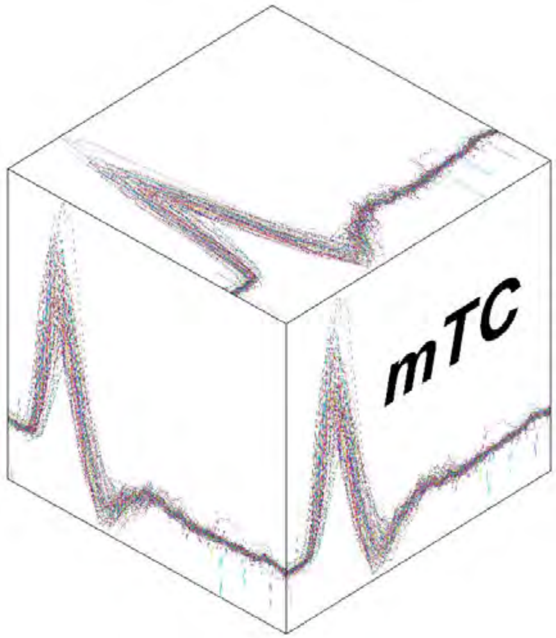
miniTimeCube

Building the world's smallest neutrino detector

Viacheslav A. Li

Department of Physics and Astronomy
University of Hawai'i at Manoa



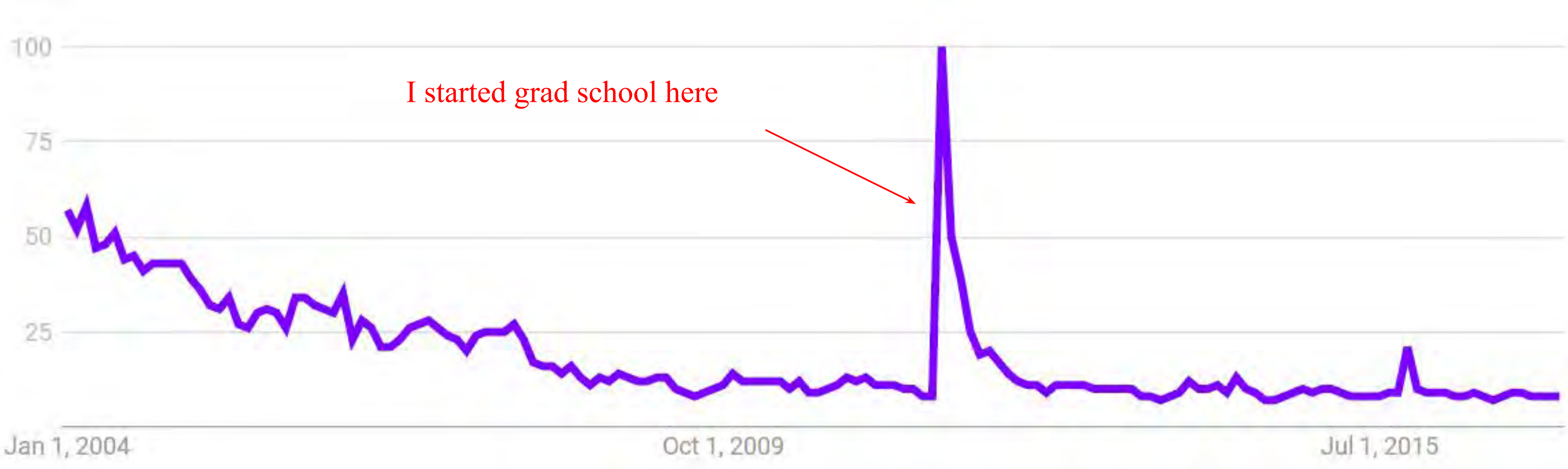
Interview talk for
Kavli Institute for the Physics and
Mathematics of the Universe

April 20, 2018

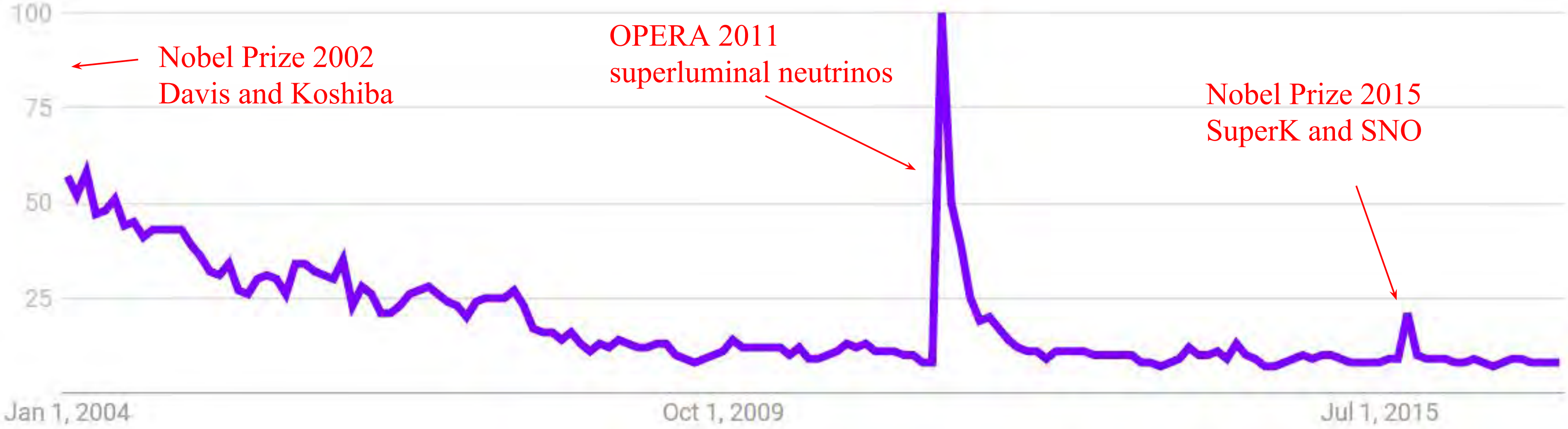
mTC: Compact collaboration

- **University of Hawaii**: Ryan Dorrill, Mark Duvall, Andrew Druetzler, John Koblanski, John Learned, Viacheslav Li, Luca Macchiarulo, Shigenobu Matsuno, Sergey Negrashov, Kurtis Nishimura, Marc Rosen, Gary Varner
- **Ultralytics LLC**: Glenn Jocher
- **University of Maryland**: Kristi Engel, William McDonough, Scott Wipperfurth
- **National Institute of Standards and Technology**: Pieter Mumm
- **National Geospatial-Intelligence Agency**: Shawn Usman

Google trend of "neutrino"



Google trend of "neutrino"



Outline

- **miniTimeCube**
- **Contributions**
- **Future/Summary**

Why build another neutrino experiment?

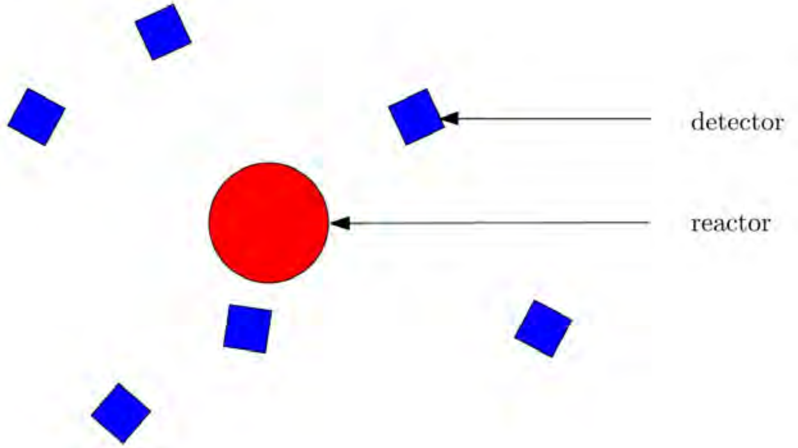
- Neutrino oscillations at very short baselines are not well understood.
- Only a couple of detectors were directional.
- Paving road to geo-neutrino detection (better understanding of the Earth’s interior)

<u>Potential applications:</u>

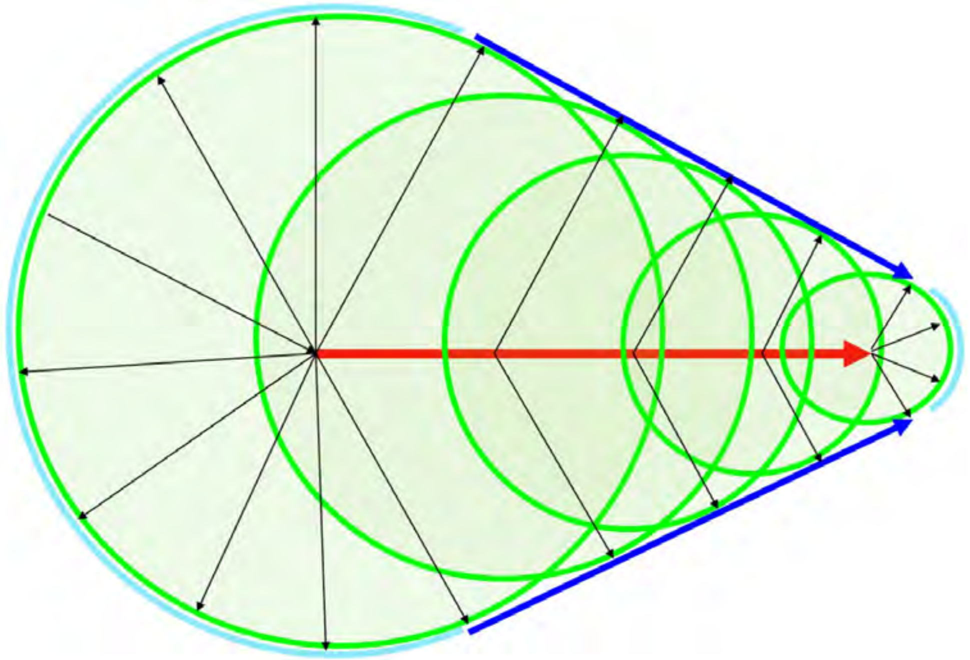
Non-proliferation of nuclear weapons

SNM detection (neutron detection)

Reactor fuel monitoring

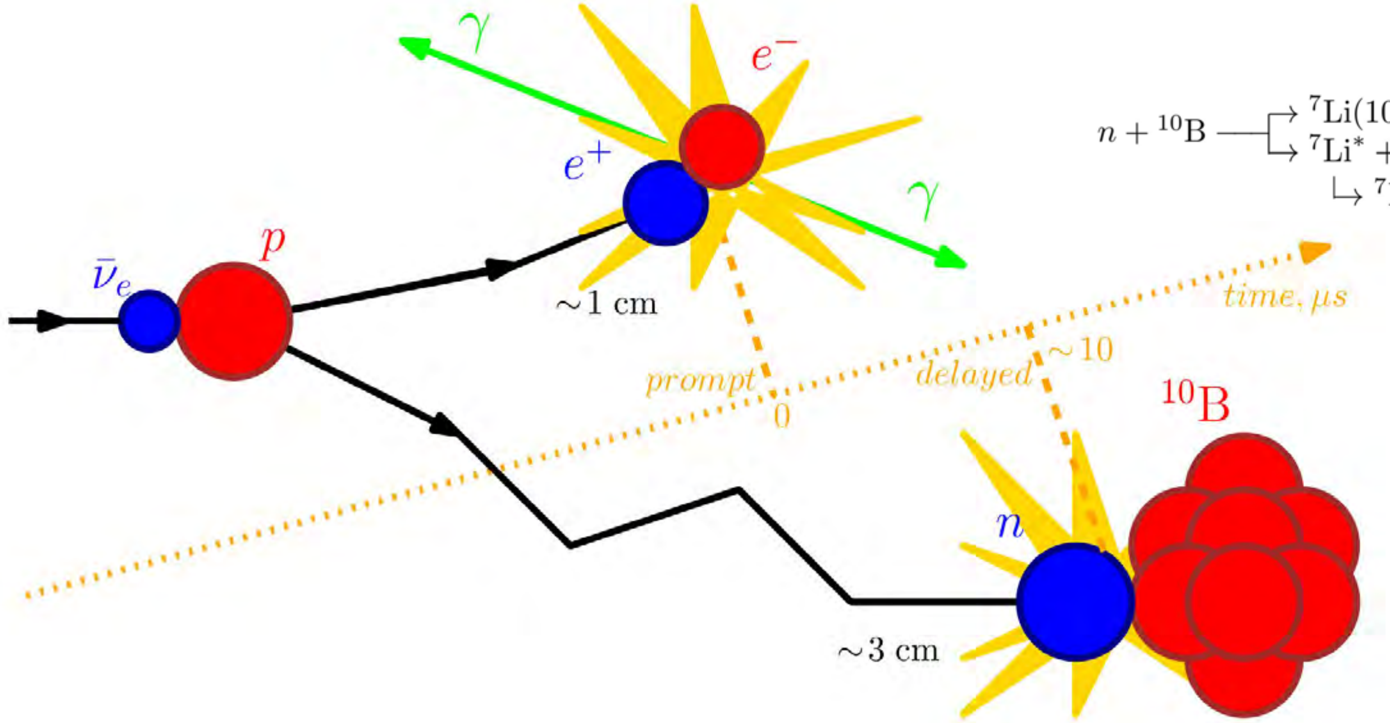


mTC: John's idea



Charged particle moving in a scintillator, first photon arrival times.

mTC: Inverse β decay in the mTC

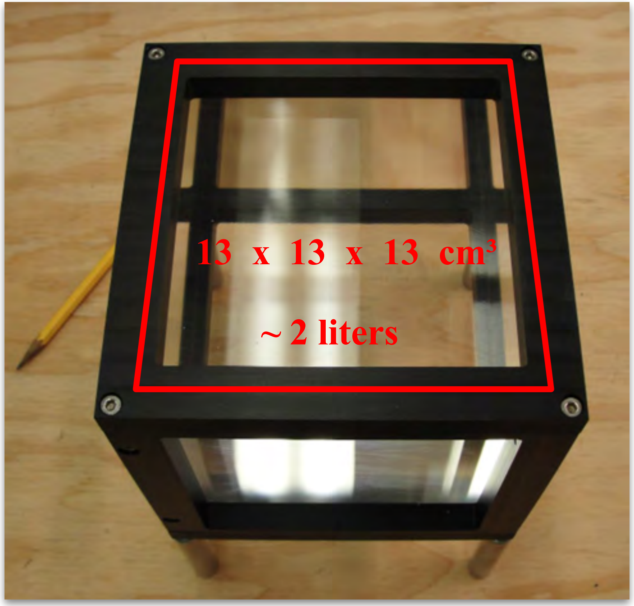


$$n + {}^{10}\mathrm{B} \longrightarrow {}^{7}\mathrm{Li}(1015\ \mathrm{keV}) + {}^{4}\mathrm{He}(1775\ \mathrm{keV}) \quad \sim 6\%$$

