VT Physics CNP Research Day, May 2019

Introduction to NuLat: A Compact, Segmented, Mobile Anti-neutrino Detector

Presented by Tristan Wright
for the NuLat Collaboration:

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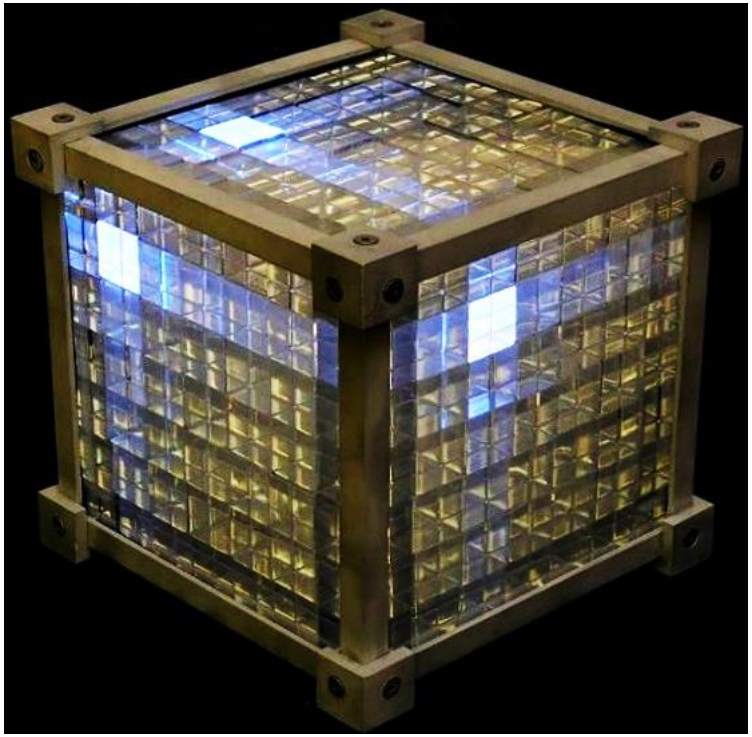
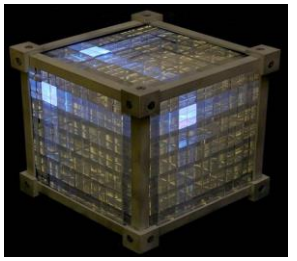
1:LLNL, 2:LSU, 3:NIST Gaithersburg, 4:NCCU, 5:Ultralytics LLC, 6:University of Hawaii, 7:Virginia Tech, 8: ORNL



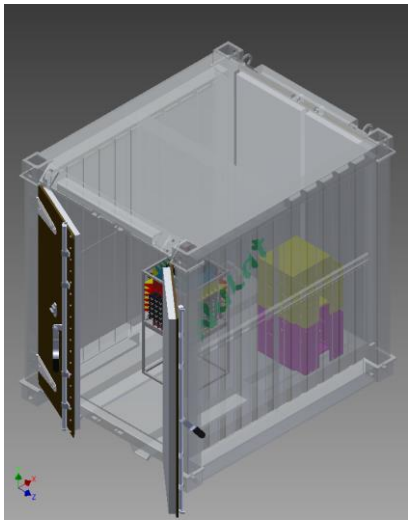
Adapted from talks by Dorrill, Learned, and Vogelaar

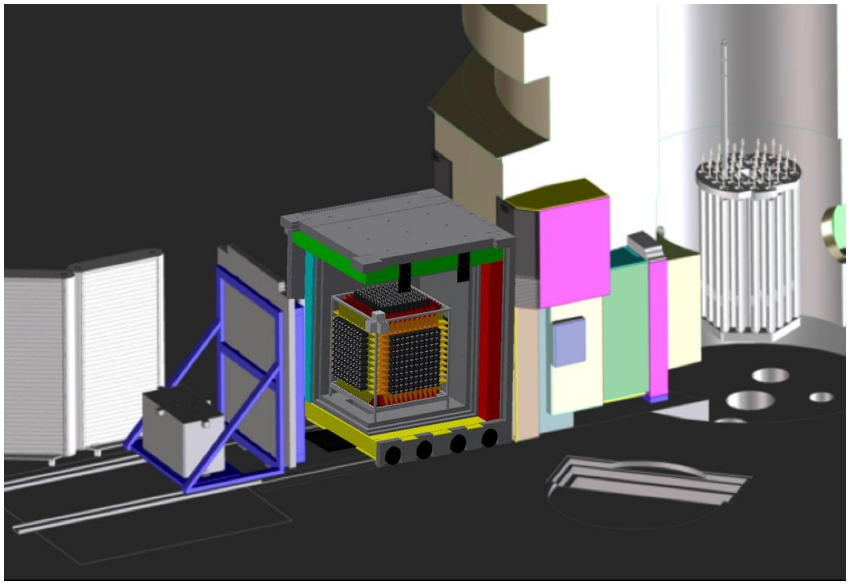
NuLat Motivation

- **Probe reactor anomalies**
  - Sterile neutrino search
  - Precision ν_e energy spectrum measurement
- **Demonstrate reactor monitoring capabilities**
  - Security monitoring
  - Commercial burn-up monitoring
- **Investigate fast neutron directionality capabilities**
  - Detection of special nuclear material
- **Exceptional background rejection**
  - **full 3D *precision*** segmentation (256 cubic centimeters)
  - complete event 'topology' (dE,x,y,z,t)
  - exceptional light collection (600 pe/MeV)
  - sub-nanosecond timing



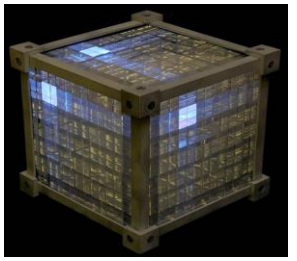
Outside North Anna Power Station… core 24m distant





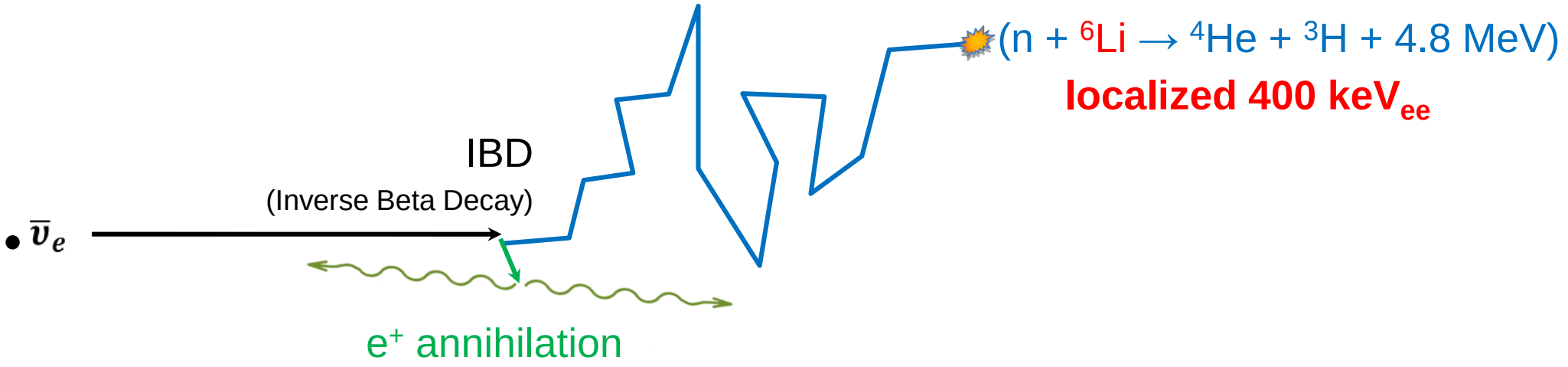
NIST NCNR Reactor 5m distant

Classic $\overline{\nu}_e$ Signature

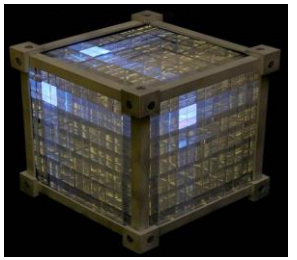


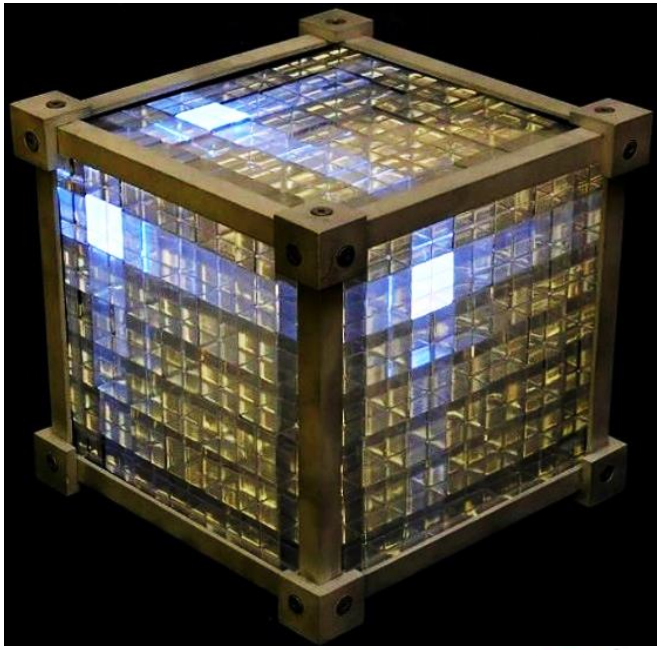
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

