Update on NuLat: A Compact, Segmented,Mobile Anti-neutrino Detector

John Learned

for the NuLat Collaboration:

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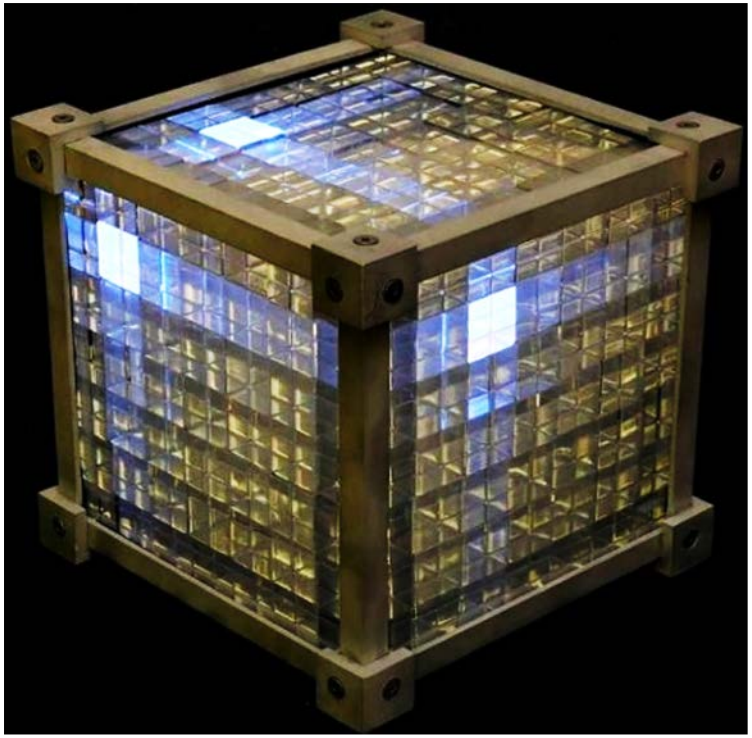
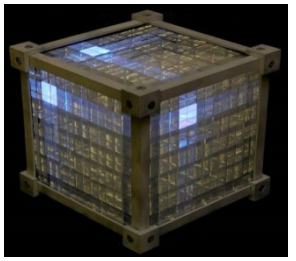
1: *Drexel,* 2: *Johns Hopkins,* 3: *LSU,* 4: *NIST Gaithersburg,* 5: *NCCU, 6: Kapiolani College:* 7: *University of Hawaii,* 8:*Virginia Tech, 9: Oak Ridge National Lab.*

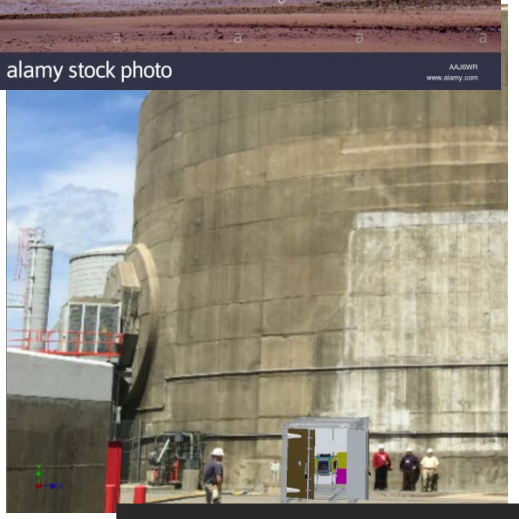
And a number of others who have helped along the way.

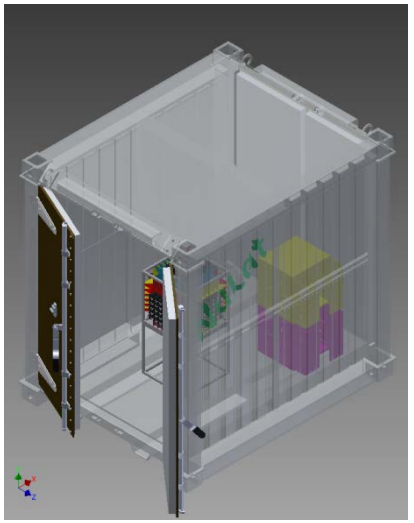


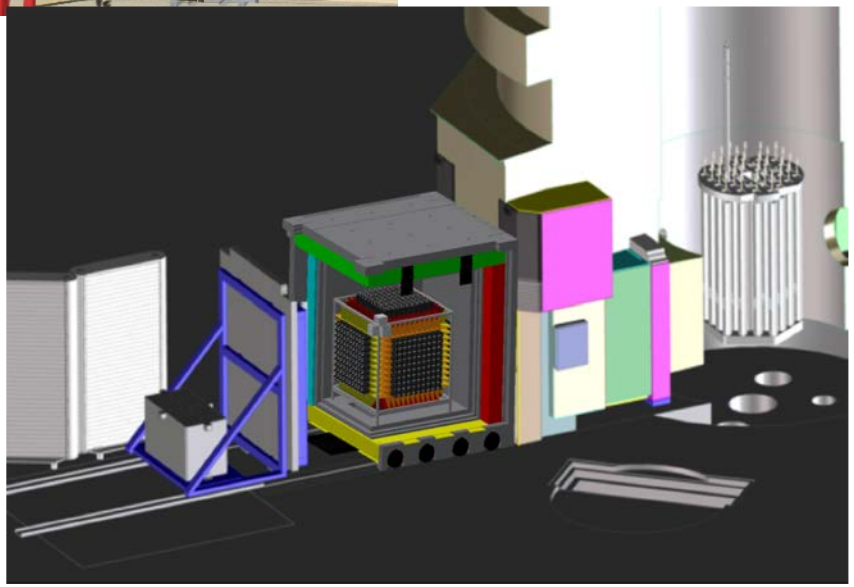
NuLat Motivation

- Demonstrate reactor monitoring capabilities
  - Security monitoring
  - Commercial burn-up monitoring
- Investigate fast neutron directionality capabilities
  - Detection of special nuclear material
- Probe reactor anomalies
  - Sterile neutrino search
  - Precision ν_e energy spectrum measurement
- 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



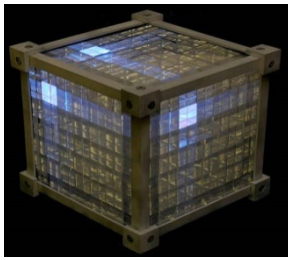






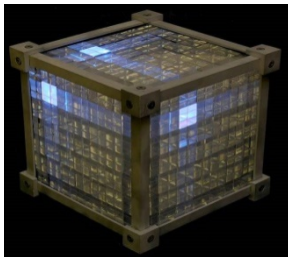
NIST NCNR Reactor

NuLat Features



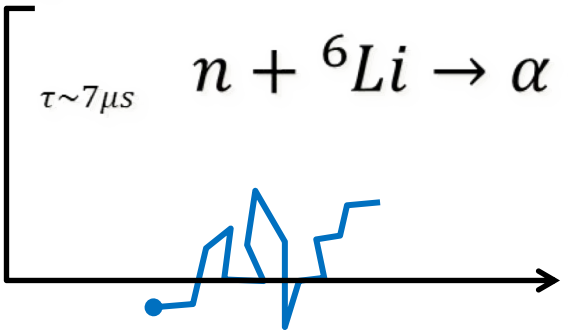
Feature	Rational
Excellent Energy Resolution	Precision Spectral Analysis – Distortions from prediction
Unique Start Signal	separate positrons from gammas, neutrons, and electrons
Unique Stop Signal	separate n-capture from backgrounds
Short Time Delay	improves real/random
Fine Segmentation	smaller improves real/random
E,x,y,x,t complete event topology	best method to remove residual backgrounds
Minimal Wall Material	improves systematics and signal degradation
Fast Timing (Sub Nanosecond)	time-ordering of energy deposits
Minimal Fiducial Cut Required	minimizes shielding size
Strong neutrino source	L/E easier at shorter distances, better S/B
Movable	Vary L without E, multiple sources and uses

