miniTimeCube

for Neutrino Physics and Applications

mTC collaboration

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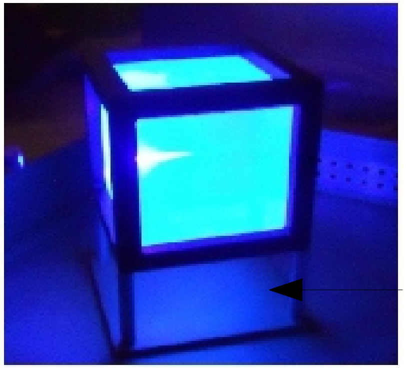
Ultralytics LLC: Glenn Jocher

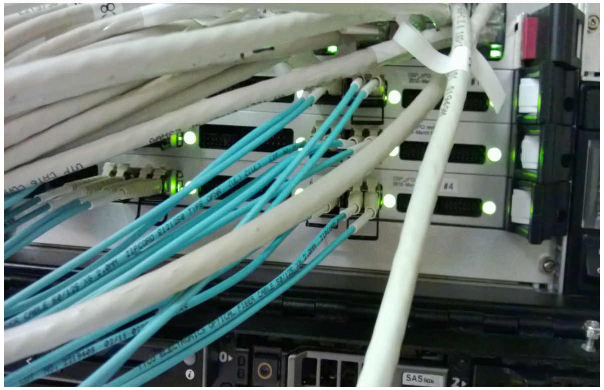
Micro-Channel Plate Based Detectors 2014

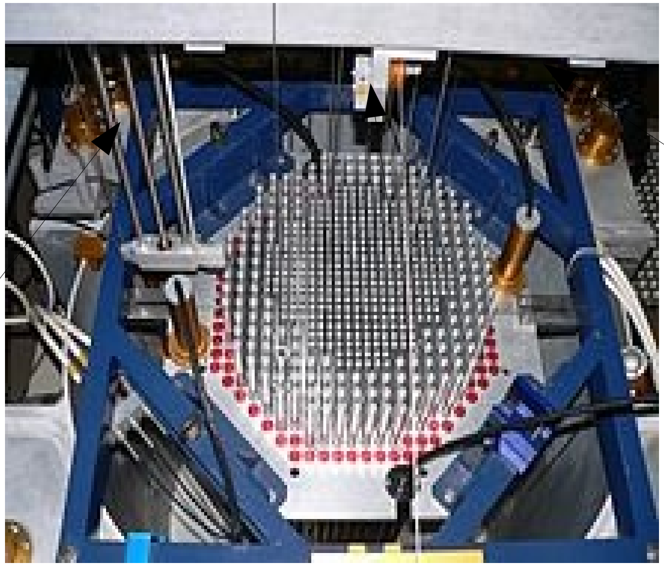
3 December, Argonne National Laboratory, IL

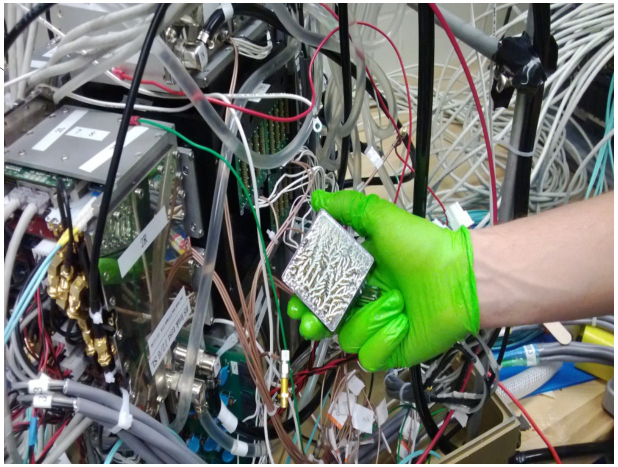
MTC: A Compact Detector

- Goals and motivation
- miniTimeCube hardware
- mTC software
- Tracking particle events
- Plans for the future









Goals and Motivation

Building a detector of reactor antineutrinos:

Compact, Mobile, Remote, Scalable, Directional & Real-time

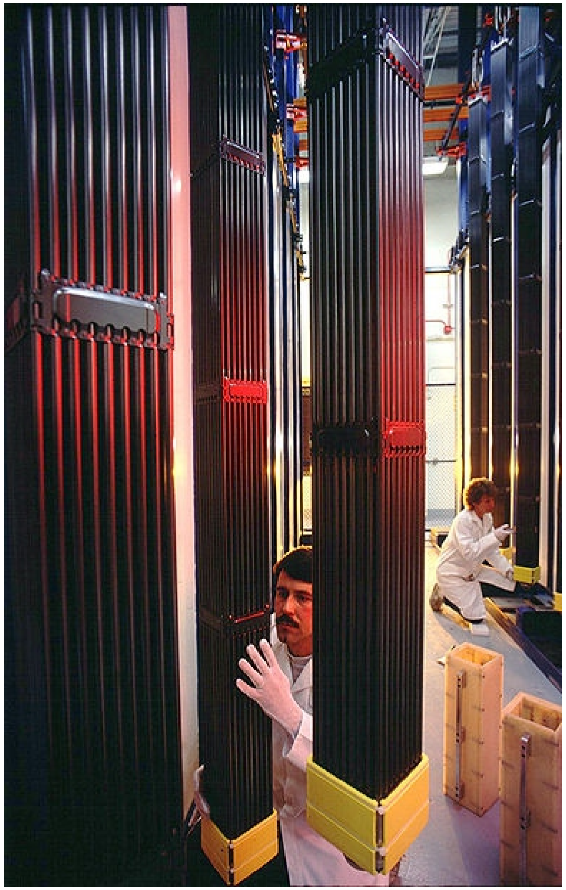


Photo from the NRC

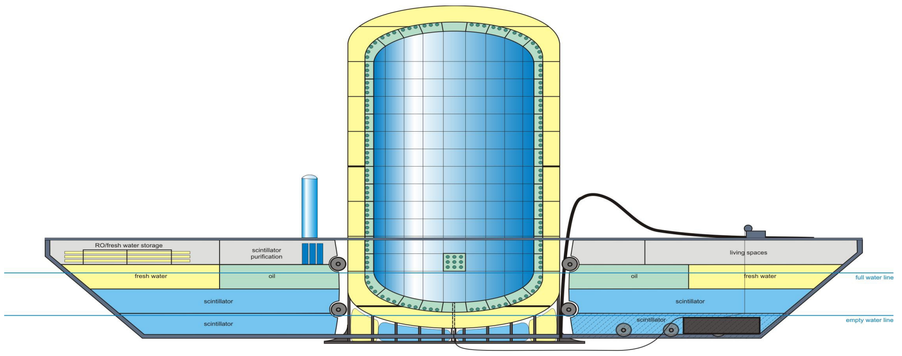
Applications

- Reactor Monitoring
- Non-proliferation of nuclear weapons (e.g. E. Brubaker's talk)
- Nuclear fuel monitoring

Goals and Motivation 2

Potential Scientific Applications

- Short Baseline Neutrino Oscillations
- Exploration of the neutrino mass hierarchy
- Checking recalculations of neutrino fluxes from reactors
- Reactor Neutrino Anomaly (6% deficit of “nuebar”s at short distances)
- Sterile neutrino searches
- Next steps: NuLat, Hanohano



The proposed HanoHano

How to detect reactor antineutrinos?

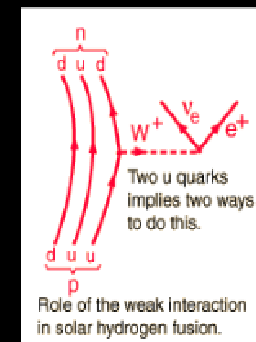
IBD – only one unique identifier

mTC

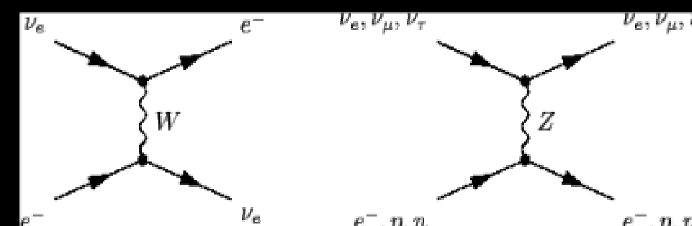
Not a unique identifier

Any type of neutrino

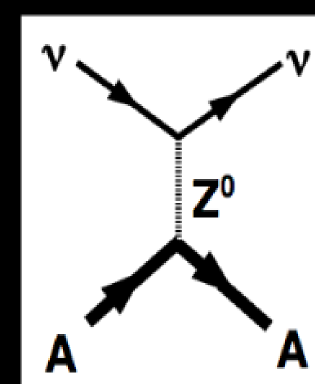
- **Inverse Beta Decay (IBD)**
  - p + anti-ν_e → e^+ + n
  - cross section @2 MeV : 5 10^{-43} cm^2
  - scale as E^2



- **Neutrino-Electron Scattering**
  - e^- + anti-ν_e → e^- + anti-ν_e
  - cross section @0.8 MeV : 5 10^{-45} cm^2
  - scale as E

