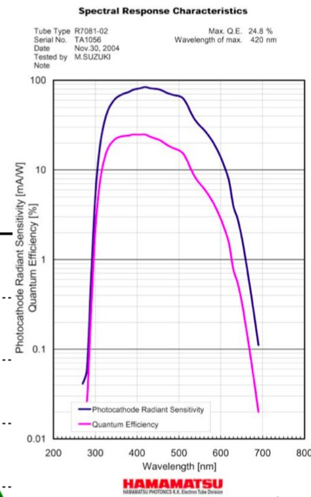
(Cherenkov Light Emission)

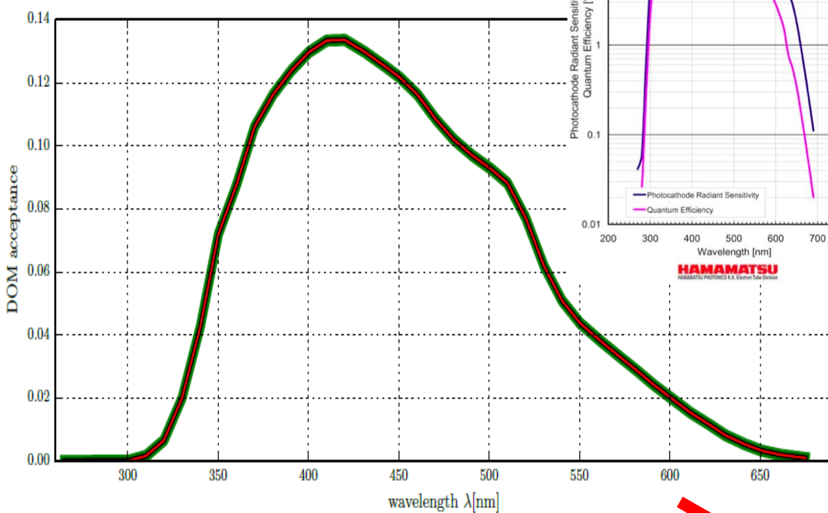
$$\frac{dE}{dx\, d\omega} = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right)$$



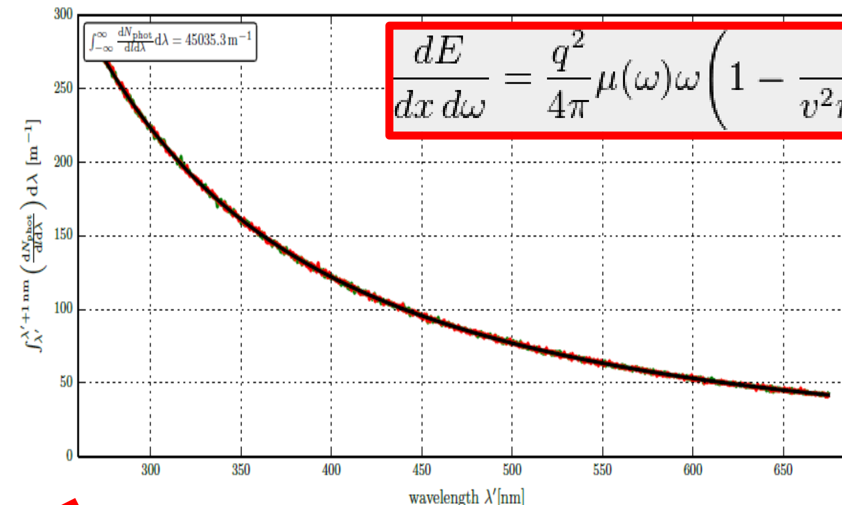


PMT Acceptance

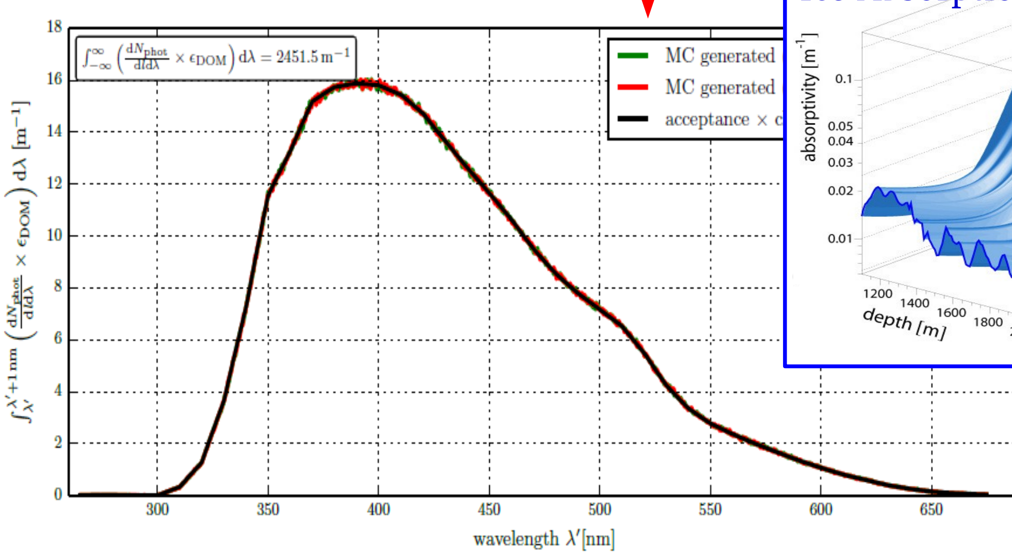


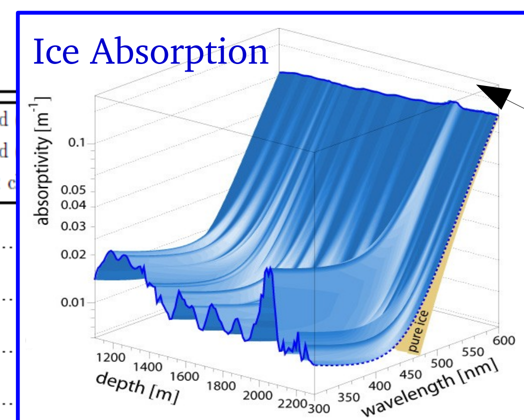


"Frank-Tamm" Formula
(Cherenkov Light Emission)



$$\frac{dE}{dx\,d\omega} = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right)$$

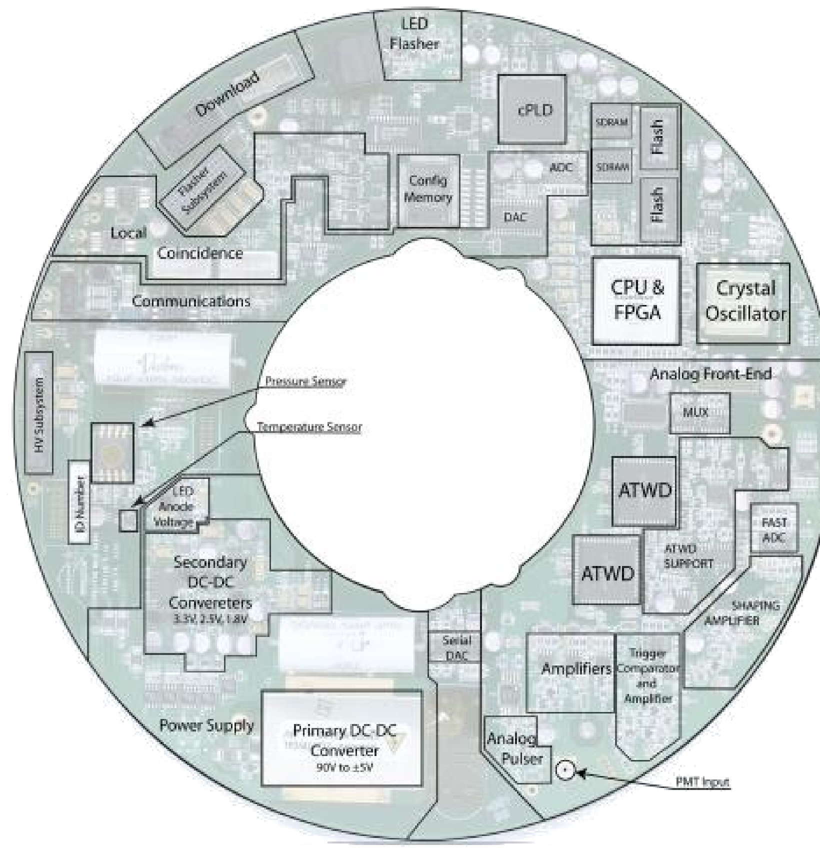




Not included!

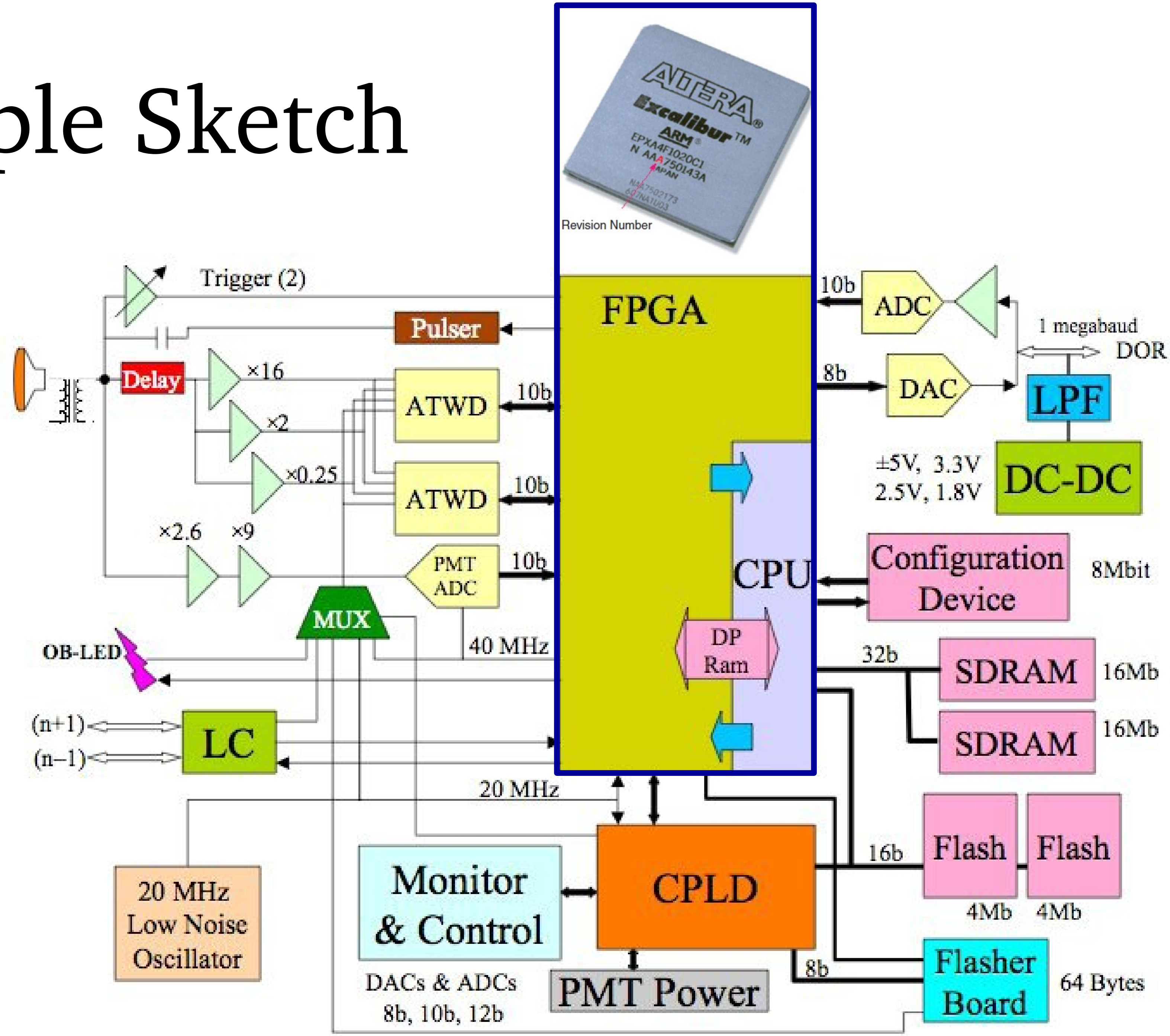
(Handled by photon propagation in simulation)

Main Board

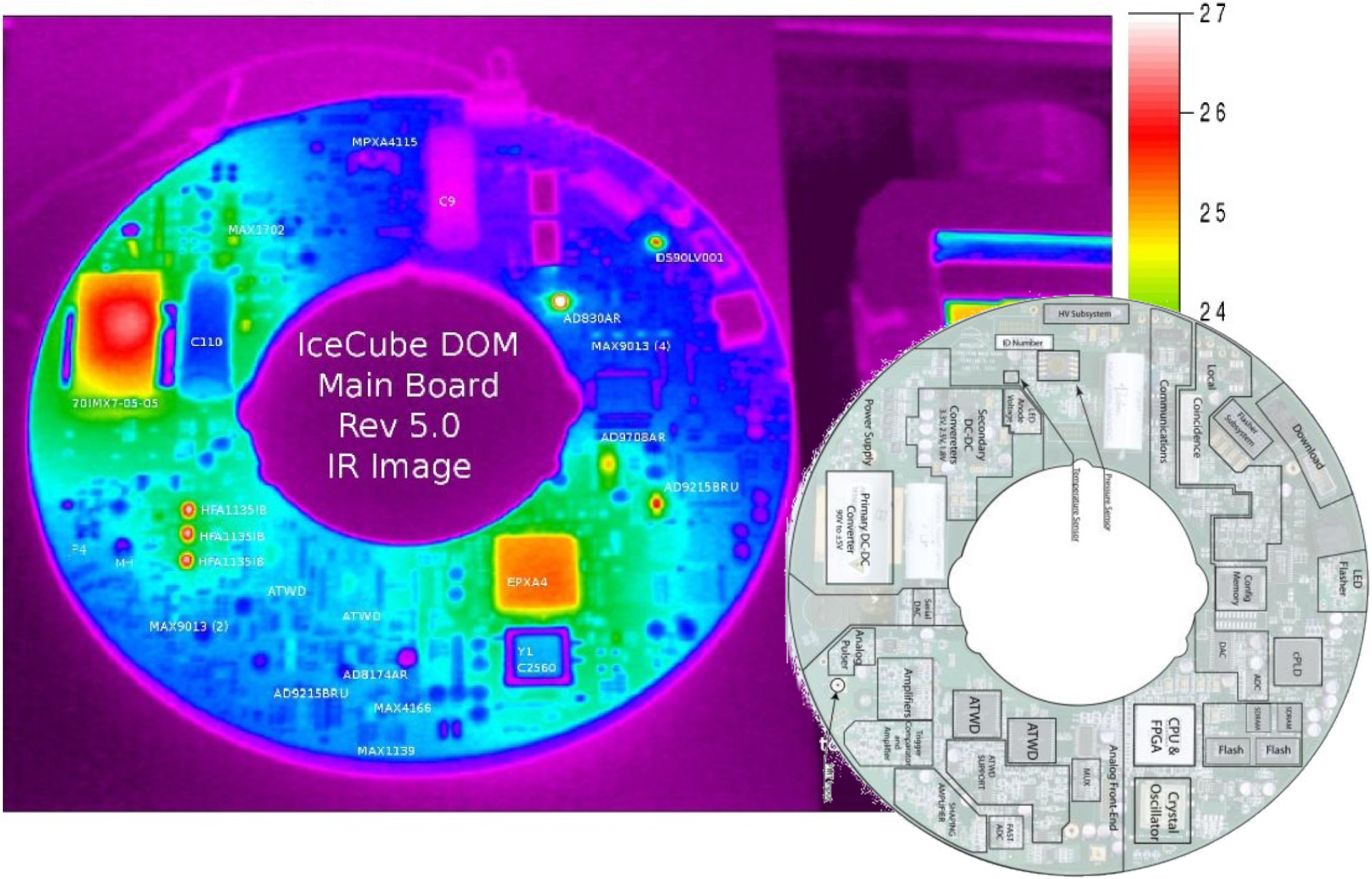


PMT Signal Digitization
Local Coincidence Trigger Condition
Calibration Equipment (LEDs)
Slow Control and Monitoring