Classic $\overline{\nu}_e$ Signature



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

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



IBD

(Inverse Beta Decay)

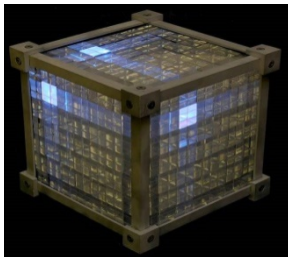
- $\overline{\nu}_e$

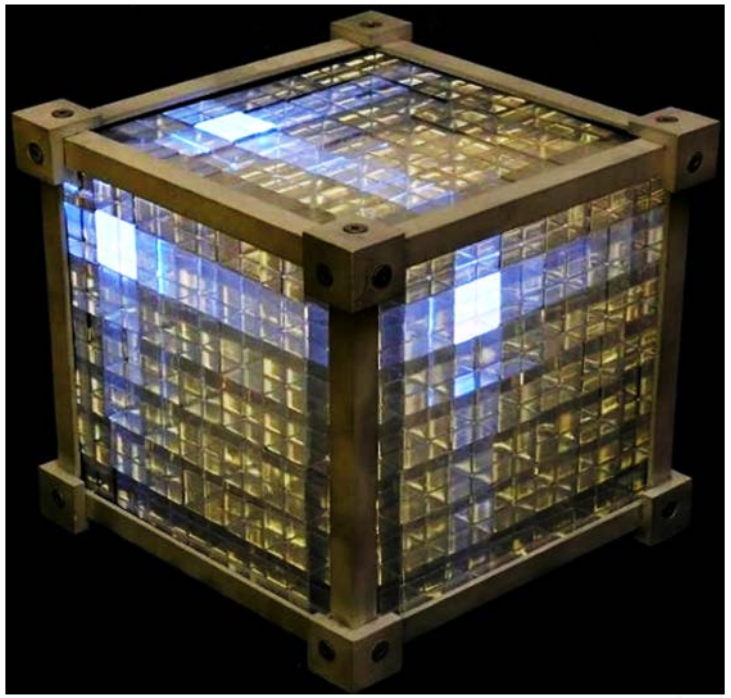
e^+ annihilation

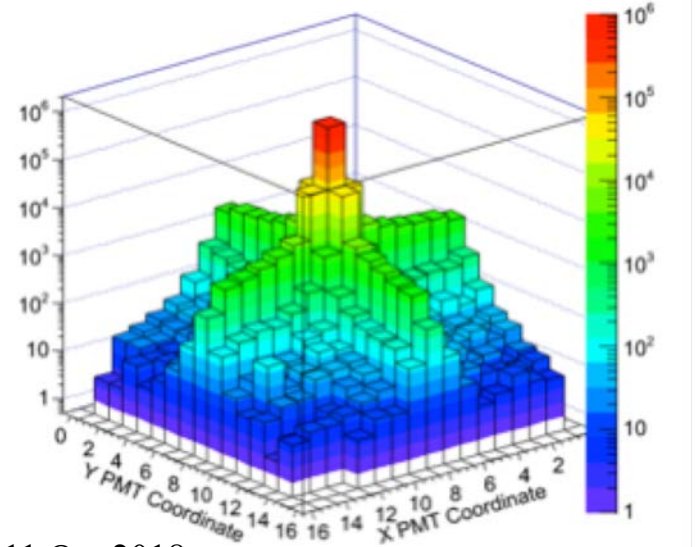
- ($n + {}^6Li \rightarrow {}^4He + {}^3H + 4.8$ MeV)

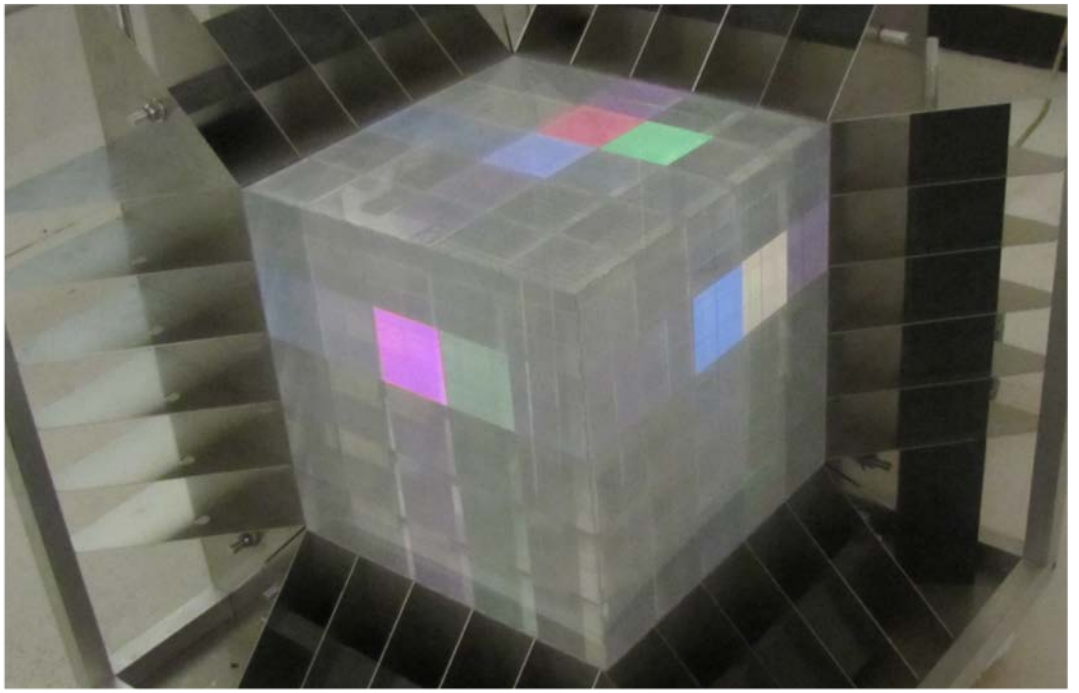
localized 400 keV_{ee}

Raghavan Optical Lattice



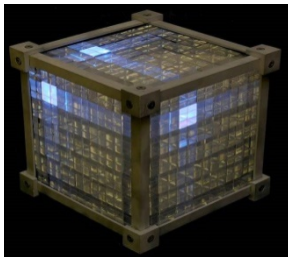






- light channeling via total internal reflection
- full 3D light collection along principle axes
  - Breaks degeneracies present in other detection schemes