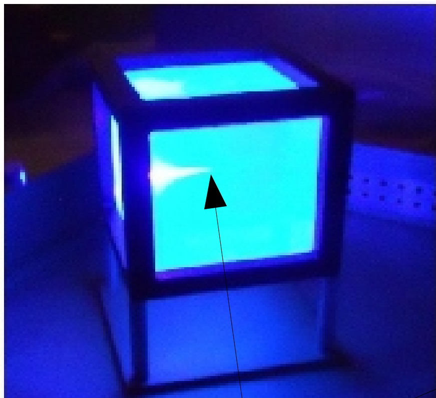


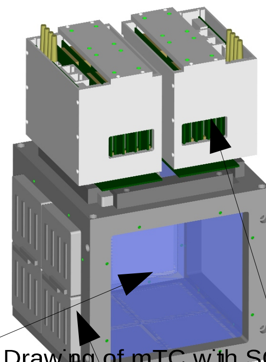
- **Neutrino-Nucleus Coherent Scattering**
  - A + anti-ν_e → A + anti-ν_e
  - cross section @2 MeV > 10^{-41} cm^2
  - scale as E^2
  - scale as N^2



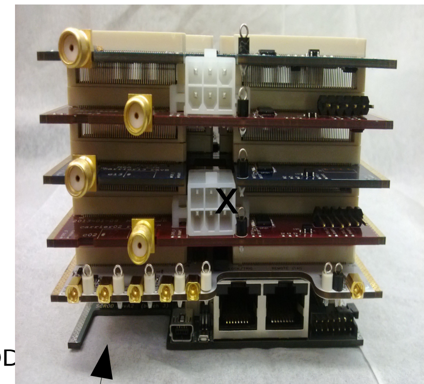
Lasserre, AAP 2012

MiniTimeCube Hardware





CAD Drawing of mTC with SCROD Modules. (M. Rosen)

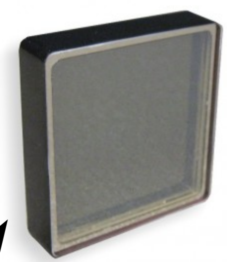


DAQ

2.2 liter EJ-254 scintillator

SCROD - board stack

HV&LV



Planacon (~PMT)

The packed mTC

Al enclosure

UPS

Not shown: PC to program SCROD and store data, PC to operate LV&HV modules

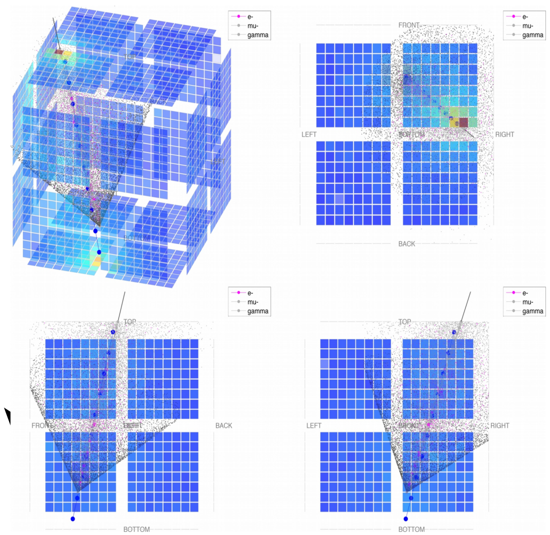
MiniTimeCube
Further Details

- **Scintillator**

  2.2 liters EJ-254

  1% natural boron (0.2% B-10)

  loaded plastic scintillator



- **PMT's**

  24 Planacon's XP85112

  8x8 pixels each

  = 1532 channels/pixels

- **Electronics**

  SCROD (IRS digitizer),

  DAQ

FAST
COMPACT
DIRECTIONAL
REAL-TIME

- **Software**
  - **initialization**
  - **control**
  - **analysis**

Fast timing imaging (~100ps), not optics (time reversal imaging)

Reconstruction of neutrino direction

Rejects noise on the fly

~10/day anti-neutrino events (inverse beta decay signature, for a large nuclear reactor @ ~20m)

mTC plastic scintillator EJ-254

EJ-254 BORON-LOADED PLASTIC SCINTILLATOR

This is blue-emitting plastic scintillator contains natural boron at concentrations up to 5% by weight. It is a clear, stable plastic with physical properties similar to the standard Eljen plastic scintillators. Its principal applications are fast neutron spectrometry and thermal neutron detection. The primary function of the boron is to provide a unique scintillation signal for low energy neutrons. The standard formulation contains 5% boron, and practical boron concentrations down to 1% are available.

The isotopic fraction of ^{10}B in natural boron is 19.9%, and hence, the 5% loaded plastic contains nearly 1% of ^{10}B. The neutron capture reaction on the boron $^{10}B(n,\alpha\gamma)^{7}Li$ has a Q value of 2.78 MeV of which 2.34 MeV is shared by the alpha and lithium particles. This energy is fully captured in the plastic to produce a scintillation signal approximately equivalent in amplitude to that of a 76 keV electron. For delayed coincidence timing of the capture of fast neutrons, the time delay from the prompt recoil-proton pulse is typically 2.7μs for 5% B-nat plastics. This delay is inversely proportional to the boron loading.

Physical and Scintillation Constants	5% B	2.5%B	1%B
Light Output, % Anthracene	48	56	60
Scintillation Efficiency, photons/1 MeV e⁻	7,500	8,600	9,200
Wavelength of Max. Emission, nm	425	425	425
Decay Time, ns	2.2	2.2	2.2
No. of C Atoms per cm^3, x 10^{22}	4.44	4.55	4.62
No. of H Atoms per cm^3, x 10^{22}	5.18	5.17	5.16
No. of ^{10}B Atoms per cm^3, x10^{20}	5.68	2.83	1.14
No. of Electrons per cm^3, x 10^{23}	3.33	3.33	3.33
Density at 20^{o}C, g/cc:	1.026	1.023	1.021

FAST

Polymer Base: .... Polyvinyltoluene
Refractive Index: 1.58
Vapor Pressure: .... Is vacuum-compatible
Coefficient of Linear Expansion: .... 7.8 x 10^{-5} below +67°C

Light Output vs. Temperature:
At +60°C, L.O. = 95% of that at +20°C
No change from +20°C to -60°C

Chemical Compatibility: Is attacked by aromatic solvents, chlorinated solvents, ketones, solvent bonding cements, etc. It is stable in water, dilute acids and alkalis, lower alcohols and silicone greases. It is safe to use most epoxies with EJ-254.

Comparison of Capture Mechanisms for ^{10}B and ^{1}H for Thermal Neutrons in EJ-254

Competing capture reactions: $^{10}B(n,\alpha)$ σ=3840b $^{1}H(n,\gamma)$ σ=0.332b

Natural B Loading	Ratio: $\Sigma(^{10}B)\div\Sigma(^{1}H)$
5%	127.6
2.5%	62.4
1%	25.6

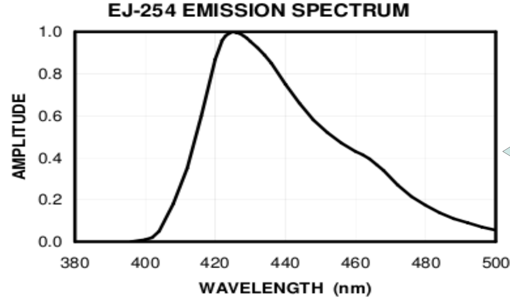
Capture time ~ 700 ns
Decay time ~ 2.2 ns

Linear Attenuation Coefficients for Neutron Capture by ^{10}B in EJ-254

Neutron Energy	Cross Section Barns/Atom	Linear Attenuation Coefficient, Σ (cm^{-1}) 5% B	2.5% B	1% B
0.025 eV	3836.00	2.15	1.07	0.43
0.1 eV	1929.00	1.08	0.54	0.22
1 eV	610.00	0.34	0.17	0.068
10 eV	193.00	0.11	0.054	0.022
100 eV	60.60	0.034	0.017	0.0068
1 keV	19.00	0.011	0.0053	0.0021
10 keV	5.89	0.0033	0.0016	0.00066
20 keV	4.17	0.0023	0.0017	0.00047
30 keV	3.41	0.0019	0.00095	0.00038
40 keV	2.98	0.0017	0.00083	0.00033
50 keV	2.68	0.0015	0.00075	0.00030
100 keV	1.96	0.0011	0.00055	0.00022
120 keV	1.80	0.0010	0.00050	0.00020
150 keV	1.61	0.00090	0.00045	0.00018
200 keV	1.36	0.00076	0.00038	0.00015
225 keV	1.28	0.00072	0.00036	0.00014
250 keV	1.19	0.00067	0.00033	0.00013

Large Xsec thermal neutrons

EJ-254 EMISSION SPECTRUM



To match PMTs

References
1. L.R. Greenwood and N.R. Chellew, *Rev. Sci. Instrum.*, 50 (4) 466-471 (April, 1979)
2. D.M. Drake, et al, *Nucl. Instr. & Methods in Physics Res.*, A274, 576-482 (1986)

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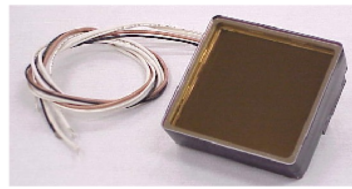
Website: www.eljentechnology.com

mTC multichannel PMT's

Photon Detector — XP85112

PLANACON®

10µm MCP-PMT
53 mm Square, 8x8 Anode
- Superior Magnetic Field Immunity
- Enhanced Timing Performance



Applications
- ✓ Specialized Medical Imaging
- ✓ Cherenkov – RICH, TOF, TOP, DIRC
- ✓ High Energy Physics Detectors
- ✓ Homeland Security

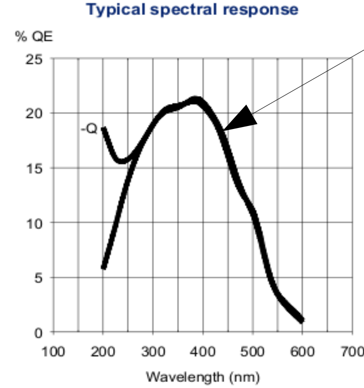
COMPACT!