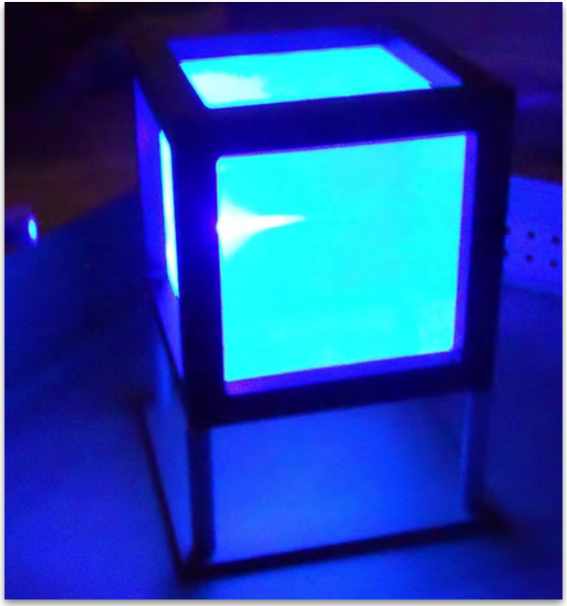
$$\hookrightarrow {}^{7}\mathrm{Li}^{*} + {}^{4}\mathrm{He}(1471\ \mathrm{keV}) \quad \sim 94\%$$

$$\hookrightarrow {}^{7}\mathrm{Li}(839\ \mathrm{keV}) + \gamma(478\ \mathrm{keV})$$

mTC: Scintillator EJ-254



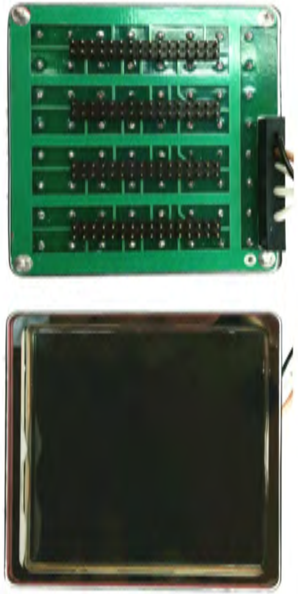
mTC scintillator cube inside Delrin frame



Blue laser illuminating the scintillator

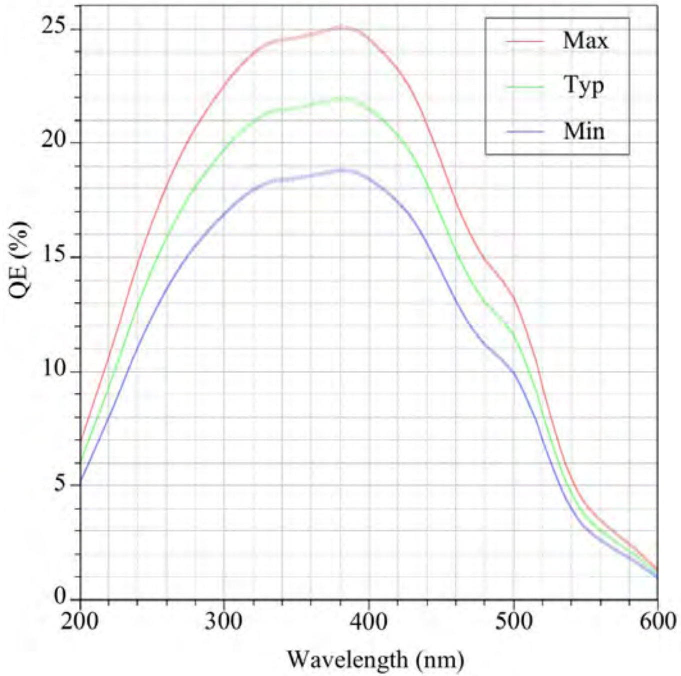
Note: ignore the scintillation decay time, the key to directionality is to detect first photons.

mTC: Micro-Channel-Plate PMT 8x8 anode



MCP-PMT

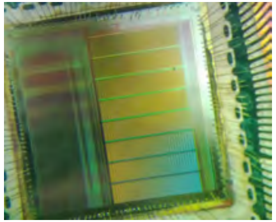
24 in total = 4 PMTs x 6 mTC faces



Quantum efficiency of MCP-PMT

mTC: Gary Varner's oscilloscope on a chip

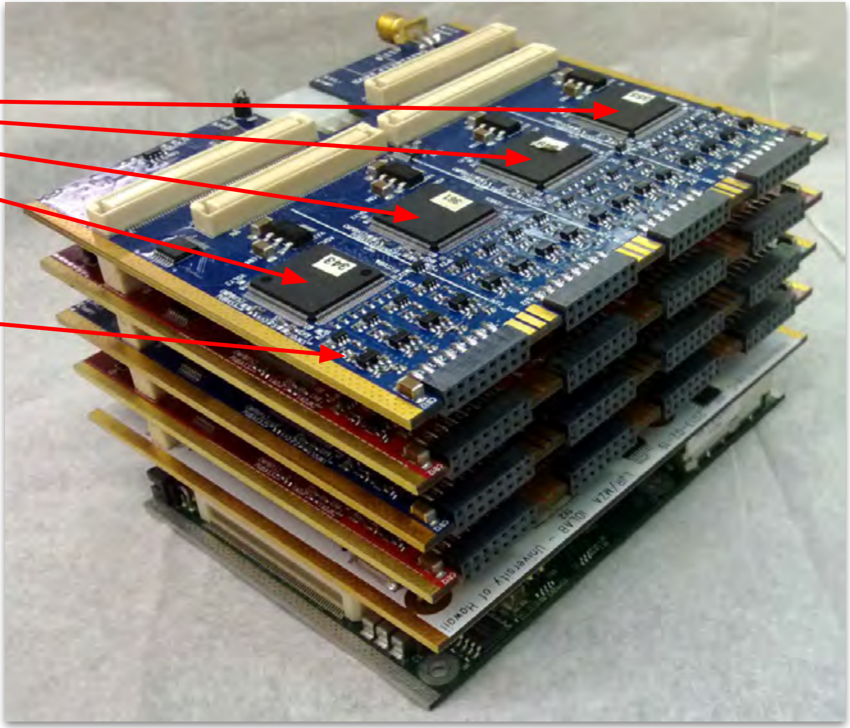
ASIC IRS



sub 50-ps timing resolution (interpolations)

Parameter	IRS Range	mTC Setting
Channels	8	
Sampling cells	128	
Storage depth	32,768	
Analog bandwidth	> 300 MHz	
Digitization	on-chip Wilkinson	
Quantization	12(9)-bits logged(effective)	
Dynamic range	~ 2 V	
Typical noise	~ 1 mV_{RMS}	
Sampling rate	1–4 GSa/s	2.73 GSa/s
Master clock	8–31 MHz	21.3 MHz
Buffer time	$(8-32)\mu s$	12.0 μs
Conversion time	> 2 μs	6.2 μs

amplifiers



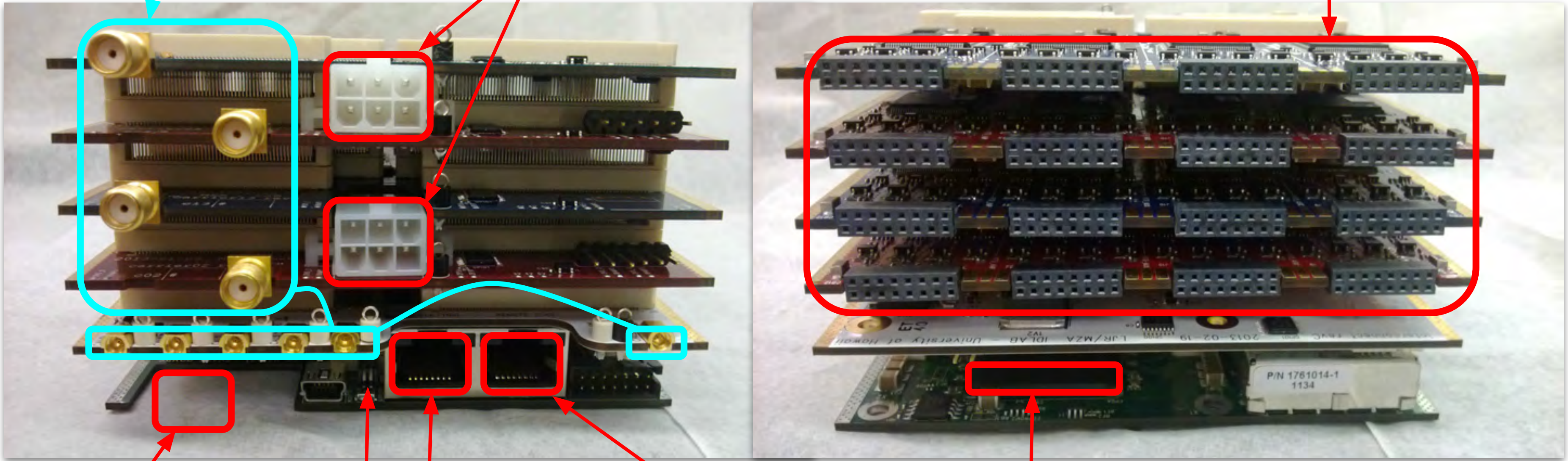
(Electronics is similar to iTOP Belle project at KEK)

mTC: Readout module

Timing calibration

Low voltage power 3/4/5V
[FPGA/ASIC/amps]

128 channels



Data via fiber optic link

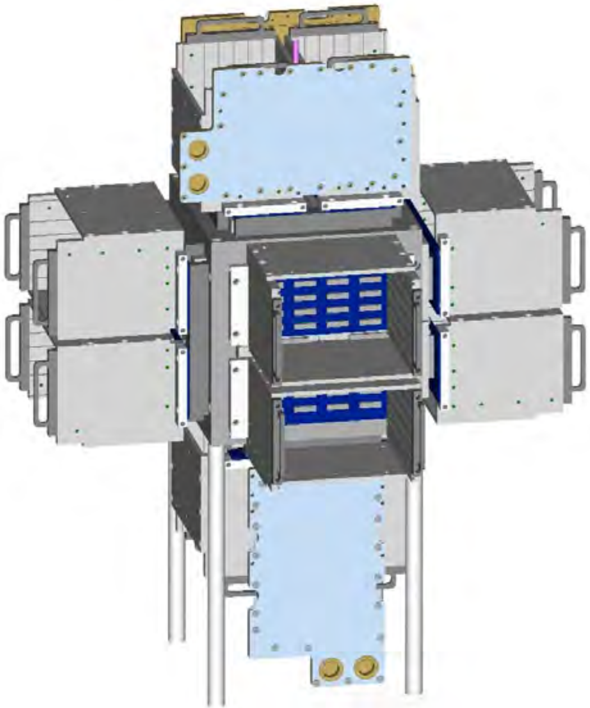
Clock (RJ45)

Programming (RJ45)

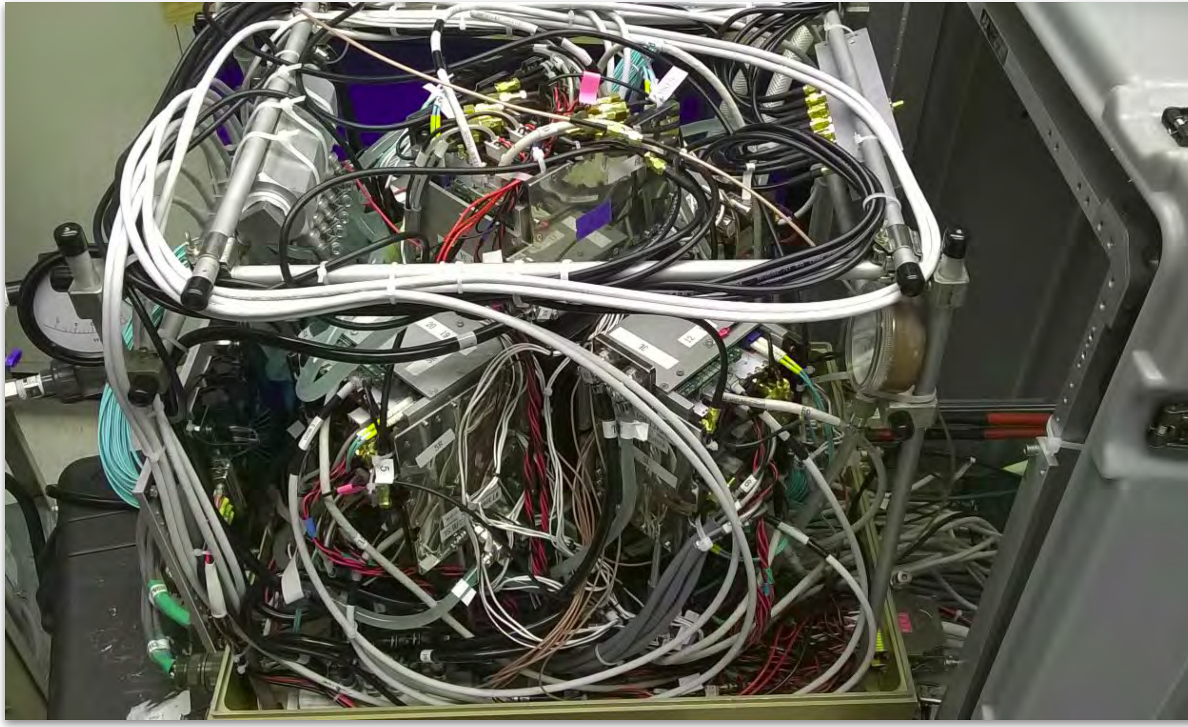
Internal clock switch

FPGA

mTC: Assembly



CAD only top/bottom chiller plates shown

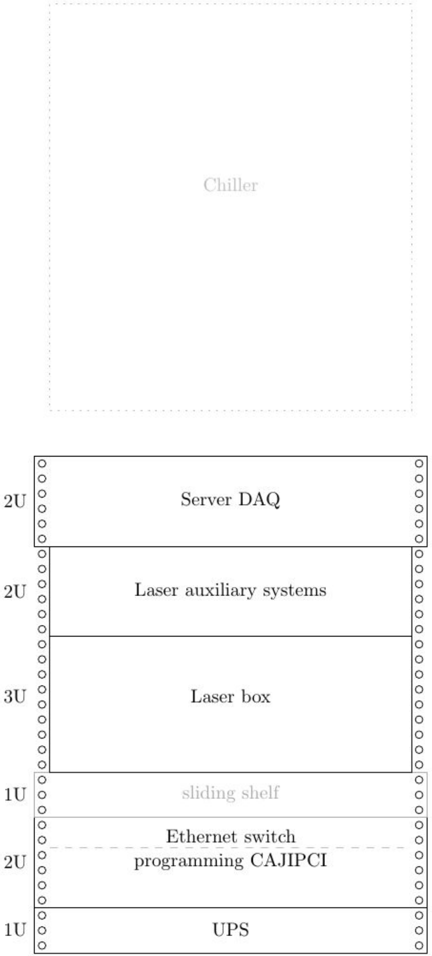


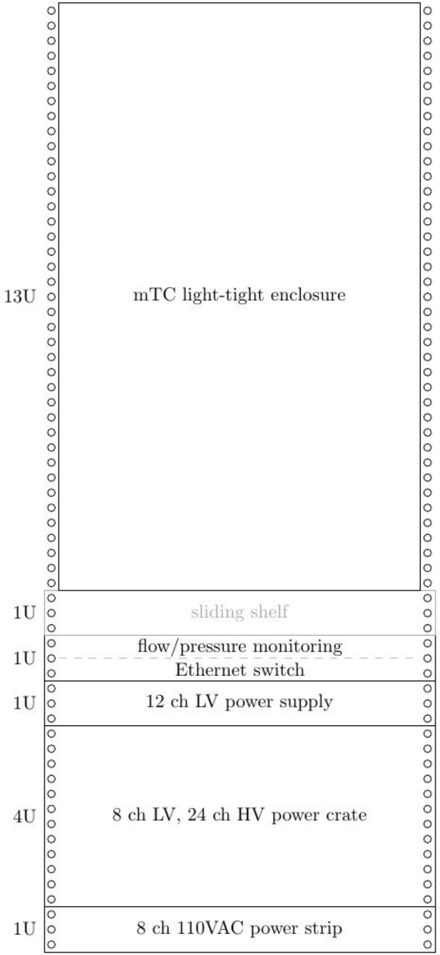
mTC opened enclosure

(active cooling of 300 W electronics)