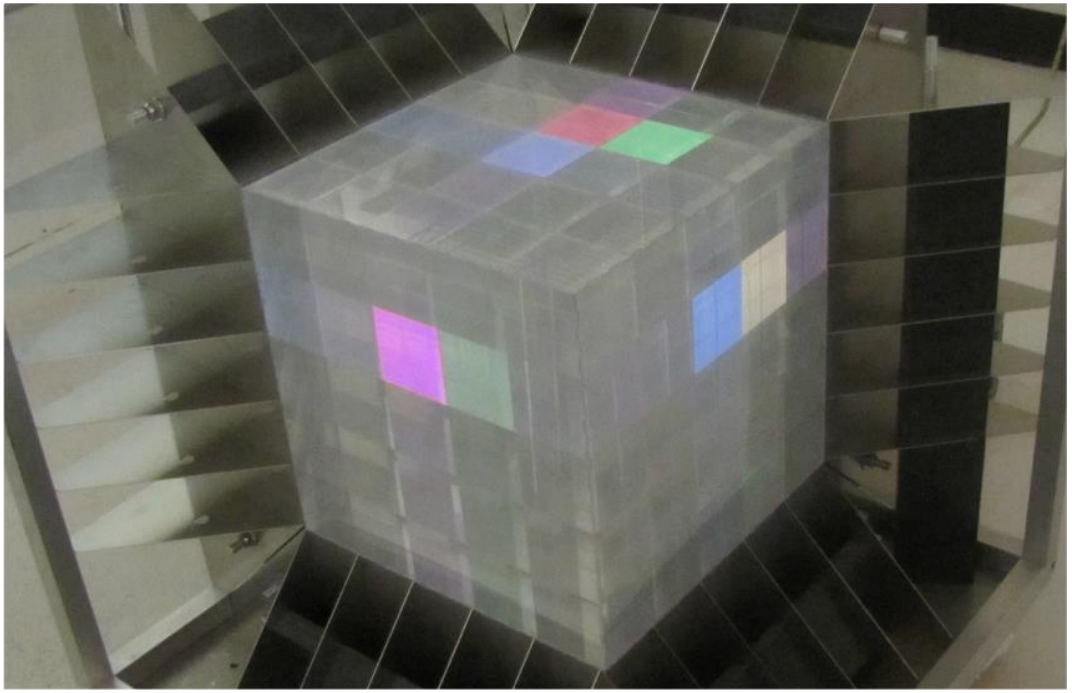
$$n + {}^6Li \rightarrow \alpha + {}^3H \quad (\tau \sim 7\mu s)$$

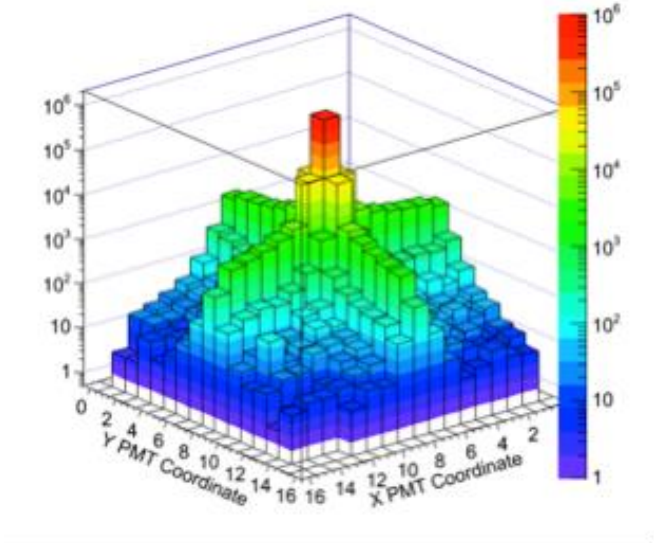


Raghavan Optical Lattice



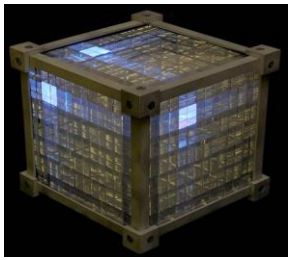




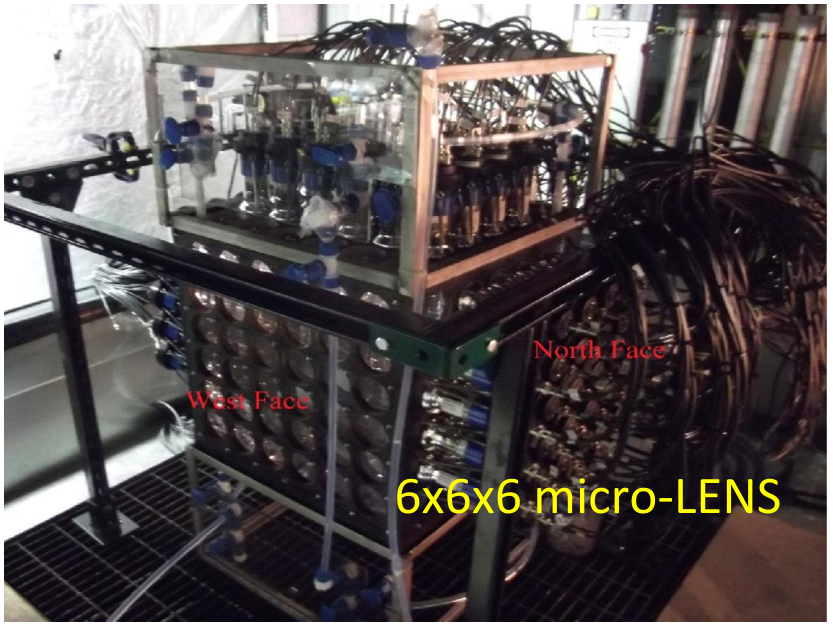


- light channeling via total internal reflection
- full 3D light collection along principle axes
  - Fewer degeneracies

Segmentation



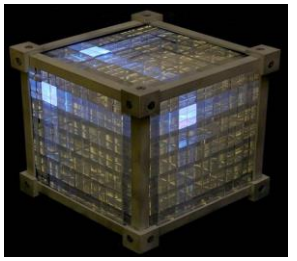
- proven technique: micro-LENS
  - operational liquid scintillator ROL detector located at KURF
  - Cell size = $(3.25")^3$
  - thin Teflon walls (0.002")
  - partial light channeling (n=1.34 and 1.49)