Description	
Window options	Schott 8337B or equivalent, UVFS (-Q)
Photocathode	Bialkali
Multiplier structure	MCP chevron (2), 10 µm pore, 60:1 L:D ratio
Anode structure	8x8 array, 5.9 / 6.5 mm (size / pitch)
Active area	53x53 mm
Package open-area-ratio	80%

Photocathode characteristics	Min	Typ	Max	Unit
Spectral range:	200		650	nm
Peak Quantum Efficiency at 380 nm*	18	22		%
Operating Characteristics	**Min**	**Typ**	**Max**	**Unit**
Overall Voltage for 10^5 Gain *		FIG	2800	V
Total anode dark current @ 10^5 gain *		2	10	nA
Spatial Uniformity		2:1		
Rise time**		0.5		ns
Pulse width**		0.7		ns
Transit time spread (σ_{tts})**		35	60	ps
Maximum Magnetic Field Operation		2		T

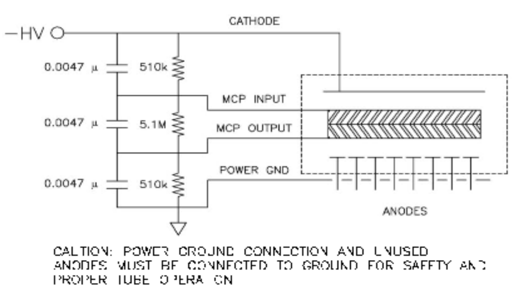
FAST!

Typical spectral response

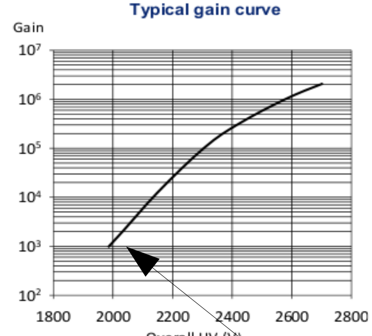


Matches scintillator

Recommended Voltage Divider (not included)



Typical gain curve



region of the gain

** Characteristic measured and recorded on the test ticket of each tube*
*** Characteristic for single photoelectrons at 405 nm.*

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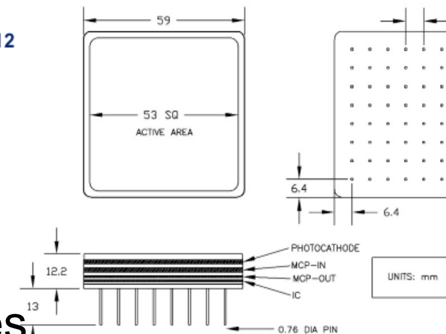
Rev02-Sept12

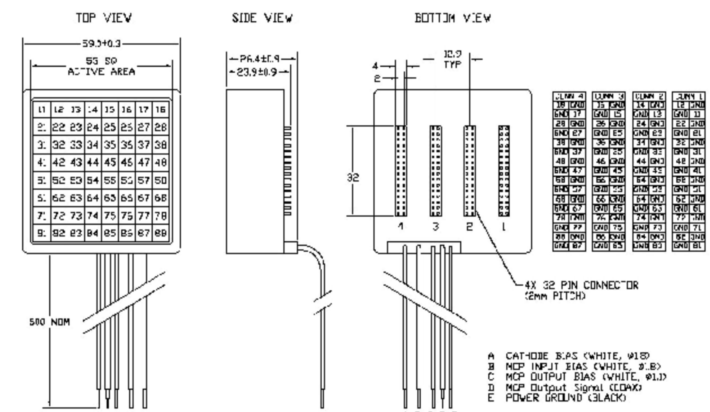
Photon Detector — XP85112

Outline (dimensions in mm)

XP85112



XP85112/A1



Mass: ~128g

Limiting values	Min	Max	Unit
Cathode to MCP_{in} voltage		500	V
MCP_{in} to MCP_{out} voltage		2400	V
MCP_{out} to Anode voltage		500	V
Overall HV when using recommended voltage divider		2800	V
Total anode current under uniform illumination		2	µA
Ambient temperature:			
Operating Temperature	0	+50	°C
Storage Temperature (for extended periods)	-15	+50	°C

* Warning: Continuous operation at maximum ratings may result in shorter product life or unreliable performance.

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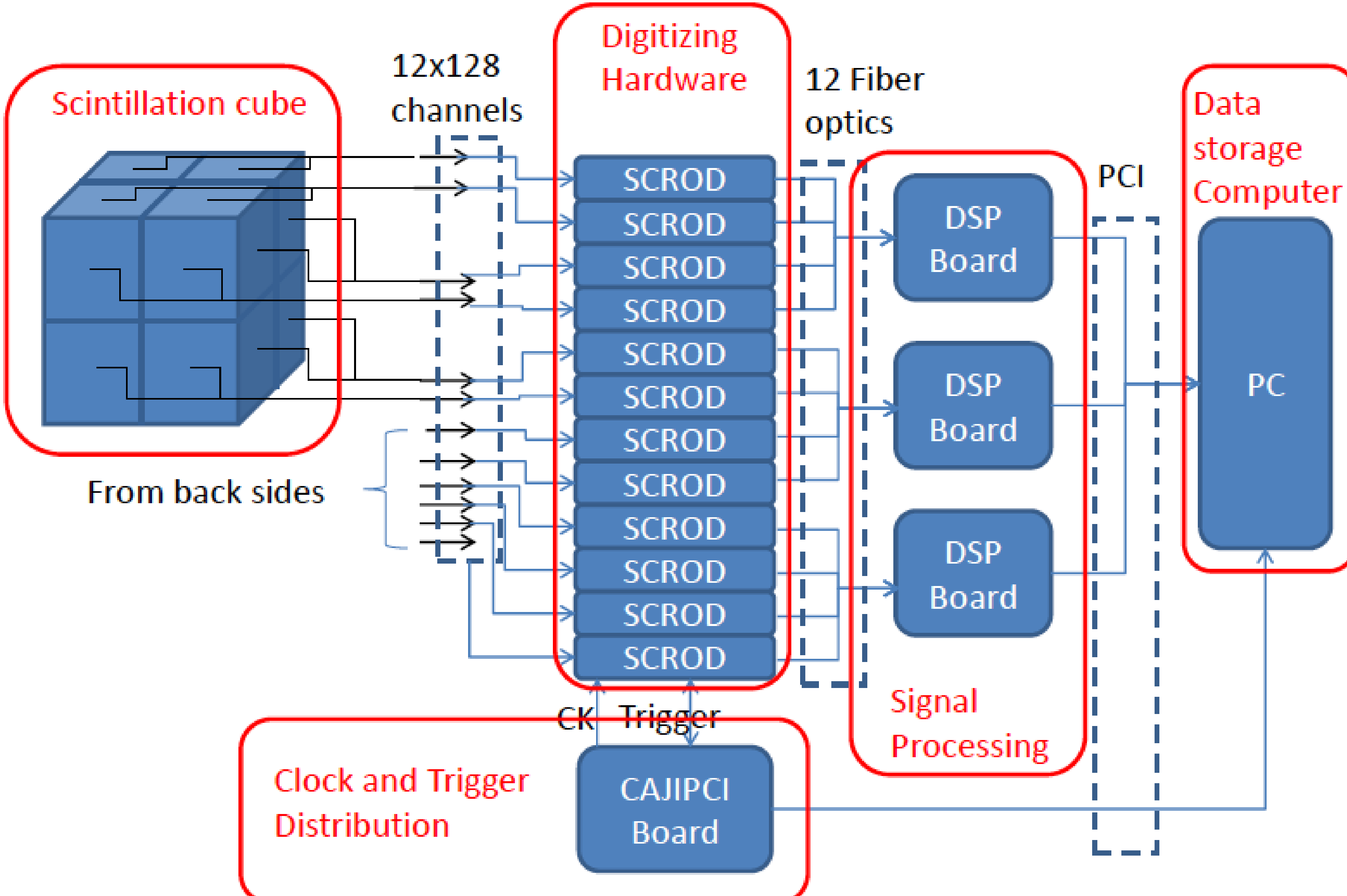
mTC Electronics