Segmentation



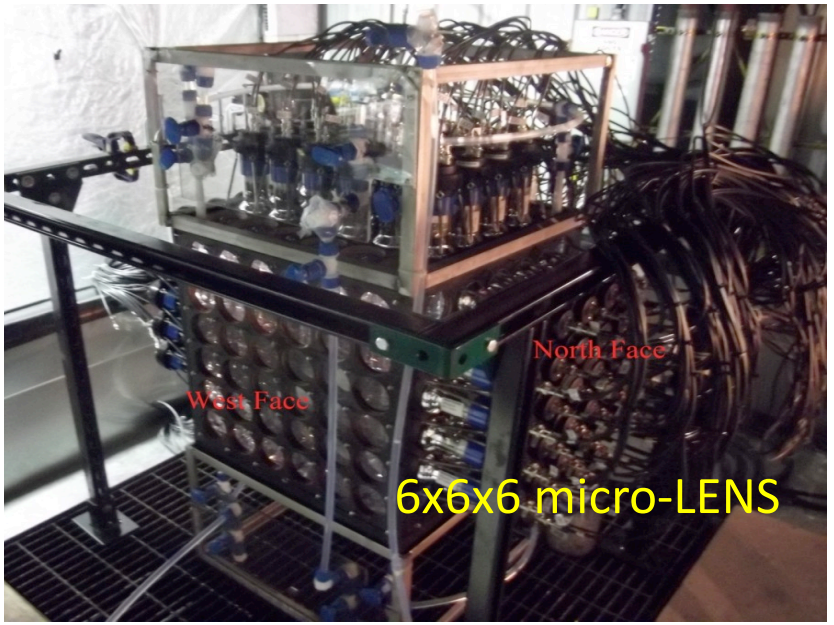
proven technique: micro-LENS

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)



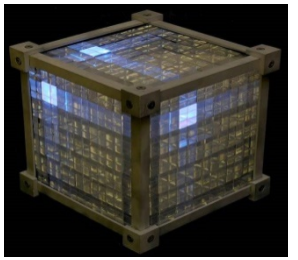
LENS 60x60x60

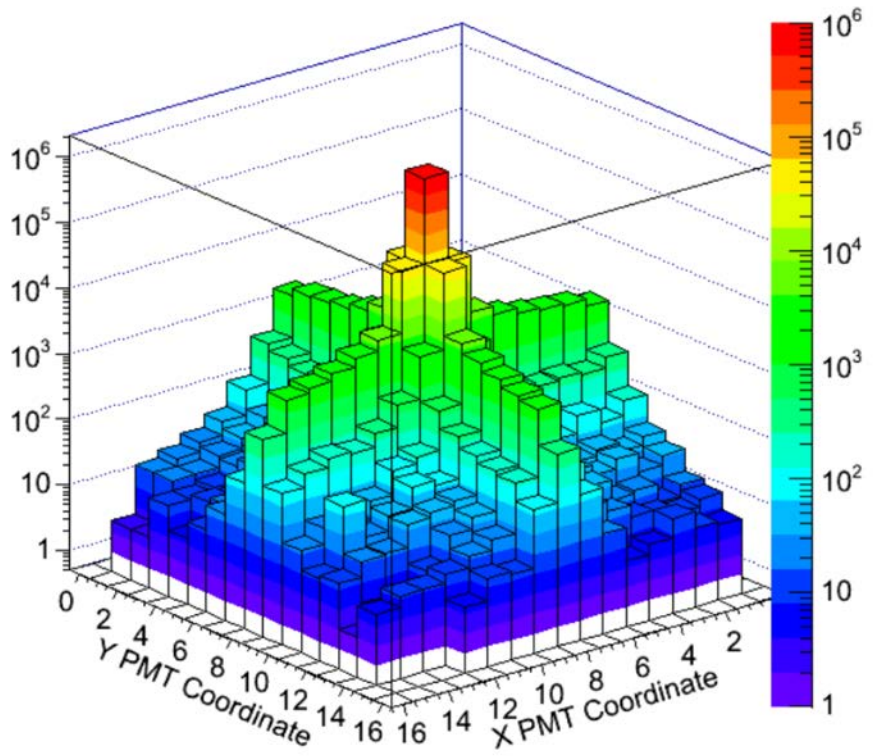
- NuLat Demonstrator (solid scintillator)
  - 5x5x5 cubes
    - effectively 125 individual detectors
  - 2.5 inch polished plastic scintillator cubes
  - 0.5% ^{6}Li by wt. loading (Eljen)
  - VM2000 reflective film 'dots' to maintain air-gap
  - ***Total*** light channeling (n=1 and 1.54)
  - Easily scalable to larger mass
  - True zero-mass wall – no energy loss

* Change to Liquid Base

Due to sold plastic inadequate optical properties, slow development and escalated cost.

Segmentation

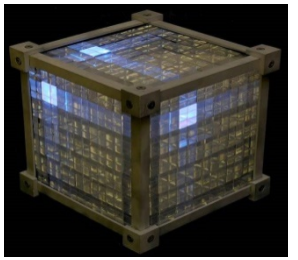




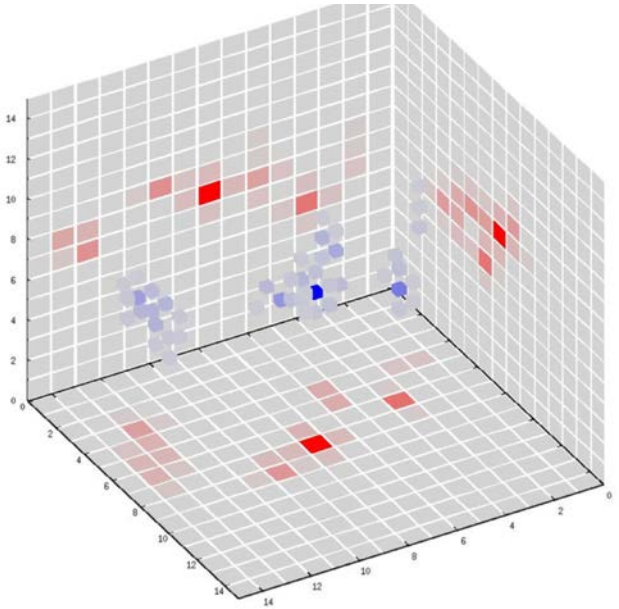
Log plot of light output on the (X-Y) face of a mirrored NuLat design via deposition of 2 MeV in the central cell

- The amount of light detected in the plane that is not directly facing the cell with the energy deposit is at the level of < 5%
- This pattern is seen in all 3 projections
- 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)

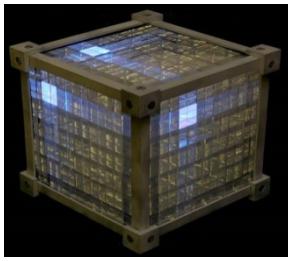
Unique Start Signal



- 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
    - ^{9}Li, ^{8}He are β- emitters with no annihilation
  - pair production reduced by primary shielding