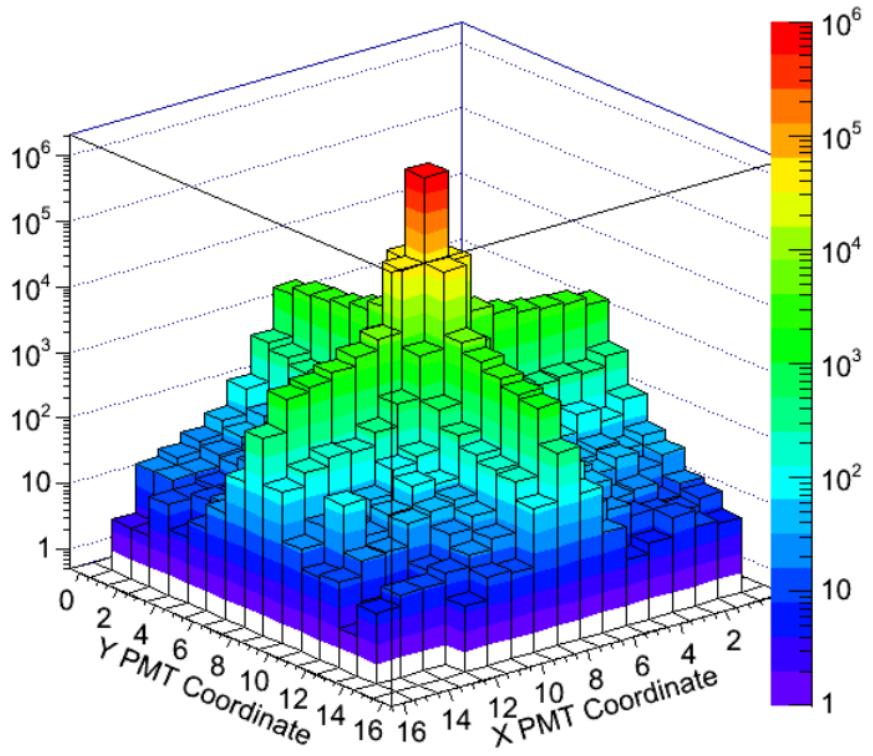


LENS 6x6x6 demonstration project
Now defunct solar neutrino detector project

- NuLat (solid scintillator)
  - Aim for 10x10x10 cubes
    - effectively 1000 individual detectors
  - 2.5 inch plastic scintillator cubes
  - 0.5% ^{6}Li by wt. loading (Eljen)
  - VM2000 reflective film 'dots' to maintain air-gap
  - ***Total*** light channeling (n=1 and 1.54)
  - Easily scalable to larger mass
  - True zero-mass wall – no energy loss
  - (Have some very preliminary schemes for kiloton scale.)

Segmentation 2

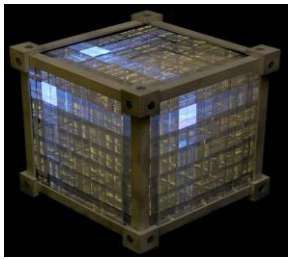


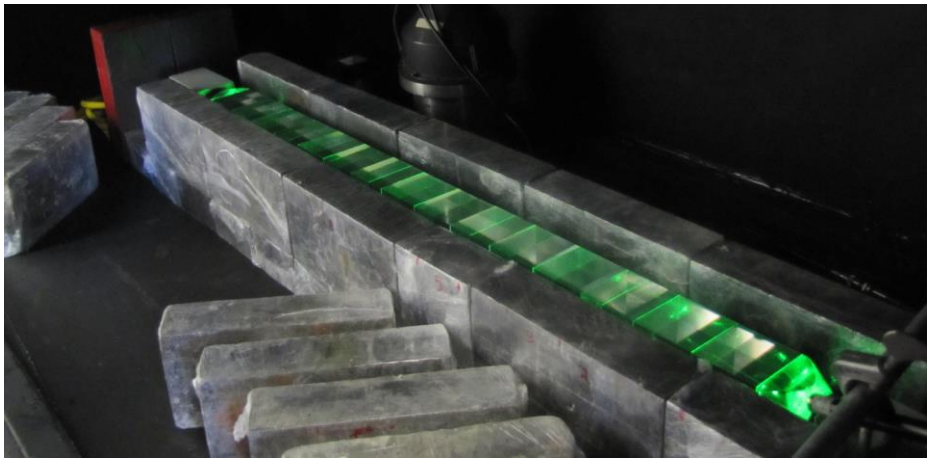


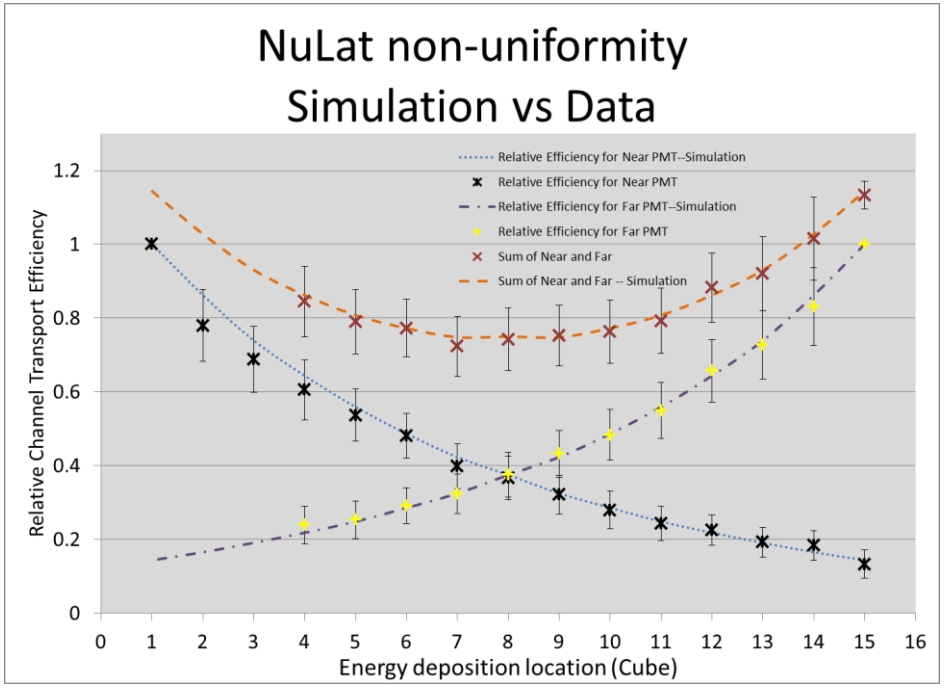
- Log plot of light output on the (X-Y) face of a mirrored NuLat design via deposition of 2 MeV in the central cell

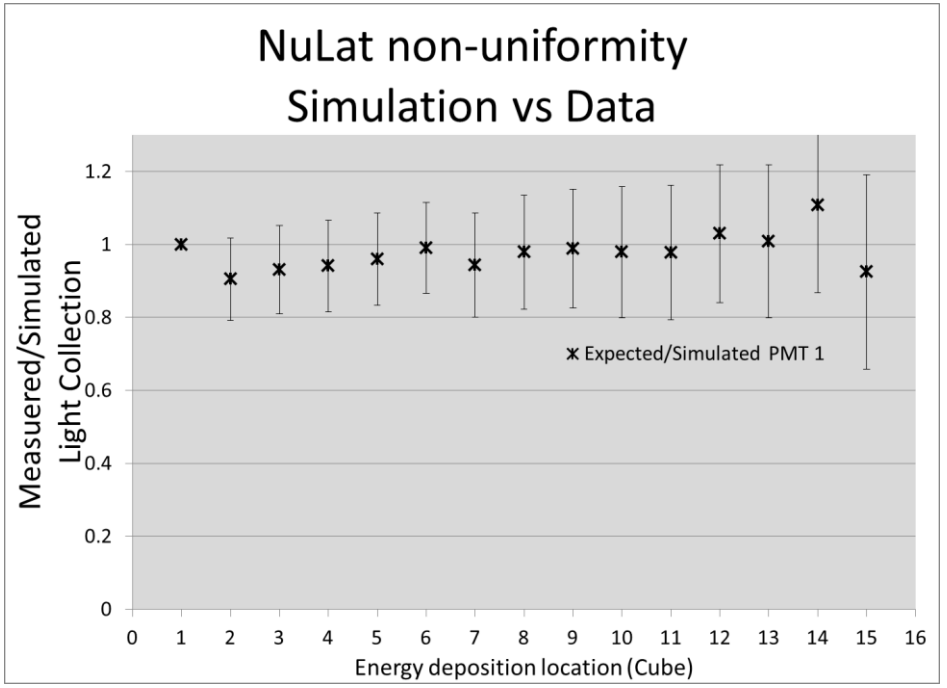
- **Most light goes to 6 direct channels!**
- The amount of light detected in the plane but off the main channel is at the level of < 5%
- The cube containing the energy deposit is identified uniquely by amplitude alone
- Detected light may further be identified by signal timing, permitted location (such as the gammas from positron annihilation must be on average in opposite directions)