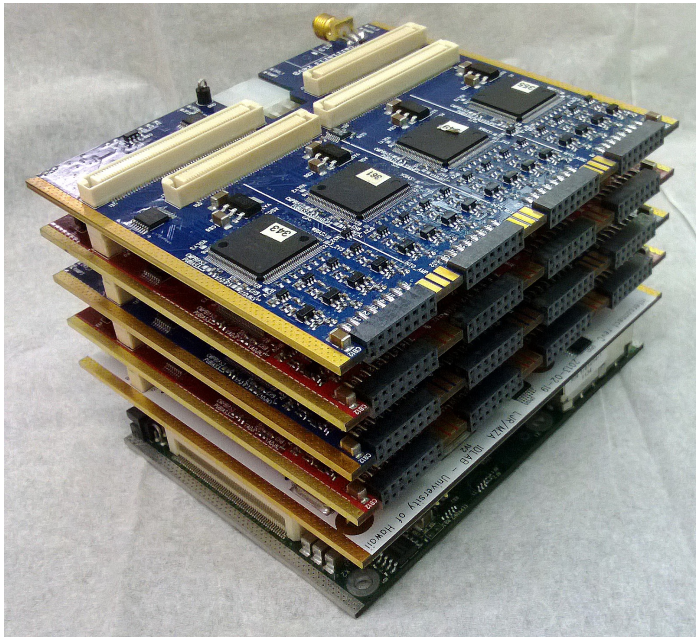


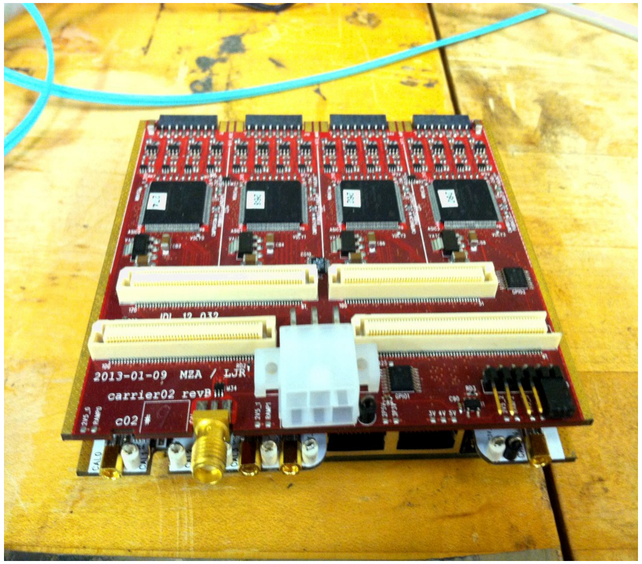
3

IRS: Custom Digitizers

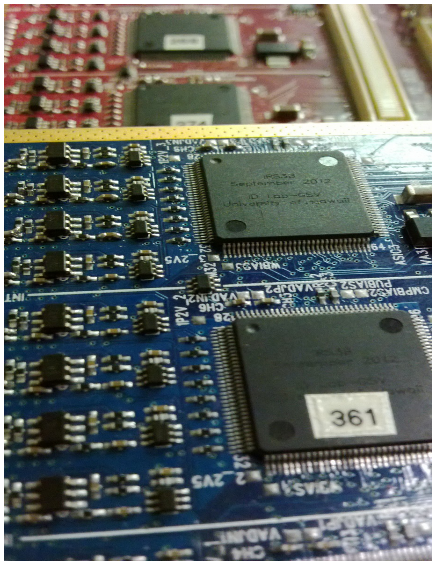
- SCROD - board stack with IRS3b chips used in Belle – 100 ps timing resolution
- Separate Data and triggering paths
- 16 chips per board stack -> seen at right
- 192 chips per cube (1536 chan)
- 8 channels per chip, 2-4 Gigasamples / s
- 32,000 sample analog storage
- For more info, see talk by

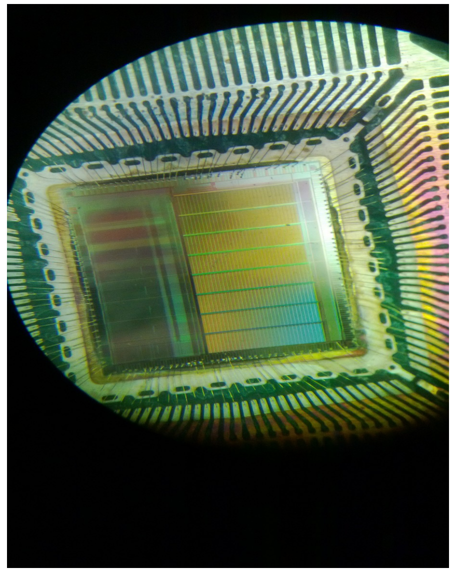
  G Varner on Thursday





Keeping it Cool



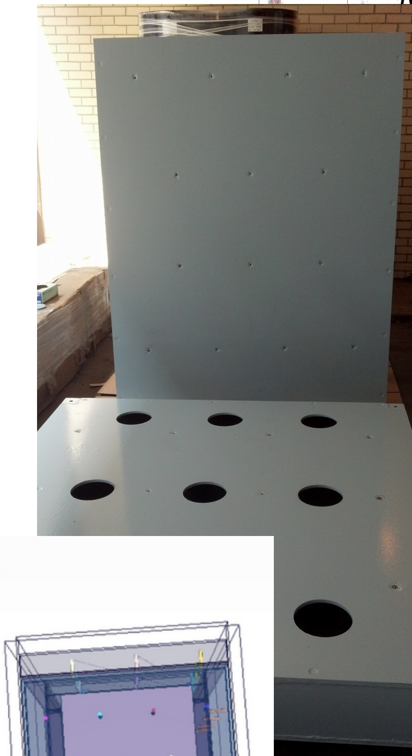


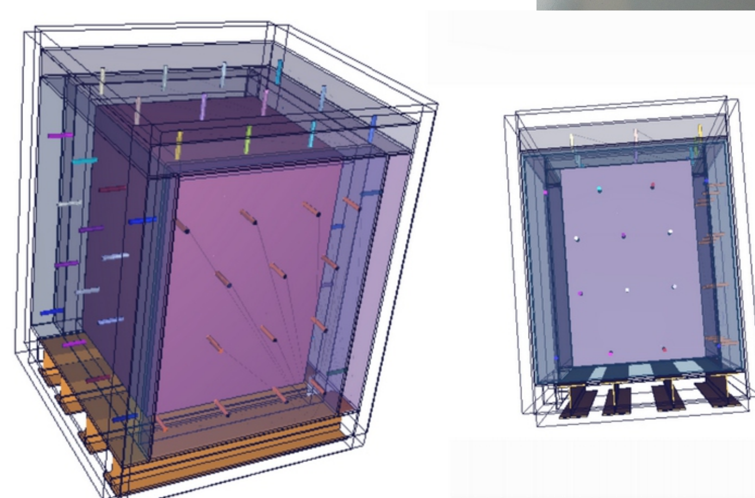
- 48 boards total, 192 IRS chips, along with amplifiers, PMTs, etc. produce ~ 400 W heat
- The cover and shielding restrict air flow

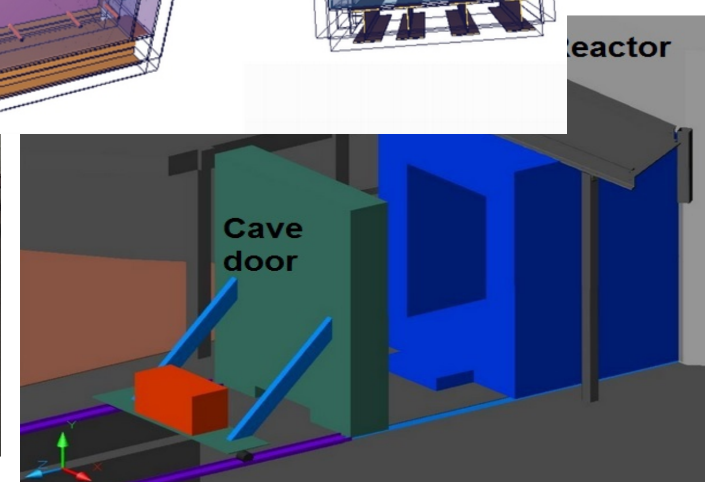
- We use the following:
  - Koolance hard drive chiller plates
  - An “Advantage” water chiller unit - 16 ℃, 2 gallon per min
- T inside → 30-40℃

The “Cave”

- Designed to shield the mTC near reactors
- Can be assembled and disassembled when needed
- Consists of steel walls with iron-shot and wax inside
- Soon to be assembled and tested