mTC: Assembly

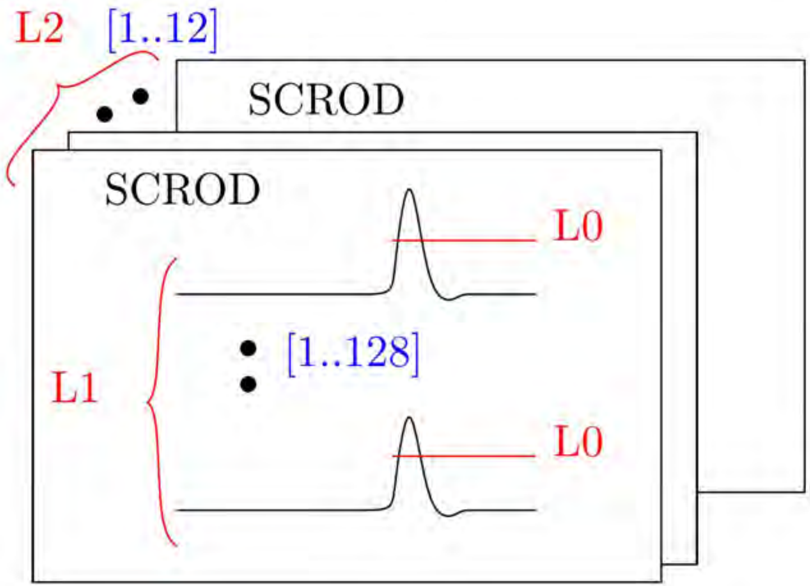
mTC: Assembly

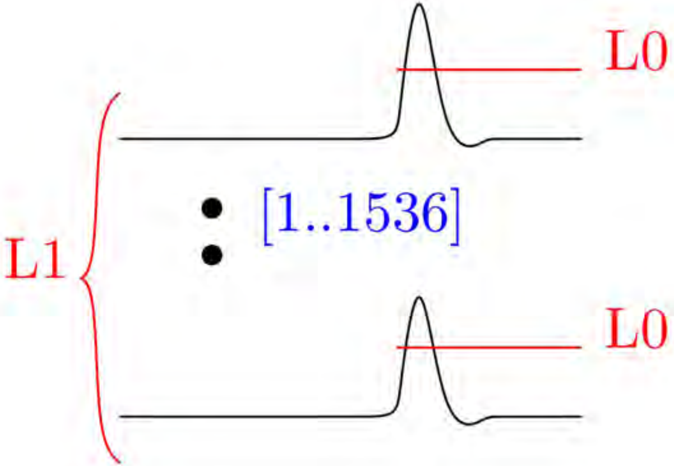




mTC: two racks 11U and 21U

mTC: Trigger 1.0 vs 2.0

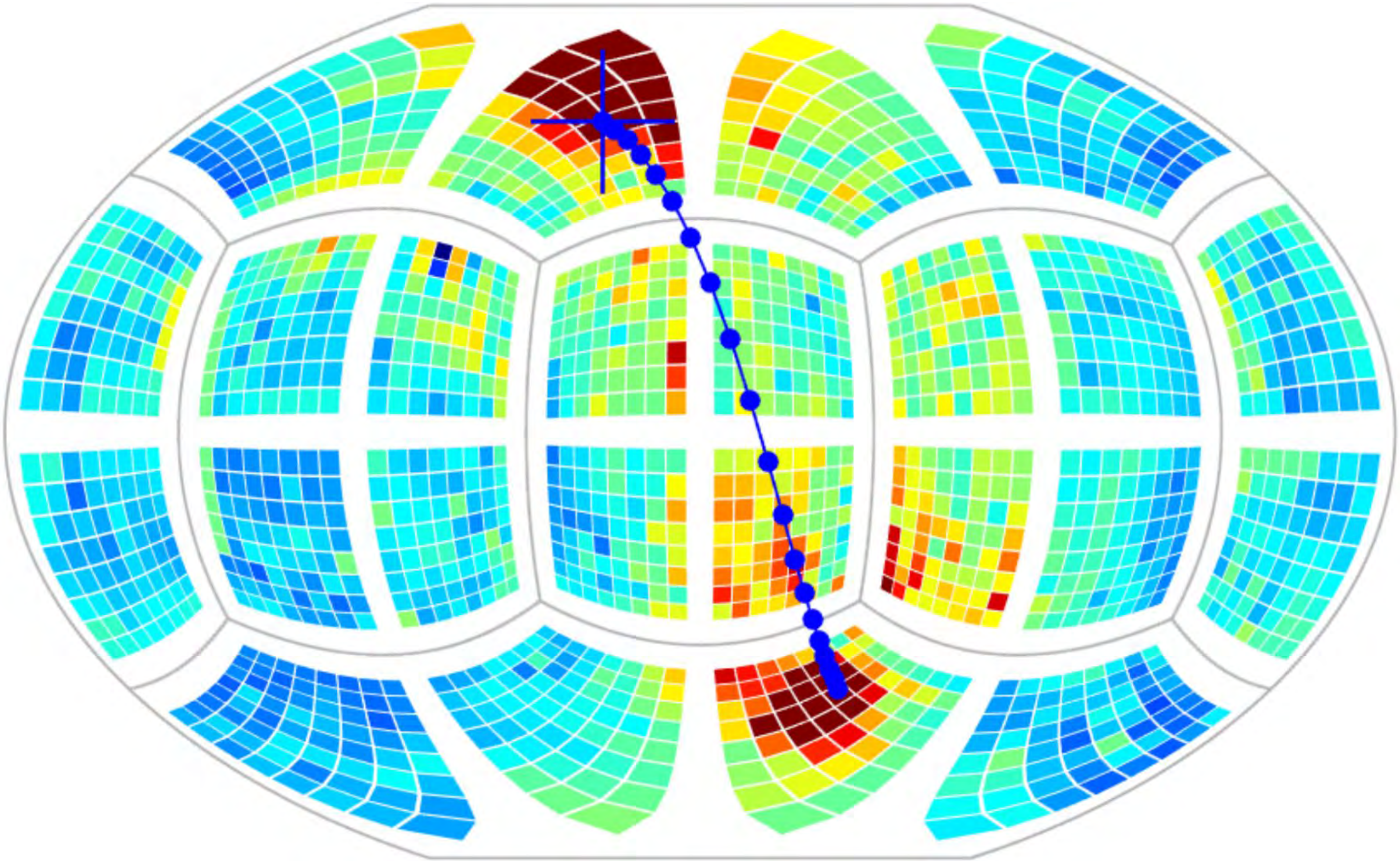




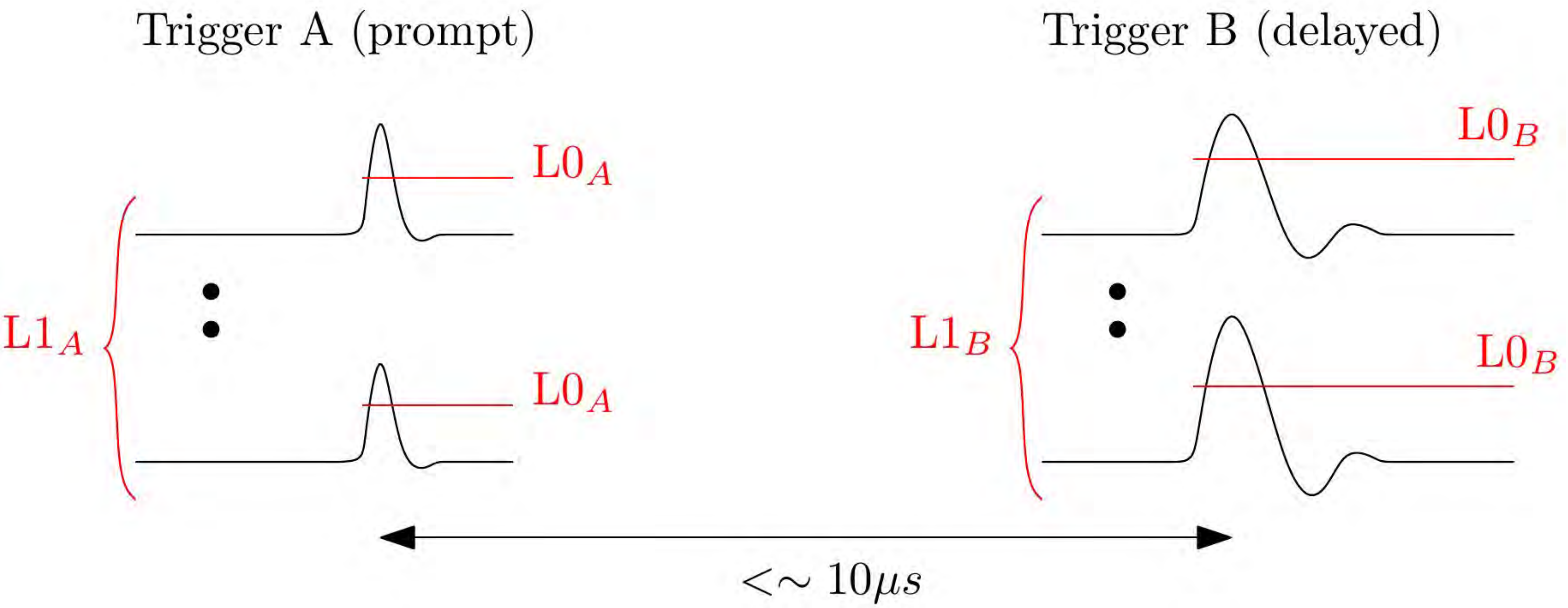
- Three-level trigger system (L0, L1, L2) : Limitation by the firmware not physics
- Two-level trigger system (L0, L1) : Easier to implement neutrino trigger

(similar to SuperK multiplicity trigger)

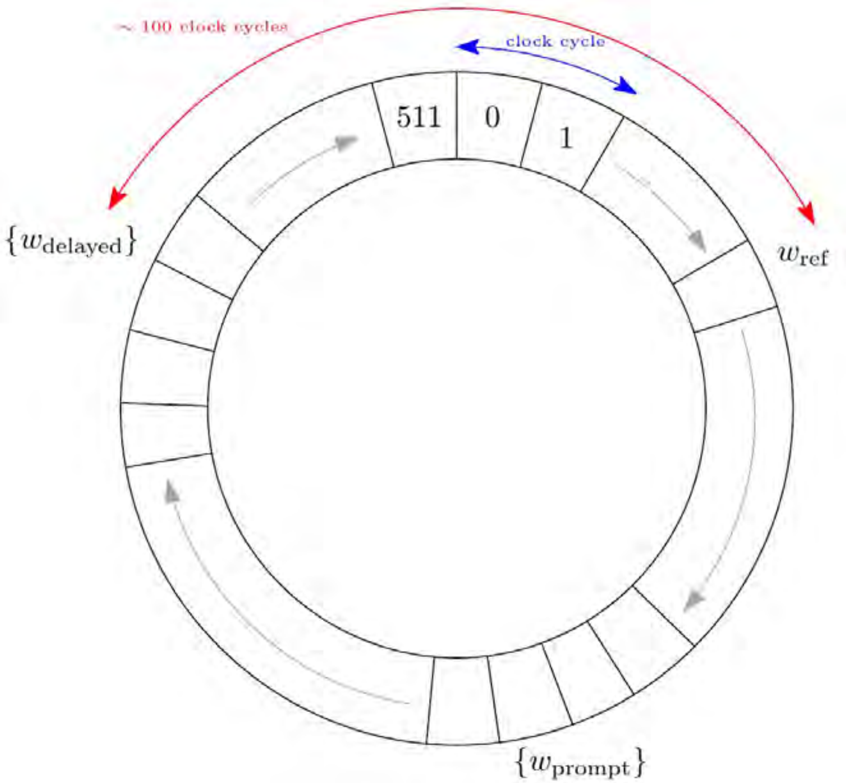
mTC: cosmic muons



mTC: Neutrino trigger



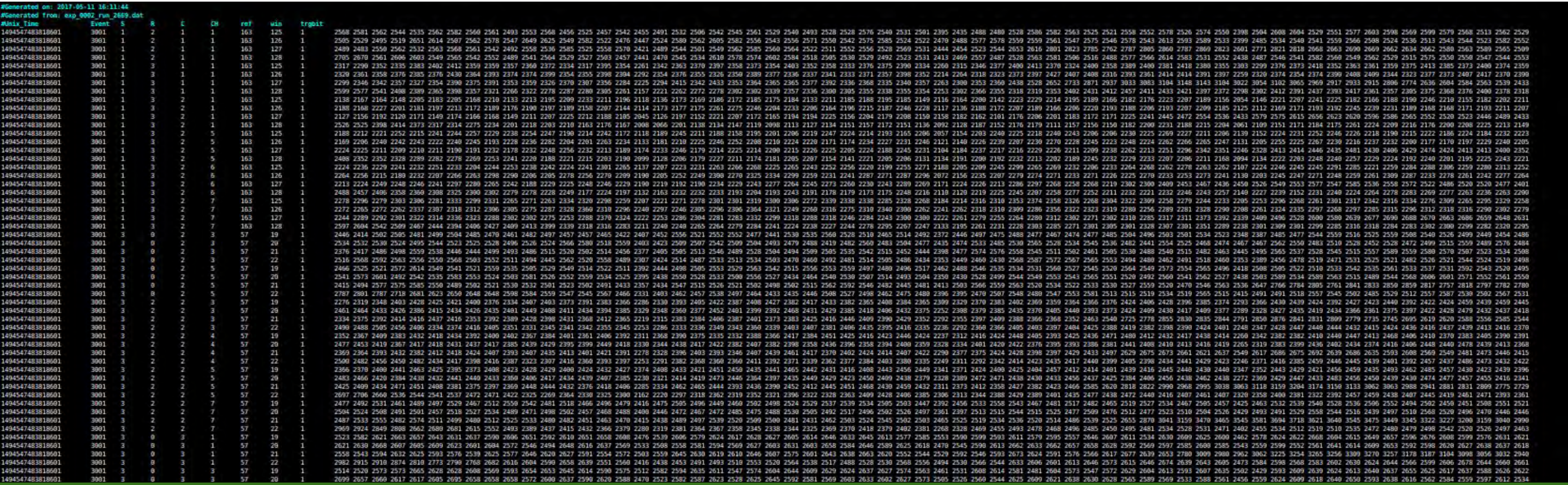
mTC: Neutrino trigger



One channel ring buffer (512 windows)

mTC: Data structure

Unix Time	Event	S	R	C	CH	ref	win	trgbit	64 voltage values
1467893327085081	2723	1	0	0	0	383	42	0	2329 2342 2400 . . .
1467893327085081	2723	1	0	0	0	383	43	1	2264 2309 2335 . . .
1467893327085081	2723	1	0	0	0	383	44	1	2182 2183 2186 . . .
.	.	.	.	.	.	.	.	.	. . . .