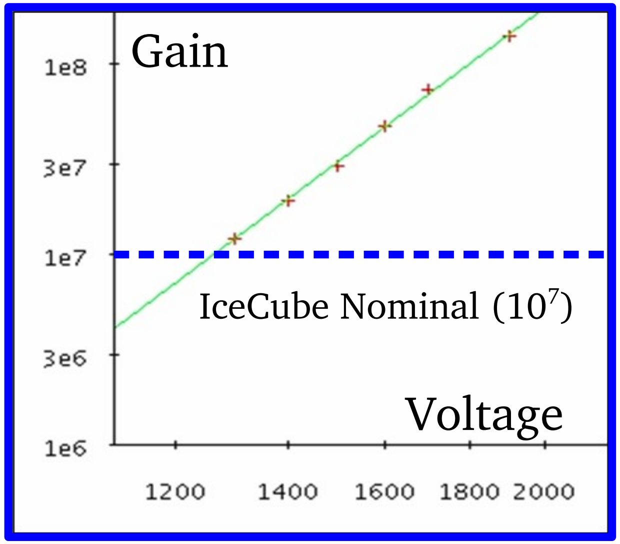
Simple Sketch

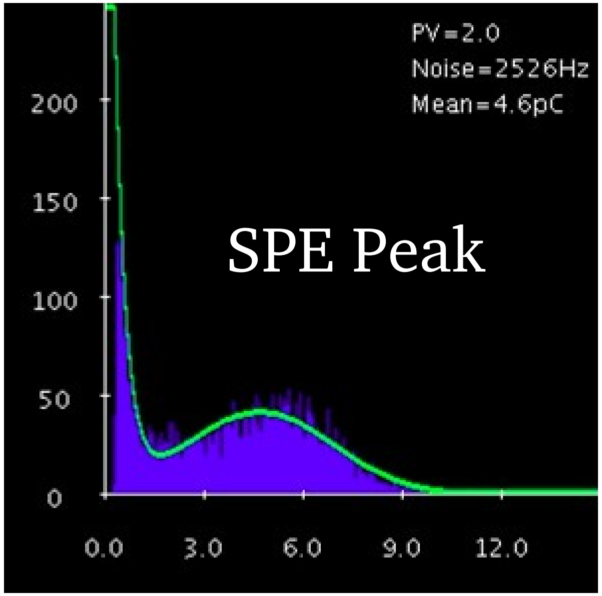


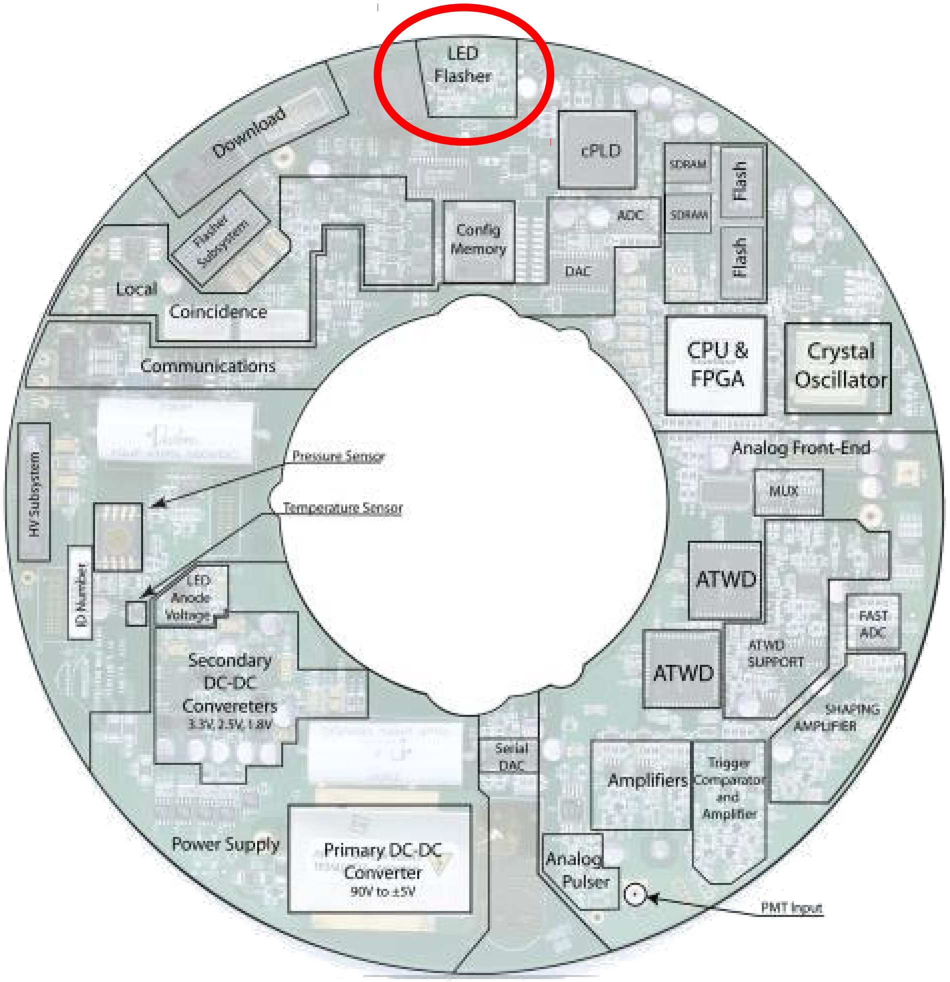
arxiv:0810.4930



In Action (Lab, Idling)



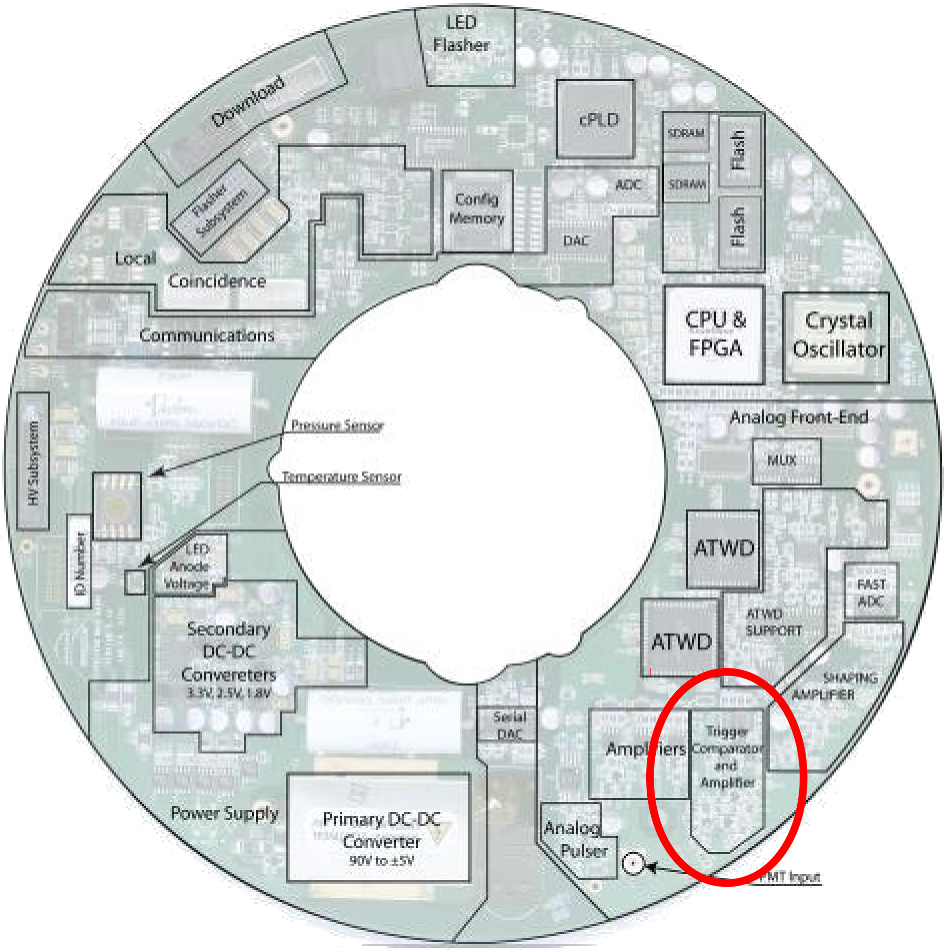


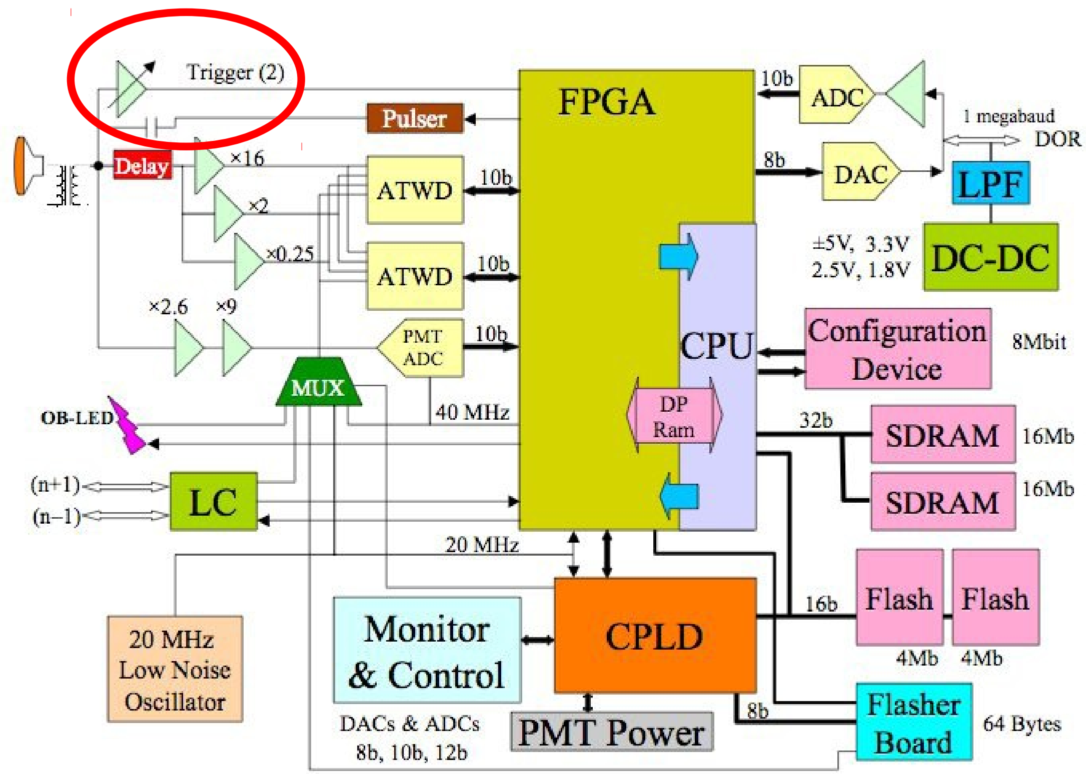


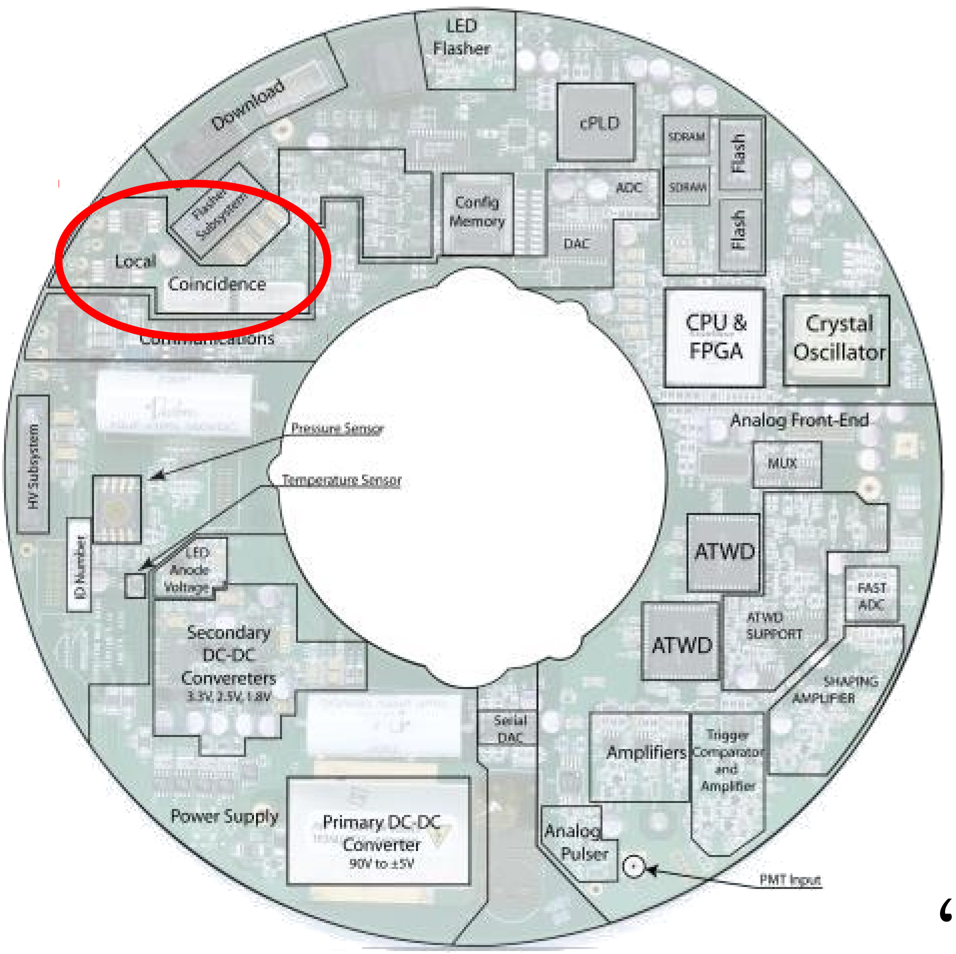
Dedicated Calibration: Only once per year(!)
Continuous monitoring based on physics data.

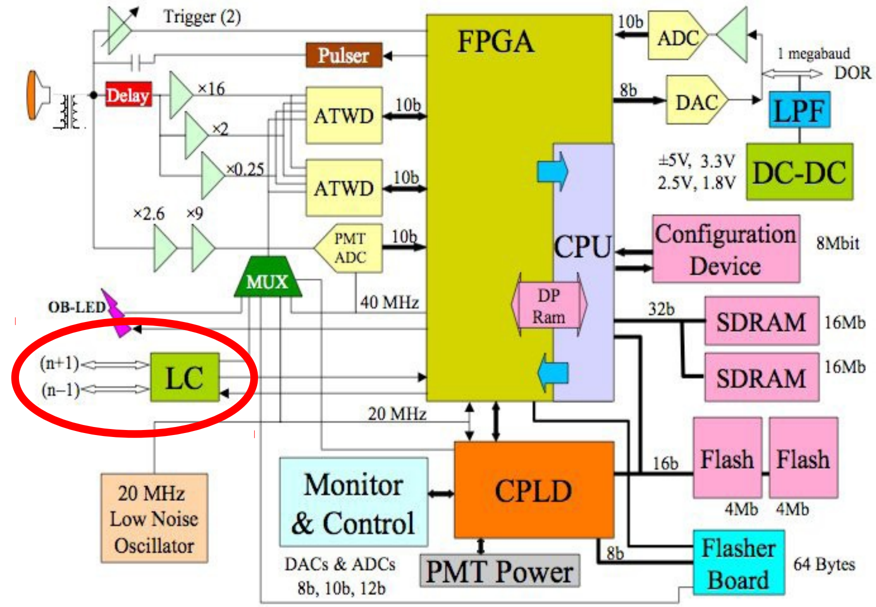
Trigger (Single DOM)

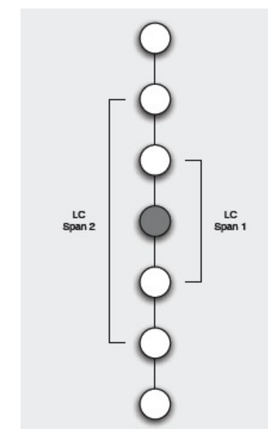
Threshold: 0.25 p.e.









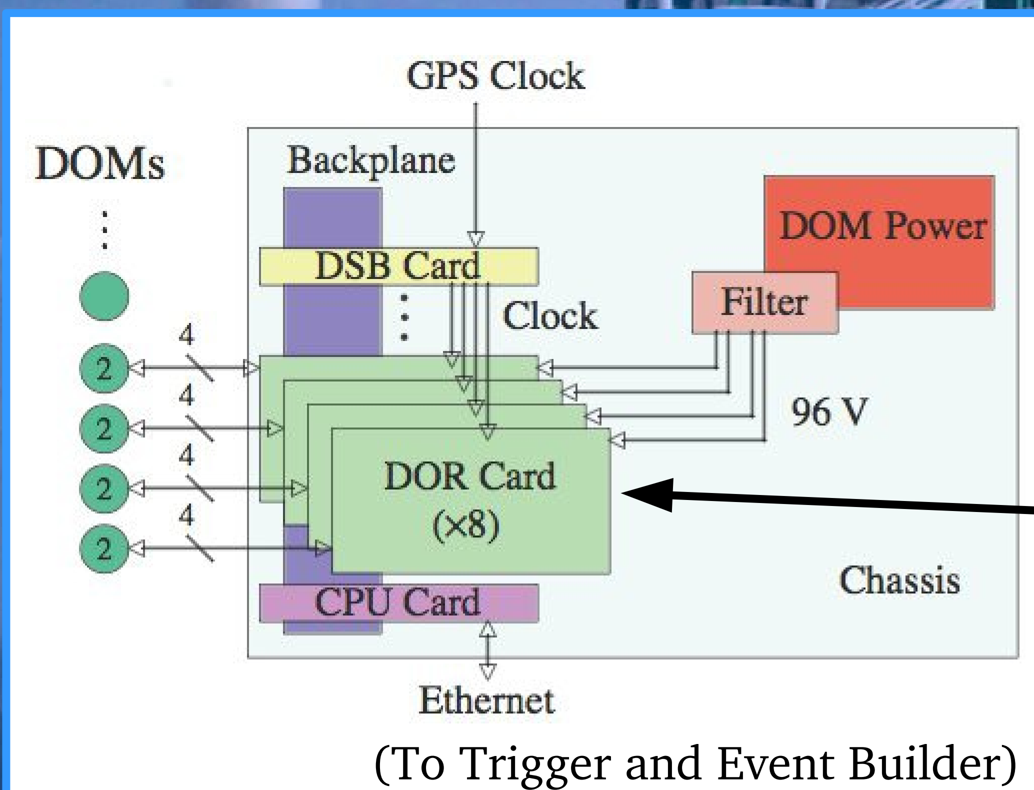


“Local Coincidence”:

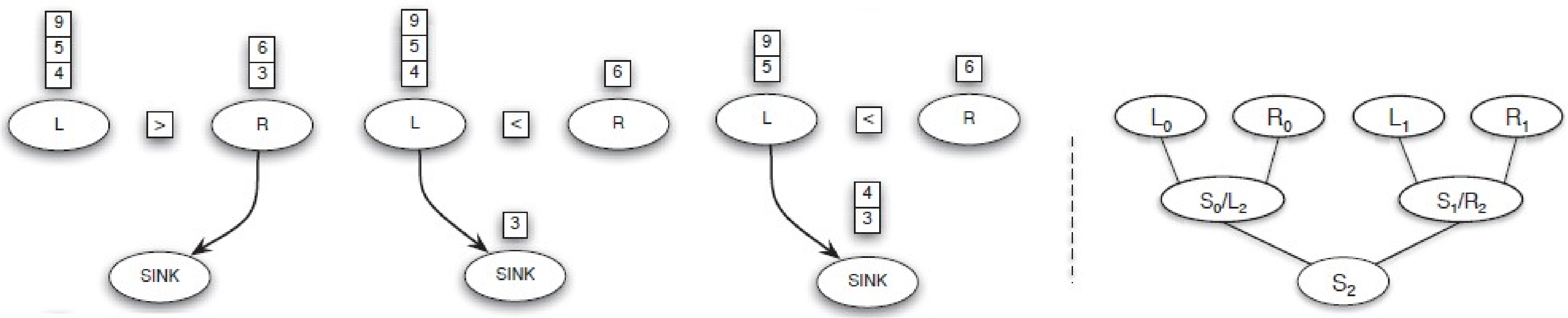
DOMs communicate with their neighbors

Waveform digitization is initiated
only if adjacent modules triggered (within 1 μs)

IceCube Laboratory (ICL)



Detector Triggering



"Cascaded Binary Merge Tree"

J. Kelley et al.: AIP Conf. Proc. 1630, 154 (2014)

Continuous sorting of hit stream (60k/sec)

Trigger	DOM set	N HLC hits	Window (μs)	Topology	Rate (Hz)
SMT	in-ice	8	5	—	2100
SMT	DeepCore	3	2.5	—	250
SMT	IceTop	6	5	—	25
Volume	in-ice	4	1	cylinder (r=175m, h=75m)	3700
String	in-ice	5	1.5	7 adjacent DOMs on a string	2200
SLOP	in-ice	$N_{\mathrm{tuple}} = 5$	$T_{\mathrm{prox}} = 2.5, T_{\mathrm{max}} = 500$	$\alpha_{\mathrm{min}} = 140°,\ v_{\mathrm{rel}}^{\mathrm{max}} = 0.5$	12
FRT	all	—	—	—	0.003

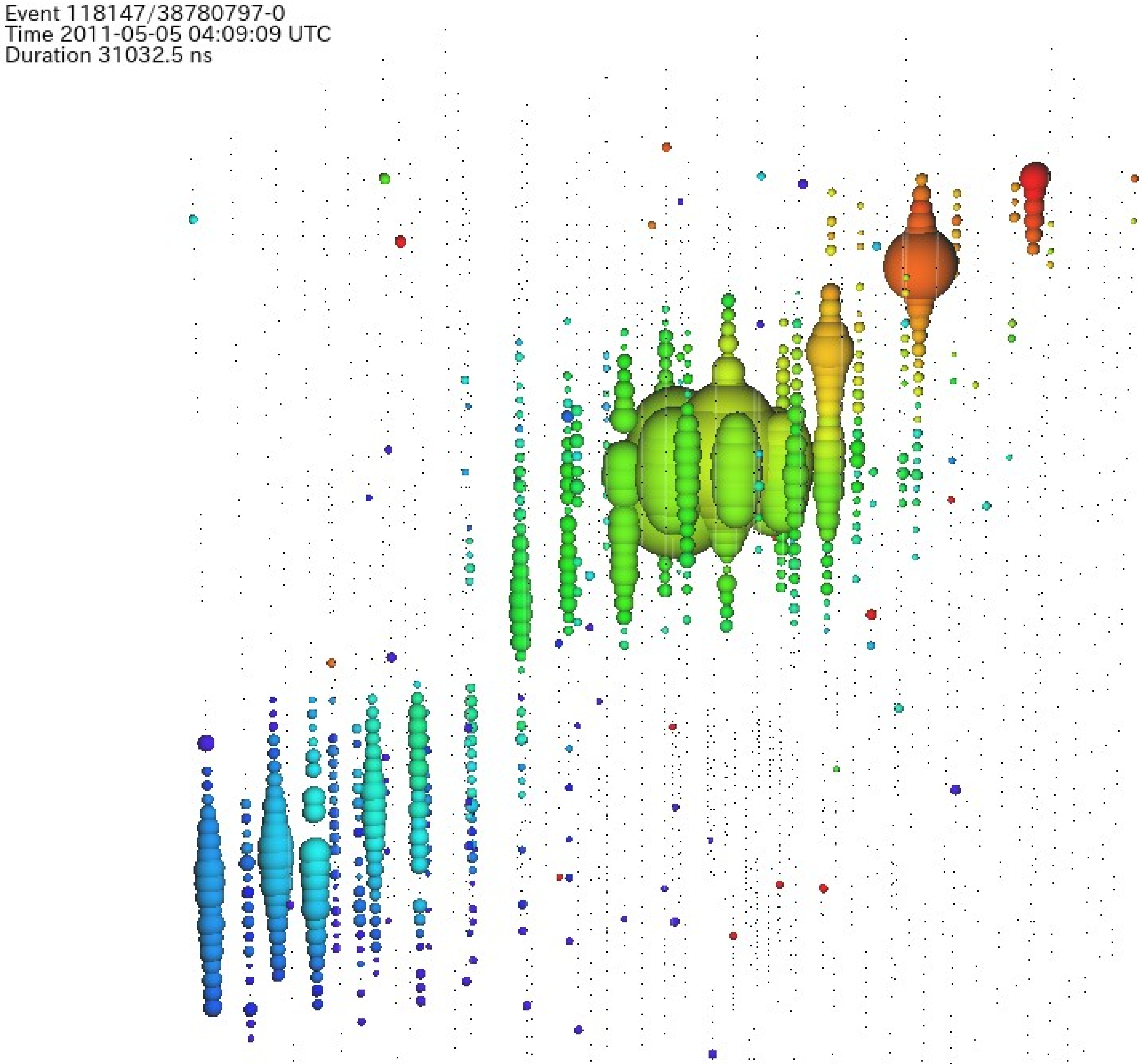
Detector Triggering

Main Physics Trigger:
Simple Majority Trigger requiring 8 DOMs with Local Coincidence

"SMT8"

Rate: 2100 s^{-1} (99.9999% atm. muons)

Trigger	DOM set	N HLC hits	Window (μs)	Topology	Rate (Hz)
SMT	in-ice	8	5	—	2100
SMT	DeepCore	3	2.5	—	250
SMT	IceTop	6	5	—	25
Volume	in-ice	4	1	cylinder (r=175m, h=75m)	3700
String	in-ice	5	1.5	7 adjacent DOMs on a string	2200
SLOP	in-ice	$N_{\text{tuple}} = 5$	$T_{\text{prox}} = 2.5, T_{\text{max}} = 500$	$\alpha_{\text{min}} = 140°,\ v_{\text{rel}}^{\text{max}} = 0.5$	12
FRT	all	—	—	—	0.003

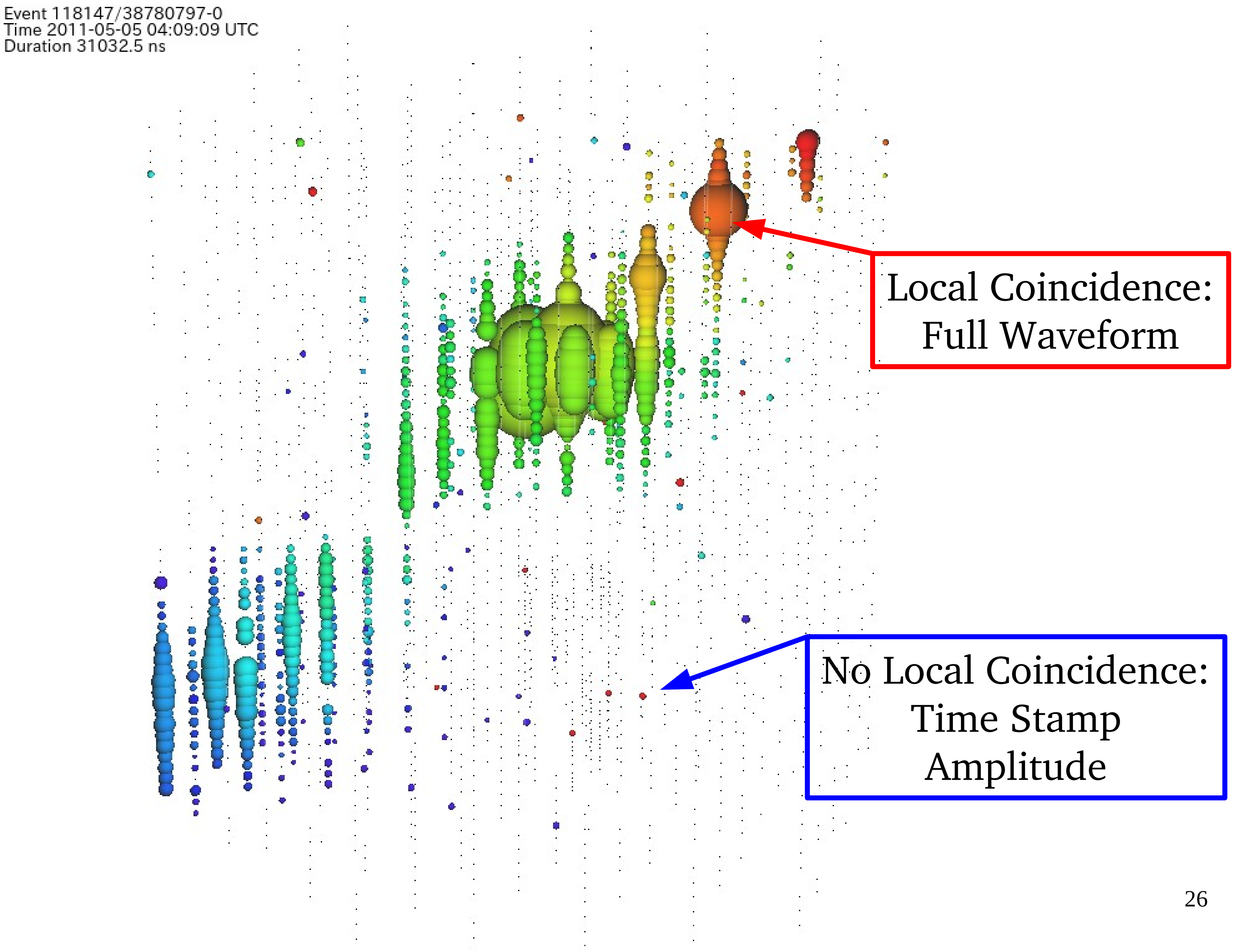


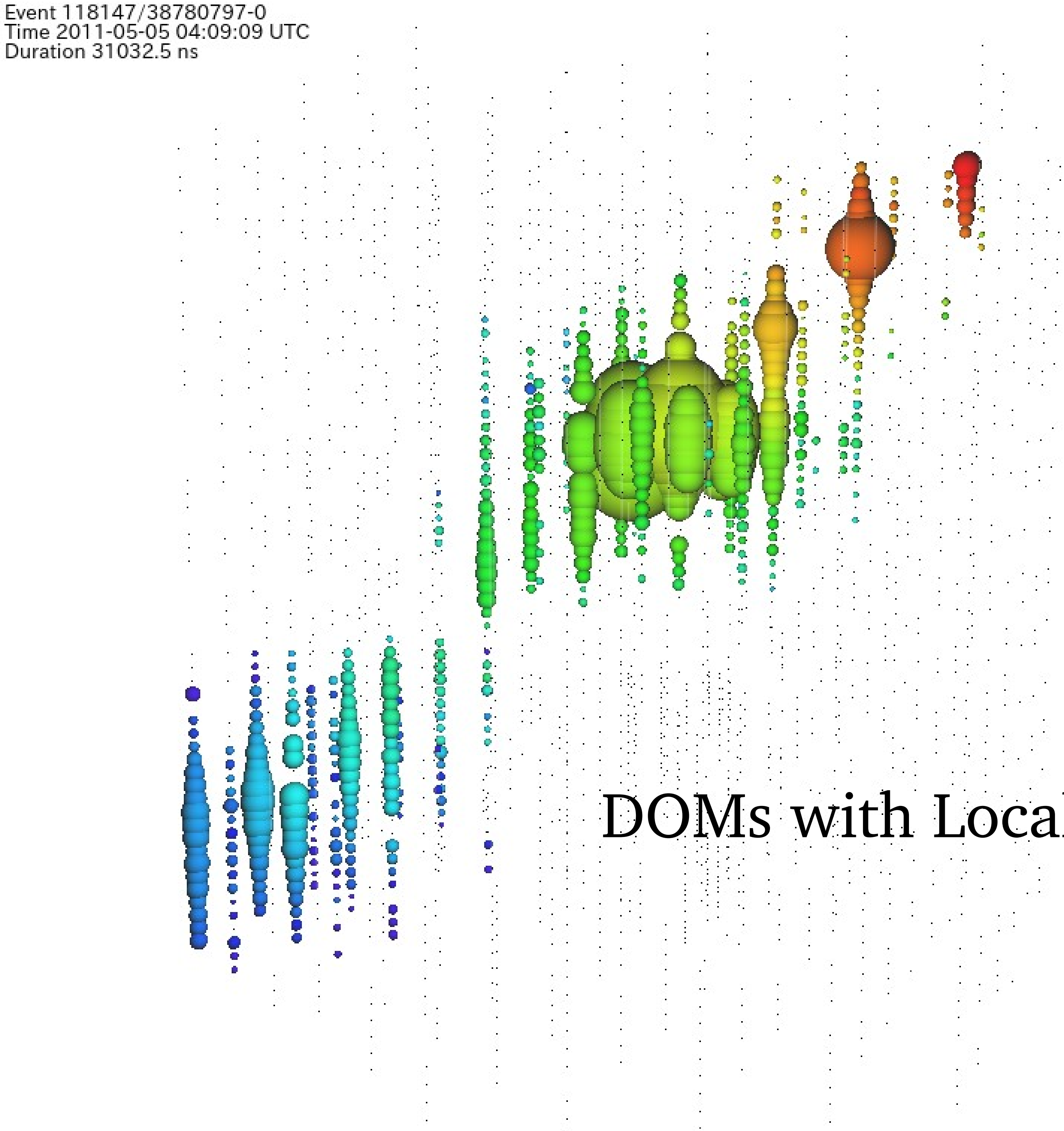
Color: Time

Volume: N_{pe}

Readout Window: [-10µs ; +22µs]

[3km; 6.6km]

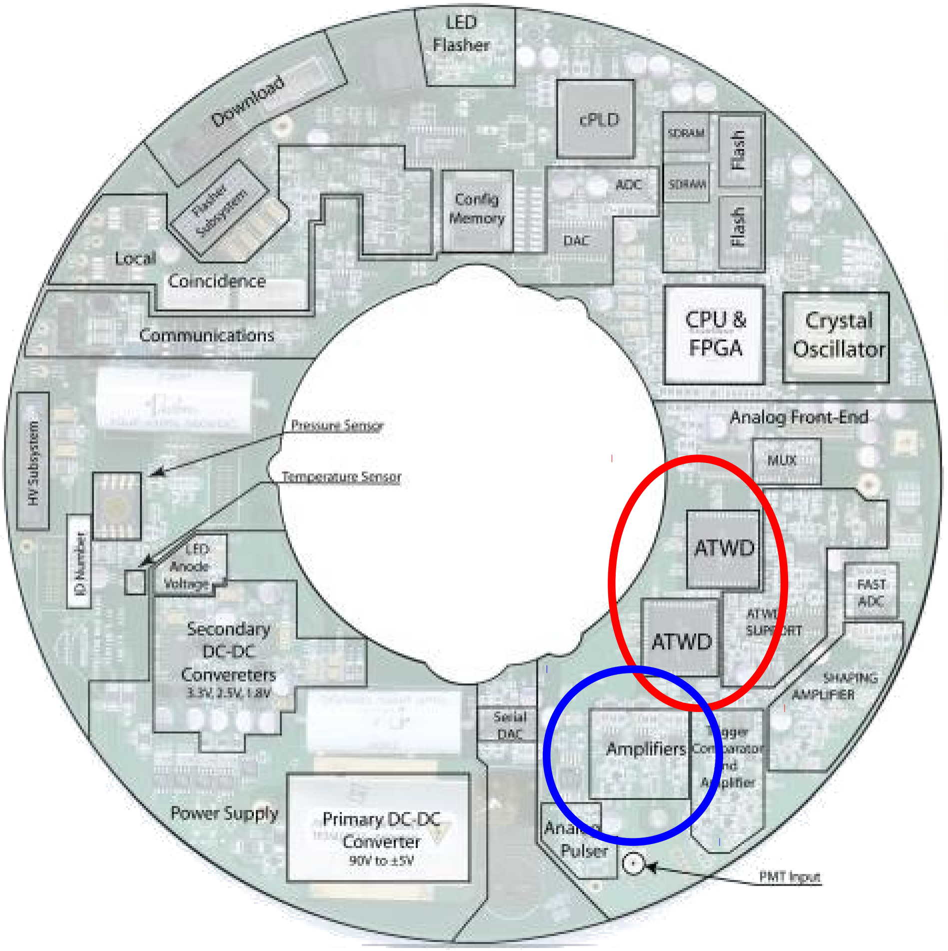

Event 118147/38780797-0
Time 2011-05-05 04:09:09 UTC
Duration 31032.5 ns
Local Coincidence:
Full Waveform
No Local Coincidence:
Time Stamp
Amplitude