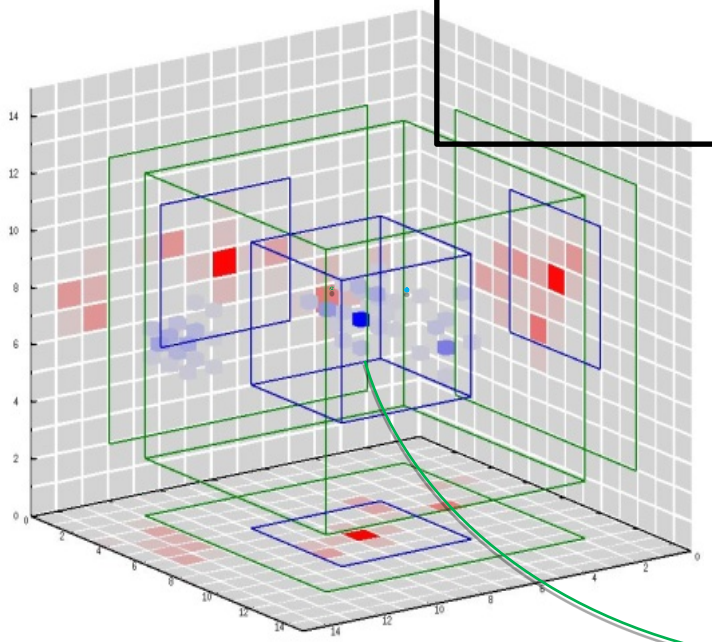
Event Topology

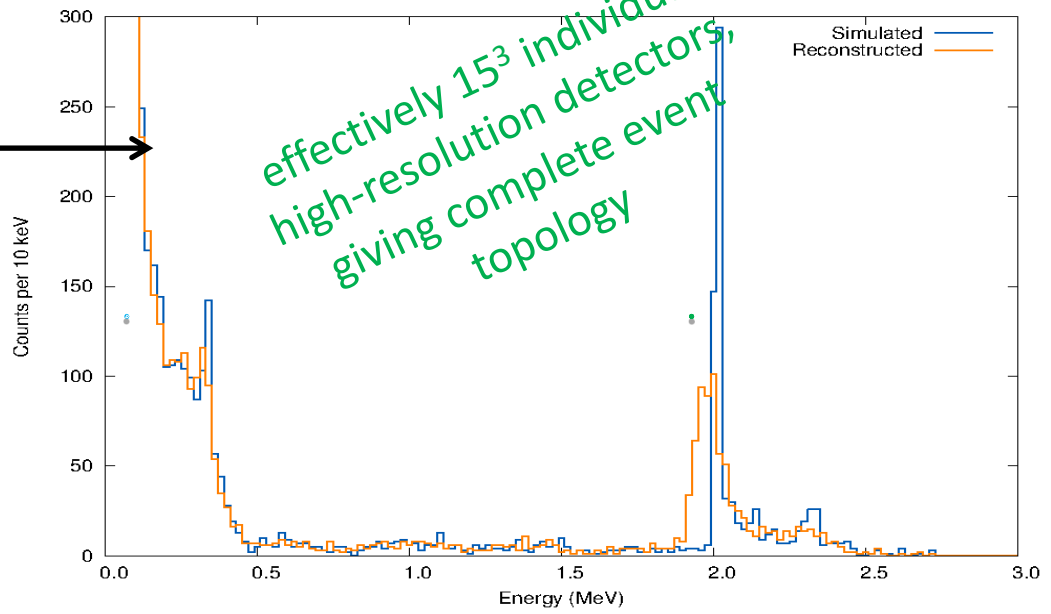


$\overline{\nu_e} + p \rightarrow e^+ + n$

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

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



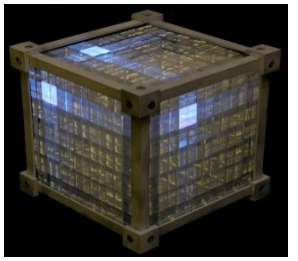


effectively 15^3 individual high-resolution detectors, giving complete event topology

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

Changes in Primary Design



Plastic scintillator on hold

Li loaded production delayed ~2yrs

Optical properties not as needed (transmission, pulse shape ID)

Cost much escalated

May go back later – easy change

Revert to LENS liquid design

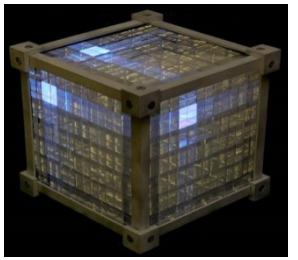
Use available Li loaded scintillator

Change from Teflon film to acrylic hollow windows

fill/drain & calibrate through small vertical tubes

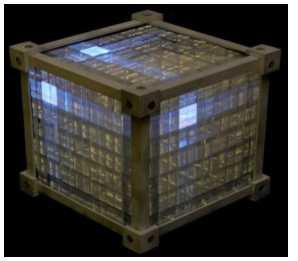
Assembly underway now.

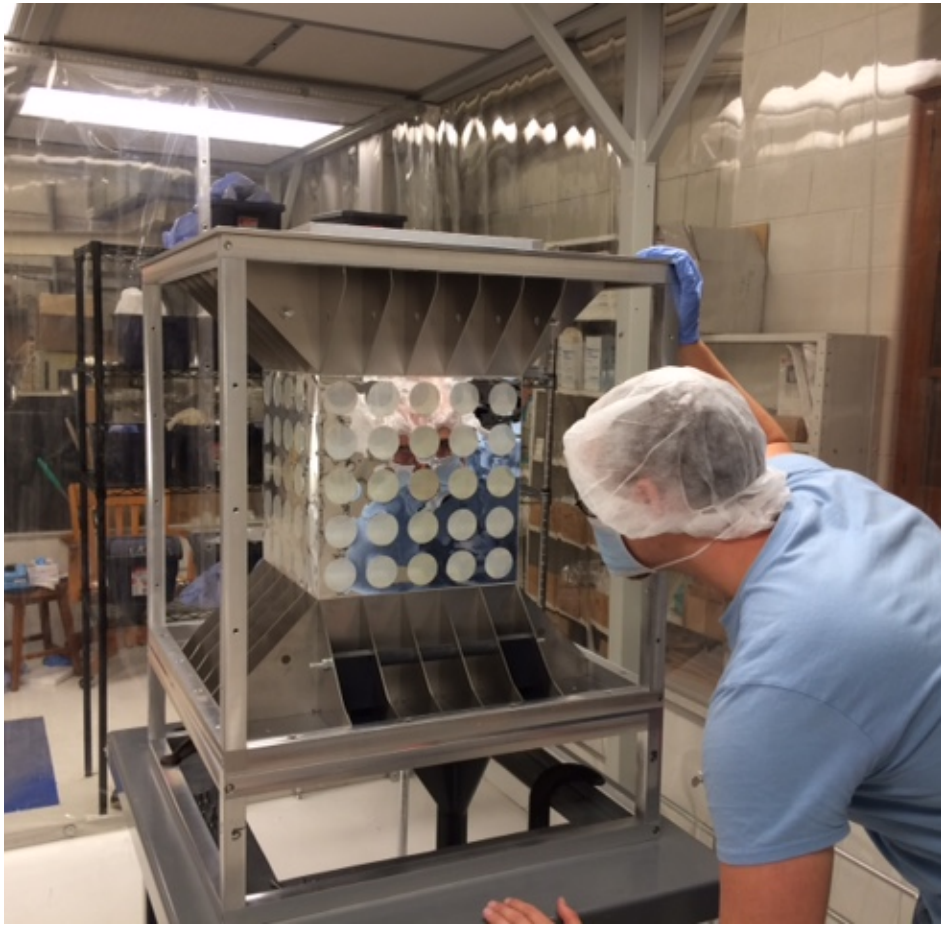
Hollow clear plastic windows



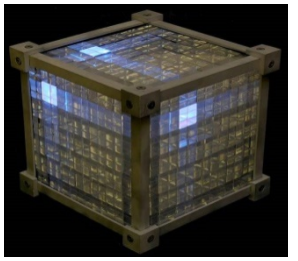
Bruce Vogelaar invention and implementation
Now using laser cutter, and will try laser welding