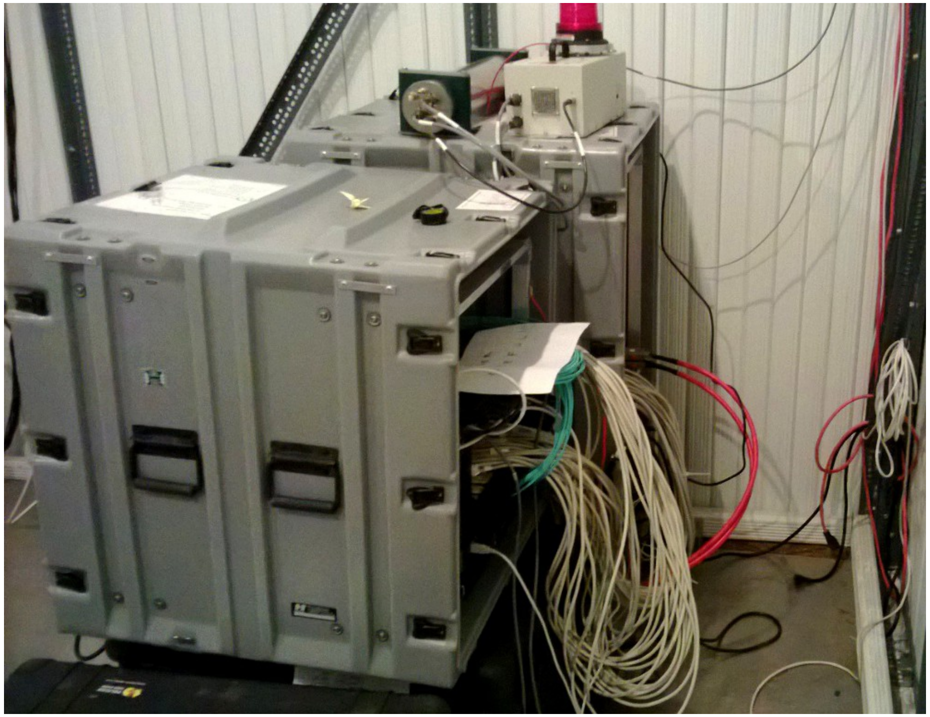




miniTimeCube Now: Ongoing Work and Testing at NIST

- Calibration, initialization system, timing tests
- Observing cosmic ray muons
- Observations near neutron sources
- Preparations for moving

  to the reactor, observe backgrounds, test the cave

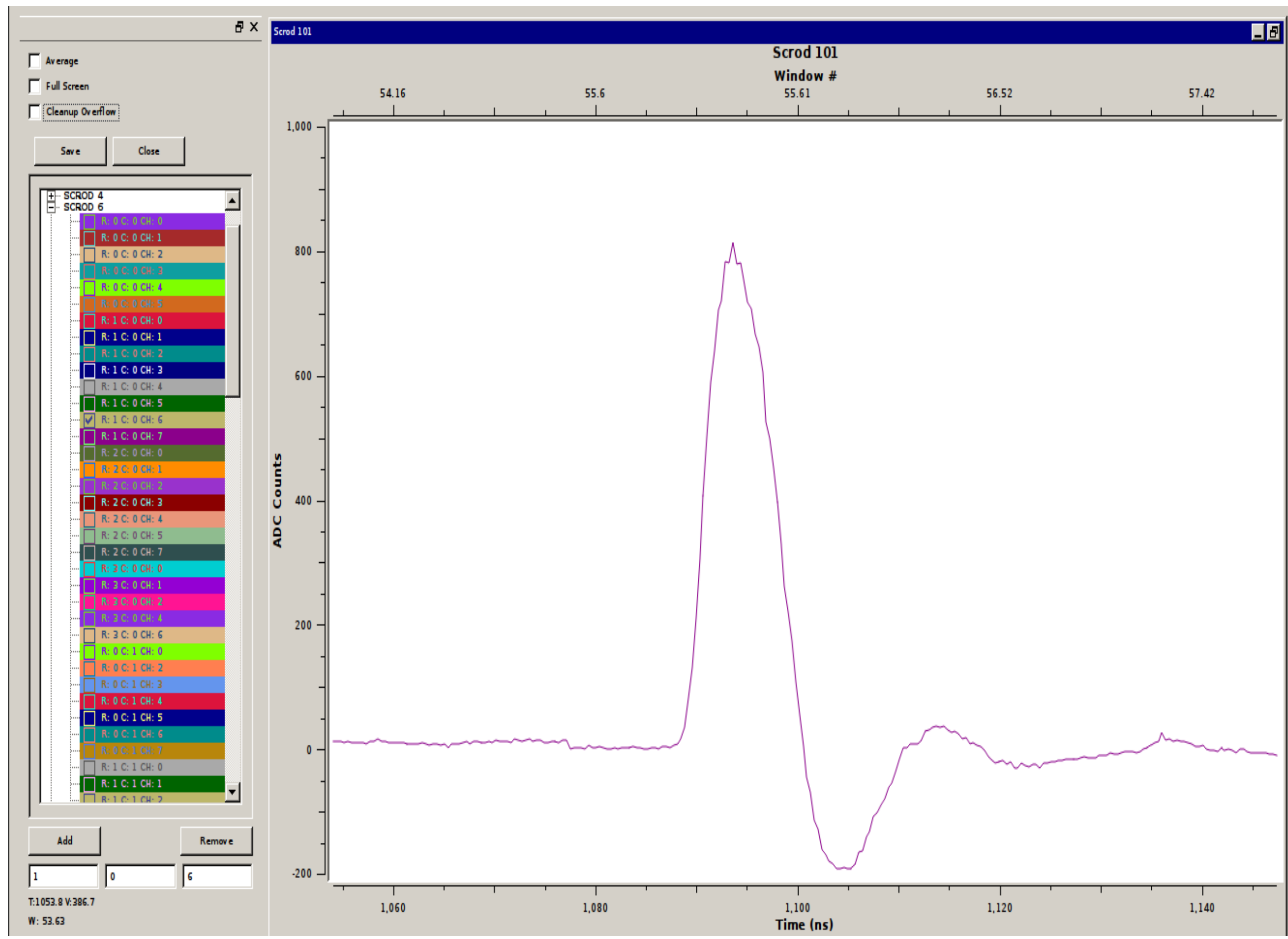


Testing with neutron sources

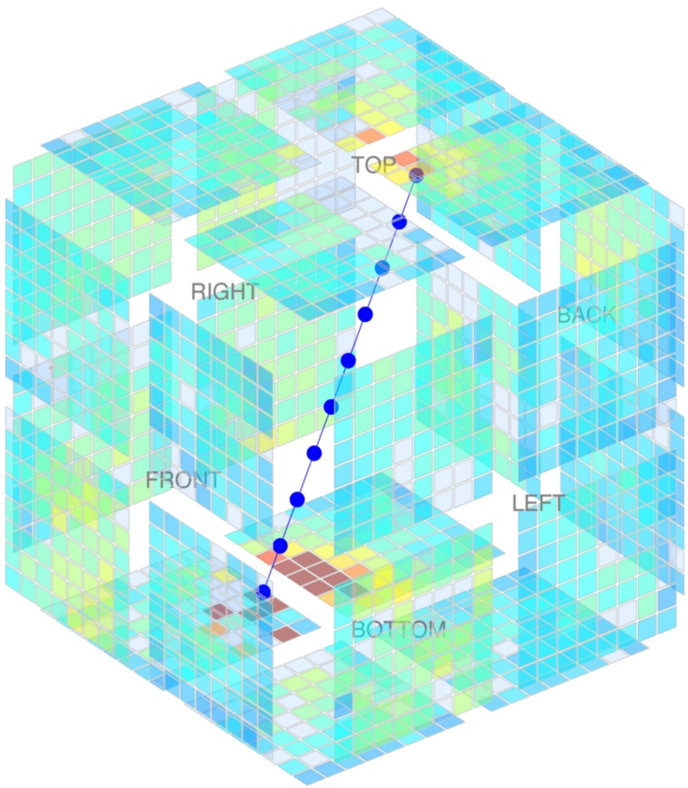
mTC Software, Analysis, and Particle Tracking

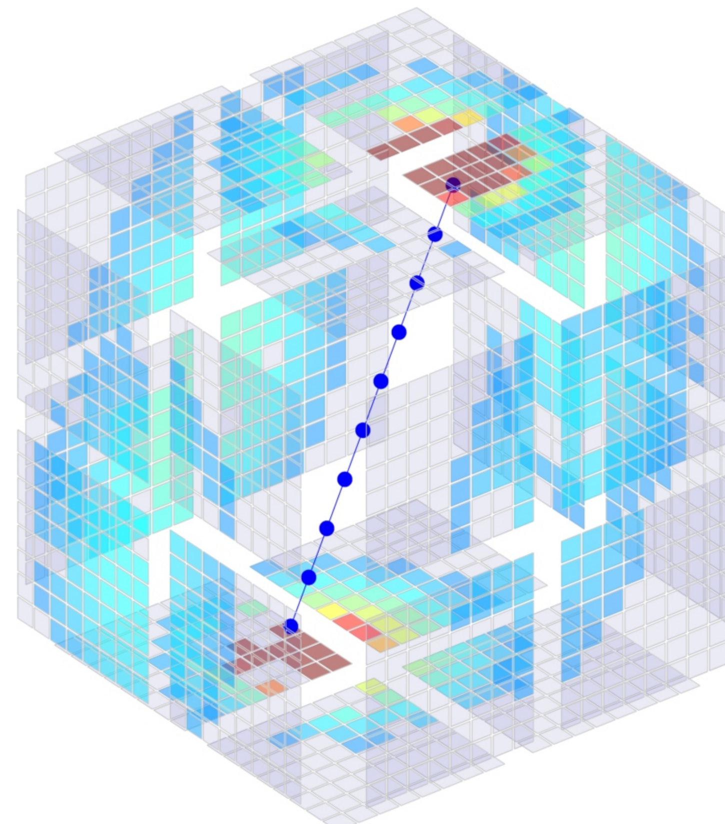
Event Viewer

- Displays pulses for an event, channel by channel
- Works in real time as well as on data sets
- Can show many pulses / channels at once