NuLat 15 Cube
Full Channel Module Testing

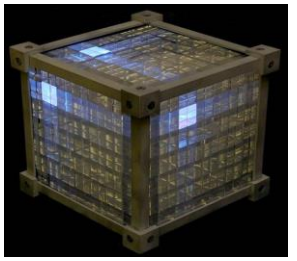




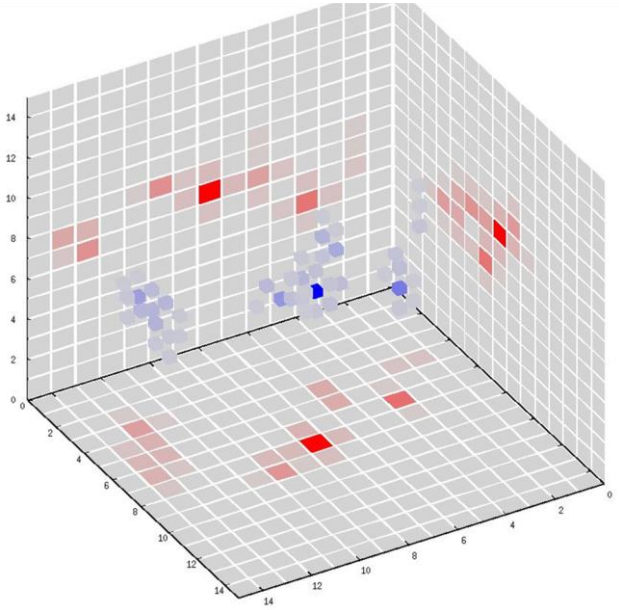




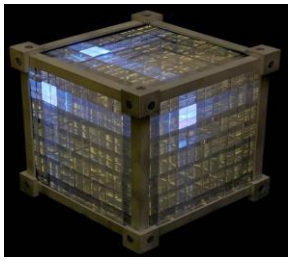
Unique Start Signal



- Positron plus annihilation gammas
  - large single cell (or two), small halo (0.1-1.0 MeV total), in that **time order**
  - **rejects most gammas** (primary reduction via passive shielding when close to reactor)
    - single Compton within detector with no halo
    - multiple Compton within detector
    - with too large a halo
    - single P.E. effect with no halo
  - **rejects most cosmogenic backgrounds**
    - pulse-shape discrimination rejects fast
    - Neutrons by PSD
    - ^{9}Li, ^{8}He are β- emitters with no annihilation
  - pair production reduced by primary shielding



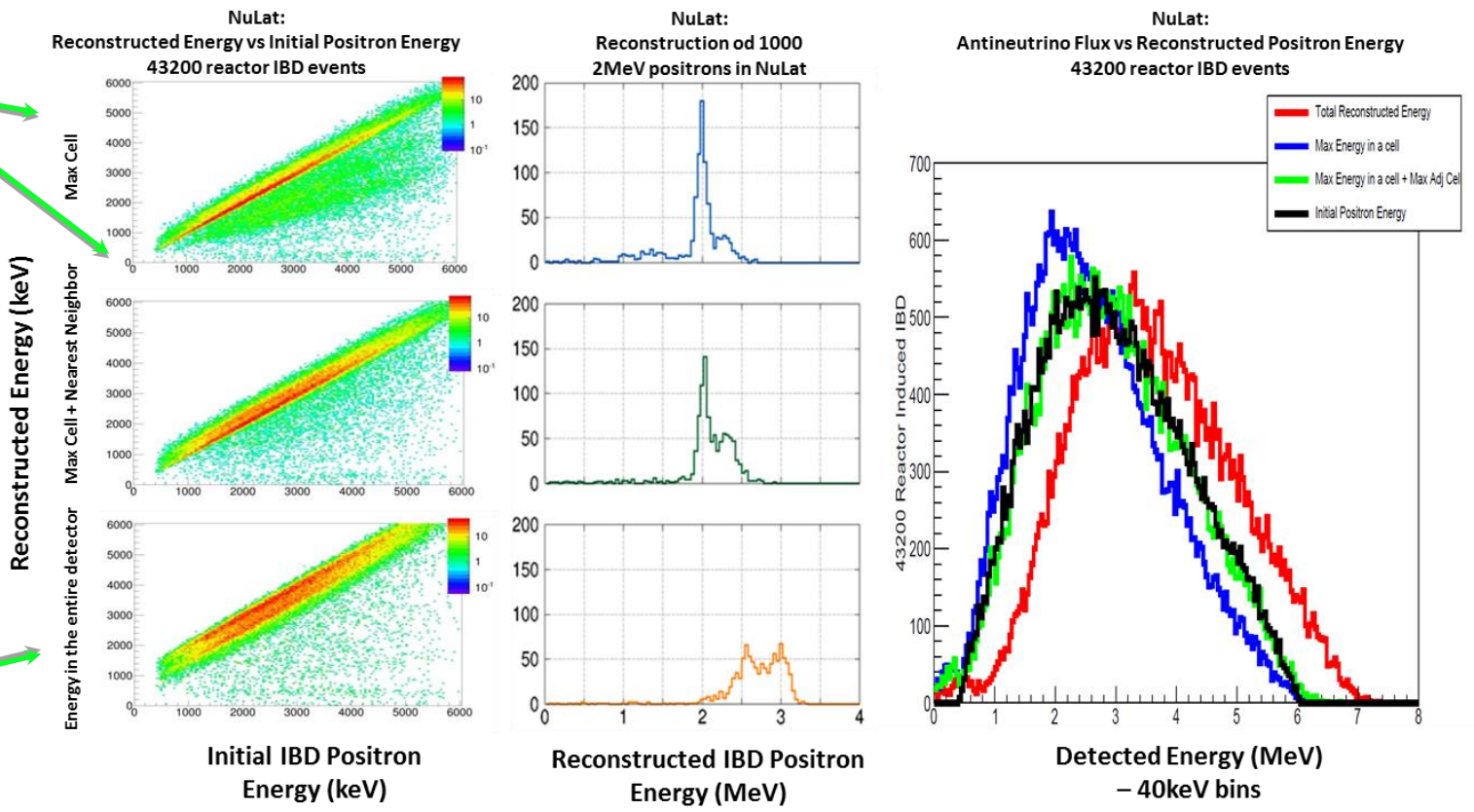
Energy Resolution



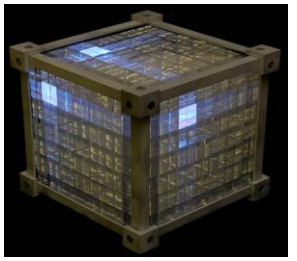
- $E_\nu = E_{e+} + 1.8$ MeV
- full positron energy in one cell or at most two (vertex cell)
- minimal contamination by annihilation gammas in vertex cell
- allows excellent neutrino energy resolution throughout the ***complete*** detector