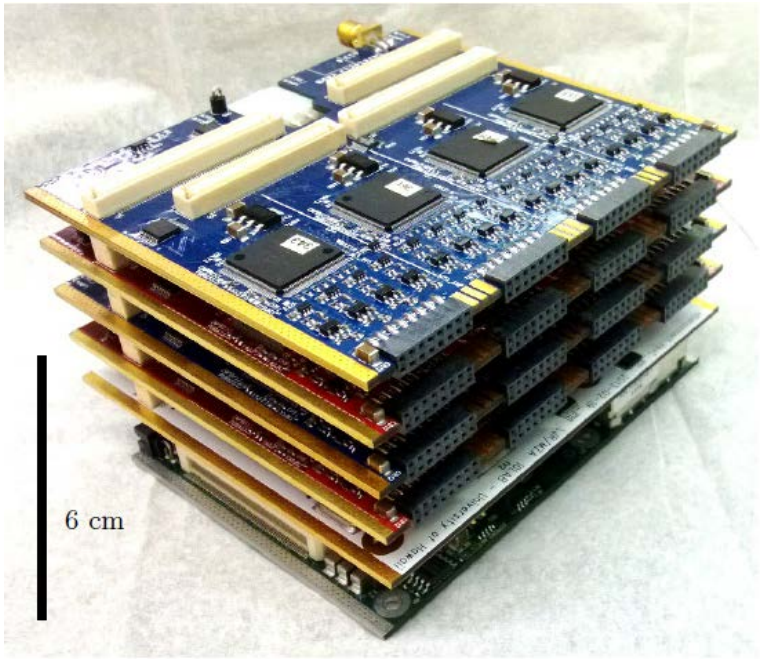
Prototype in Lab





Electronics Improvement





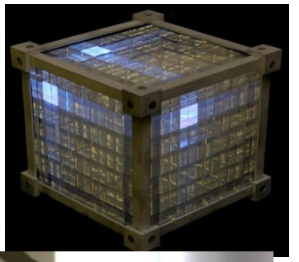
We utilize digitizers made at UH for miniTimeCube

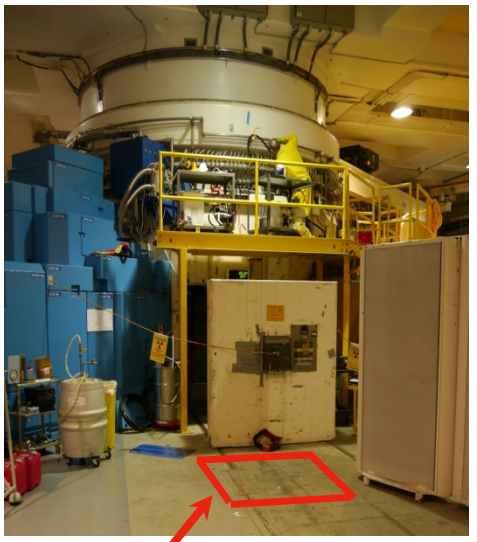
First triggering utilized simple multiplicity

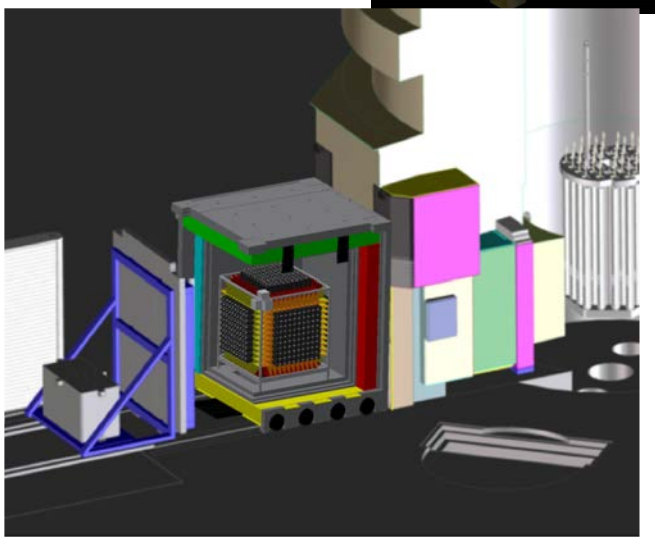
Upgrade almost ready, employing trigger specific to one cube in lattice (or with neighbors)

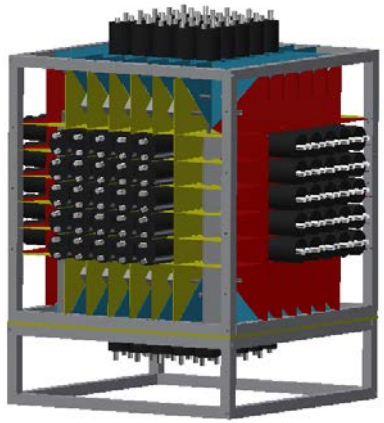
ROL 5^3 Antineutrino Detector

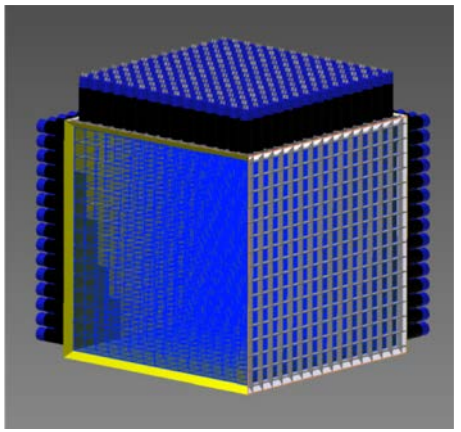
- Design Re- Finalized
- All major material in hand
- Construction to be completed ~late 2018
- Deployment:
  - Ready in Early2019
  - Venue(s) TBD… various alternatives

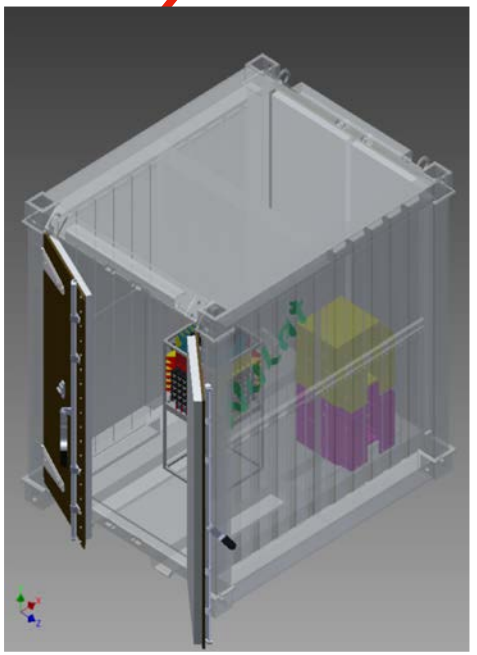




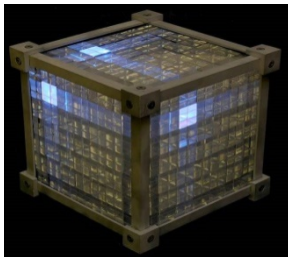




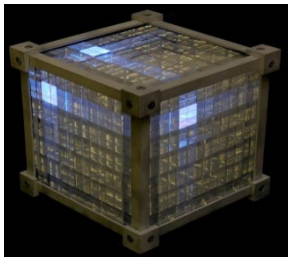




Conclusion

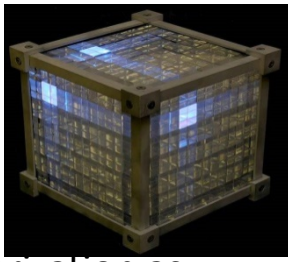


- NuLat design:
  - Precision topology capabilities E(x,y,z,t)
  - Short mean time for coincident signal
  - Pulse shape discrimination for both start and stop signals
  - Several methods of evaluating systematics
- NuLat addresses
  - Reactor neutrino physics
  - Reactor monitoring
  - Special nuclear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