Muon Track Reconstruction in Matlab



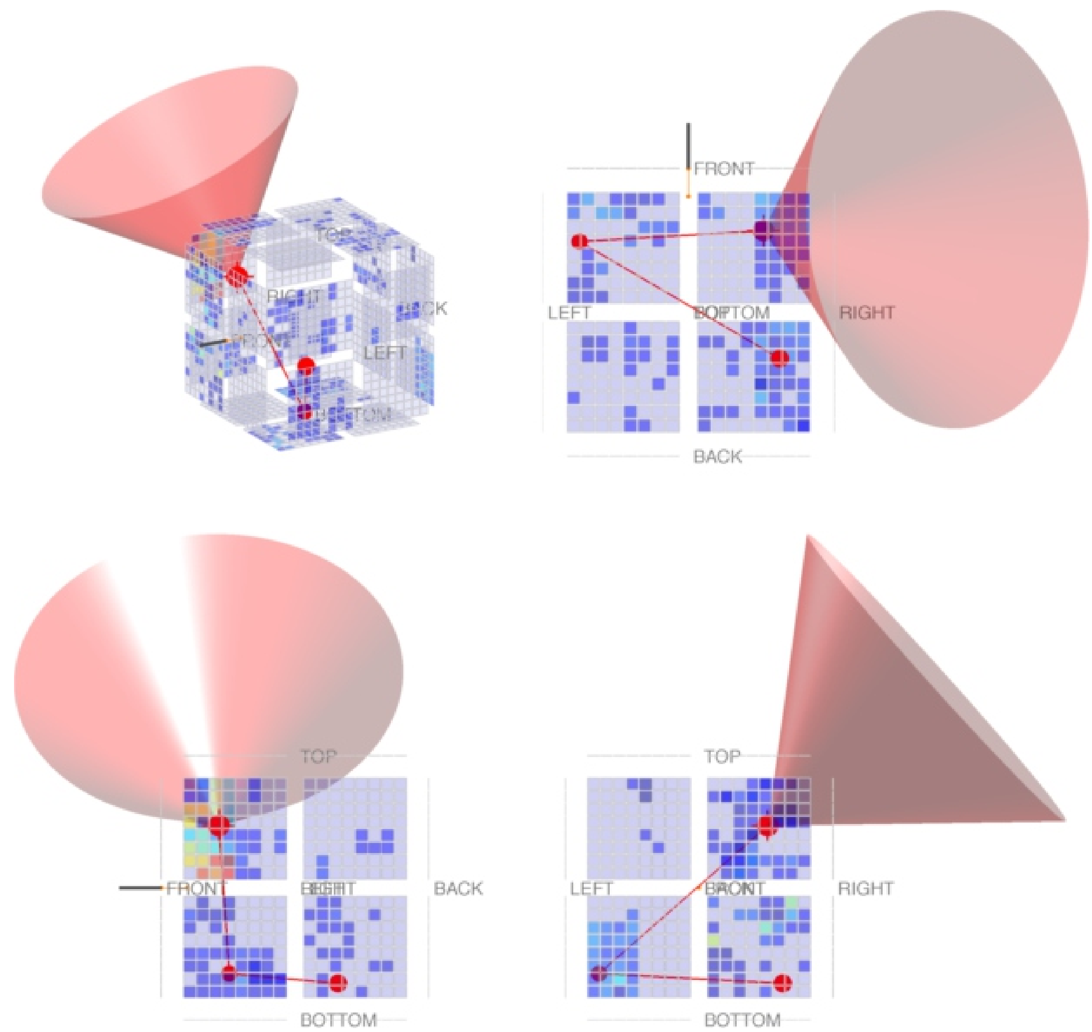


- Reconstructed muon track through the mTC
- Simulated muon track in Matlab

Plots courtesy of Glenn Jocher

Neutron Events

- Capable of neutron path reconstruction
- Sources used include Cf 252, Pl-240 and deuterium / tritium neutron generators
- Uses kinematics and signals from neutron bounces to create an event cone



Neutron Event Reconstruction From 2 Bounces

- A. The incoming neutron energy = KE after first bounce + ΔE of first bounce.

- B. The KE after first bounce = $\frac{1}{2}mv^2$, where $v = \Delta x/\Delta t$, where Δx = (bounce-2 pos) - (bounce1 pos), and Δt = (bounce2 time) - (bounce 1 time).

- C. The direction vector dx from b is what we establish an angle cone about.

- D. To get the angle cone: sin^2theta = (dE of first bounce) / (incoming neutron energy)

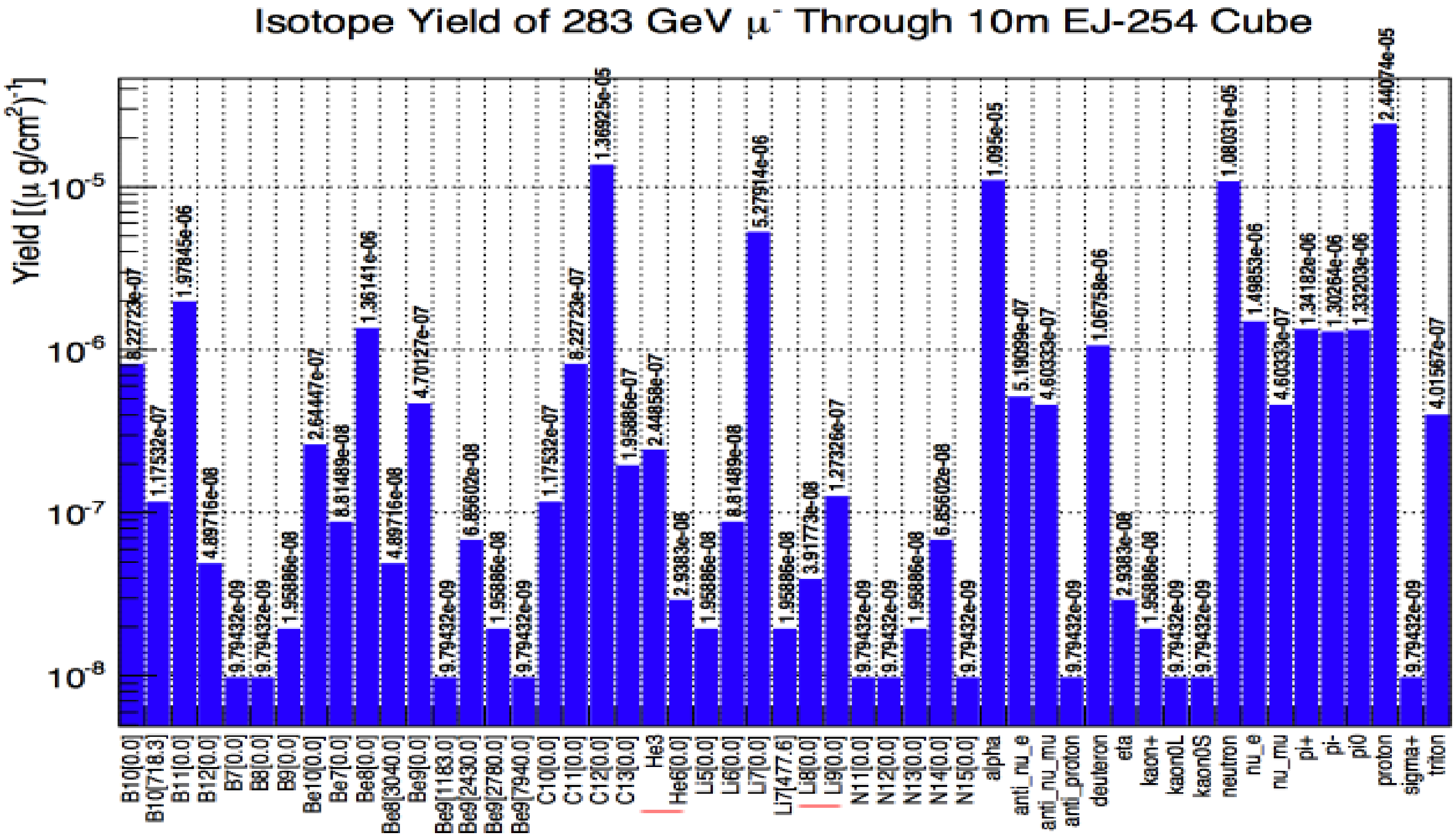
Positron Cherenkov Light And neutrino track construction

- Cherekov cone first hits used to reconstruct vertex
- Relative small size of mTC scintillator volume (2.2 L) allows annihilation gammas to escape
- This prevents “smearing” of vertex during analysis
- The subsequent neutron capture then helps us construct the neutrino's path
- Some tests done with neutrons, bg tests near reactor and neutrino searches coming soon (Winter-Spring 2014 at NIST)

Positron Cherenkov Light
And neutrino track construction

Video: Positron Track Reconstruction

BG Simulations on Cosmogenic Isotopes from 283 GeV mu$^-$



- Studying long-lived isotopes (8He, 9Li) for background rejection
- x10 increase in statistics → ~ x10 increase in ^{9}Li
- ^{8}He not seen with 10^5 muon events