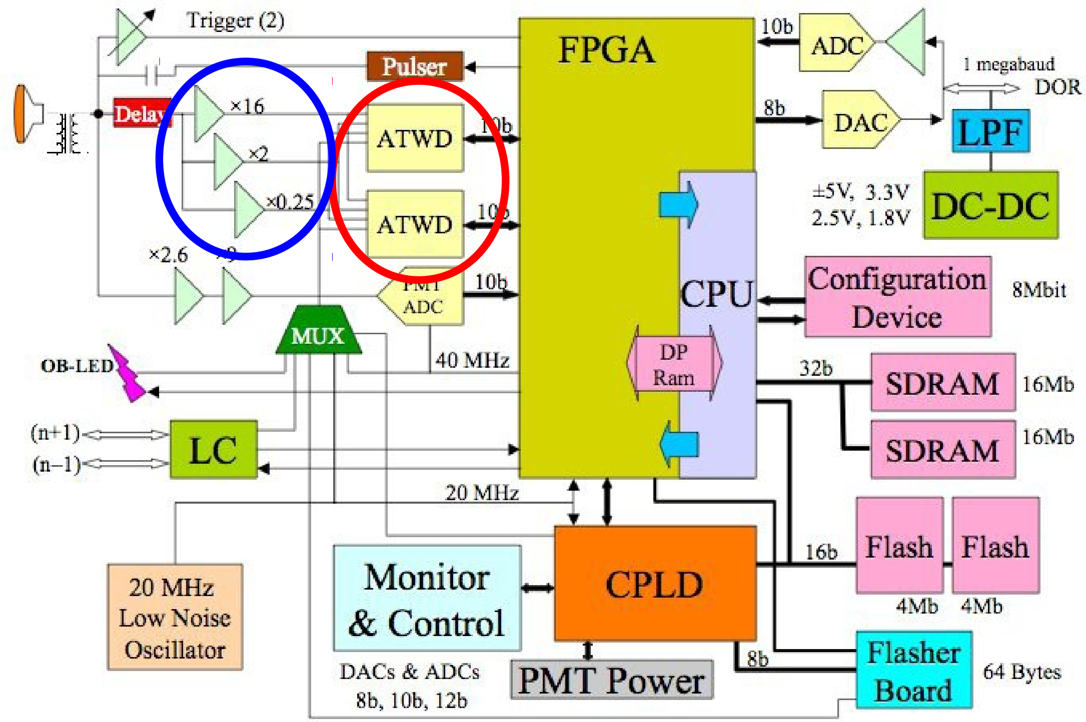


DOMs with Local Coincidence

ATWD

(Analog Transient Waveform Digitizer)





ATWD

(Analog Transient Waveform Digitizer)

Custom chip developed
at LBNL (Berkeley)

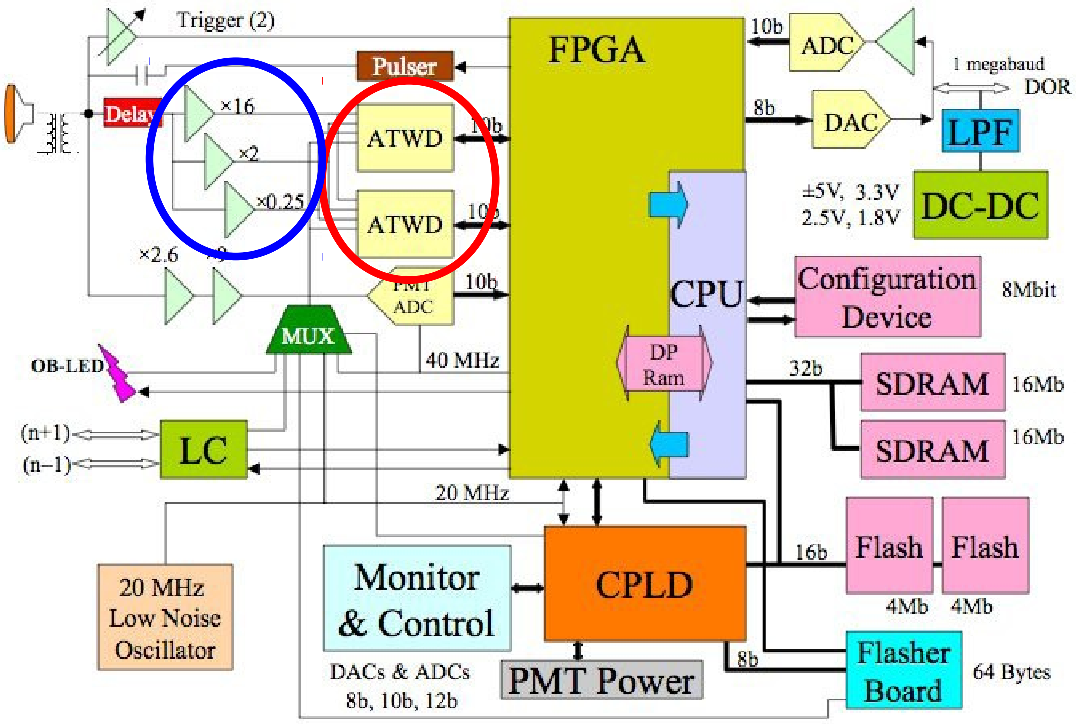
Sampling Rate:
300 Mhz / 422 ns (128 bins)

Two chips on board,
used alternatingly.

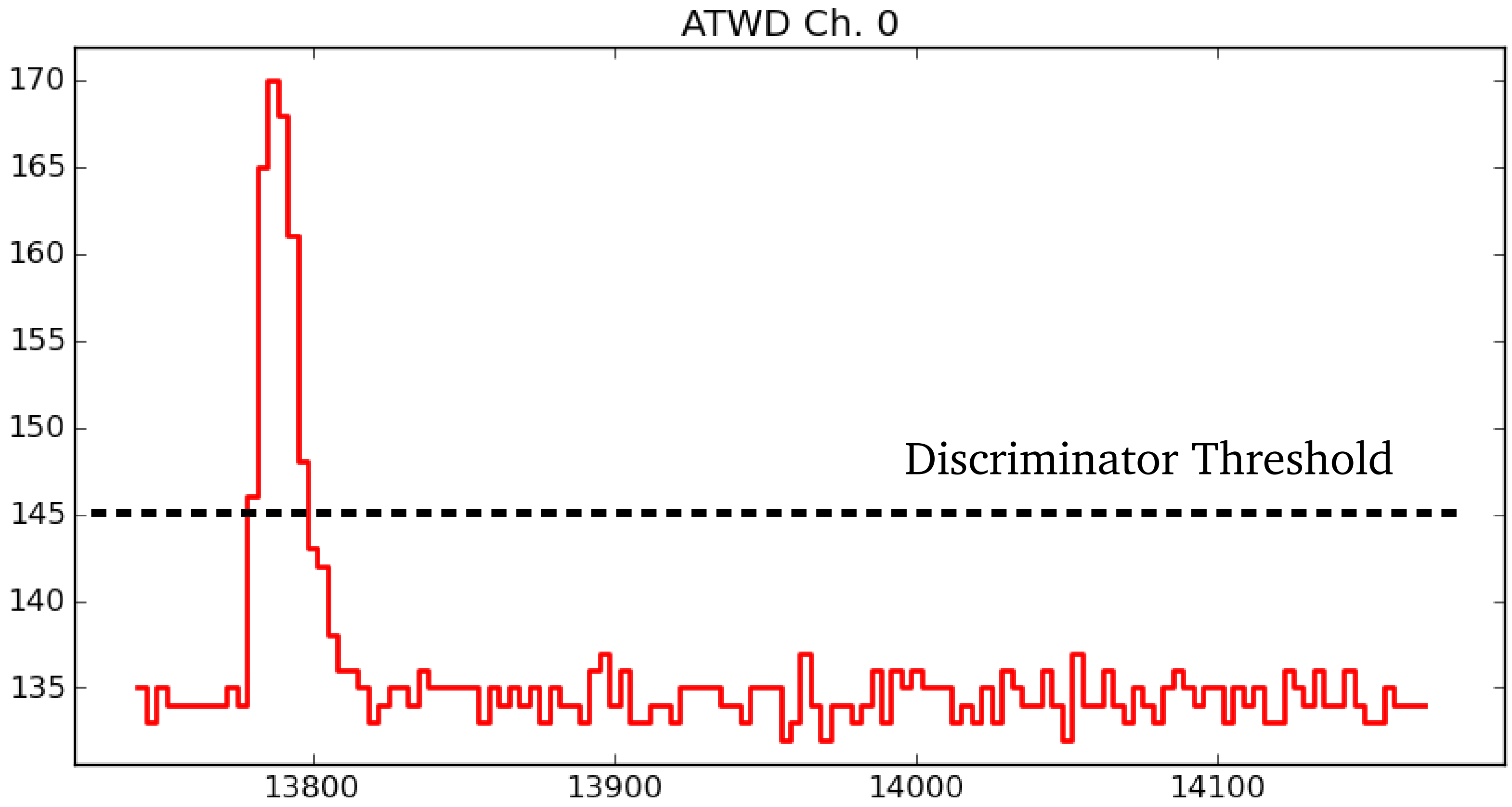
Input range: 0-3V

Three amplifiers for large
dynamic range.

Output: 13 bit (0-1023)



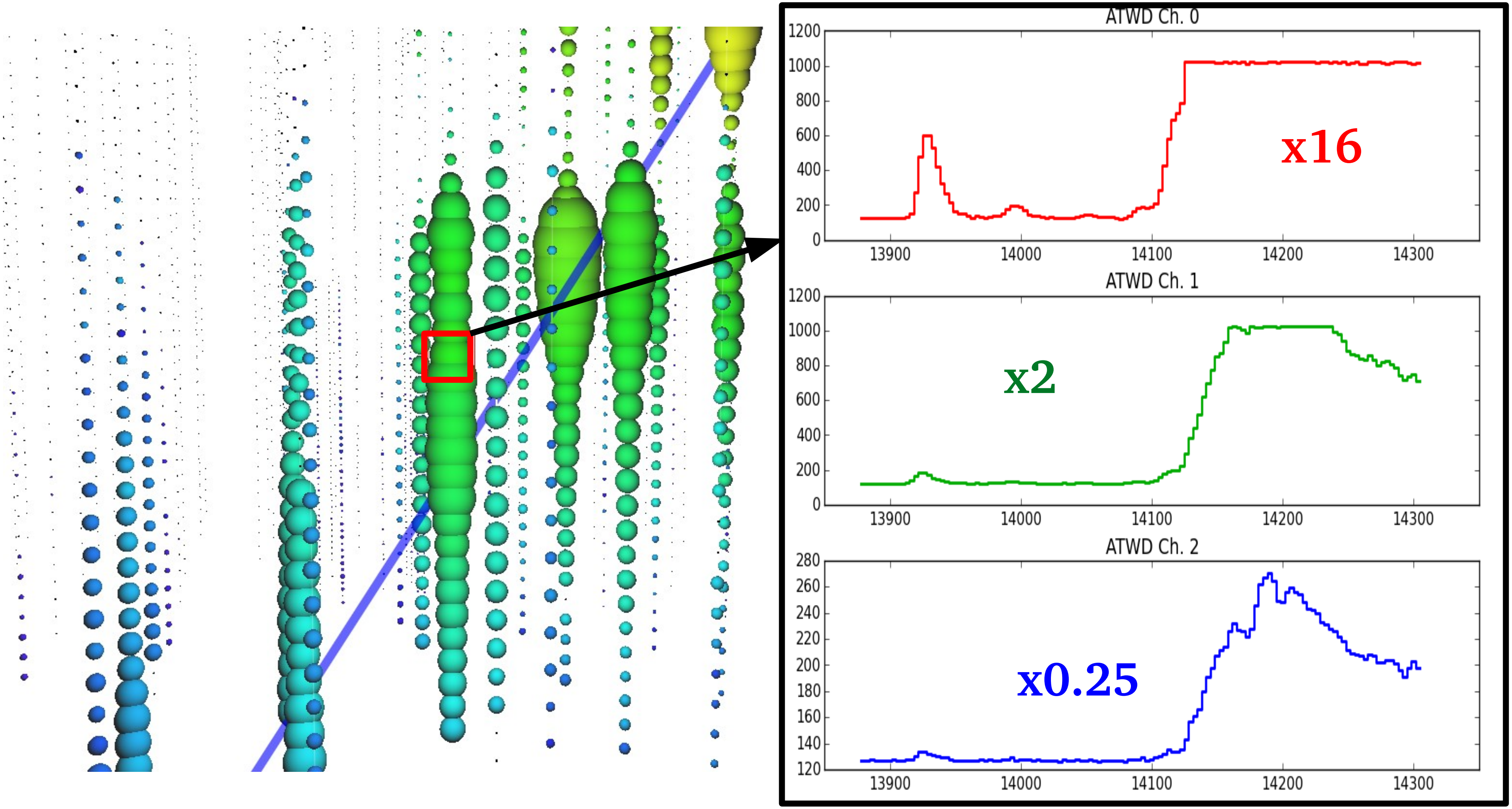
One Photo-Electron



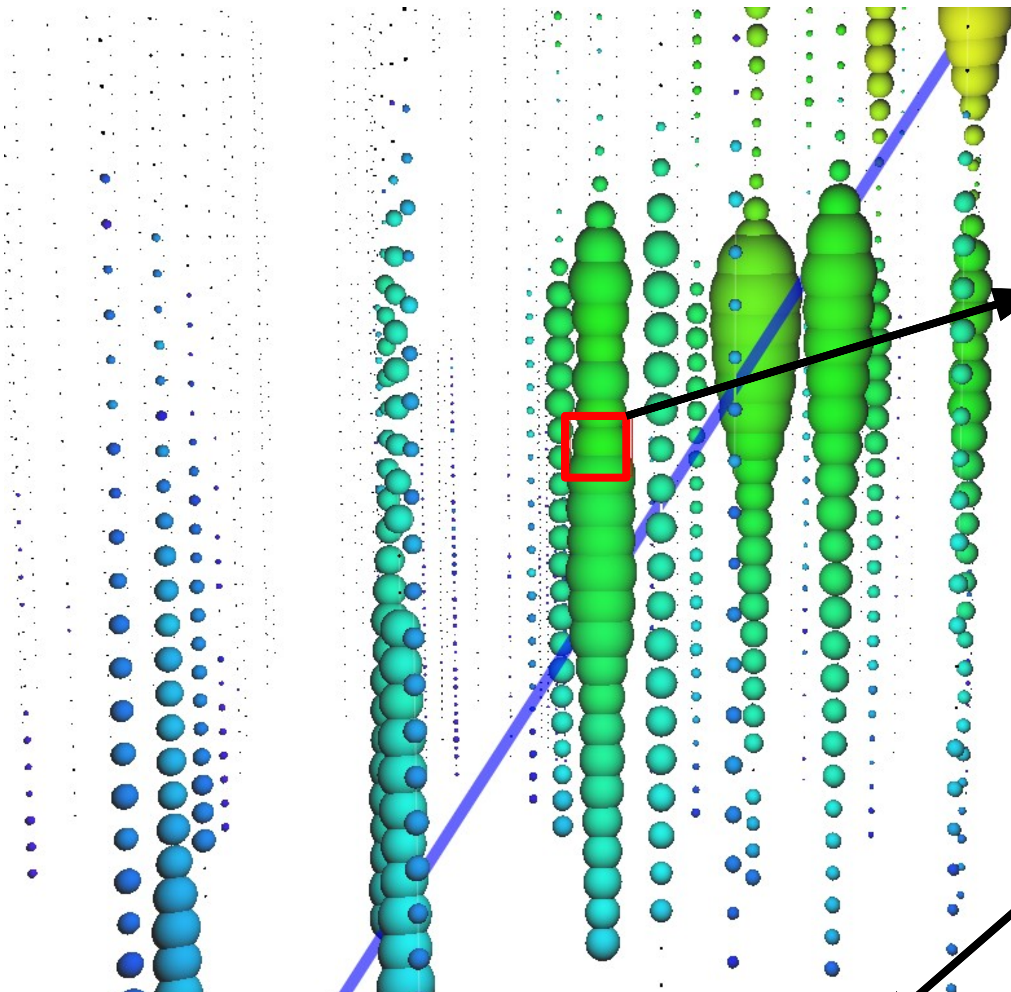
Gain | Width | Amplification | Range

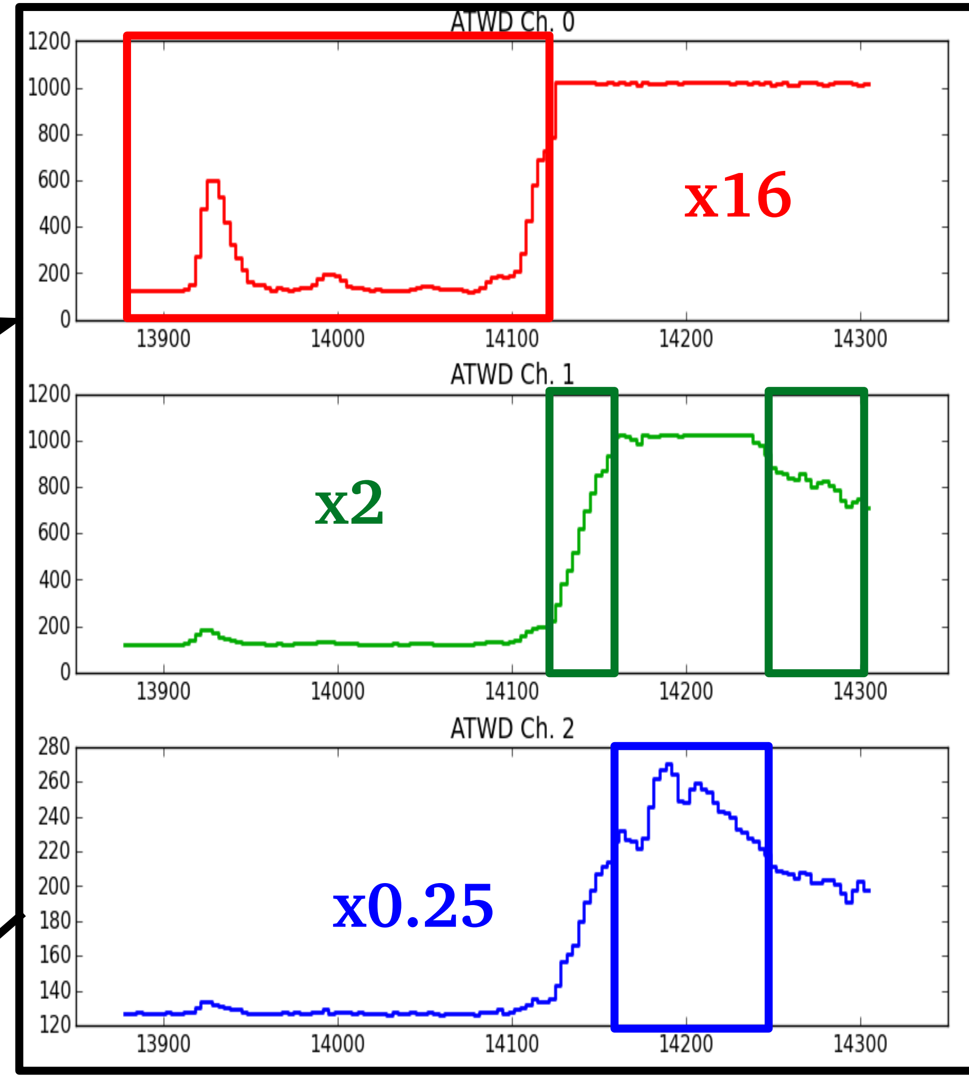
$$1.6\cdot10^{-19}\,\text{As} \times 10^{7}/10^{-8}\,\text{s} \times 50\Omega \times 16 \times 3\text{V}/\ 1024\ \text{counts}$$