mTC: how many nu's to expect at NIST reactor

$$N_{235} = 0.93 \times 6\bar{\nu}_e/\text{fission} \times 20\ \text{MW}/(201.7\ \text{MeV}/\text{fission}) = 3.45 \times 10^{18}\ \bar{\nu}_e/s$$

$$N_{238} = 0.07 \times 6\bar{\nu}_e/\text{fission} \times 20\ \text{MW}/(205.0\ \text{MeV}/\text{fission}) = 2.55 \times 10^{17}\ \bar{\nu}_e/s$$

$$N_{\bar{\nu}_e} = \frac{1}{4} n_{\text{H}}\ V\ \sigma\ \frac{dN_{\bar{\nu}_e}}{dt}\ \frac{1}{4\pi L^2}\ t_{\text{day}}$$

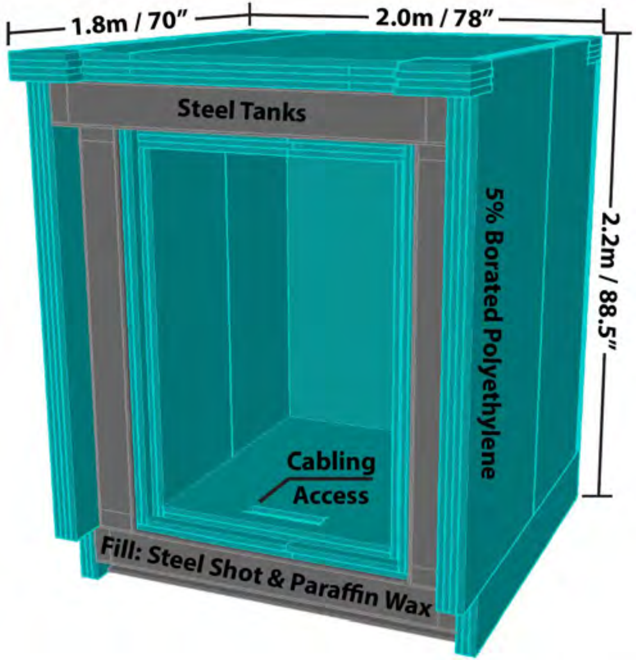
$$N_{\bar{\nu}_e} = \frac{1}{4}\frac{5.16 \times 10^{22}}{\text{cm}^3}\ 13^3\text{cm}^3\ 5 \times 10^{-43}\text{cm}^2\ \frac{1.6 \times 10^{12}\ \bar{\nu}_e}{\text{cm}^2 s}\ 86400s = 2\ \bar{\nu}_e/\text{day}$$

$$2 \times .40 \approx 1\bar{\nu}_e/\text{day}$$

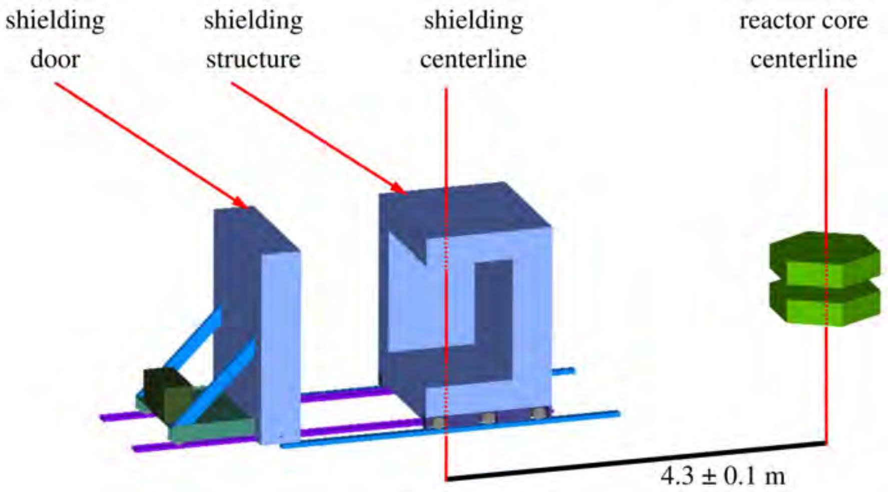
mTC: shielding by UMD

	Material	Dimension (cm)
1	Borated polyethylene	10
2	A36 steel	1
3	Steel shot & paraffin wax	15
4	A36 steel	1
5	Borated polyethylene	10

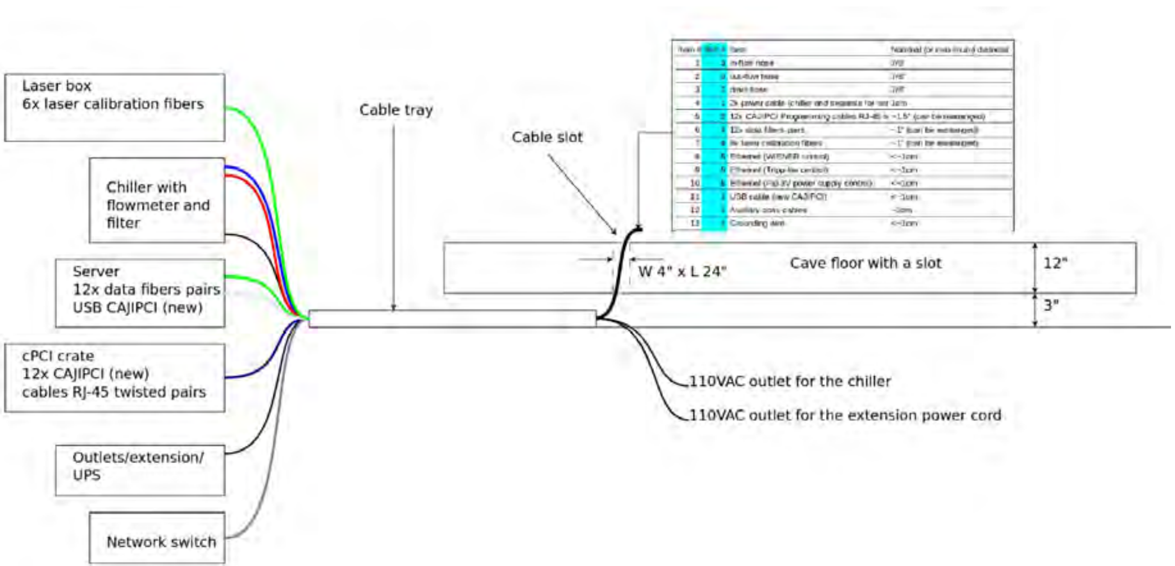
Polyethylene layer used is doped with 5% boron.
Steel layer and steel shot is A36 steel.
Steel shot & paraffin wax mixture comprised of 75% steel, 25% wax.



mTC: Shielding



mTC: Installation by reactor



mTC: Shielding adds space constraints

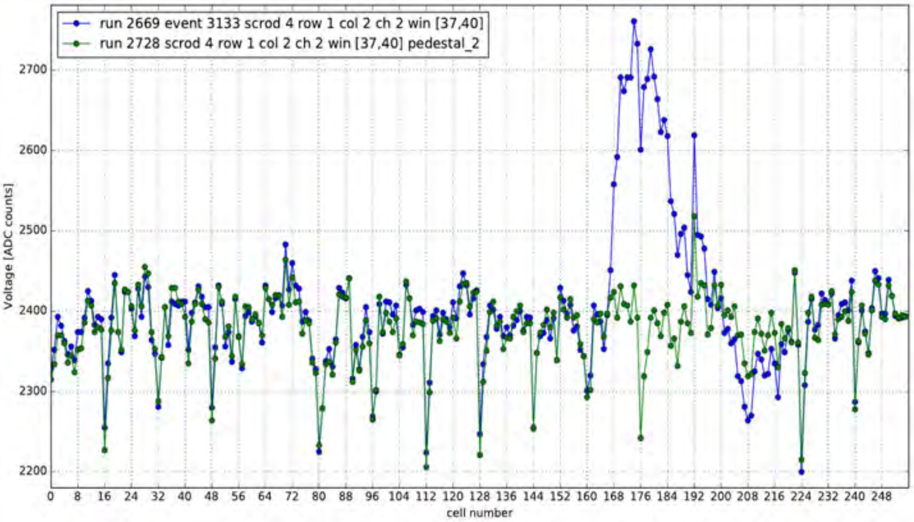
Detector is less accessible

mTC: Shortcomings

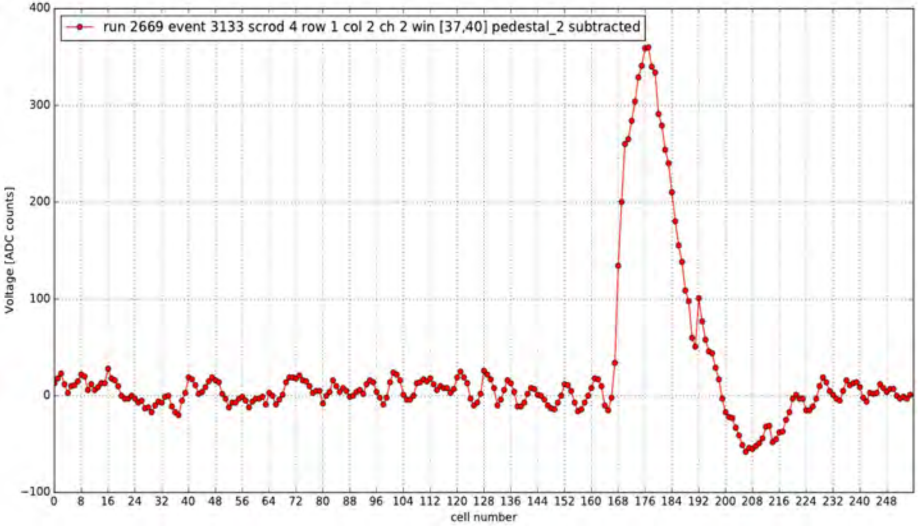
- Electronics timing hasn’t reached the desired sub-100 ps level
- Half of the MCP-PMTs burned out (shortly before the deployment by the reactor)
- Background rates were unexpectedly high and unpredictable
- MCP-PMTs had a major issue with ion-feedback and charge sharing effect