Studying long-lived isotopes (8He, 9Li) for better background rejection

	GEANT4 Model III	GEANT4 Model IV	FLUKA	Borexino	KamLAND
		— $\langle E_\mu \rangle = 283 \pm 19\,\mathrm{GeV}$ —			$\langle E_\mu \rangle = 260 \pm 8\,\mathrm{GeV}$
Isotopes			Yield $[10^{-7}\,(\mu\,\mathrm{g/cm^2})^{-1}]$		
^{12}**N**	1.11 ± 0.13	3.0 ± 0.2	0.5 ± 0.2	< 1.1	1.8 ± 0.4
^{12}**B**	30.1 ± 0.7	29.7 ± 0.7	28.8 ± 1.9	56 ± 3	42.9 ± 3.3
^{8}**He**	< 0.04	0.18 ± 0.05	0.30 ± 0.15	< 1.5	0.7 ± 0.4
^{9}**Li**	0.6 ± 0.1	1.68 ± 0.16	3.1 ± 0.4	2.9 ± 0.3	2.2 ± 0.2
^{8}**B**	0.52 ± 0.09	1.44 ± 0.15	6.6 ± 0.6	14 ± 6	8.4 ± 2.4
^{6}**He**	18.5 ± 0.5	8.9 ± 0.4	17.3 ± 1.1	38 ± 15	not reported
^{8}**Li**	27.7 ± 0.7	7.8 ± 0.4	28.8 ± 1.0	7 ± 7	12.2 ± 2.6
^{9}**C**	0.16 ± 0.05	0.99 ± 0.13	0.91 ± 0.10	< 16	3.0 ± 1.2
^{11}**Be**	0.24 ± 0.06	0.45 ± 0.09	0.59 ± 0.12	< 7.0	1.1 ± 0.2
^{10}**C**	15.0 ± 0.5	41.1 ± 0.8	14.1 ± 0.7	18 ± 5	16.5 ± 1.9
^{11}**C**	315 ± 2	415 ± 3	467 ± 23	886 ± 115	866 ± 153
Neutrons			Yield $[10^{-4}\,(\mu\,\mathrm{g/cm^2})^{-1}]$		
	3.01 ± 0.05	2.99 ± 0.03	2.46 ± 0.12	3.10 ± 0.11	2.79 ± 0.31

Table 4. Predicted yields for cosmogenic products obtained from GEANT4 (Model III and IV) and FLUKA are compared to data from Borexino . Also shown are results from the KamLAND experiment [9]. Note that the production yields depend on the number of carbon atoms per weight and the muon energy spectrum. Thus, a 10 – 20 % difference between KamLAND and Borexino results is expected.

Future Objectives

- Improved python interface
  - Faster initialization
  - Categorization of data run types

    (choose type of run: muon, neutron, neutrino, etc.)
- Real time hardware monitoring, data quality checking
- Remote detector control
- “Advisor” button
- Return to NIST in the Winter-Spring to investigate backgrounds, take more data

Acknowledgements

- The IDL group and the Belle collaboration for working on our electronics
- The Department of Physics & Astronomy at UH Manoa
- Friends from NIST, JHU, and University of MD
- Glenn Jocher and Ultralitics for his analysis and images
- The organizers of MCP 2014 for organizing our talks (and providing snacks!)
- ANL for hosting us

References

- Slava Li's talk and defense (2013)
- John Learned's talk (AAP 2012)
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- G. Jocher et al. “Theoretical Antineutrino Detection, Direction and Ranging at Long Distances” Phys. Reports 2012
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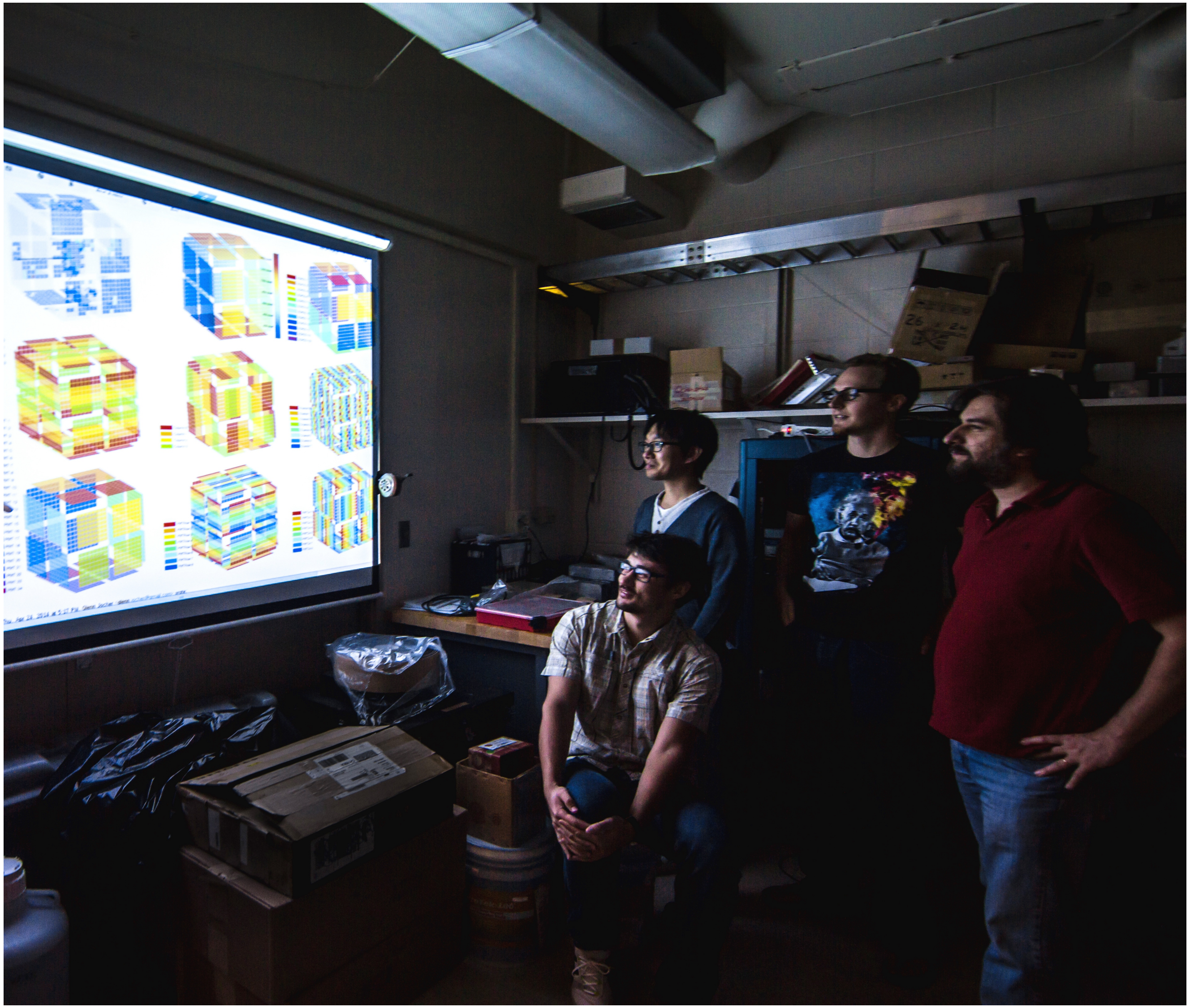
- http://www.photonis.com/en/ism/63-planacon.html
- http://www.cliontechnology.com/index.php/jooml

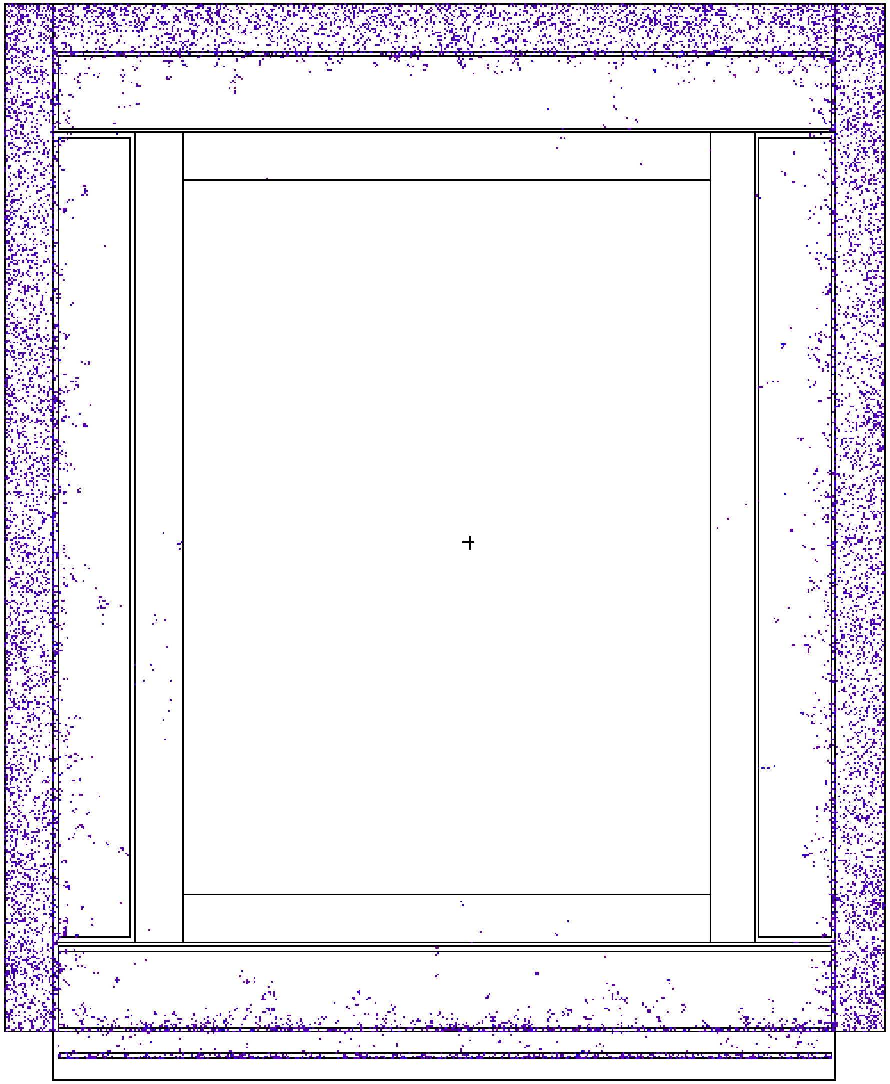
Thanks for watching!