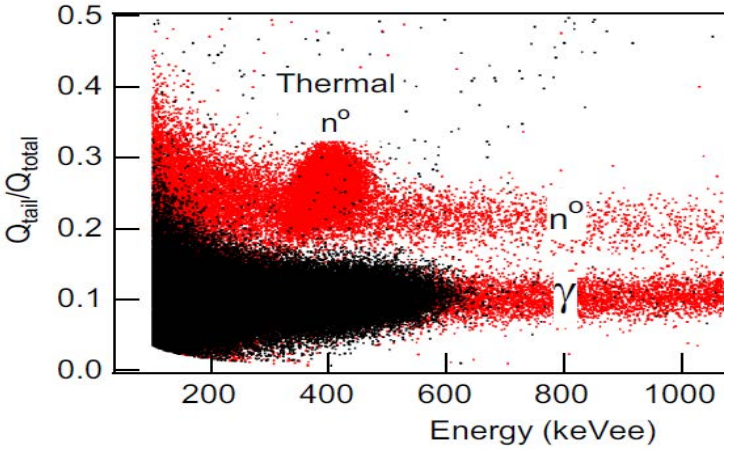
Questions?

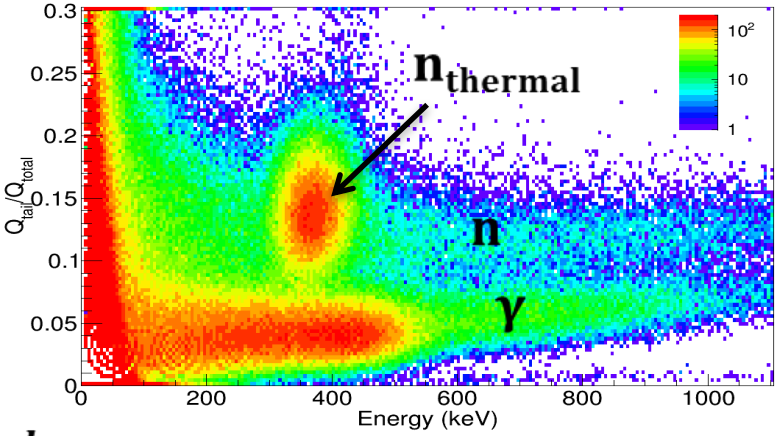
PSD in ^{6}Li Plastic



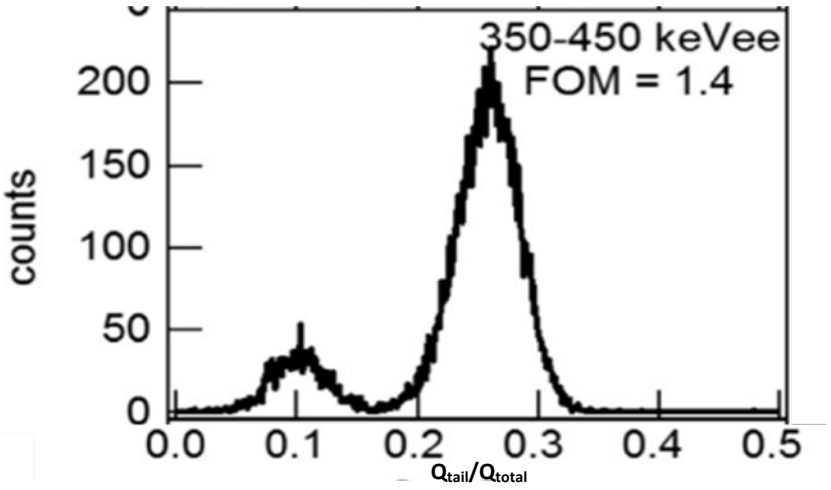
Eljen LLNL based EJ-200 ^{6}Li PSD characterization as measured at Virginia Tech

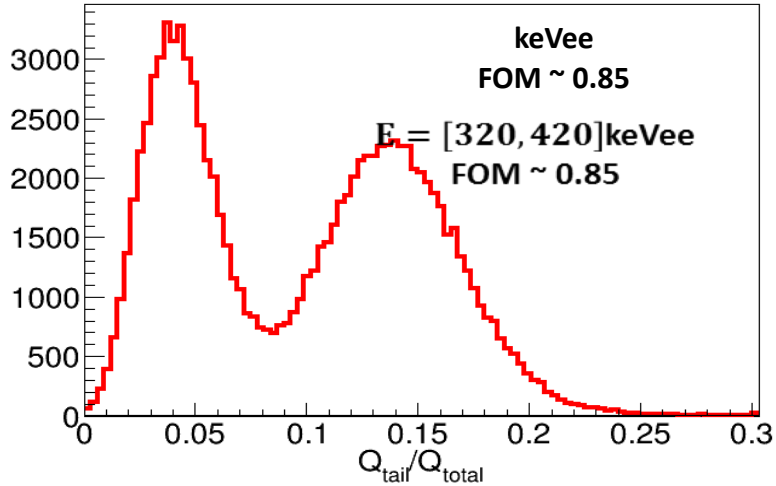
Cherepy NIM A778 2015





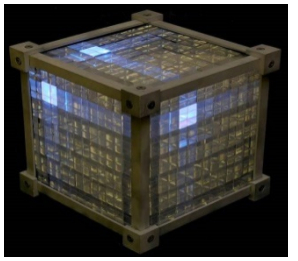
$$FOM = \frac{d}{FWHM_{\gamma} + FWHM_{n}}$$





Better energy resolution results in better background rejection.