= **30-40 counts**

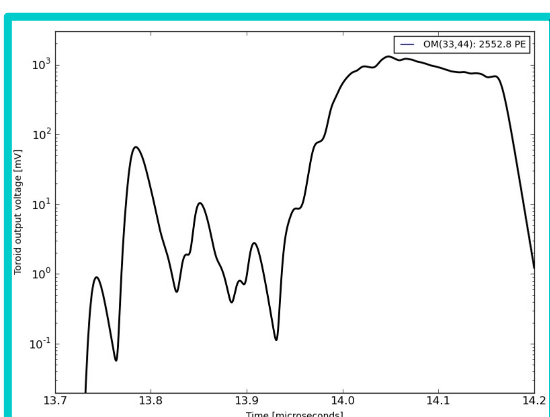


Raw Digitization





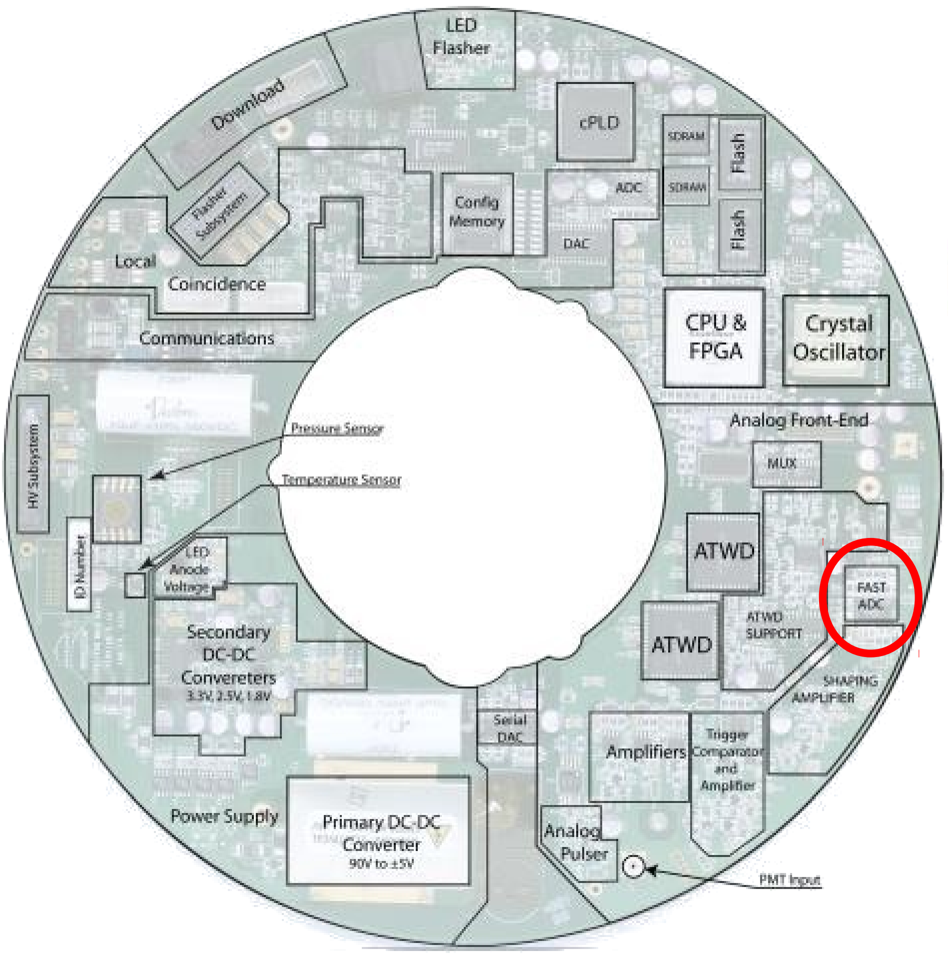
Raw Digitization

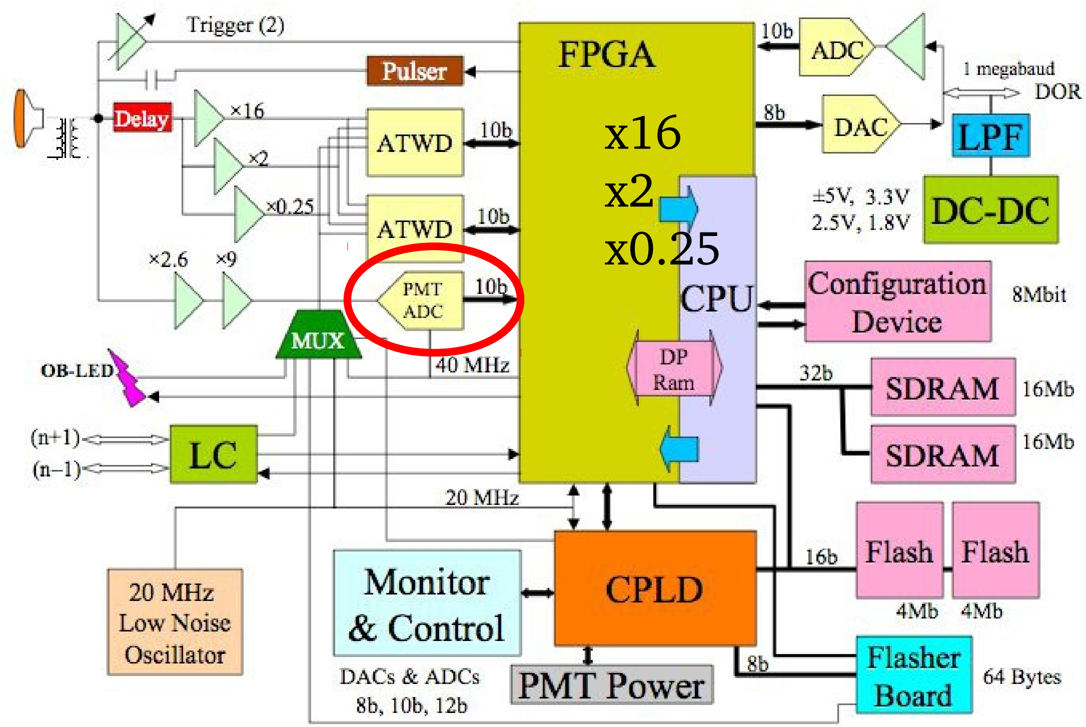


Calibrated Waveform

FADC

(Fast Analog to Digital Converter)



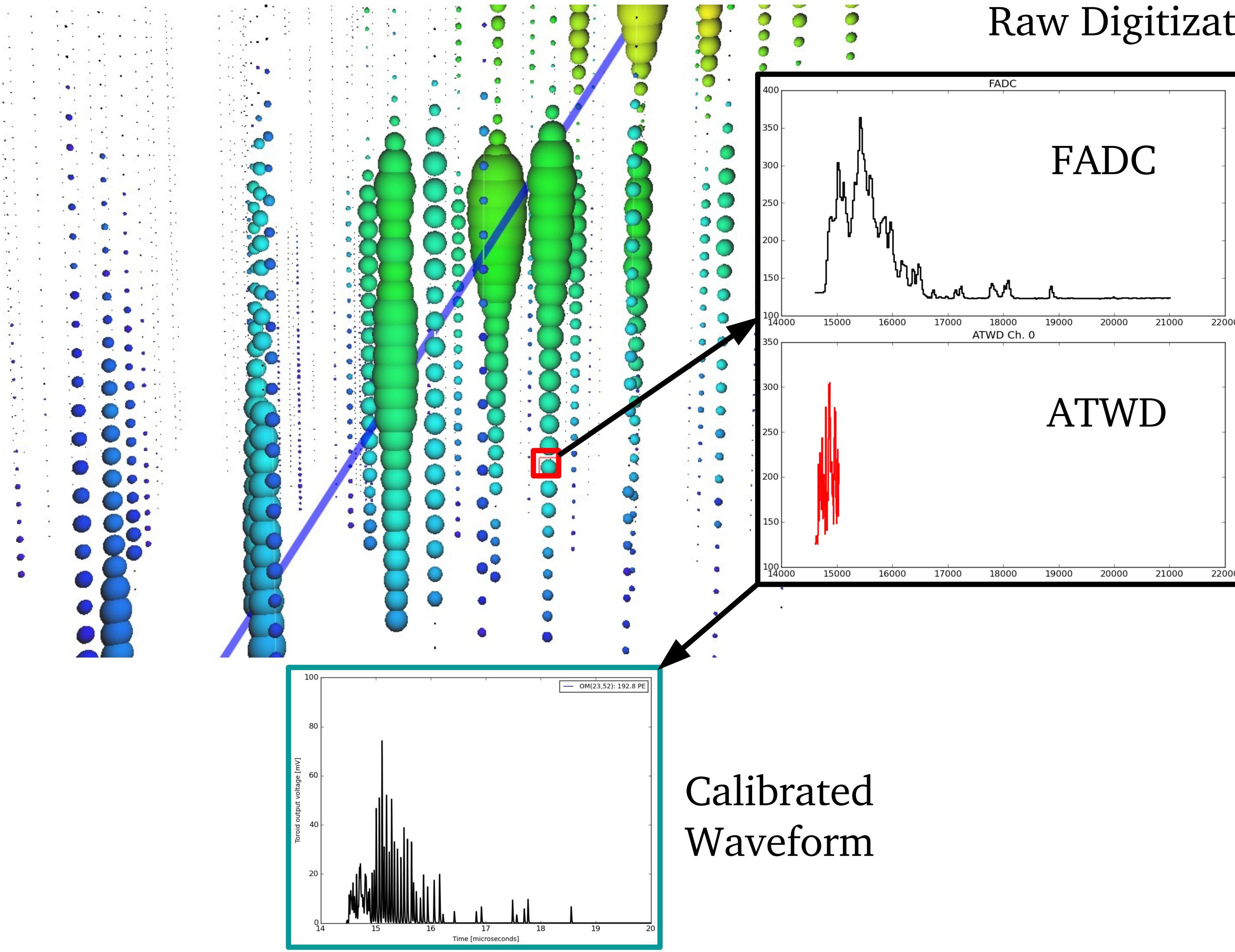


Sampling Rate: 40 MHz

Time Window: 6,400 ns

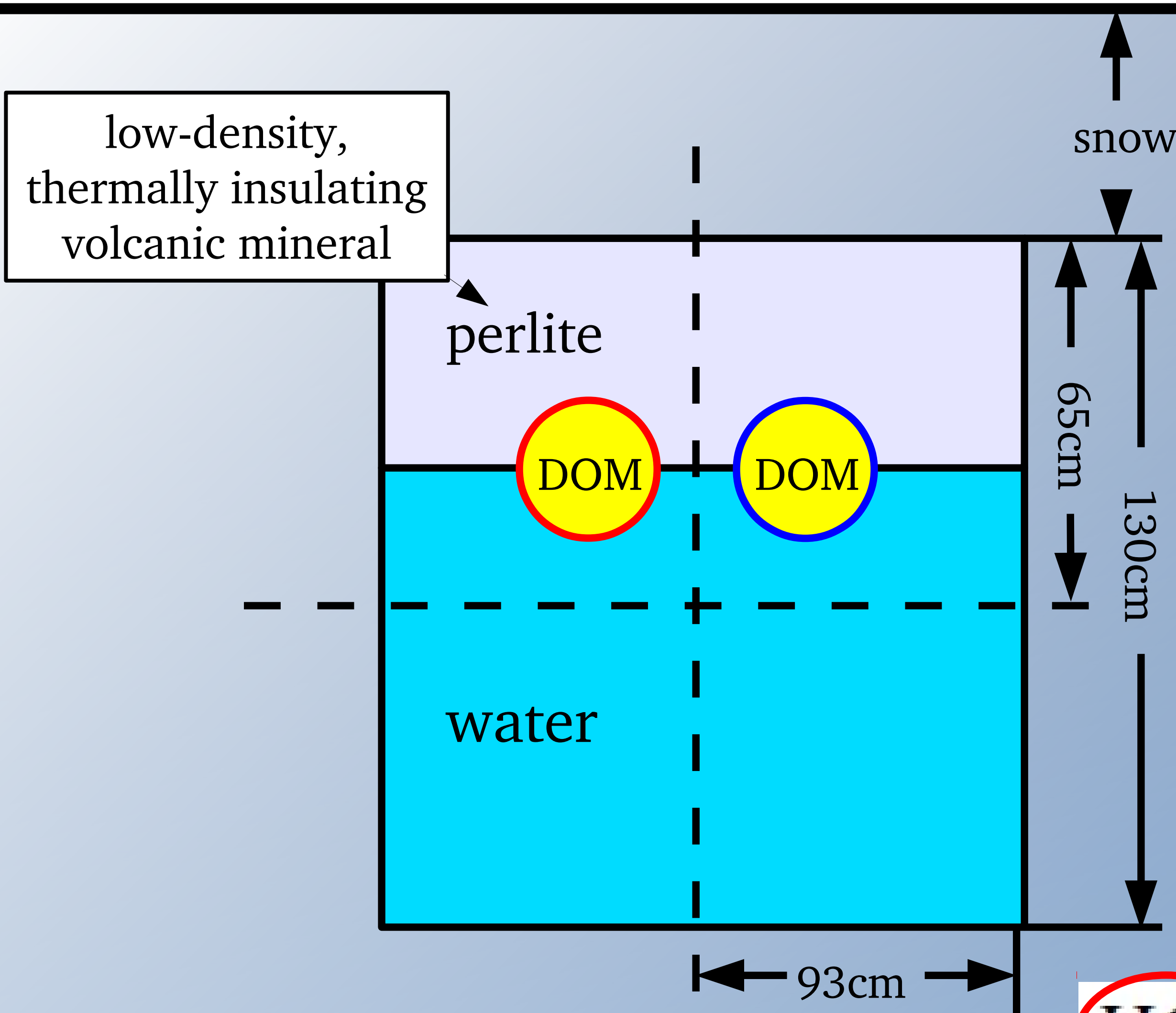
No deadtime!