Contributions: Data analysis

Waveform and pedestal

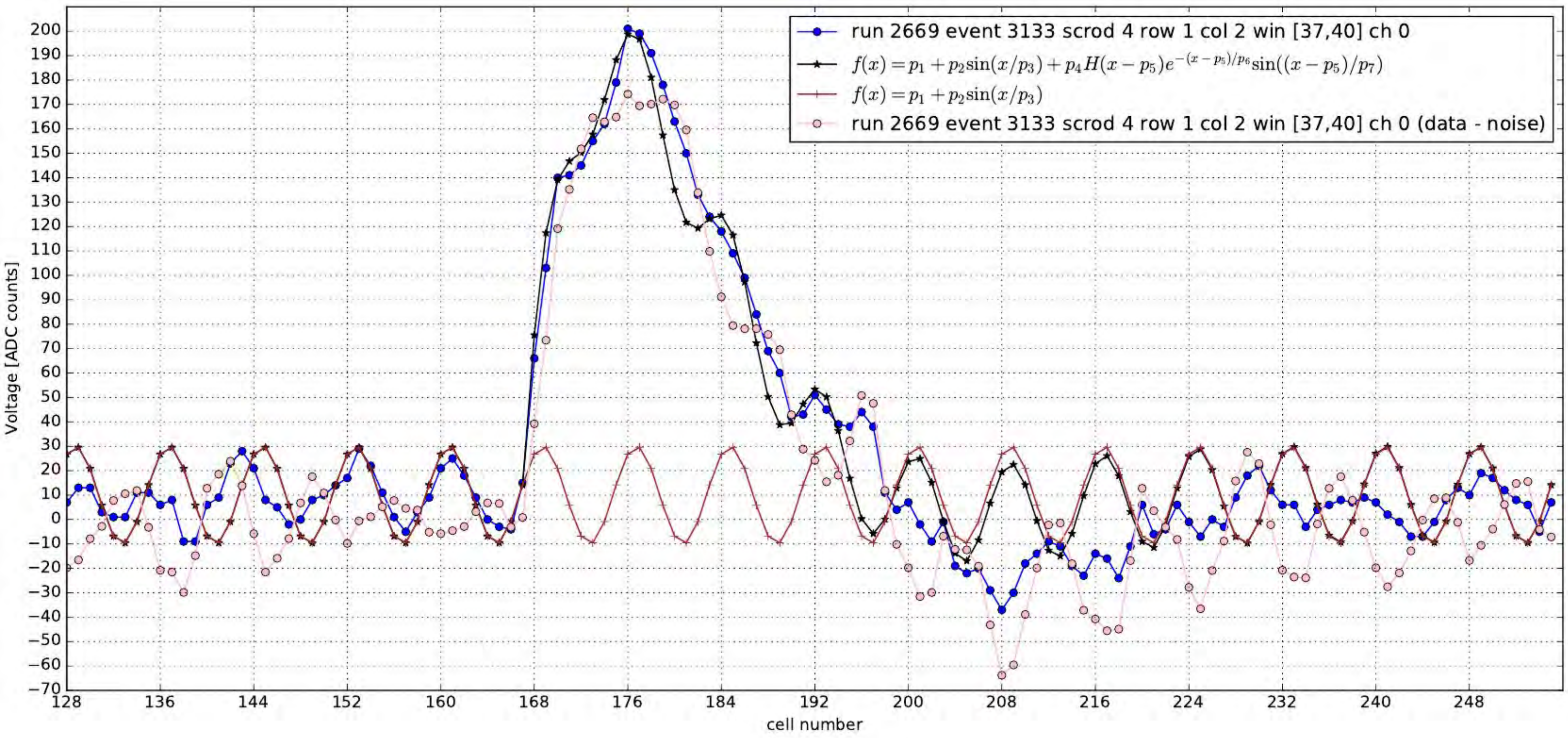


After pedestal is subtracted



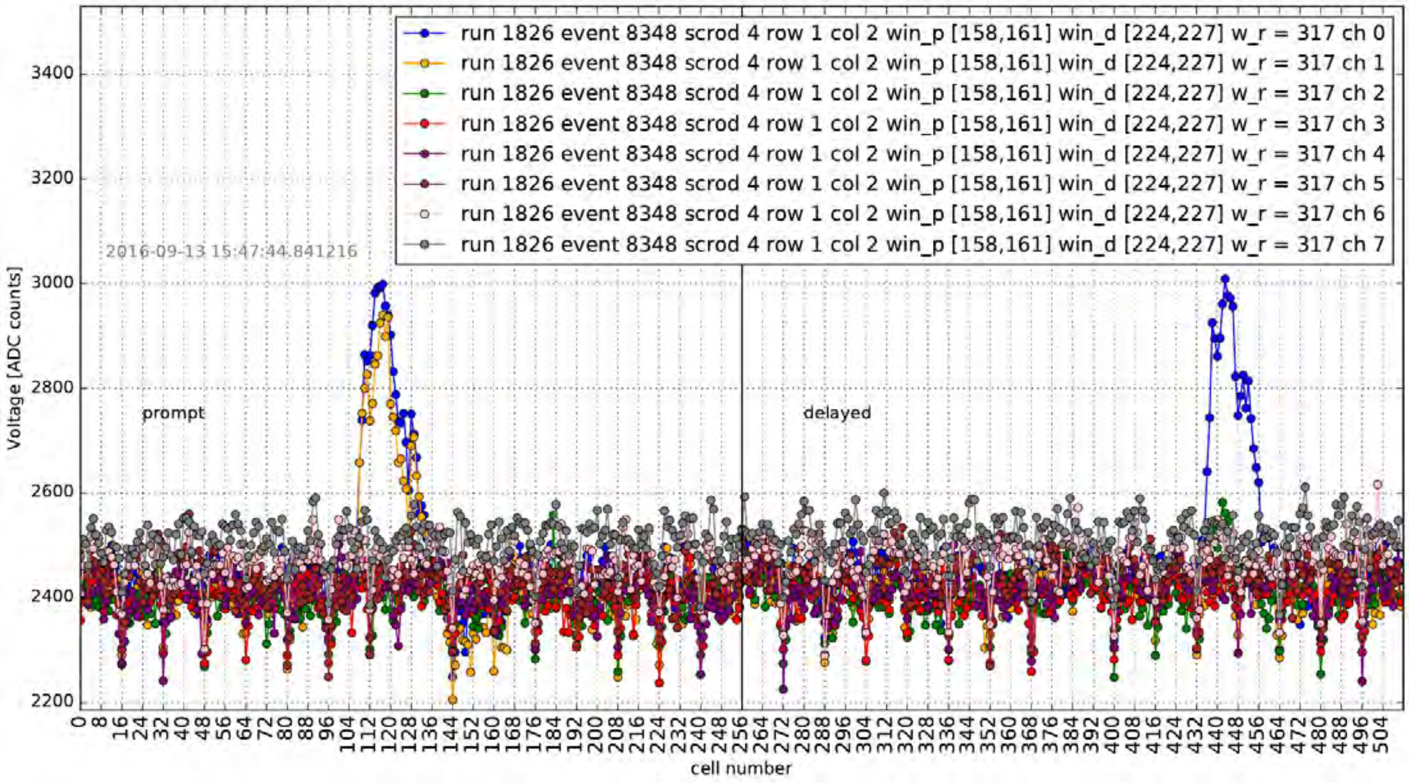
Waveform corresponds to a single photon (laser data)

Contributions: Noise analysis



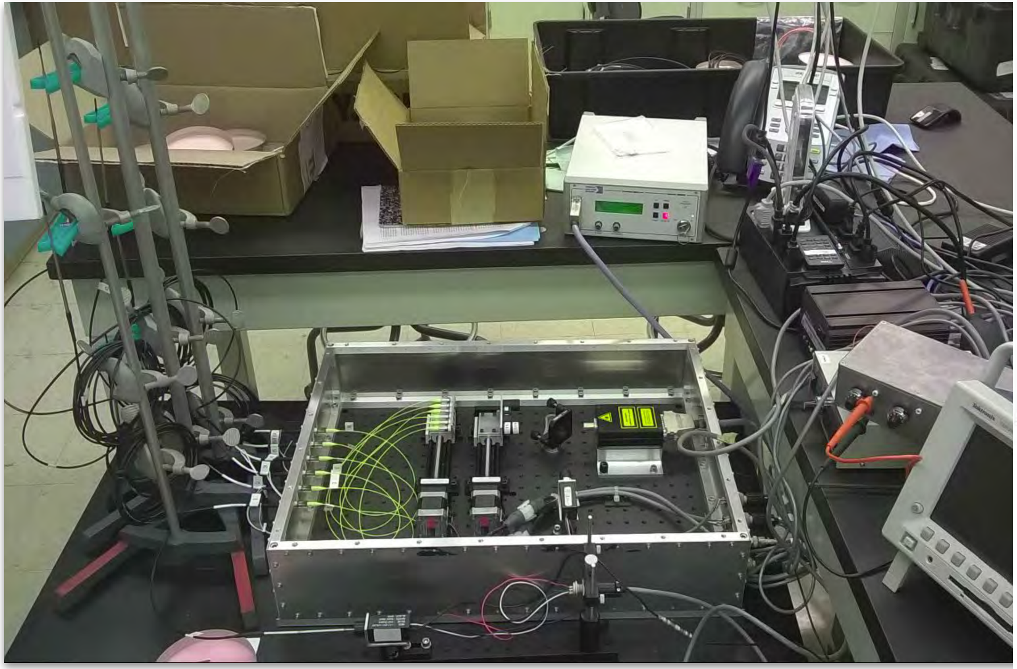
Waveform corresponds to a single photon. Noise affects timing substantially at this level.

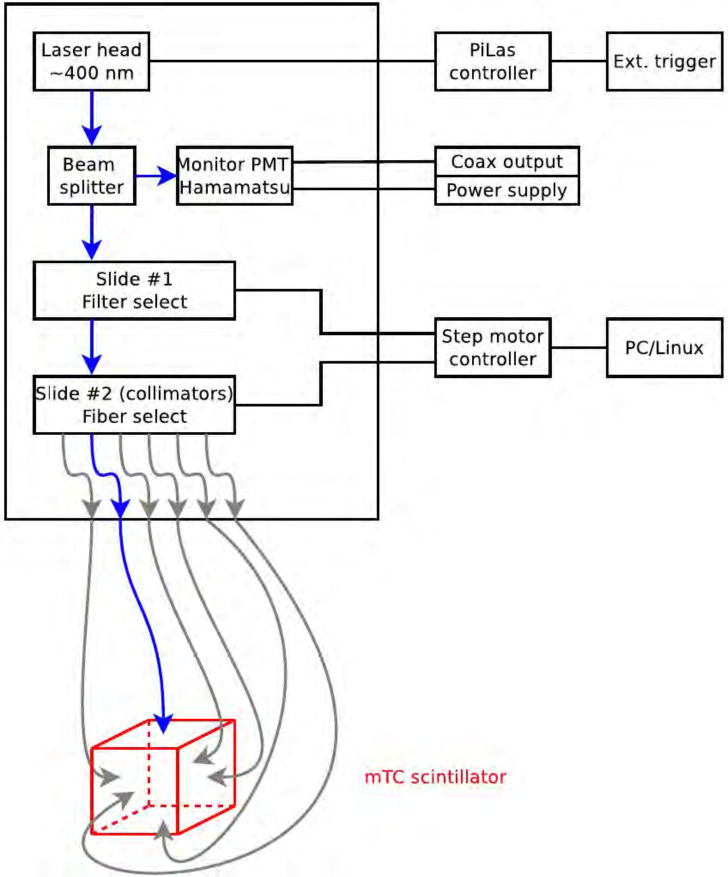
Contributions: Data analysis



One of the ~850,000 neutrino candidates collected.

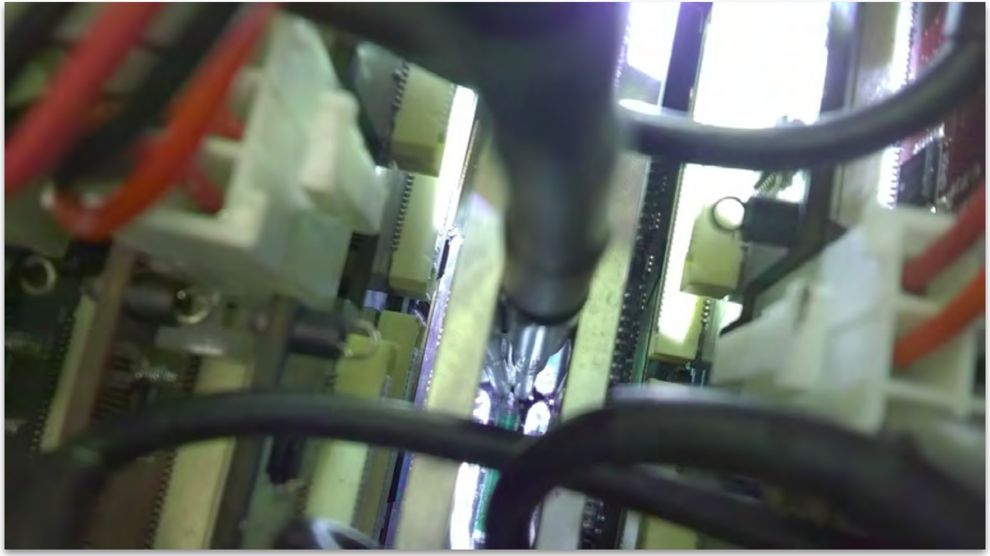
Contributions: Laser calibration system



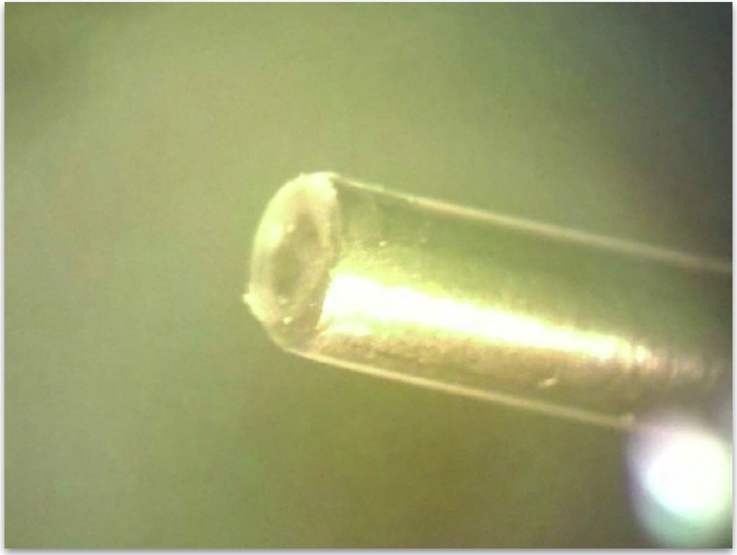


(similar to the device Shige Matsuno built for SuperK)