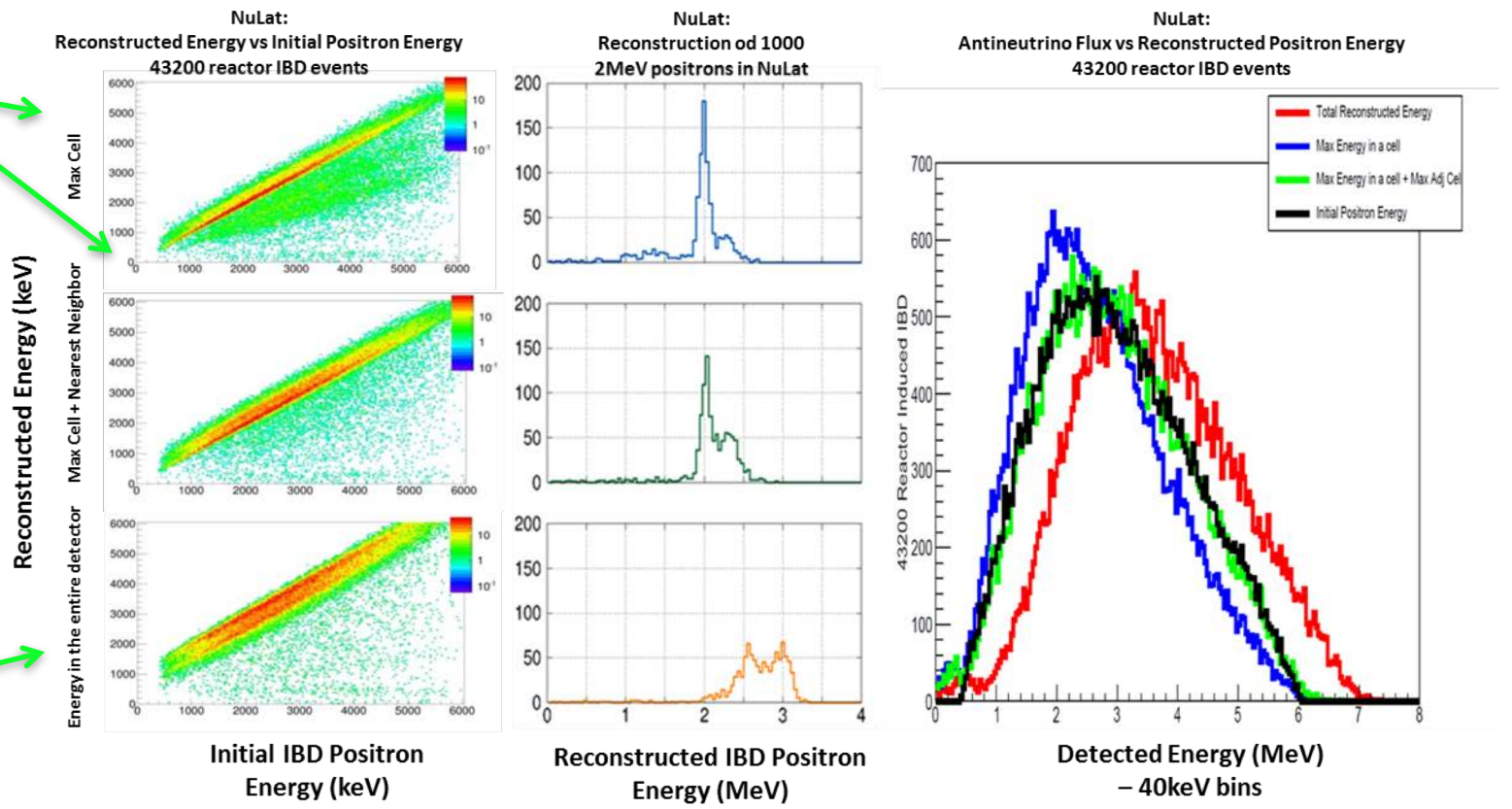
Energy Resolution



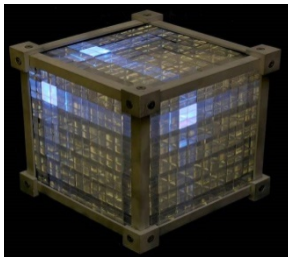
- → $E_\nu = E_{e+} + 1.8$ MeV
- → full positron energy in one cell or at most two (vertex cell)
- → minimal contamination by annihilation gammas in vertex cell
- → allows excellent neutrino energy resolution throughout the *complete* detector

unique to NuLat

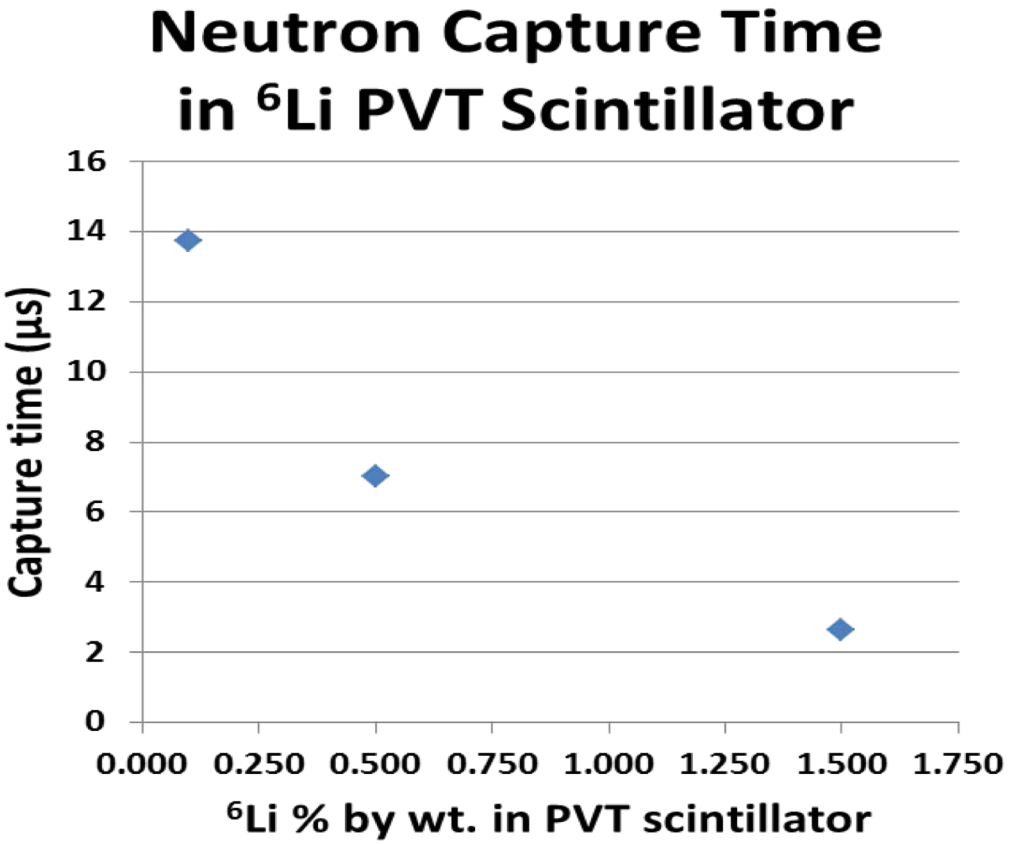
available to all integrating small detectors



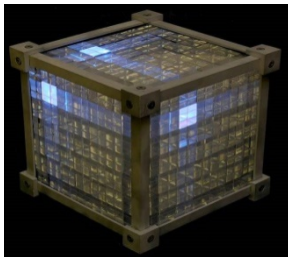
Unique Stop Signal



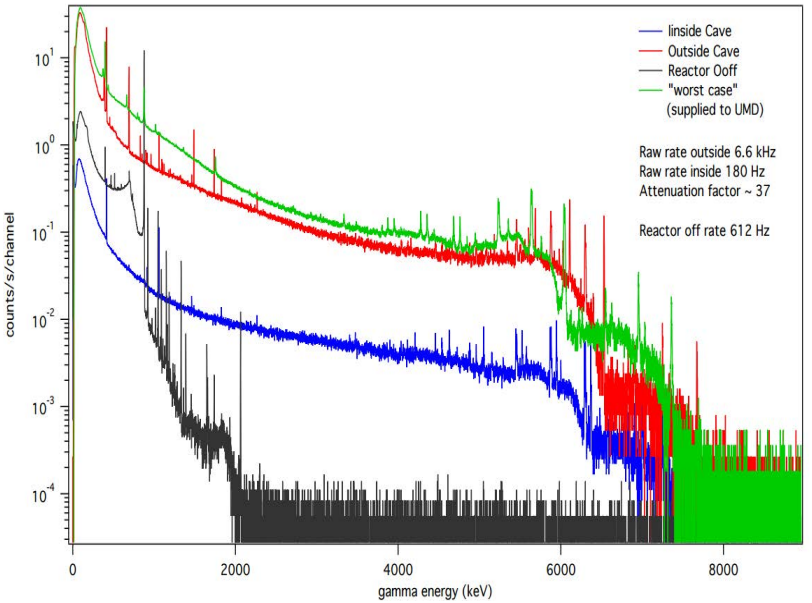
- Lithium-6 PVT
  - 7 μs time correlation
    0.5% by wt. ^{6}Li PVT
  - mono-energetic ~400 keV_{ee}
  - single cell stop tag
  - n/gamma PSD separation
  - 23% n capture in same cell as positron
  - 60% n capture in same cell as positron plus the six facing cells
  - 940 barns