unique to NuLat

available to all integrating small detectors



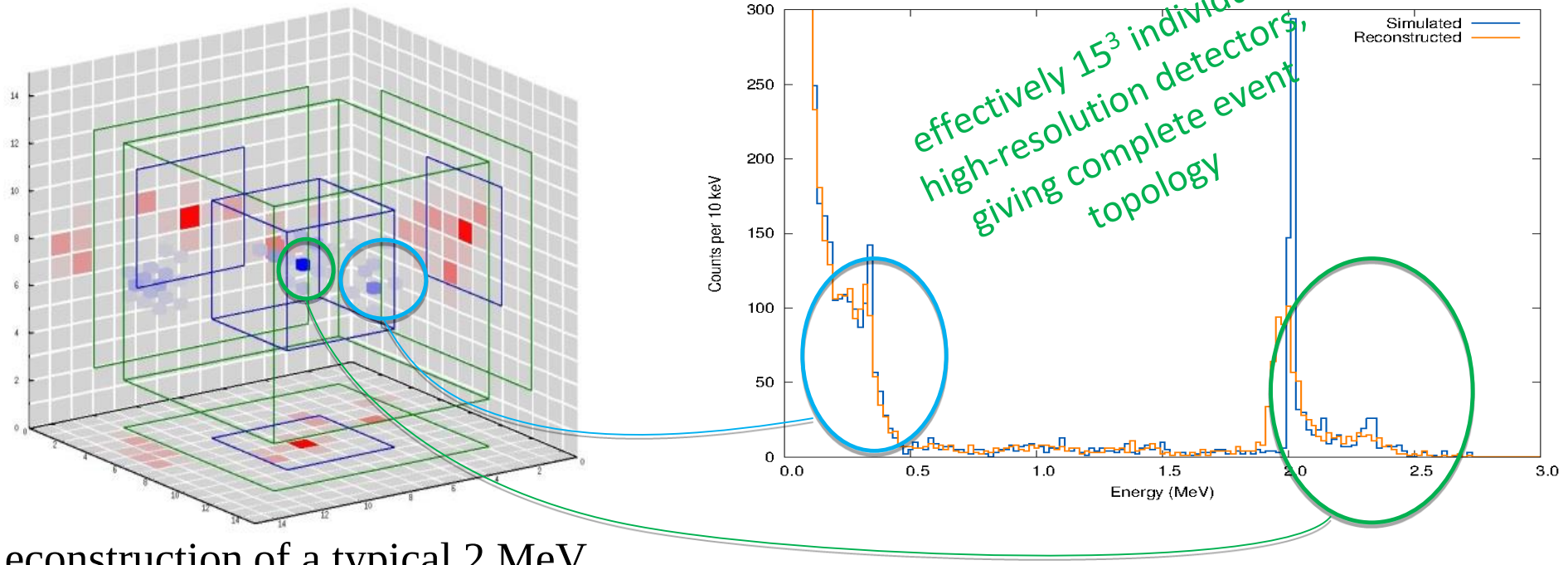
Event Topology



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

$$\xrightarrow[\tau \sim 10\mu s]{} n + {}^6Li \rightarrow \alpha + {}^3H$$

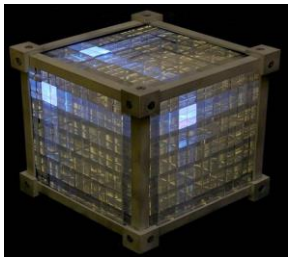
4%/600 p.e. /MeV)
single cell position (< 3 cm w timing)



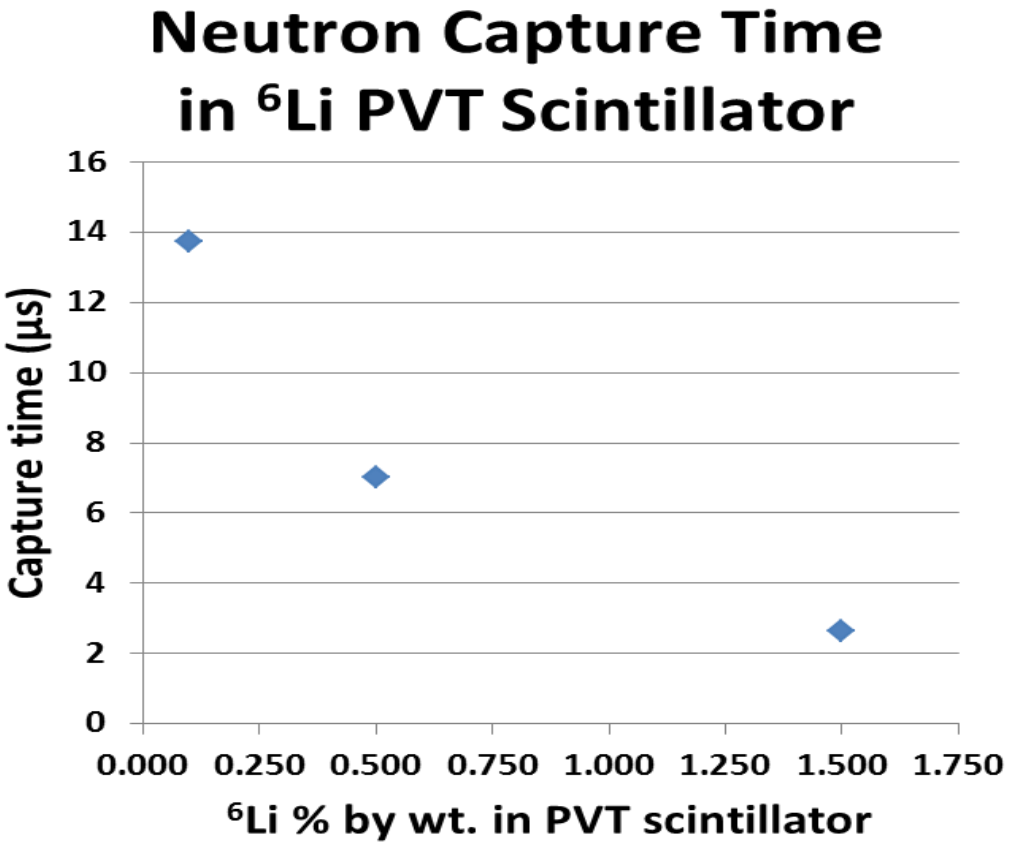
Reconstruction of a typical 2 MeV positron event.
note: 3D allows digital separation of events ***along*** channel

Average single-cell prompt response to a uniform 3.8 MeV anti-neutrino flux.
no fiducial cut

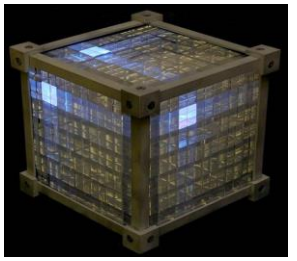
Unique Stop Signal

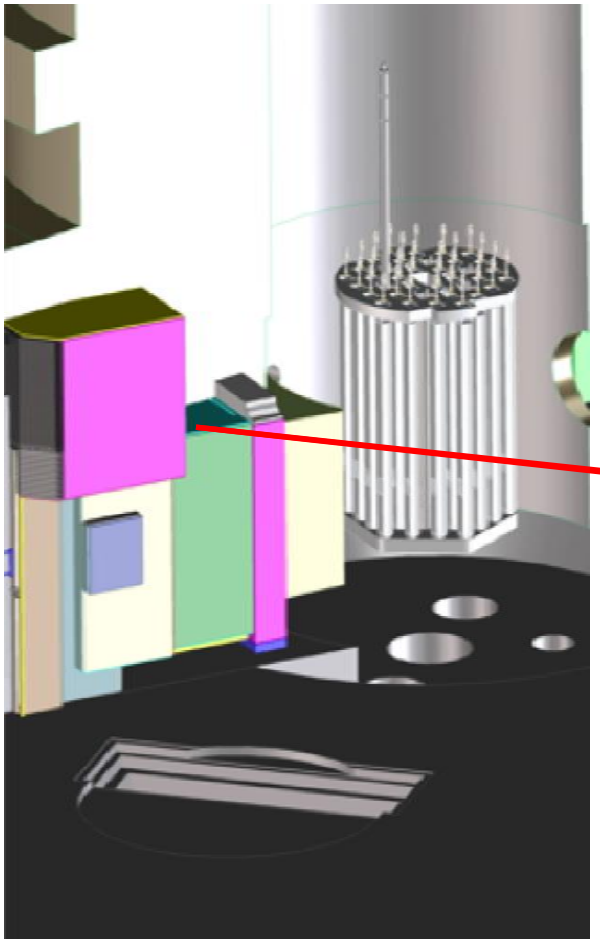


- Lithium-6 doped PVT
  - 7 μs time correlation
    0.5% by wt. ^{6}Li PVT
  - mono-energetic ~400 keV_{ee}
  - single cell stop tag
  - n/gamma PSD separation
  - 23% n capture in same cell as positron
  - 60% n capture in same cell as positron plus the six facing cells
  - 940 barns
  - Work underway on custom ‘geometric’ trigger using UH IRS3d electronics



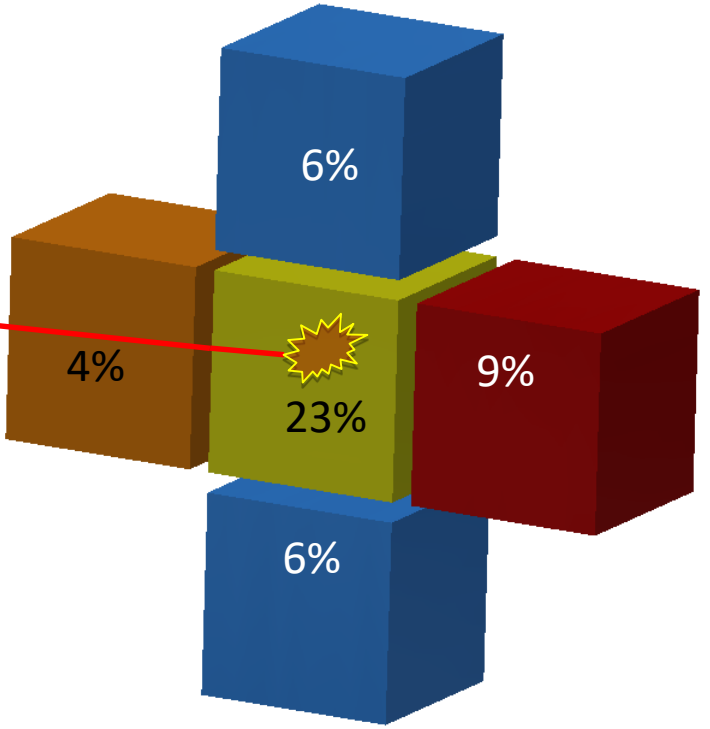
Unique Topology for the Ensemble of IBD Events