Contributions: Laser calibration system

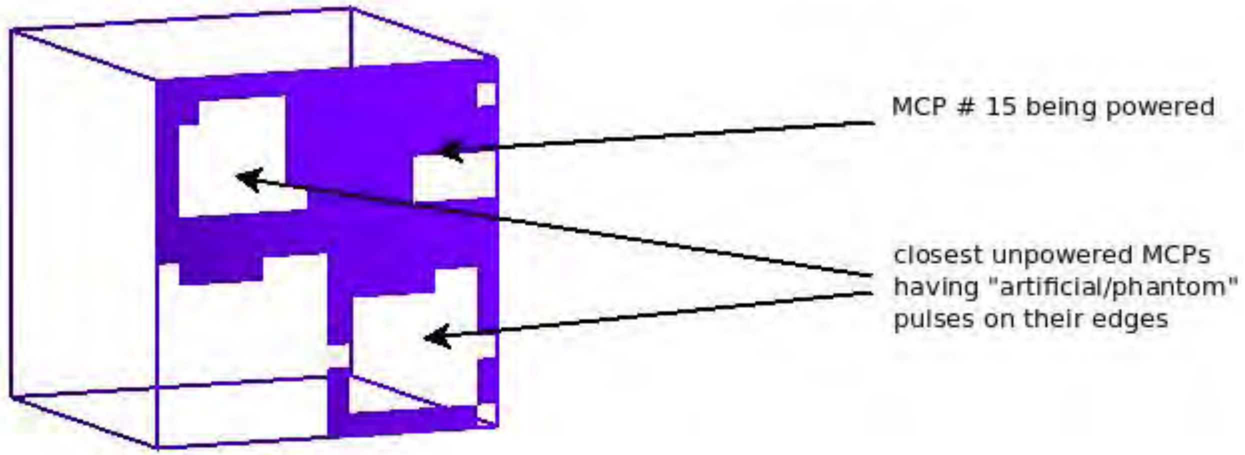


Laser fiber in between four MCP-PMTs

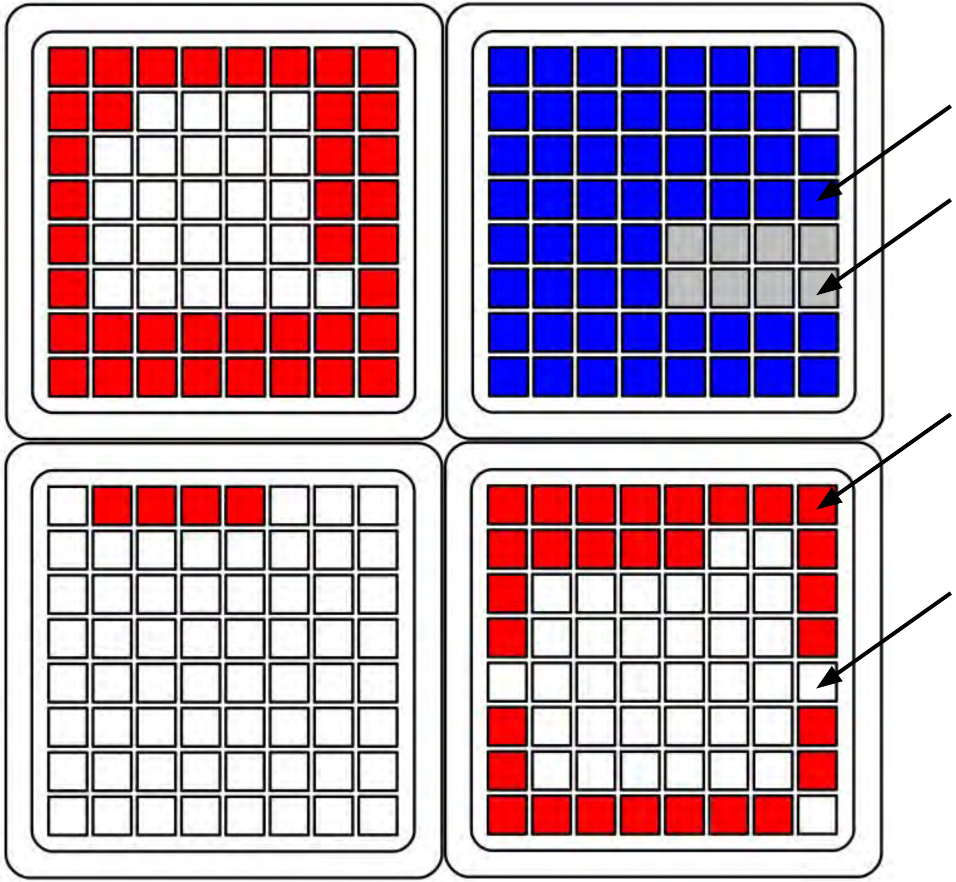


Needle connector tip

Contributions: Cross-talk 1.0



Contributions: Cross-talk 1.0



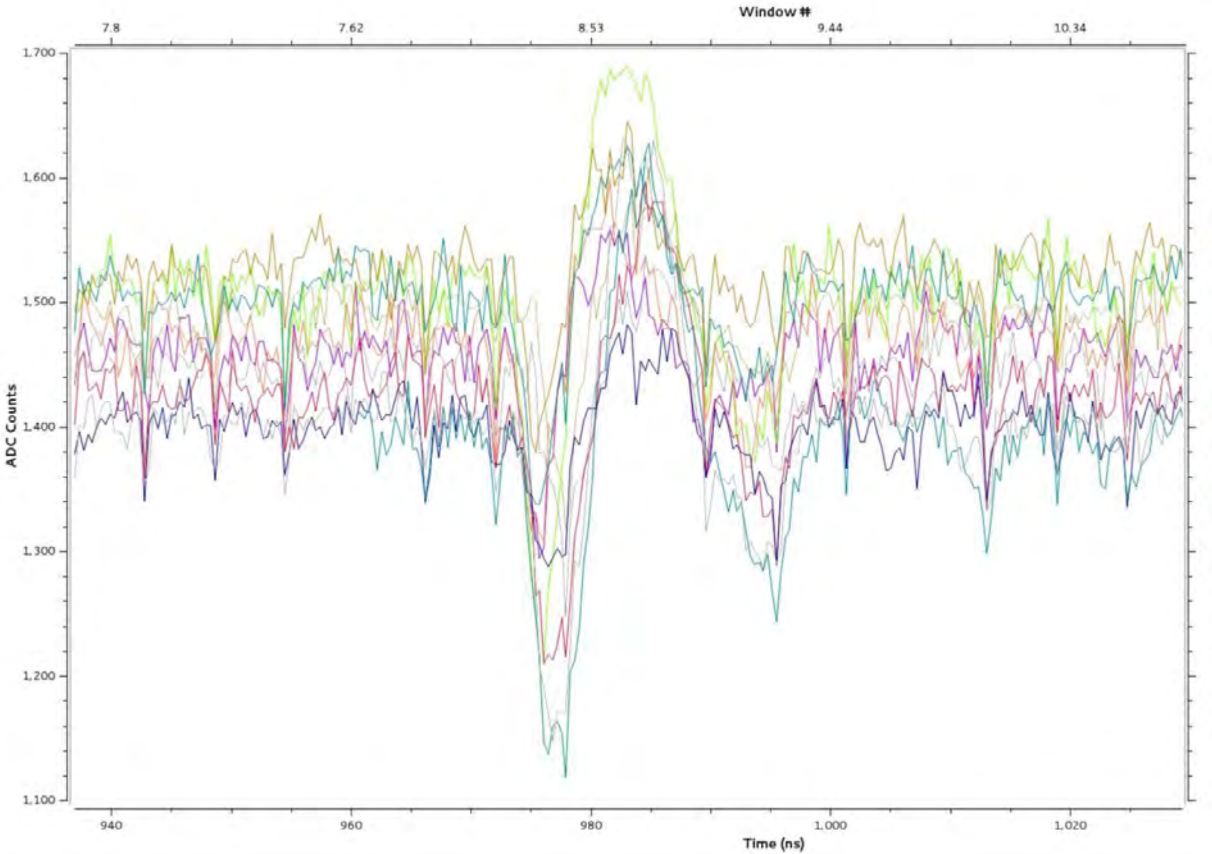
Blue — pixels with waveforms on the powered tube

Gray — 8 bad channels due to a dead ASIC

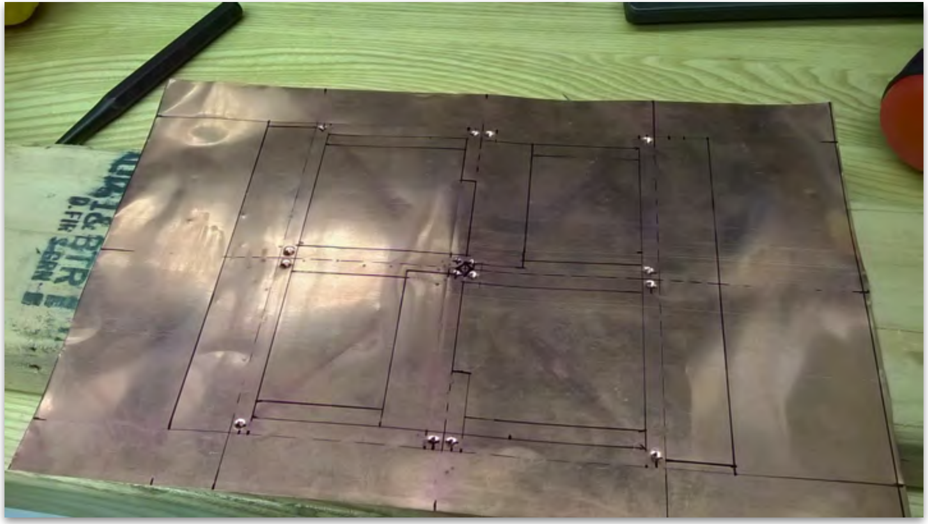
Red — pixels with waveforms on the unpowered tubes (!)

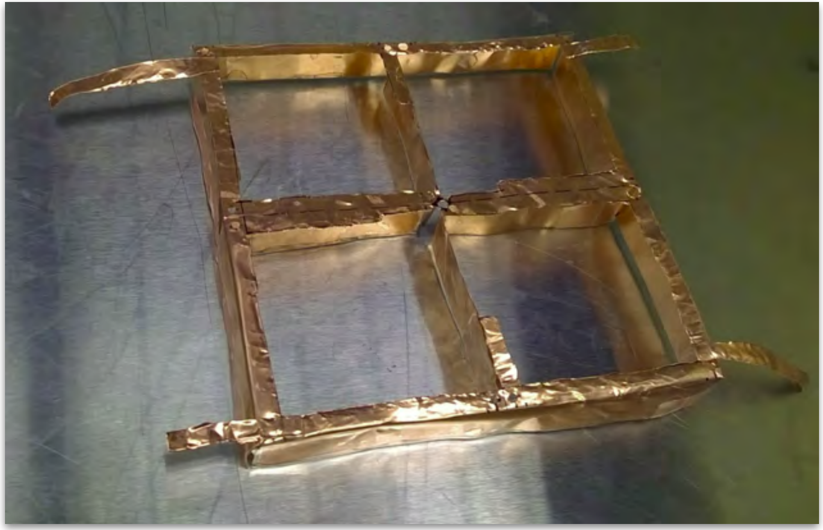
White — no trigger

Contributions: Cross-talk 1.0



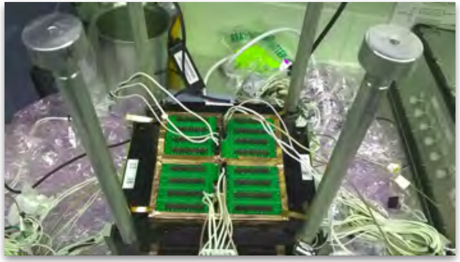
Contributions: Cross-talk 1.0 solution

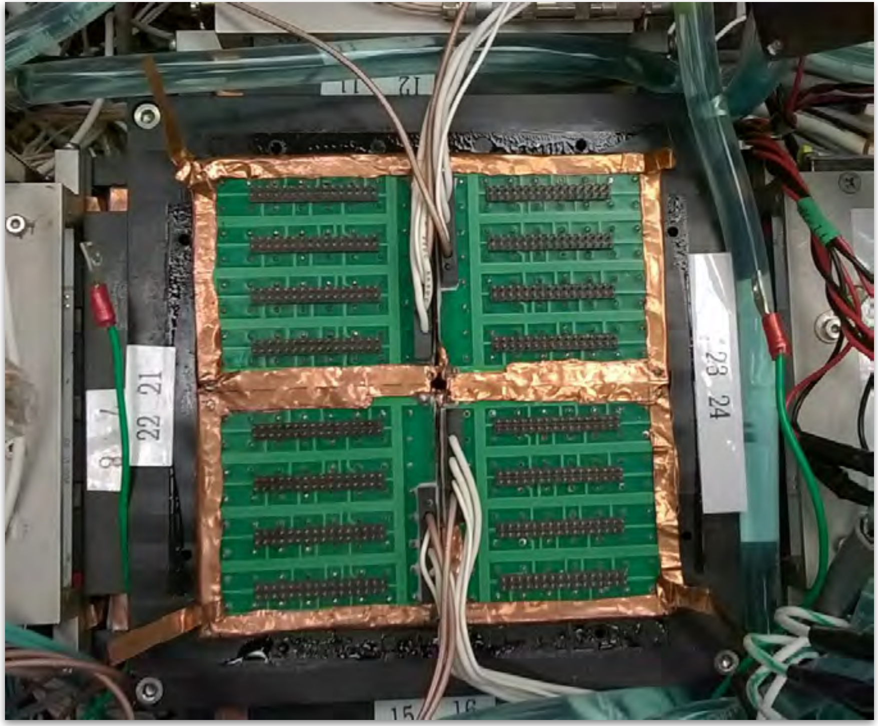




Contributions: Cross-talk 1.0 solution

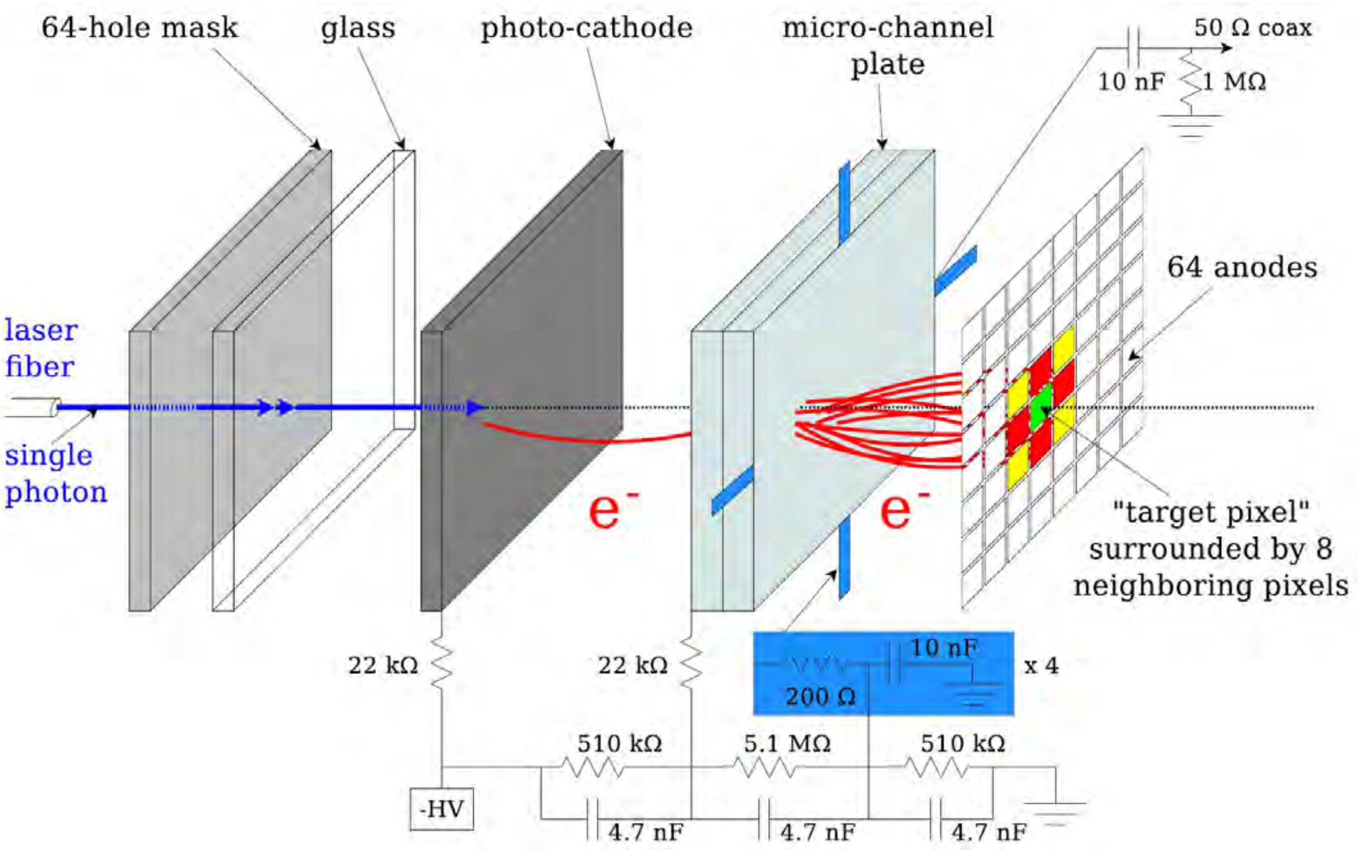
- Install the copper frame on every face
- Get rid of small ground PMT wires