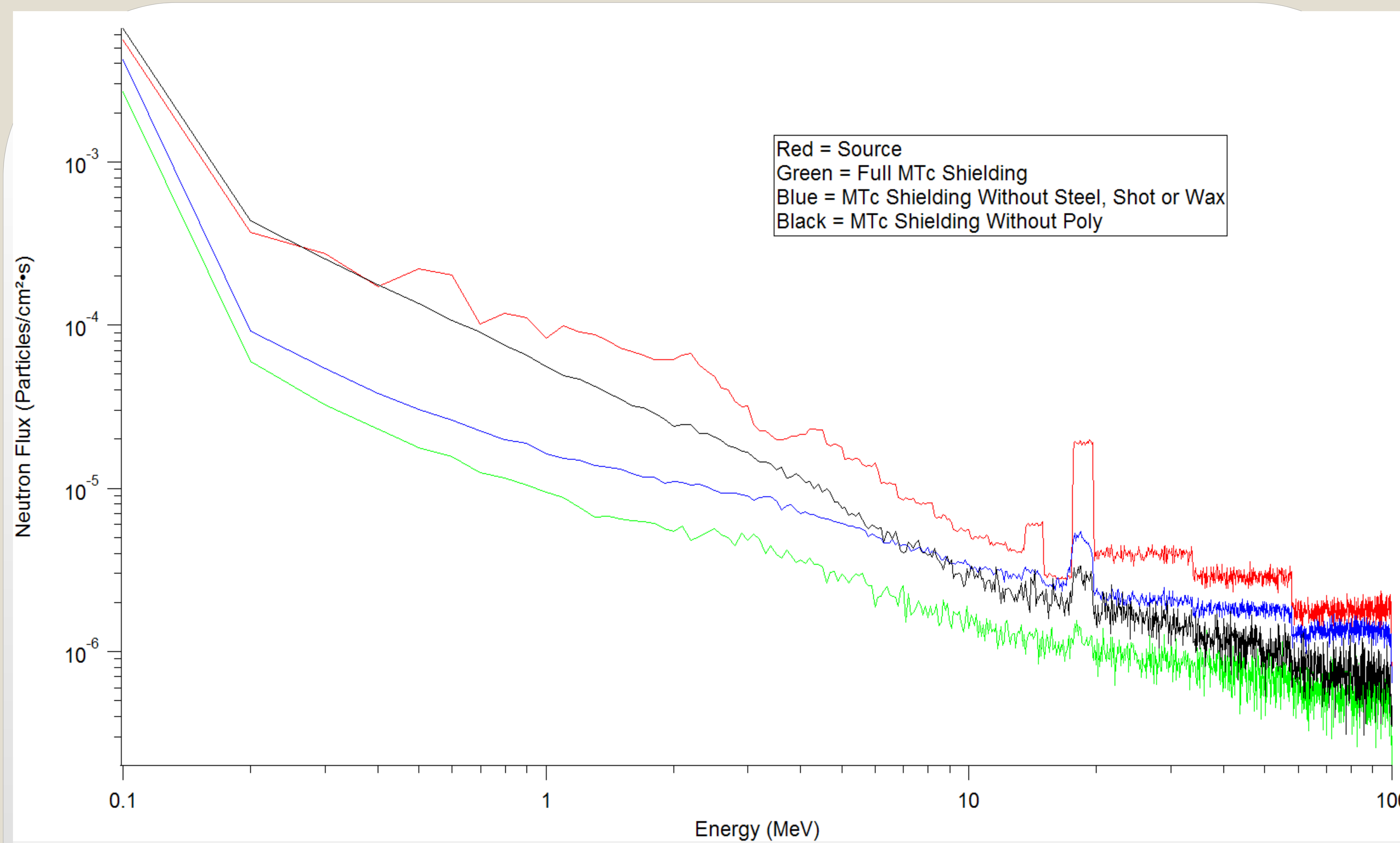
Backup Slides

More on Backgrounds

Compton Scattering scales with more electrons, which is why steel (Fe) stops gammas.



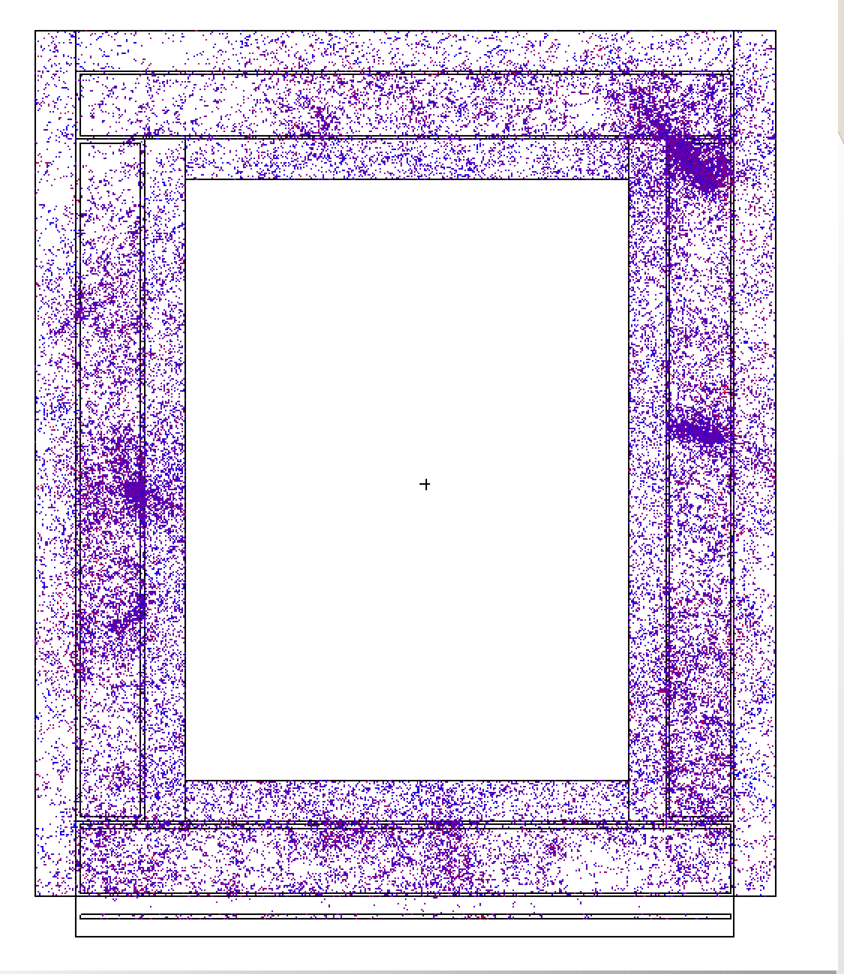
Photon Tracks


Red = Source
Green = Full MTc Shielding
Blue = MTc Shielding Without Steel, Shot or Wax
Black = MTc Shielding Without Poly
Neutron Flux (Particles/cm²•s)
10^-3
10^-4
10^-5
10^-6
0.1
1
10
100
Energy (MeV)

Results

Neutron Tracks

1. Little interaction with outer Boron, only absorbs low energy neutrons.
2. Lots of neutron scattering happens in the steel and wax which lowers neutron energy.
3. High interaction with inner Boron, neutrons are low enough energy to be absorbed.



Neutron Generators

- Two main types: DD, DT
- They work like miniature linear accelerators – colliding deuterium or tritium inside a metal hydride target (which contrains hydrogen isotopes)
- DD produces 2.5 MeV neutrons
- DT produces 14.1 MeV neutrons
- D + D -> 3H + n
- D + T -> 4He + n

Radioactive Sources Used

- Cf-252 (0.15 Bq as per 2005, half-life 2.64 years)
- Pu-240 had about the same activity

Old Cosmogenic Isotope Tally 283 GeV mu$^-$ (10^4 events)

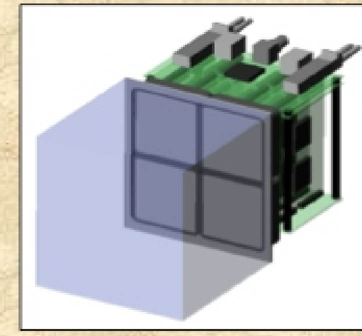
Isotopes we see from simulation

New Cosmogenic Isotope Tally 283 GeV mu$^-$ (10^5 events)

Isotopes we see from simulation

- x10 increase in statistics → ~ x10 increase in ^{9}Li
- ^{8}He not seen

mTC Virtues



- Small size avoids positron annihilation gammas which smear resolution (X_o ~42 cm).... gammas mostly escape, permitting precise positron creation point location.
- Fast pixel timing (<100ps) and fast pipeline processing of waveforms rejects background in real time.
- Having many pixels plus use of first-in light permits *mm* precision in vertex locations.
- Neutrino directionality via precision positron production and neutron absorption locations.
- No need for shielding (unlike other detectors).
- Feasible even in high noise environment, near reactor vessel, at surface (eg. in a truck).