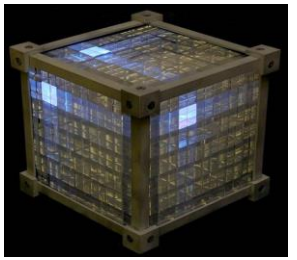


$\bar{\nu}_e$

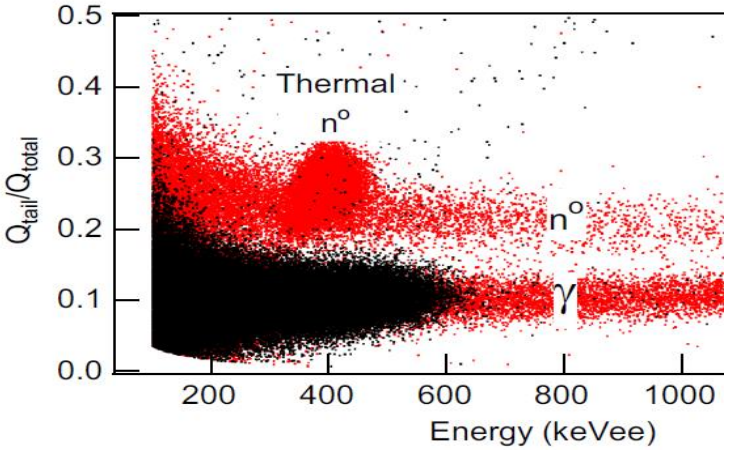
Relative location of neutron capture
to IBD positron production



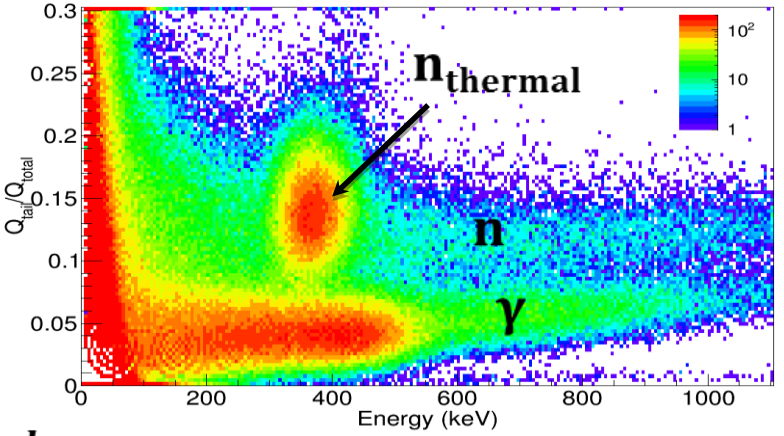
PSD in ^{6}Li Plastic



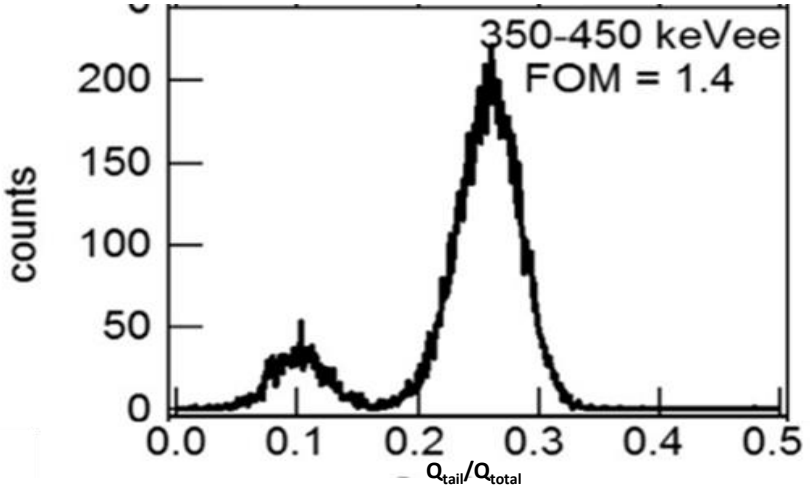
Cherepy NIM A778 2015

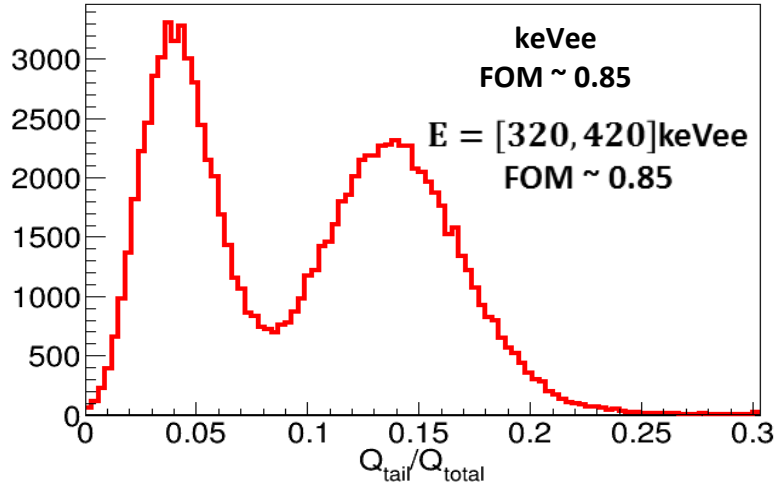


Eljen LLNL based EJ-200 ^{6}Li PSD characterization as measured at Virginia Tech



$$FOM = \frac{d}{FWHM_{\gamma} + FWHM_{n}}$$

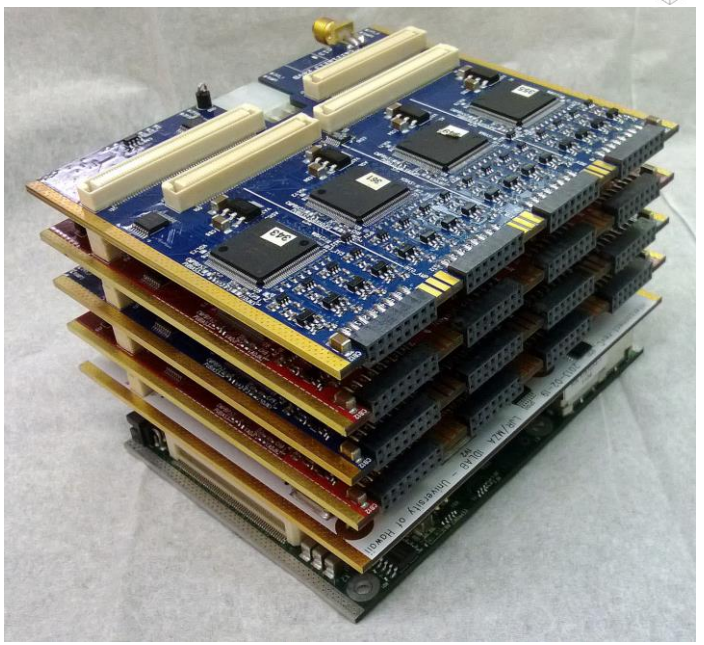


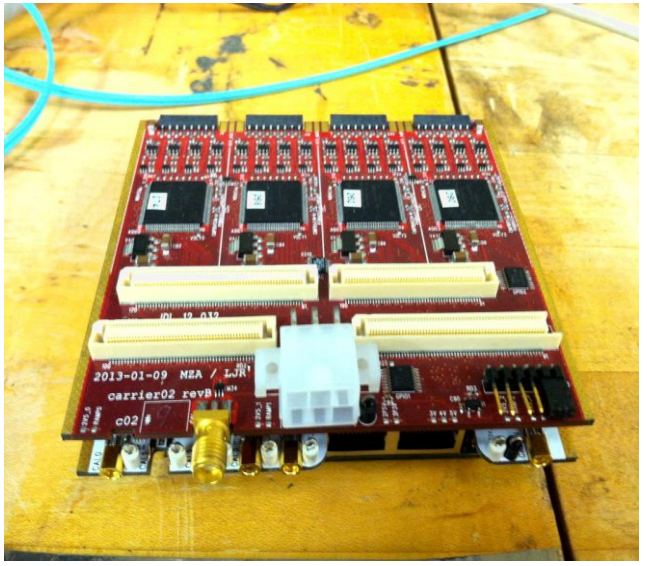


Better energy resolution results in better background rejection.