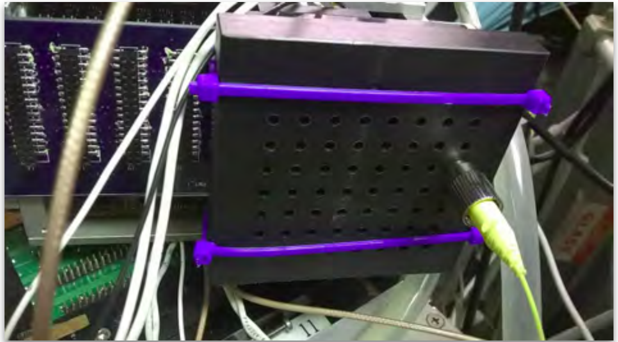


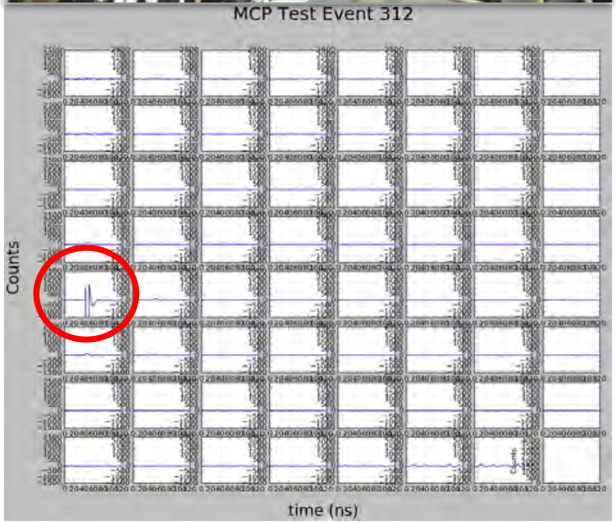
Copper frame top face

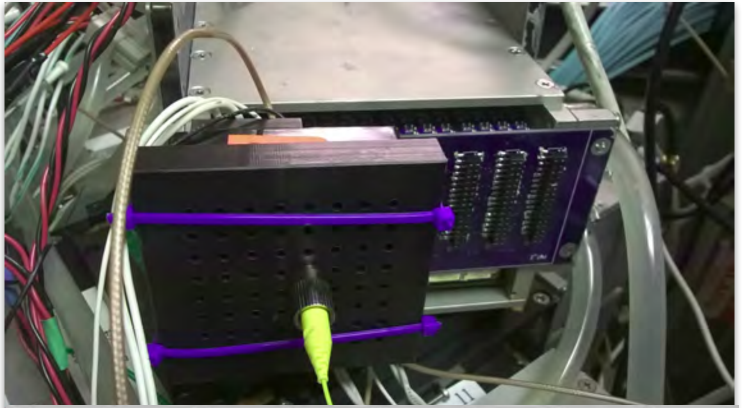
Contributions: Cross-talk 2.0

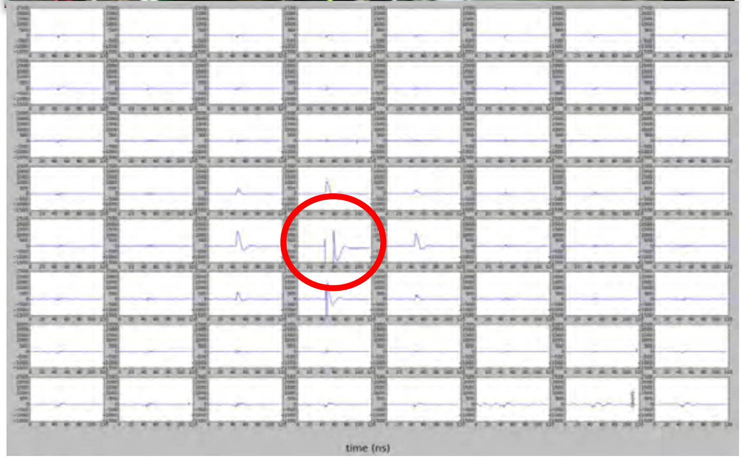


Contributions: Cross-talk 2.0

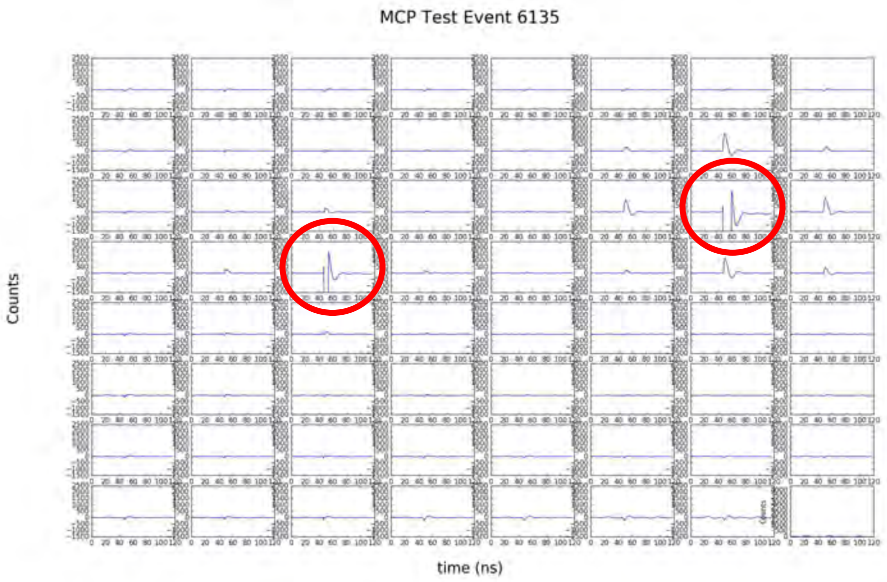




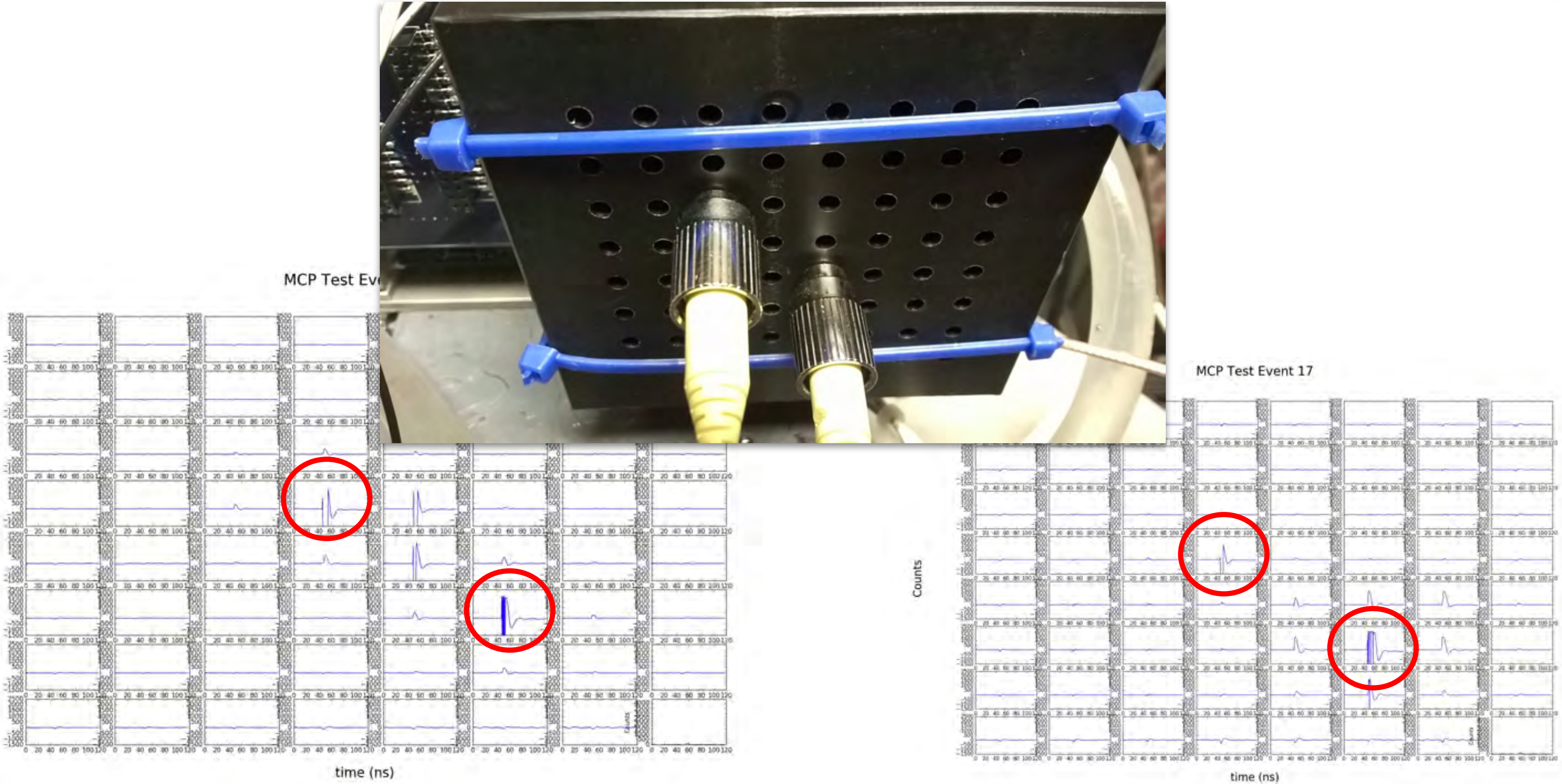




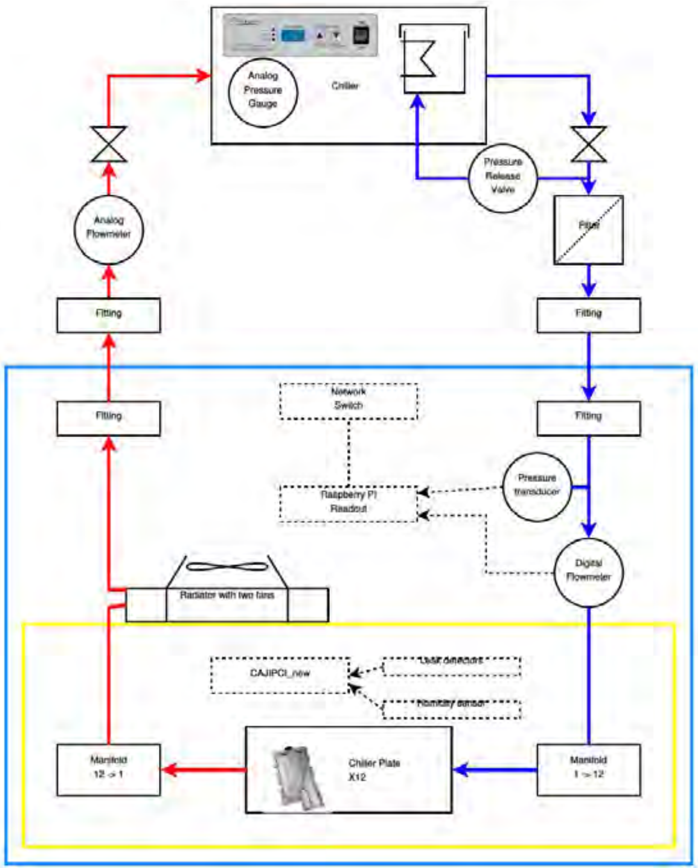
Contributions: 2-fiber test



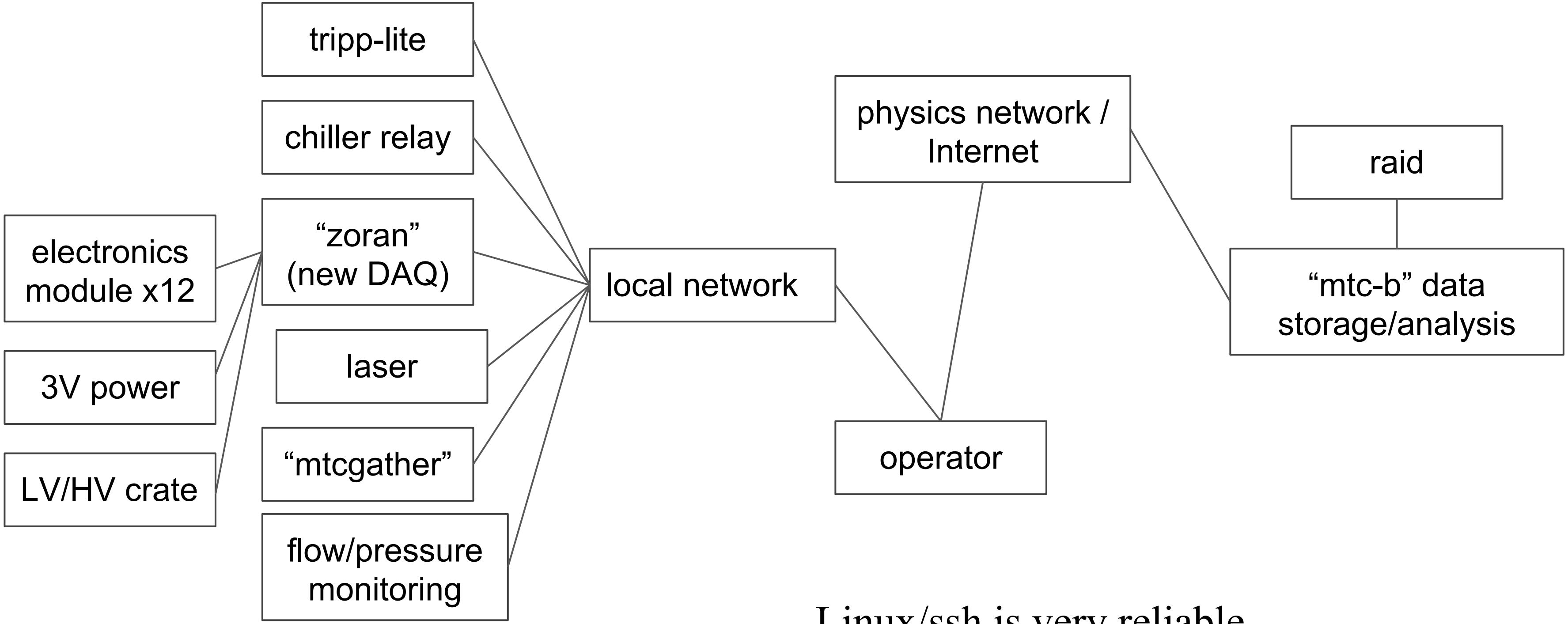
Contributions: 2-fiber test



Contributions: Electronics cooling system

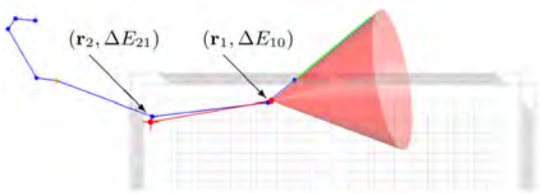


Contributions: Network for remote operations



Linux/ssh is very reliable.