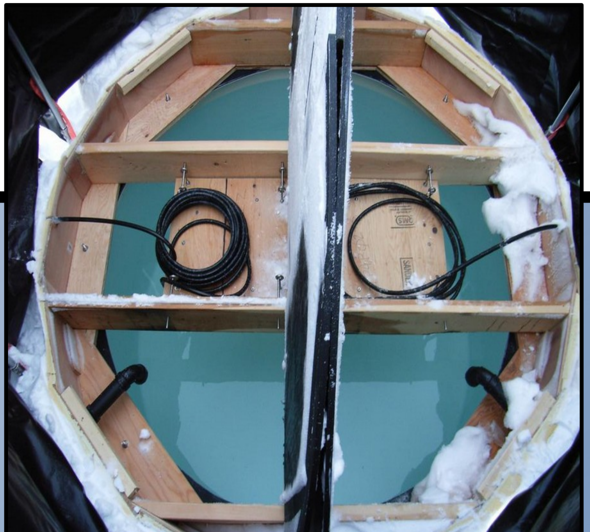
Raw Digitization



Calibrated Waveform

IceTop Tank





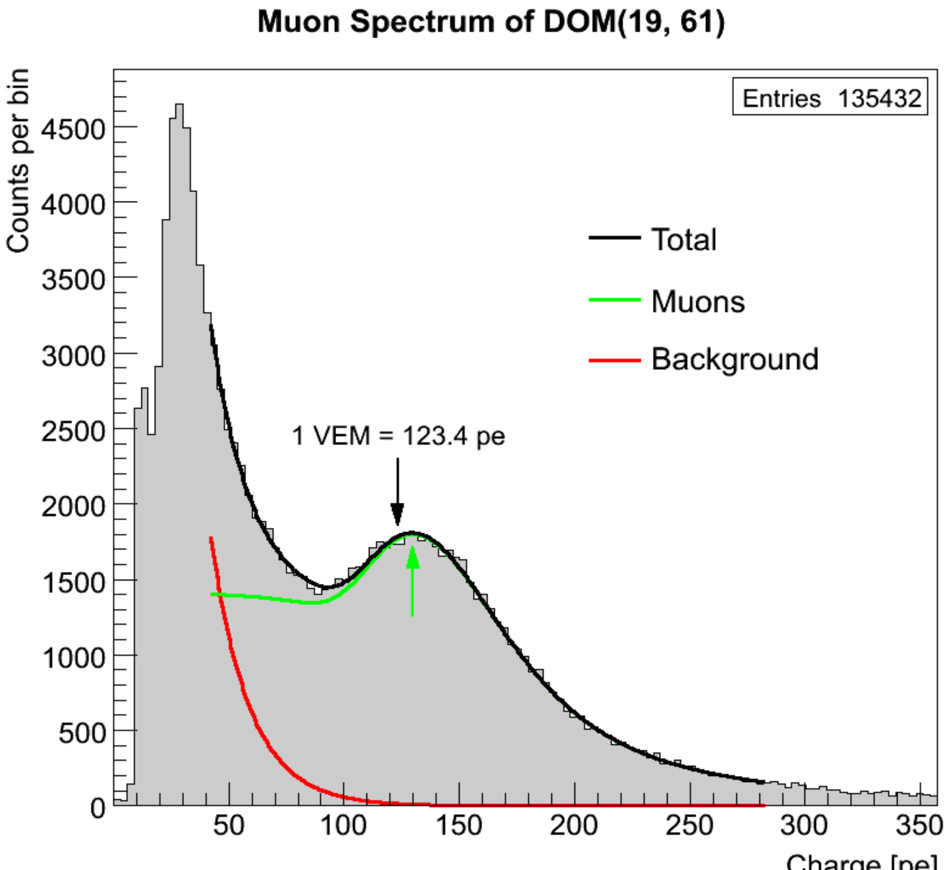
view from above, unfrozen

x2 x81

HG: 5×10^6 at ~1250 V

LG: 10^5 at ~750 V

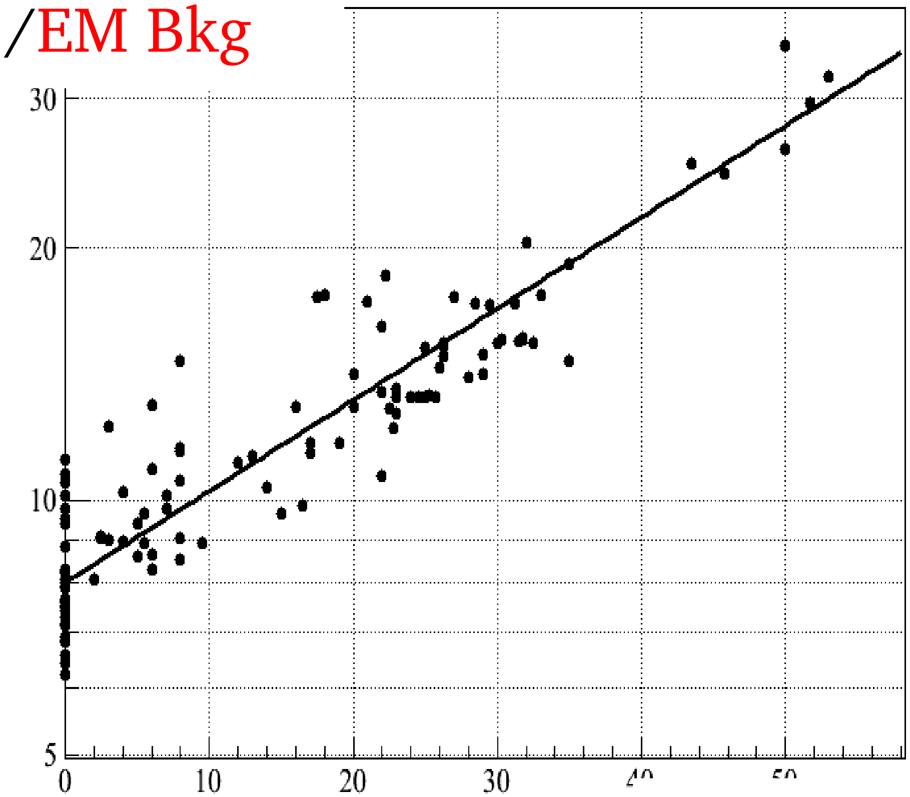
Tank Calibration



Source: T. Waldenmaier, DESY-Zeuthen

Snow reduces EM signal, muons unaffected

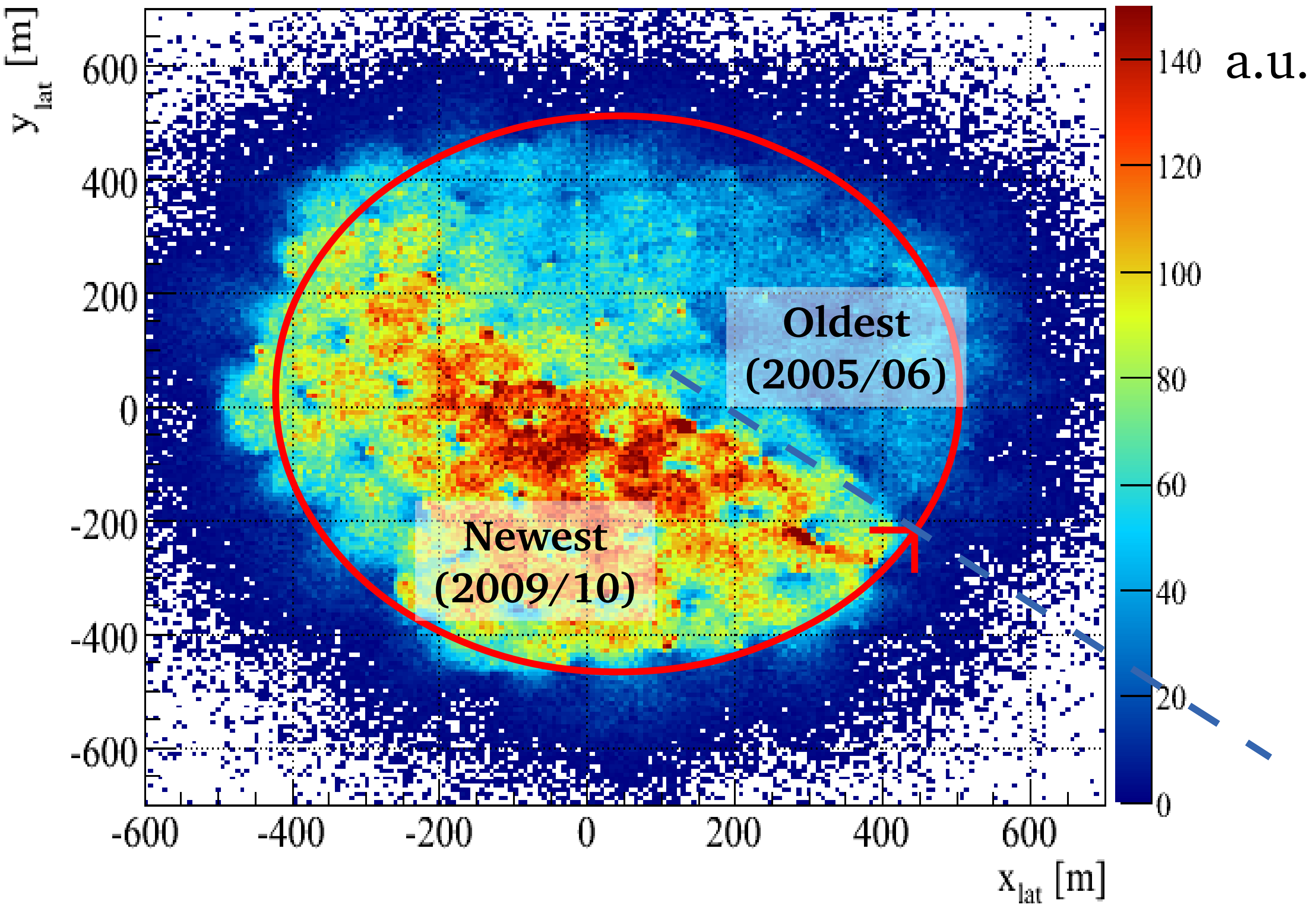
Muon Peak /EM Bkg

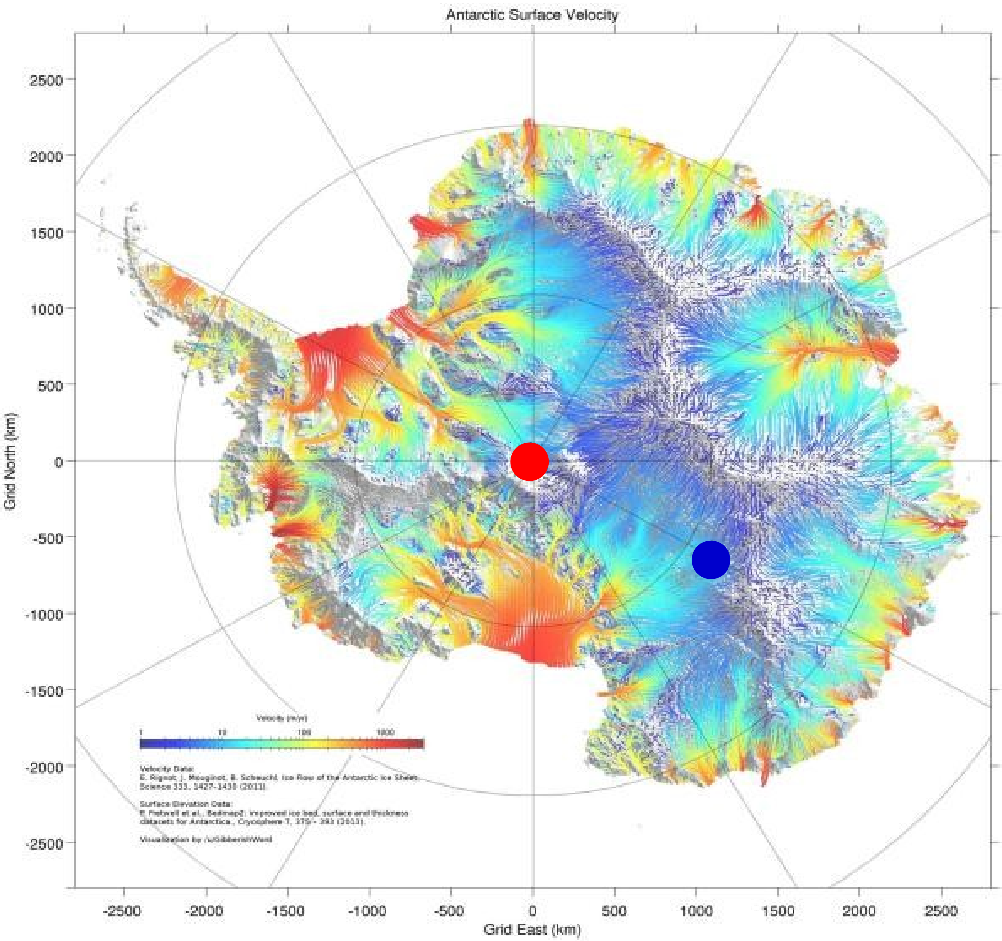


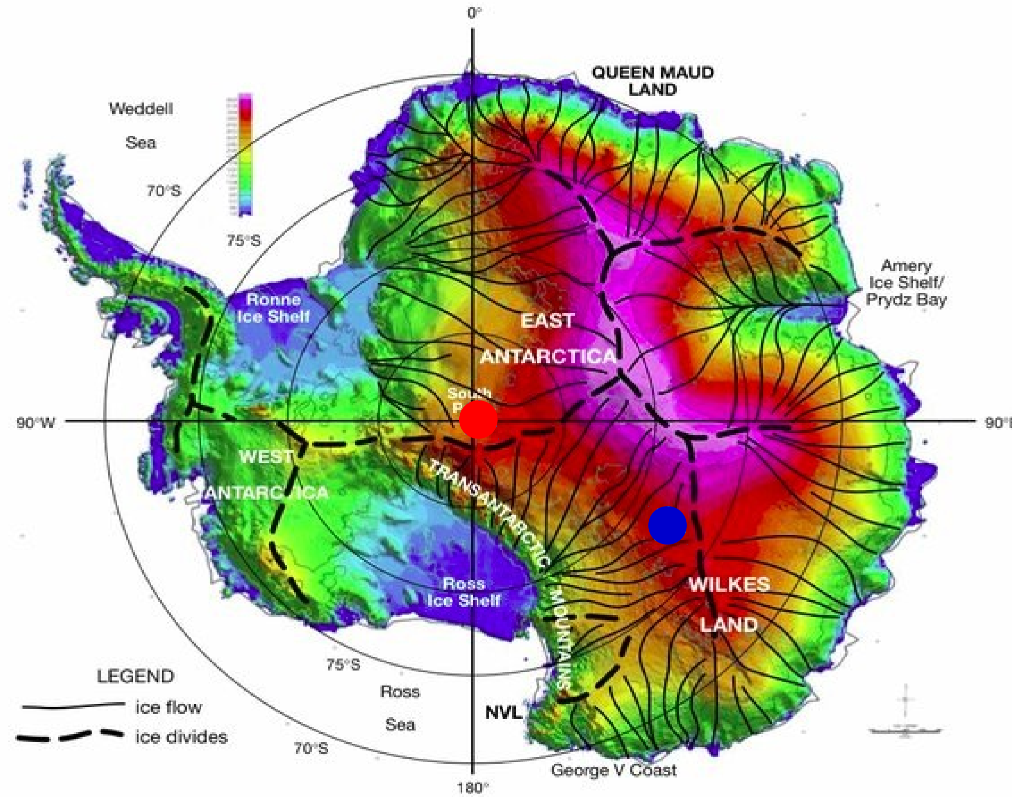
Snow Height

$$S_\mu / B_{EM} \simeq \exp\left(\frac{h_{snow}}{40.0''} + 2.08\right)$$

Effect of Snow Coverage
(Reconstructed Shower Core Position)