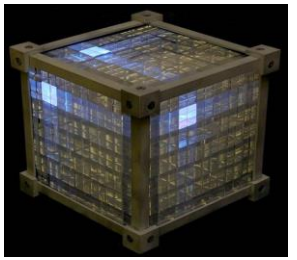
Readout from IRS3d Custom Digitizers (developed at UH)

- SCROD - board stack with IRS3d chips similar to those used in Belle – 100 ps timing resolution
- Separate Data and triggering paths
- 16 chips per board stack -> seen at right
- 8 channels per chip, 2-4 gigasamples / s (2.73 GSa/s, 366 ps)
- 128 channels per stack
- Many channels in a small space
- Downside: heat!
- Firmware under development at VT for geometric trigger





^{222}Rn Internal Calibration

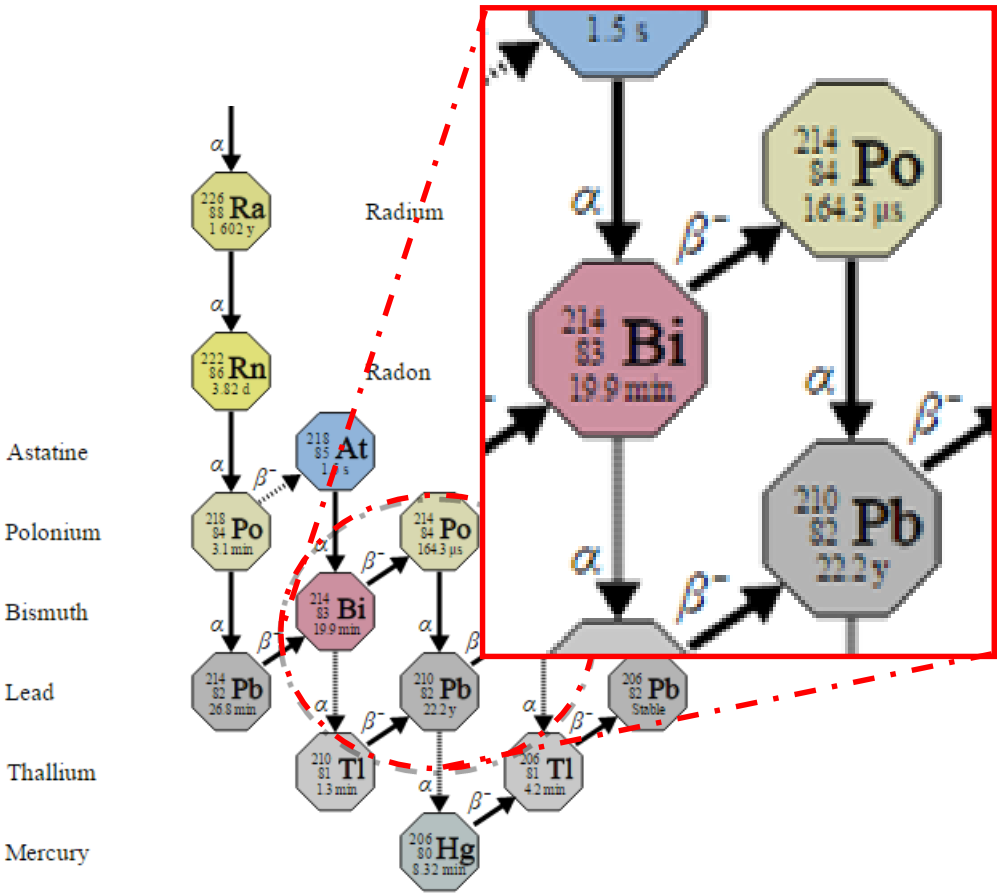


- ^{226}Ra ^{222}Rn-Generator
- Fill airgaps with ^{222}Rn rich gas
- Same/adjacent cell

  ^{214}Bi → β− + ^{214}Po

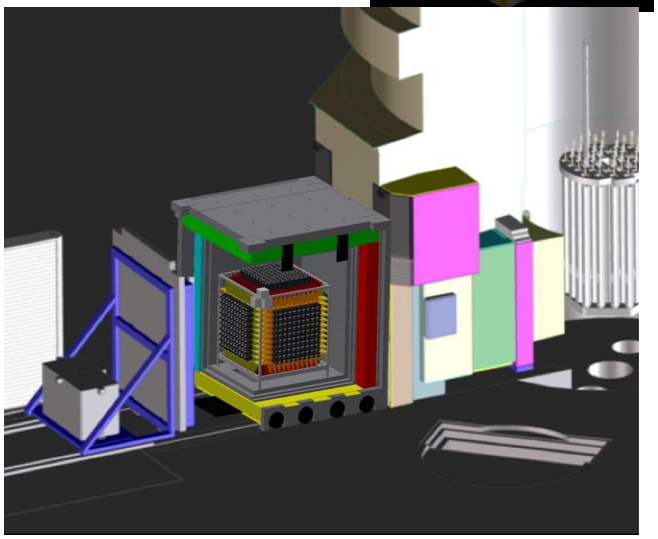
  followed by ($t_{1/2}$=164µs)

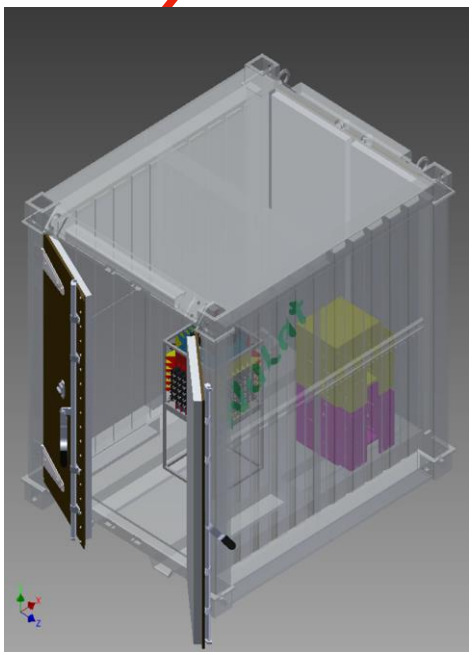
  ^{214}Po → α + ^{210}Pb
- Close temporal and spatial structure to that of a antineutrino capture
- Provides PSD stop tag
- Mean β− E = 642keV
- Mean α E ~ 700keVee
- Characterize surface scintillation effects

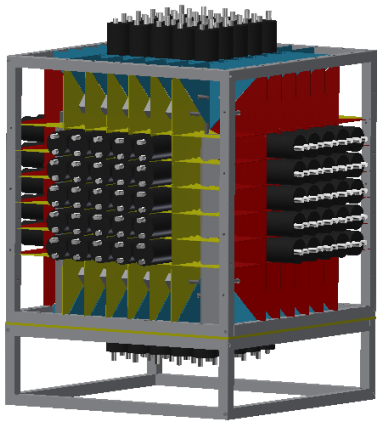


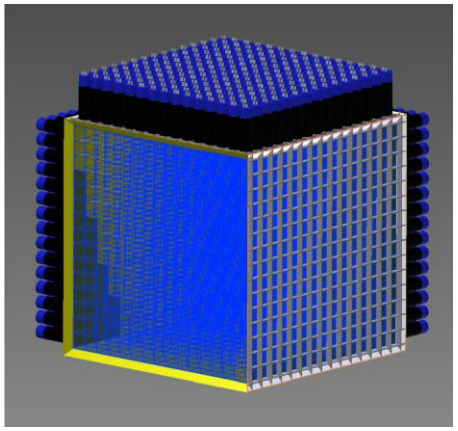
ROL 5^3 Antineutrino Detector

- Ongoing tests with Lithiated plastic
- 4 faces instrumented with PMTs, readout (125 PMTs)
- Calibrations with Rn, ^{60}Co, AmBe
- Liquid version being developed
- Construction to be completed and testing underway 2019
- Deployment:
  - NIST: L ≈ 4.7m,P = 20 MW