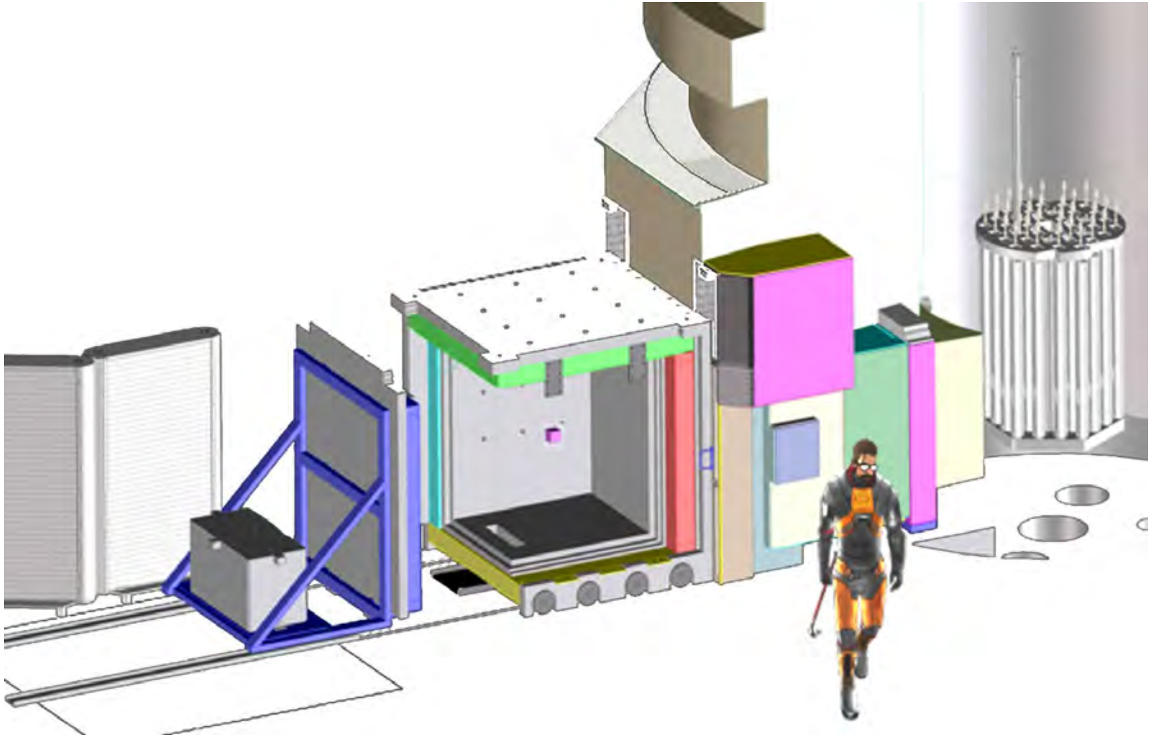
Contributions: Neutron tests



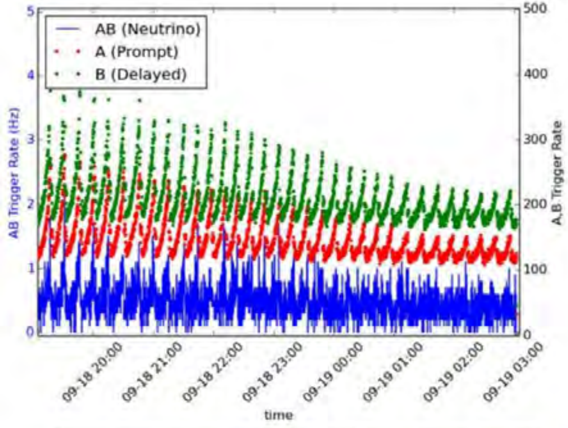
Cf-252 at UH

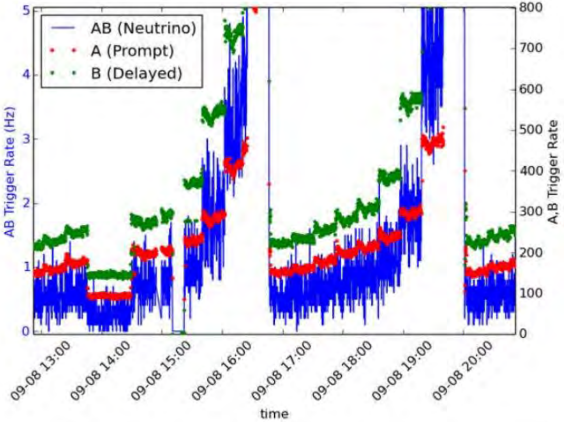
Multiple tests with Pu-240, Cf-252, DT and DD neutron generators at NIST

Contributions: Installation by the nuclear reactor



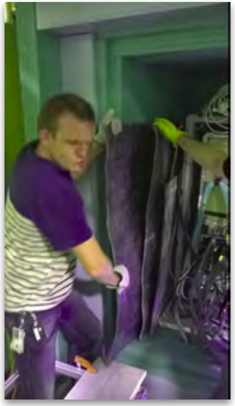
Contributions: High rates and extra shielding

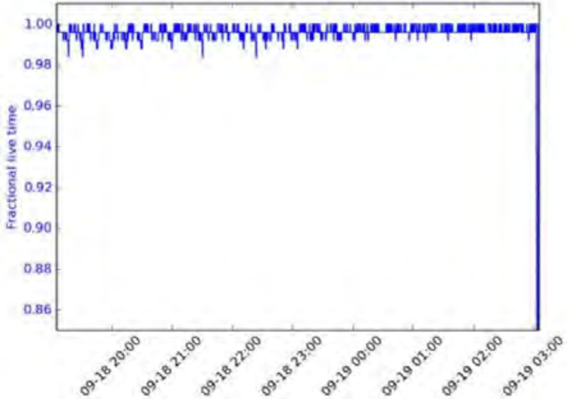


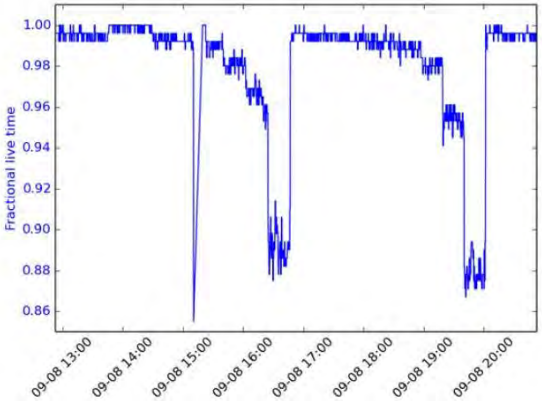


+ Different layers of lead

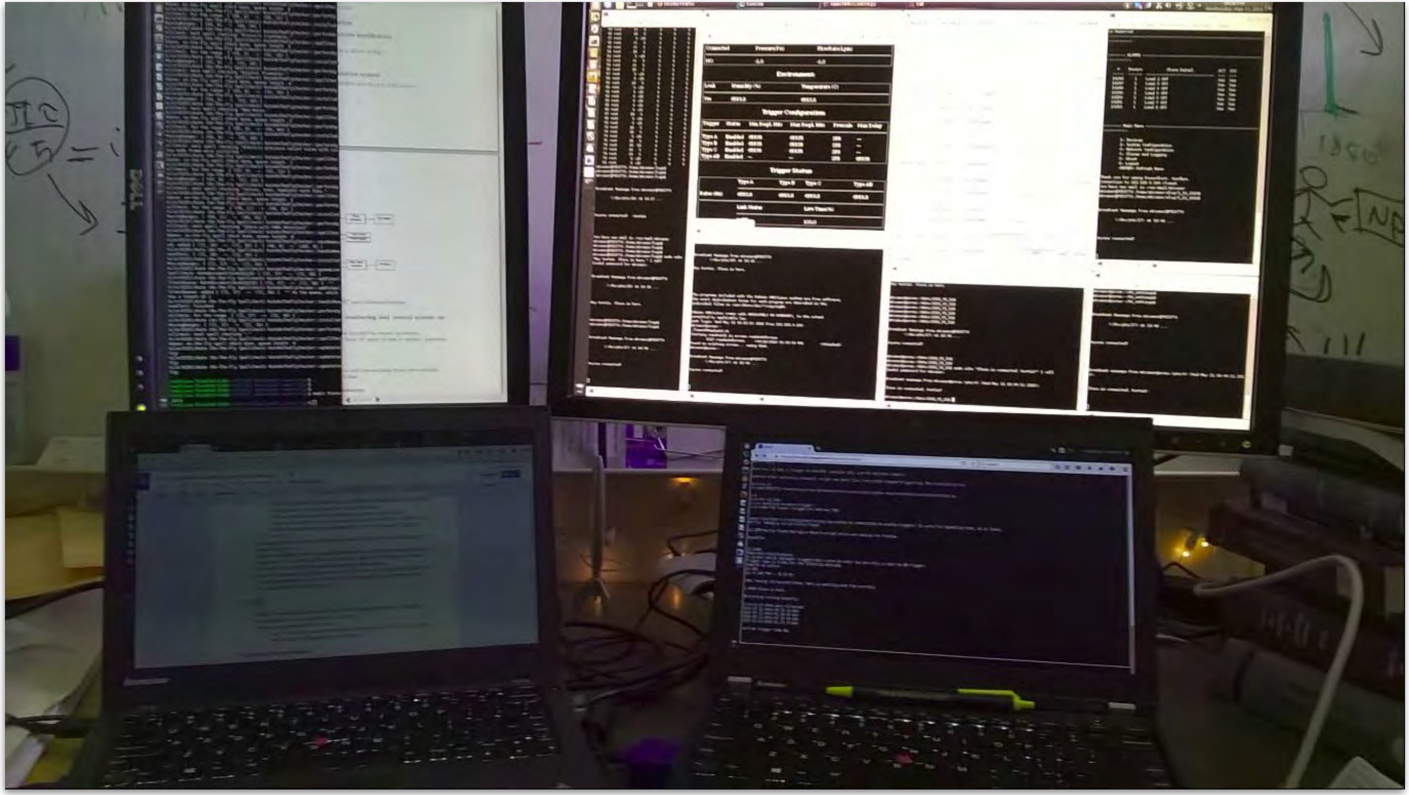
+ Borated poly in the cave slot





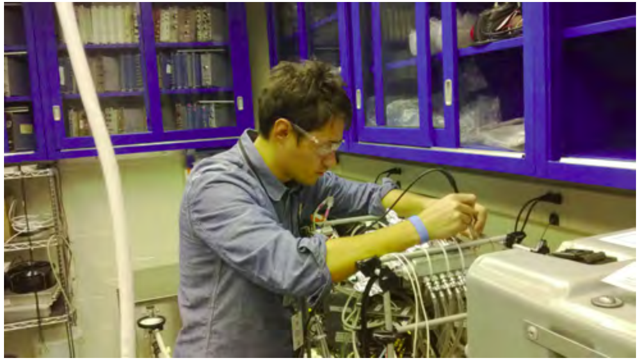


Contributions: Remote operations



Control from Hawaii of the detector in Maryland

My contributions



- Mechanical assembly, including machining parts
- Cooling system assembly and different coolant tests
- Laser calibrations
- Cross-talk 1.0 discovery and reductions
- Copper RF frame design and fabrication
- MCP-PMT cross talk 2.0 studies
- MCP-PMT recovery studies after the overheating accident
- Neutron and gamma tests
- MCP-PMT gain calibrations
- Data taking and processing, optimizing trigger parameters
- Installation of the mTC at NIST (CNIF, guide hall, lab, reactor) and UH lab
- Shift work, remote operations, maintaining elogs, online data, and website
- Publishing 1st mTC paper as RSI invited article
- Electronics upgrade, including heat sink installation
- Everyday detector maintenance, including electronics tests, fixing/adjusting power supplies, software, network, shielding, cooling, ordering parts
- Packing/shipping the mTC
- Meetings and decision making

Summary

- Invaluable experience for mTC collaboration and future particle detectors
- miniTimeCube has been an excellent prototype overall
- First really compact and low-power integrated neutrino detector
- Wide range of components/methods have been evaluated
- mTC electronics can be used in new experiments (NTC and NuLat)
- Shielding cave was constructed (reusable, for NuLat)
- Prototype for homeland security applications (SNM detection)
- Good to detect muons, neutrons and perform MCP-PMT laser tests
- Solid compact non-flammable target (not unique but only a few used it)
- First use of Boron-doped scintillator in a neutrino detector
- First use of compact pmt-mounted electronics in other than an accelerator experiment (namely BELLE), no huge bundle of cables, and bulky electronic racks
- First attempt to employ first-photon analysis to beat slow decay times in vertex location (factor of ten). Note that decay rise time is a few times the 13 cm dimension of the cube, and our studies indicated mm scale resolution
- Highest ever density of channels of waveform photon detector on neutrino target (1536 total, ~5mm square pixels)
- Designed and built our own moveable (adjust distance to reactor by 2m) walk-in radiation cave with 1000x attenuation of neutrons and gammas.
- Achieved reliable automated operations and swiftly activated remote operation capability, even to NIST in DC from Hawaii
- Though the program failed to achieve its goals, largely due to failed PMTs, we set a precedent in the field of a dozen competitors, for a new approach now being carried forward in the NuLat experiment
- We have been a training ground for new experimental physicists who have gained a full experience with creating, building, and operating an experiment, unlike the experience in a huge project where students have narrow exposure to the whole process
- Stay tuned for more updates -- mTC is not over yet

ありがとう
Mahalo
Thank you
Dziękuję bardzo
Спасибо
Merci beaucoup
Grazie
Дякую
Danke
Хвала
Баярлаа
谢谢
고맙습니다
תודה