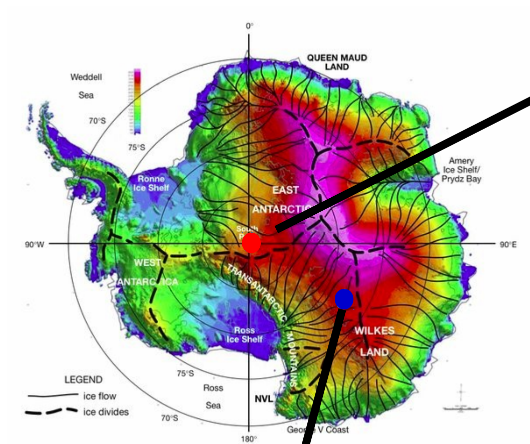


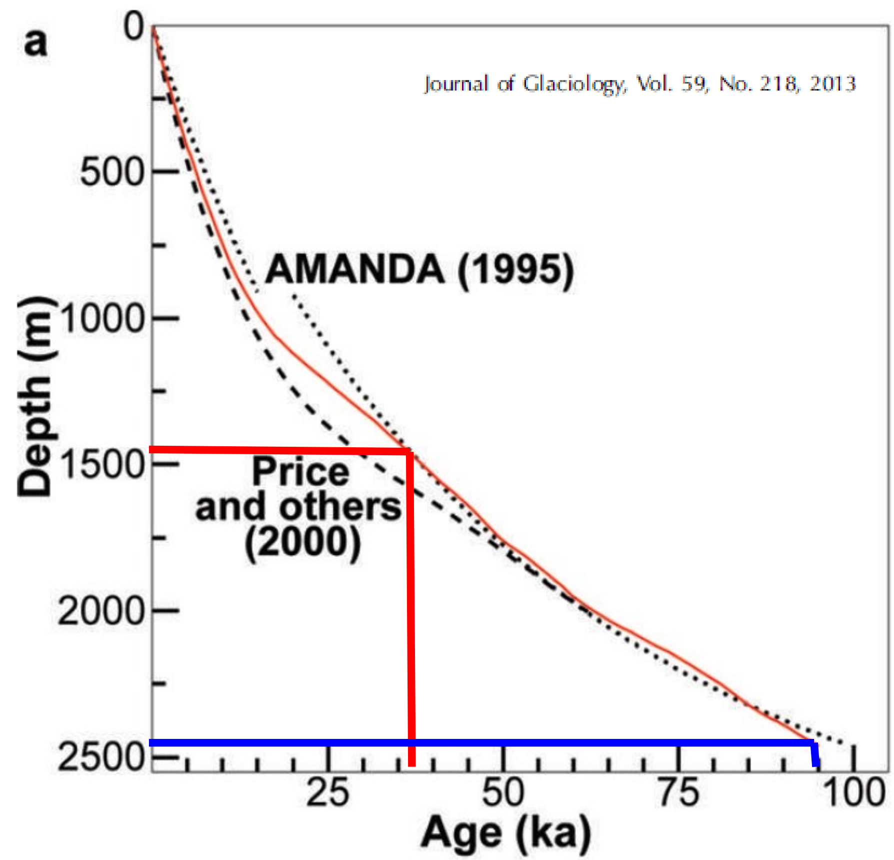
Ice Flow

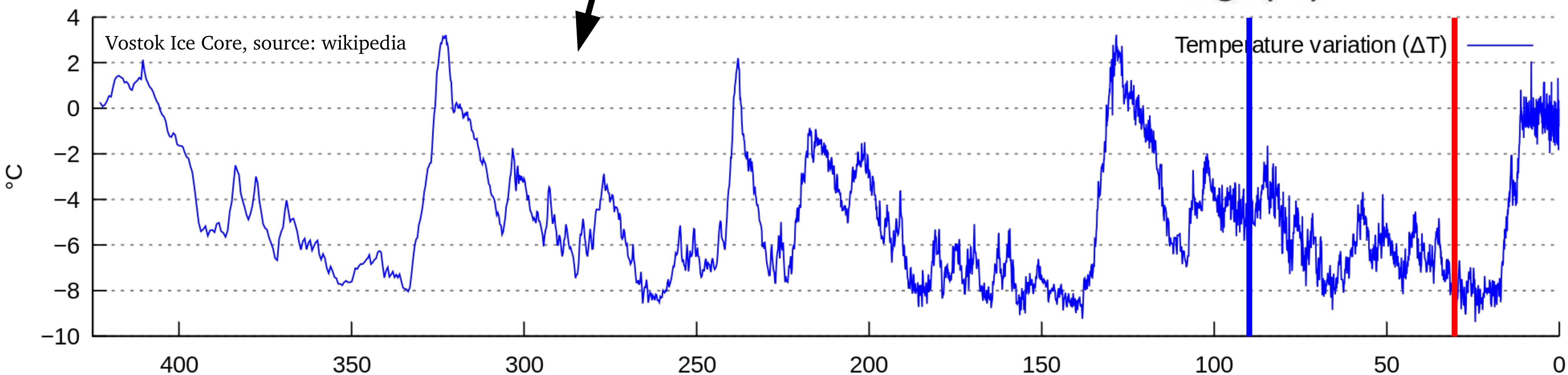
Ice Thickness

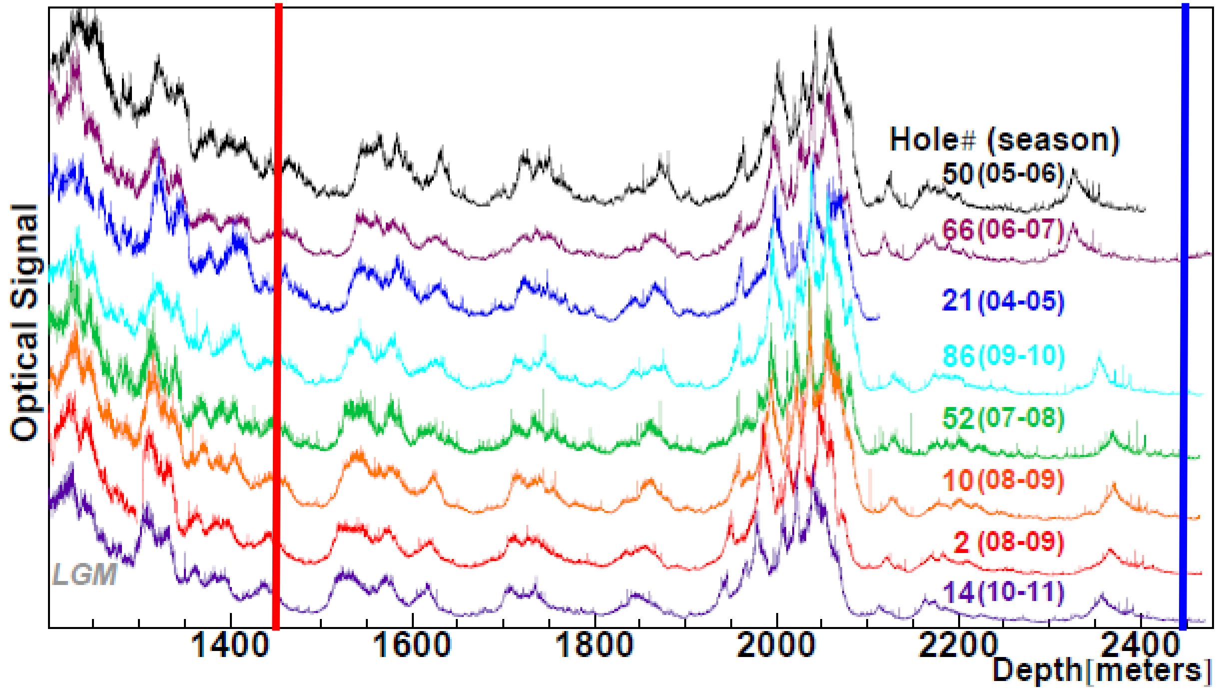
Detector deployed in ice formed from ca. 90,000 to 36,000 years ago.

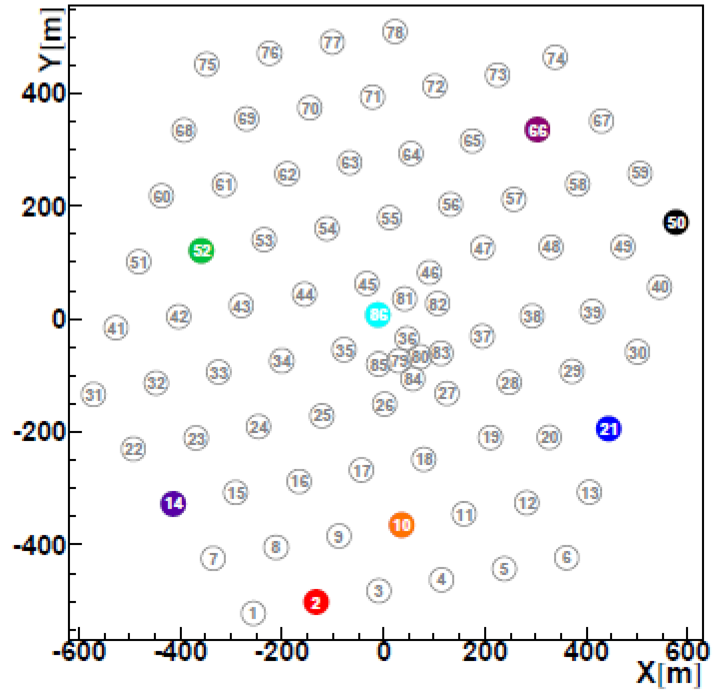
Strong climatic variations!

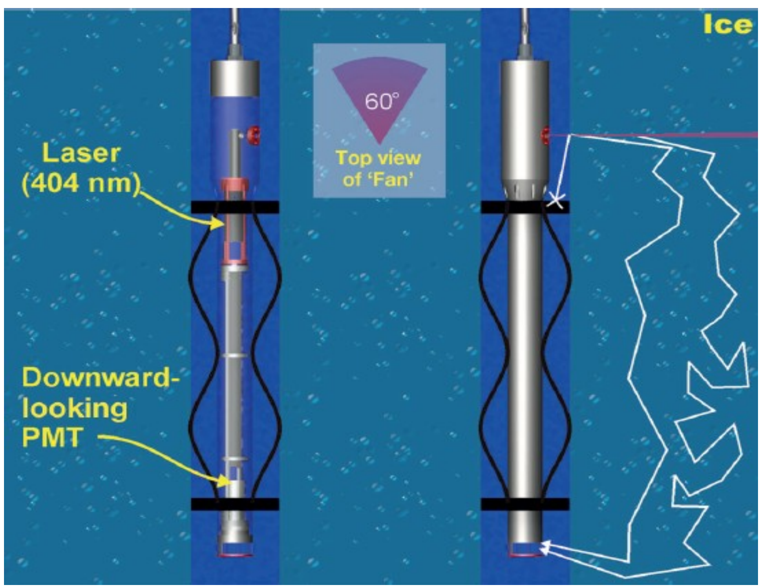




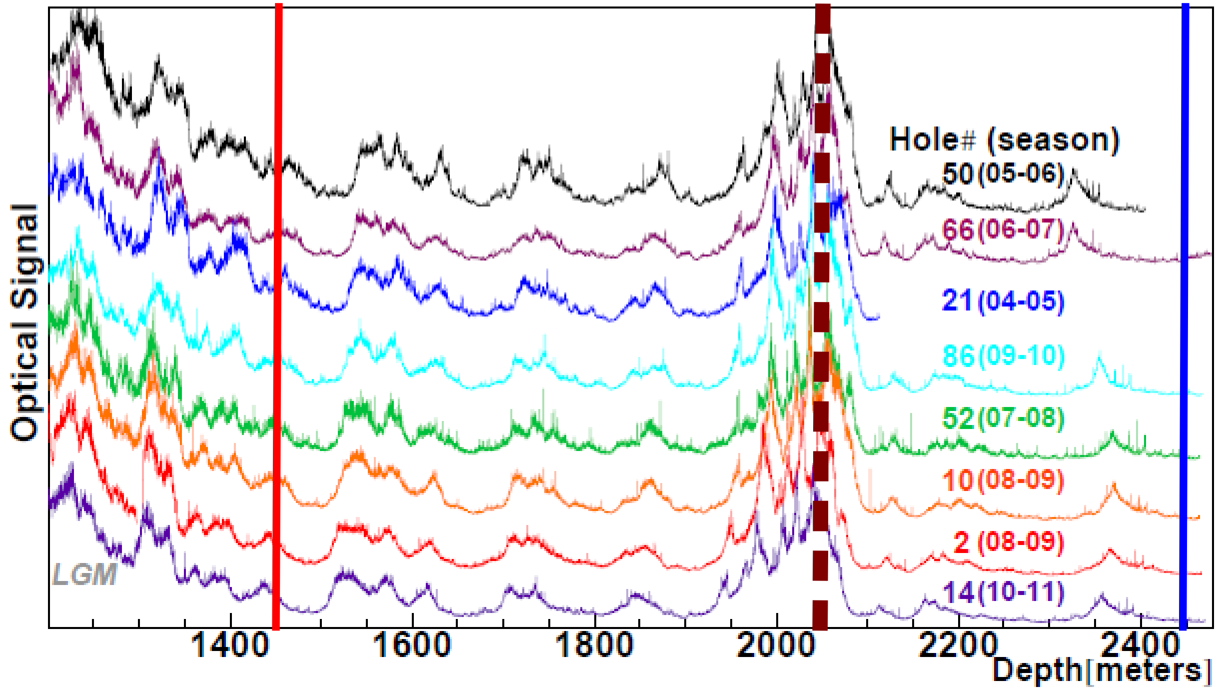


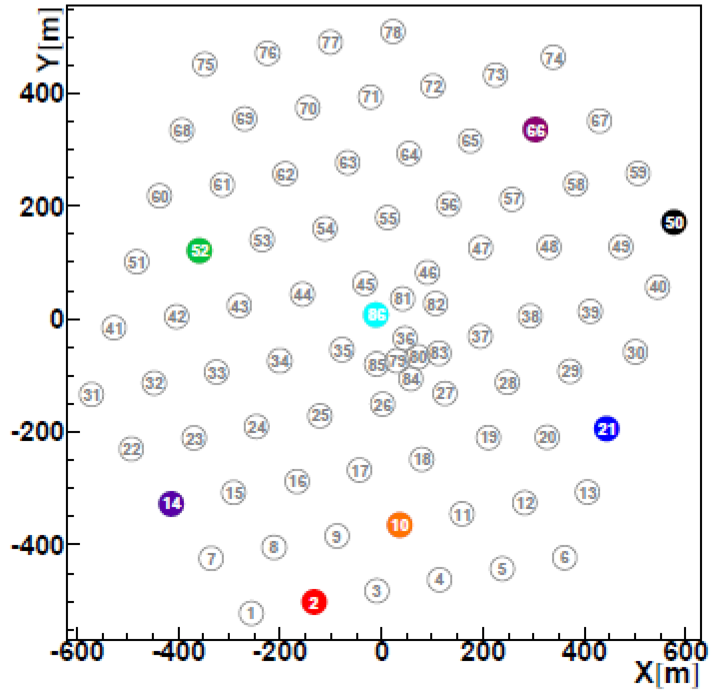


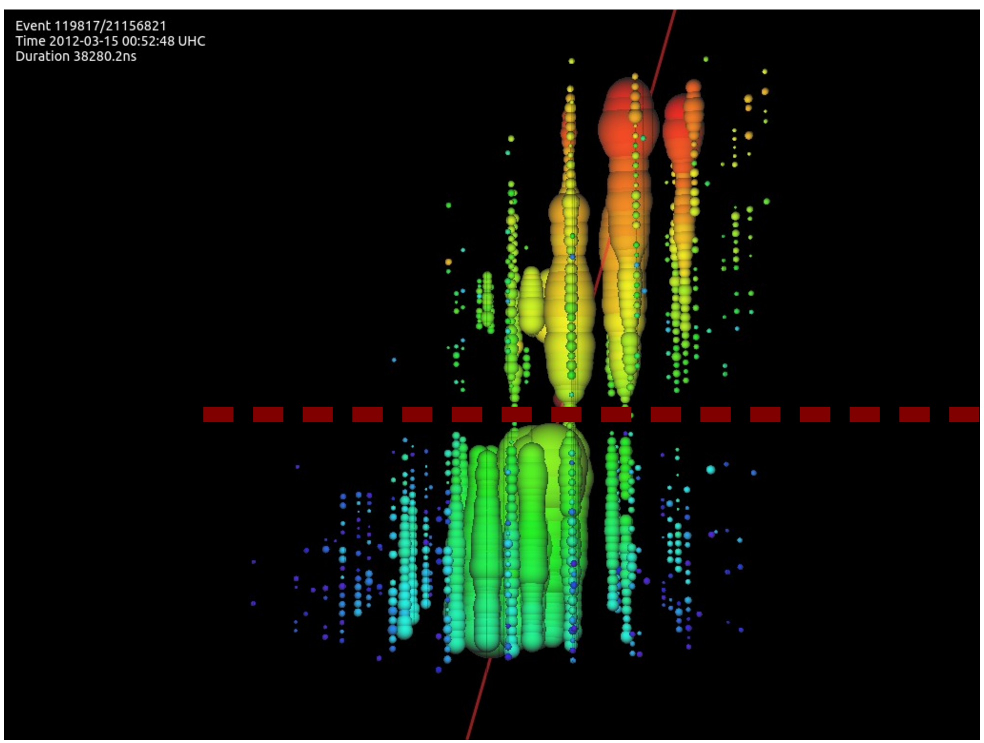




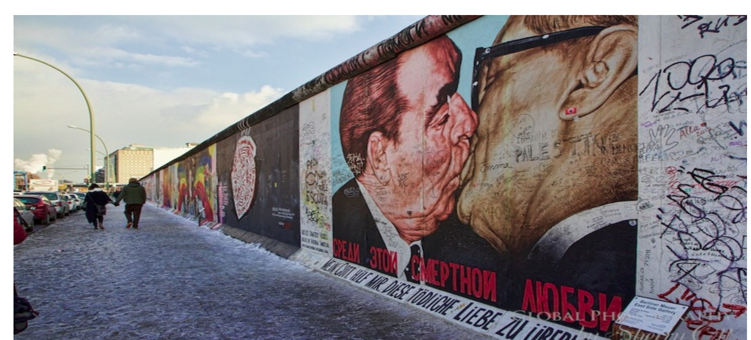
In-situ measurement of photon scattering with "dust logger".



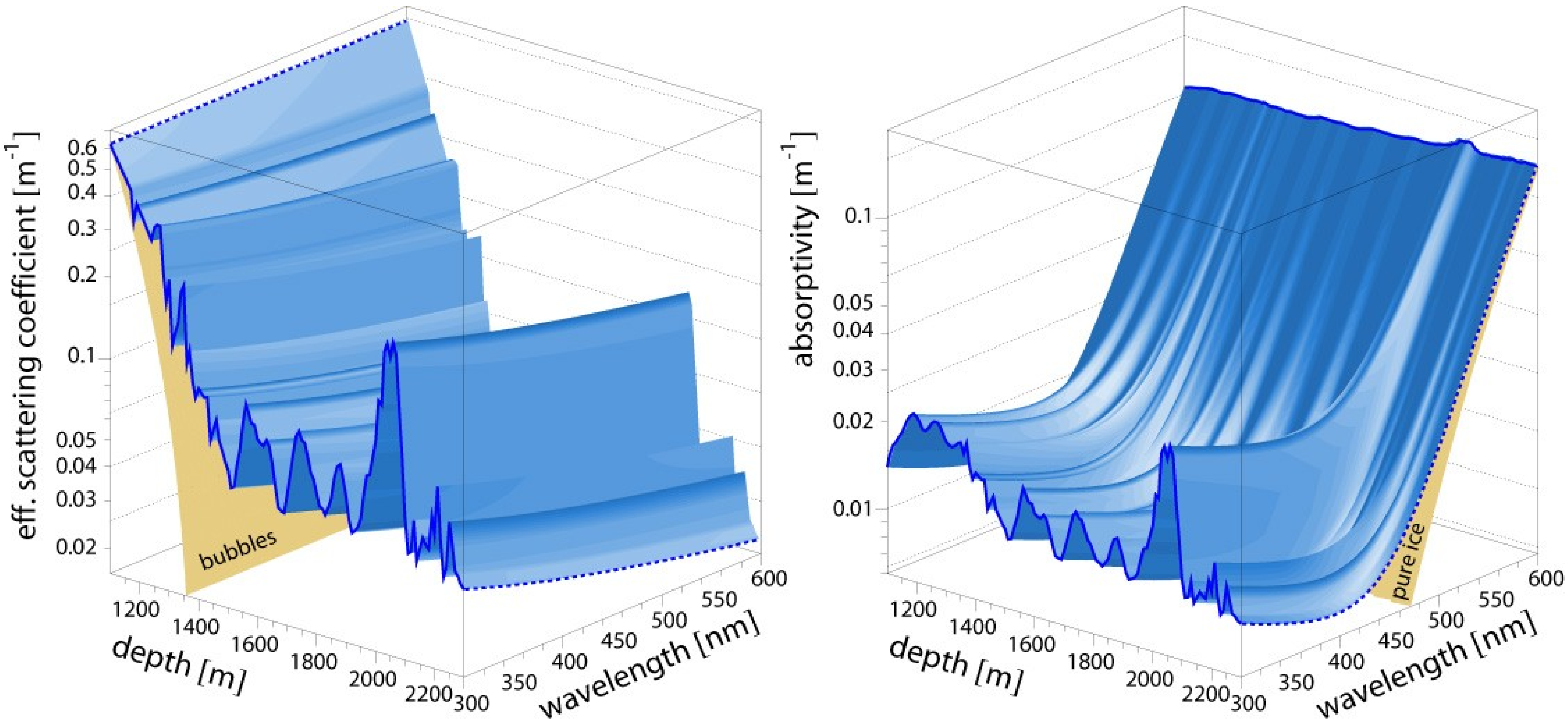




2050 meters below surface:
Intransparent "Wall" dividing
detector into two parts!