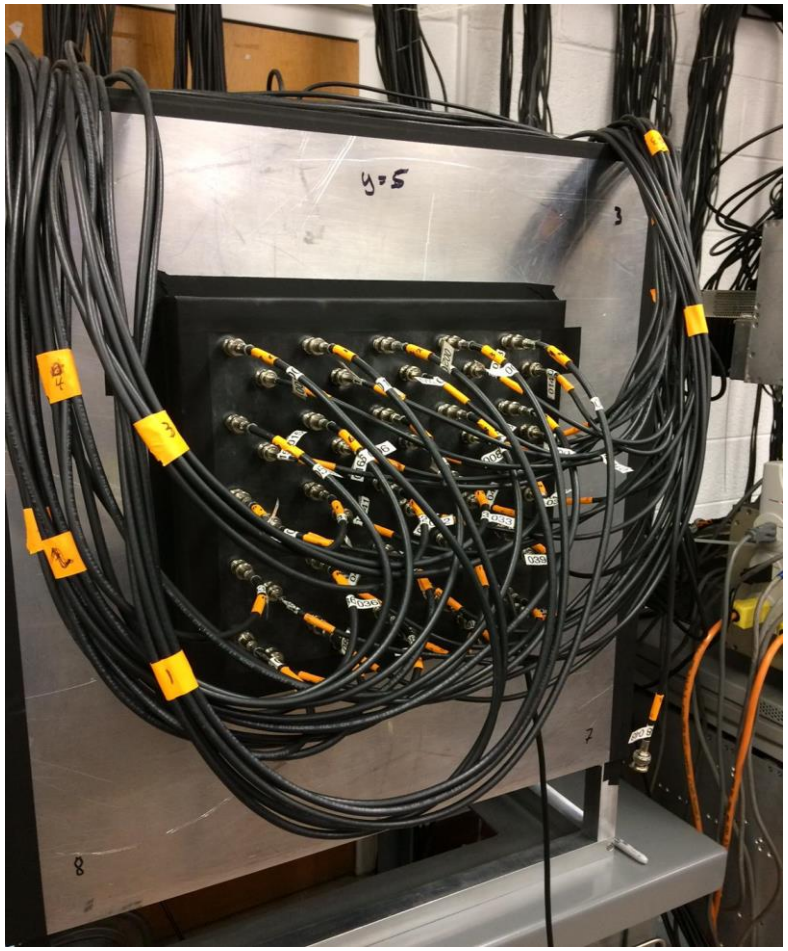


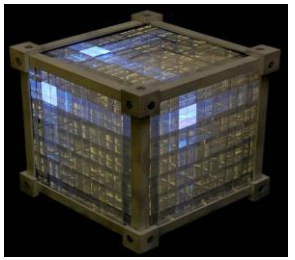


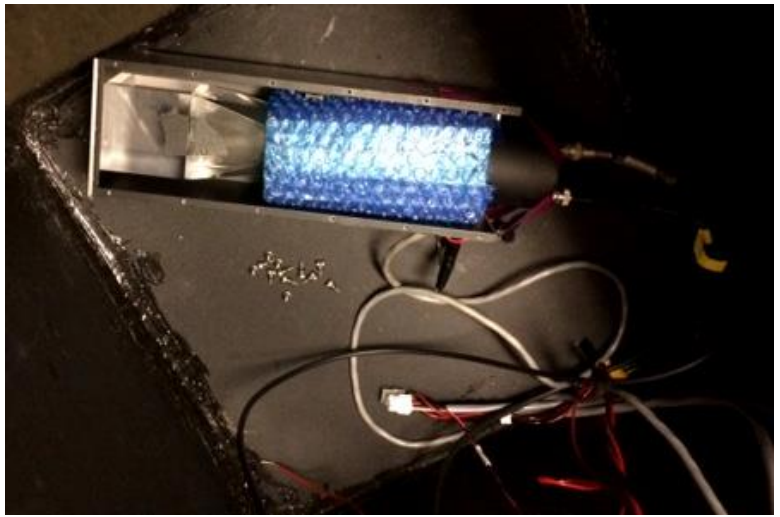


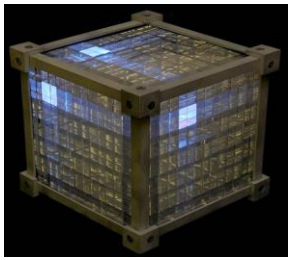


Progress Photos!



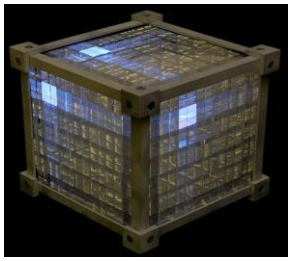






Conclusions

- NuLat design:
  - Precision topology capabilities E(x,y,z,t)
  - Short mean time for coincident signal
  - Pulse shape discrimination for both start and stop signals
  - Several methods of evaluating systematics
- NuLat addresses
  - Reactor neutrino physics
  - Reactor monitoring
  - Special nuclear material safeguards



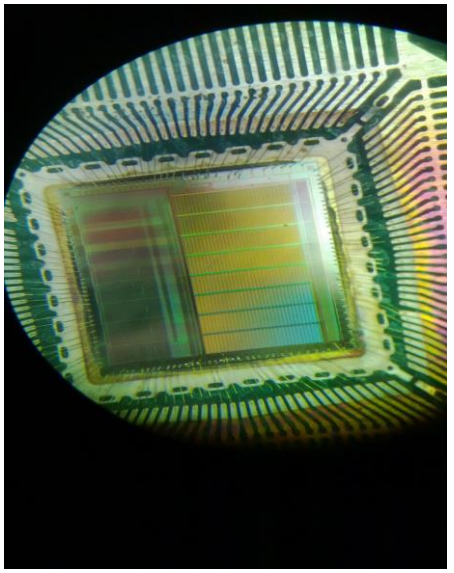
Backup Slides

Additional System Electronics

- Clock and Triggering Board
  - Provides a low-jitter clock to front-end modules (σ_t < 2 ps)
  - Issues system triggers to all boardstacks based on parameters set by the user
  - Can distribute pulses for testing and calibration
- Dell server and other computers for storing data, remote operation
- Laser calibration system

The clock and trigger board, designed by Serge Negrashov here at UH

Keeping it Cool if needed



- 84 boards total, 192 IRS chips, along with amplifiers, PMTs, etc. produce ~ 400 W heat
- The mTC's cover and shielding restrict air flow, making cooling more difficult
- Fans / air flow isn't enough!
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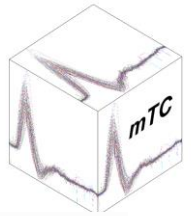
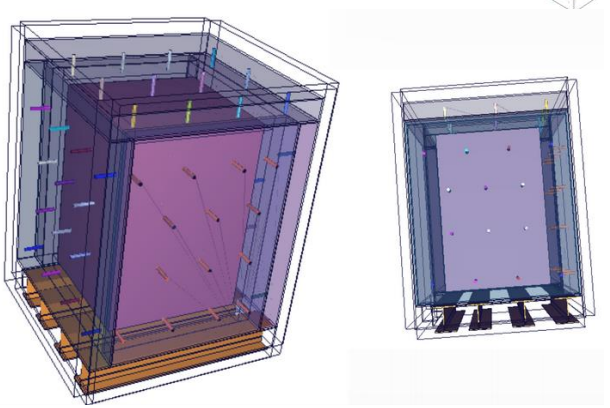
- We use the following:
  - Koolance hard drive chiller plates
  - An "Advantage" water chiller unit - 16 °C, 2 gallon per min
- $T_{inside} \rightarrow$ 20-35 °C
- $T_{chips} \rightarrow$ 35-55 °C

Keeping it Clean: The “Cave”





- Designed to shield the mTC near reactors
- Can be assembled and disassembled when needed, can be moved on wheels (though it weighs 40 tons so it’s slow!)
- Comprised of six nested “cubes”, giving dimensions: 1.8m x 2m x 2.7m
- Layers alternate between borated-
- polyethylene sheets and steel plates
- Geant4 used to model backgrounds with
- and without shielding

Type	normal #/mTC/s	shielded #/mTC/s	normal #/cm^2/s	shielded #/cm^2/s	attenuation %
Muon	15	1.72	.017	2.0×10^{-3}	88.2%
Neutron	10151	0.082	12	9.7×10^{-5}	99.9%
Gamma	860	9.03	1.0	1.1×10^{-2}	98.9%