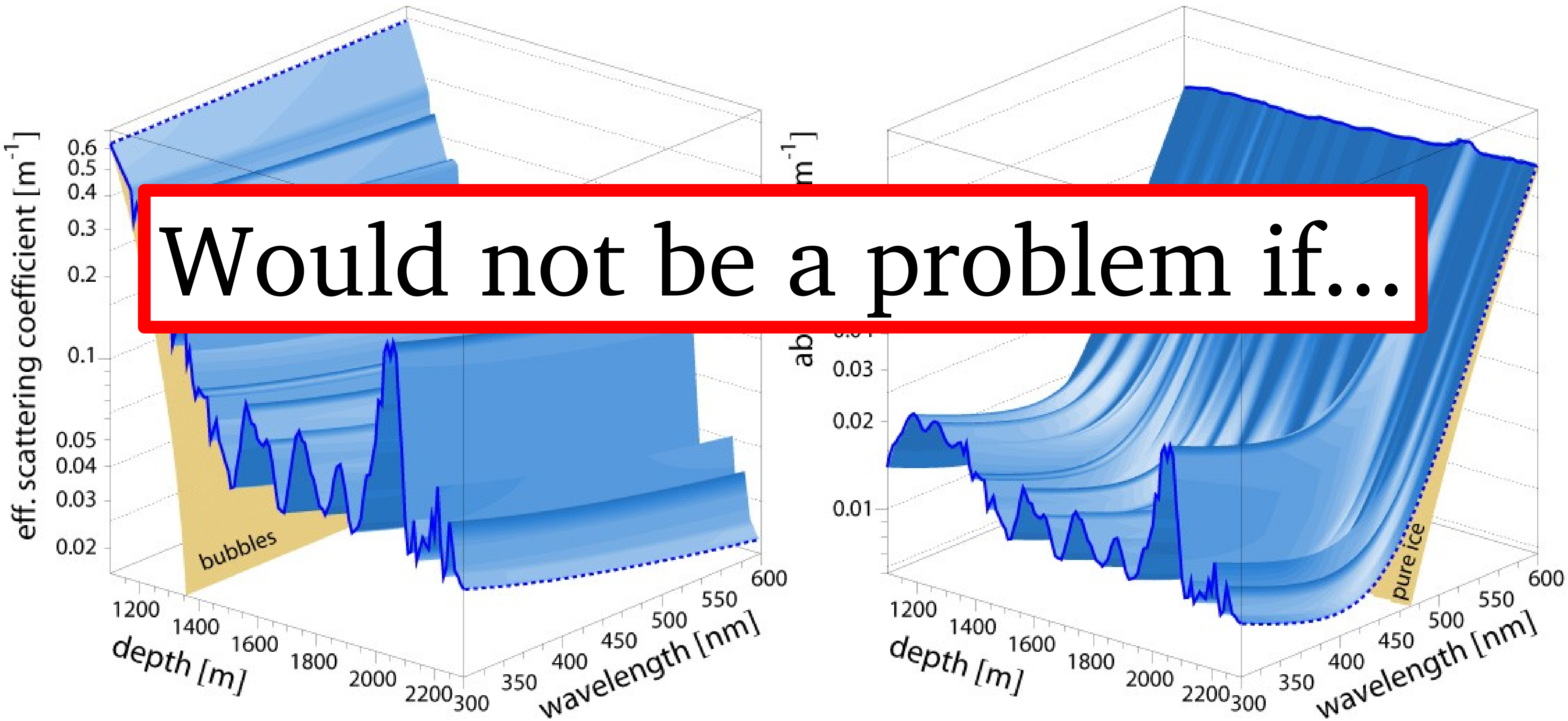


Optical Ice Properties



M. Ackermann et al.(2006), J. Geophys. Res., 111, D13203

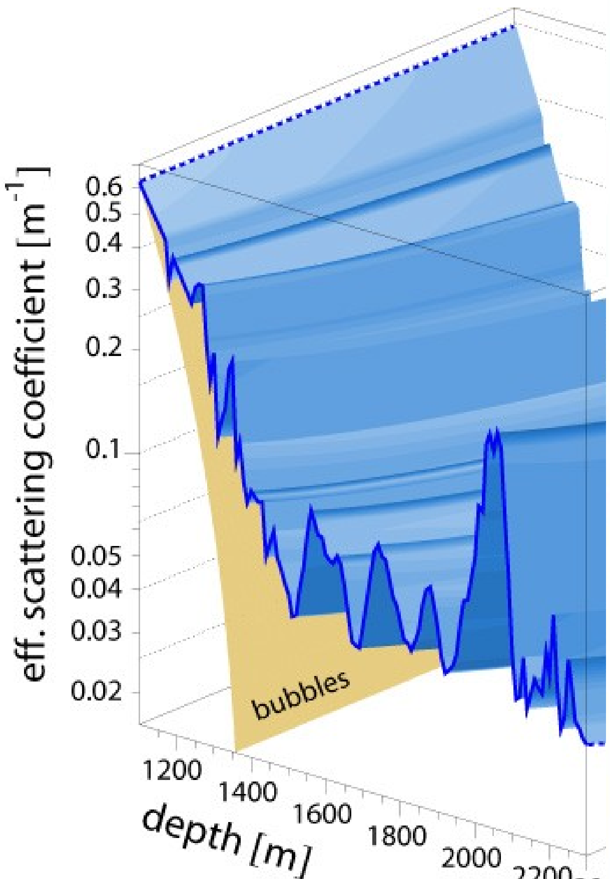
Optical Ice Properties

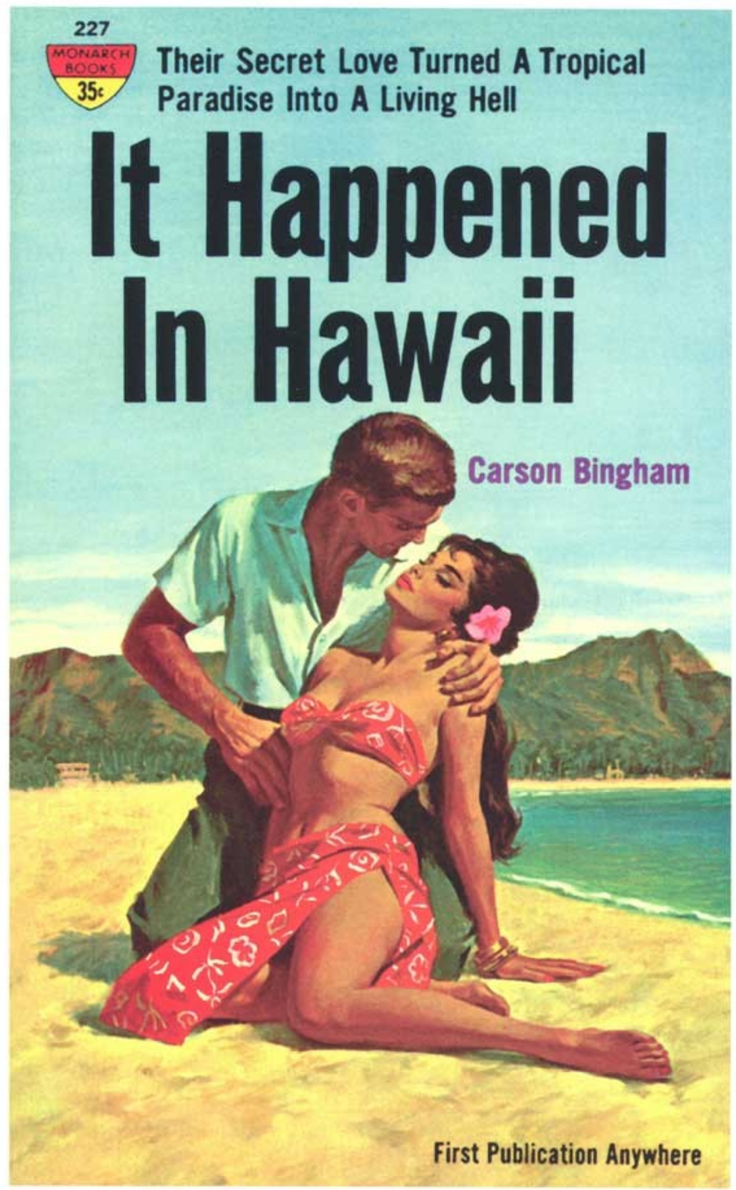


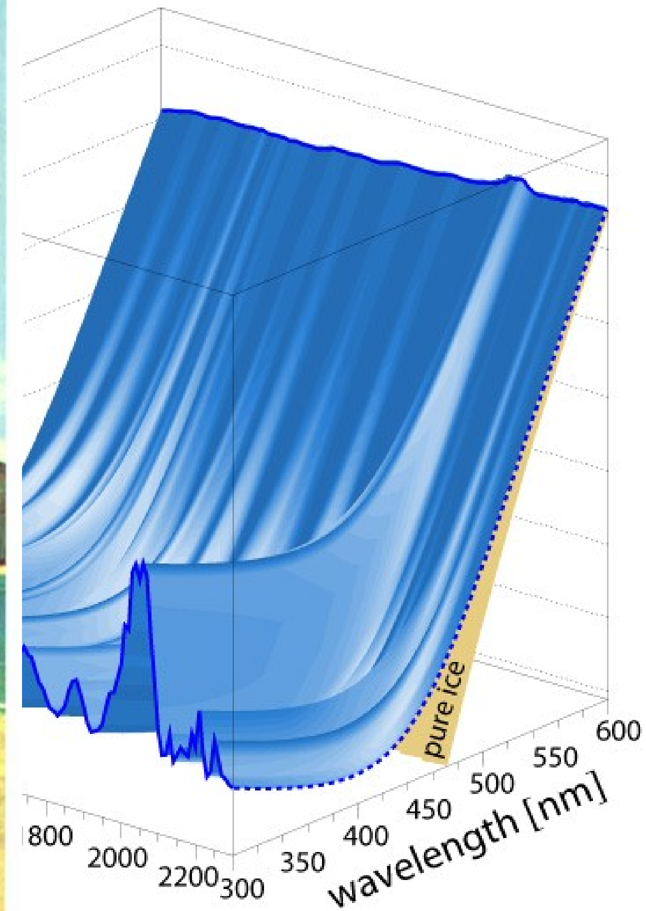
Would not be a problem if…

M. Ackermann et al.(2006), J. Geophys. Res., 111, D13203

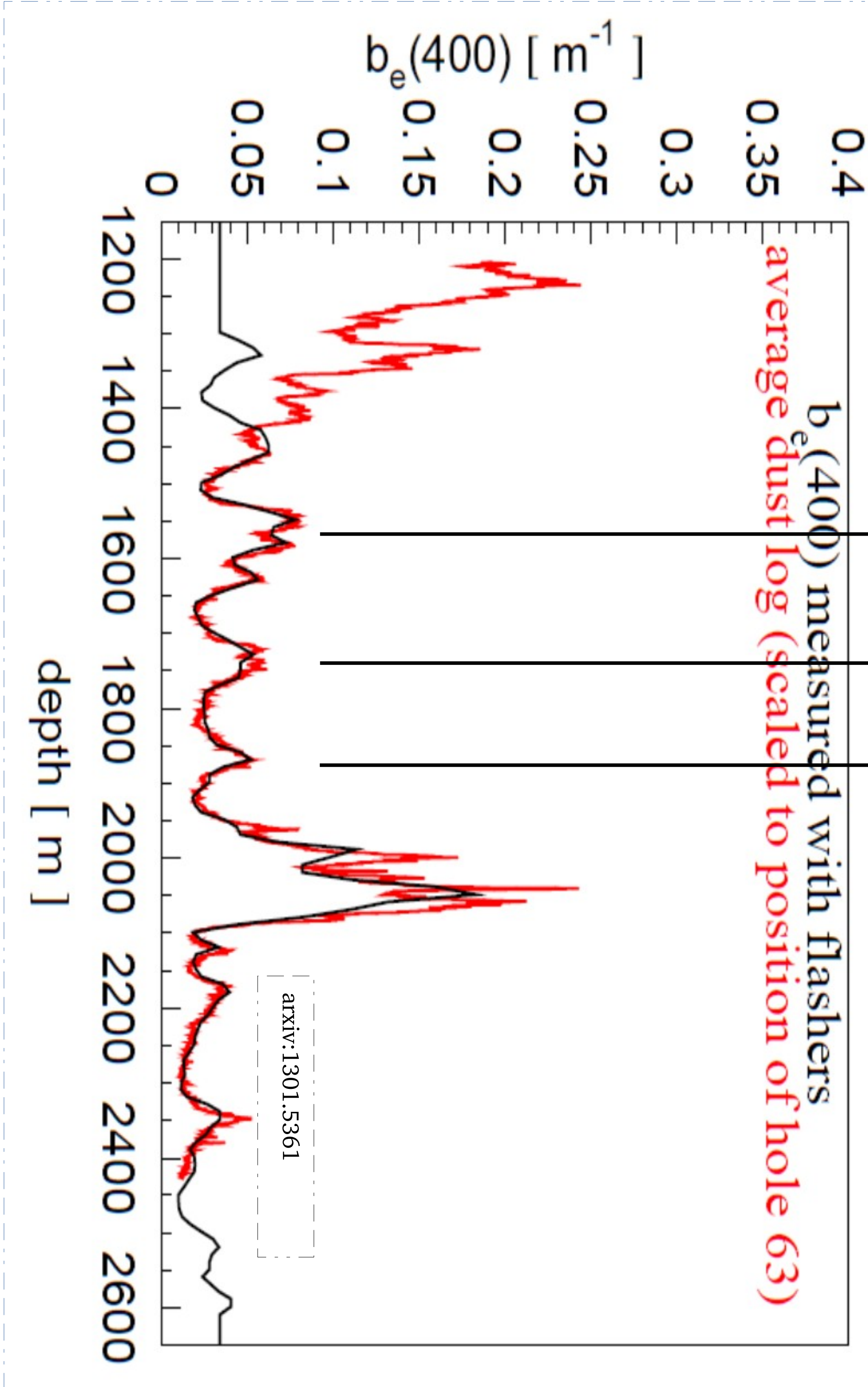
Opt rties



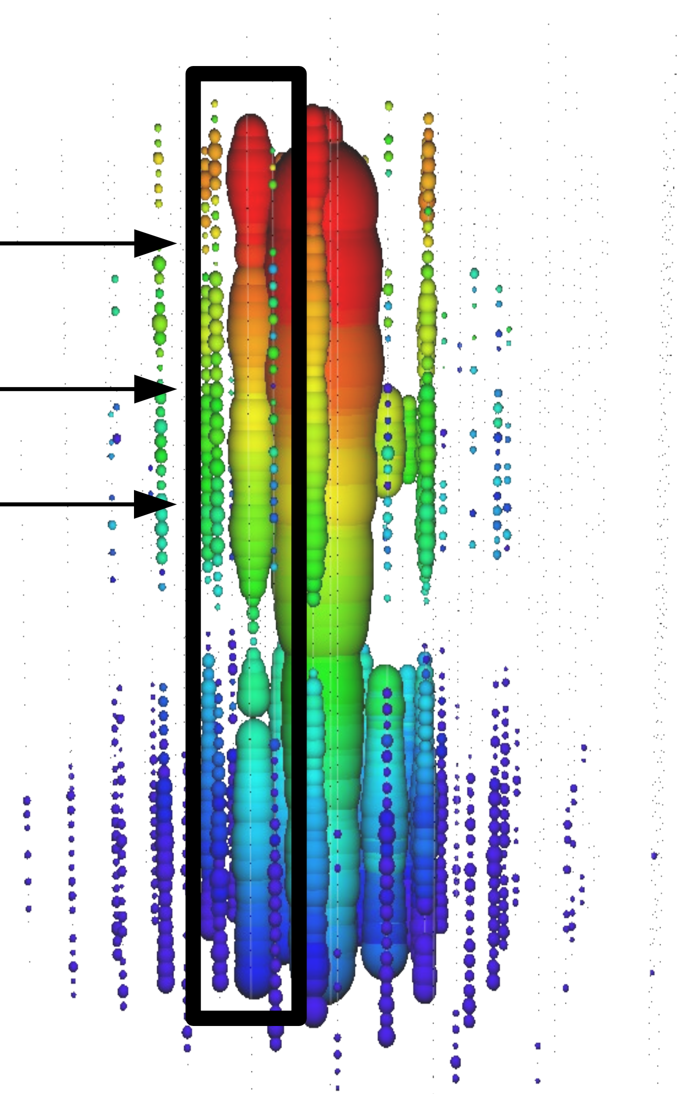




M. Ackermann et al.(2006), J. Geophys. Res., 111, D13203



Layers of high dust concentration



EeV-scale vertical CR shower

Next Time: Events!