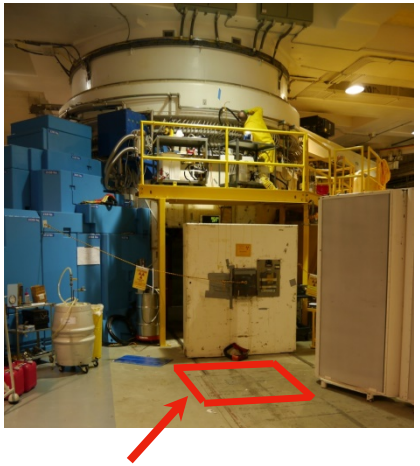


NIST Background Studies

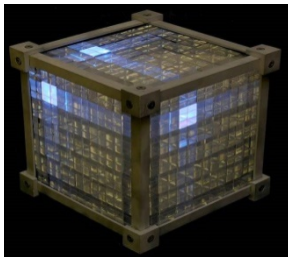


- Gamma spectrum surveyed via germanium detector (red)
- Germanium detector response to gamma model developed (blue)
- Gamma model allows for detailed simulation studies inside mTC Cave





^{222}Rn Internal Calibration

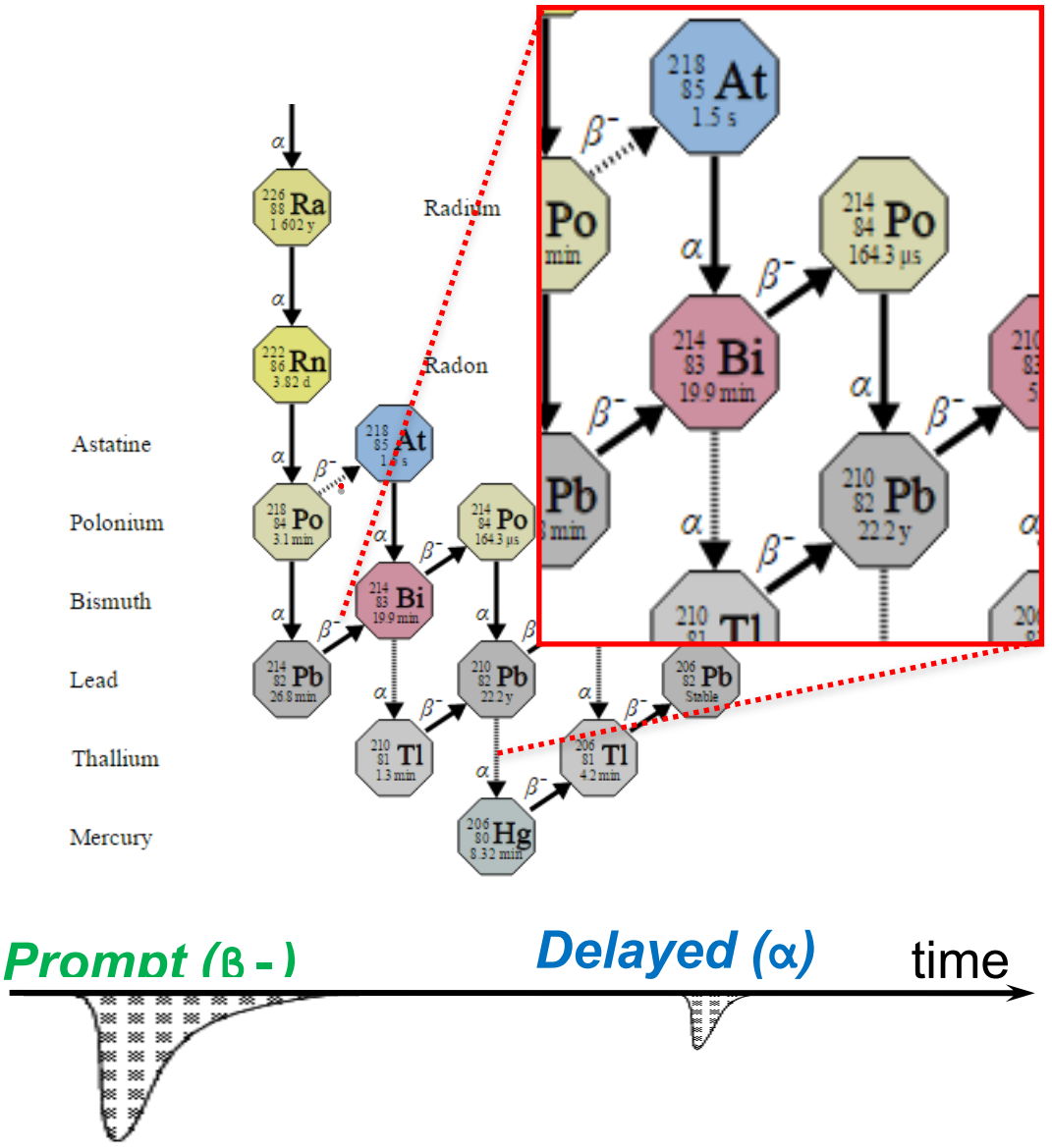


- ^{226}Ra ^{222}Rn-Generator
- Fill airgaps with ^{222}Rn rich gas
- Same/adjacent cell

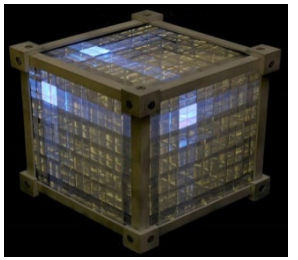
  ^{214}Bi → β- + ^{214}Po

  followed by (τ=164μs)

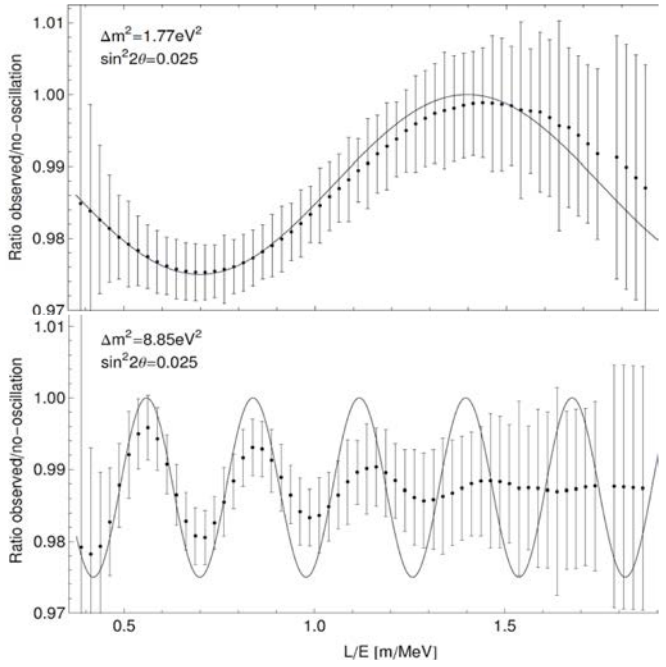
  ^{214}Po → α + ^{210}Pb
- Close temporal and spatial structure to that of a antineutrino capture
- Provides PSD stop tag
- Mean β- E = 642keV
- Mean α E ~ 700keVee
- Characterize surface scintillation affects

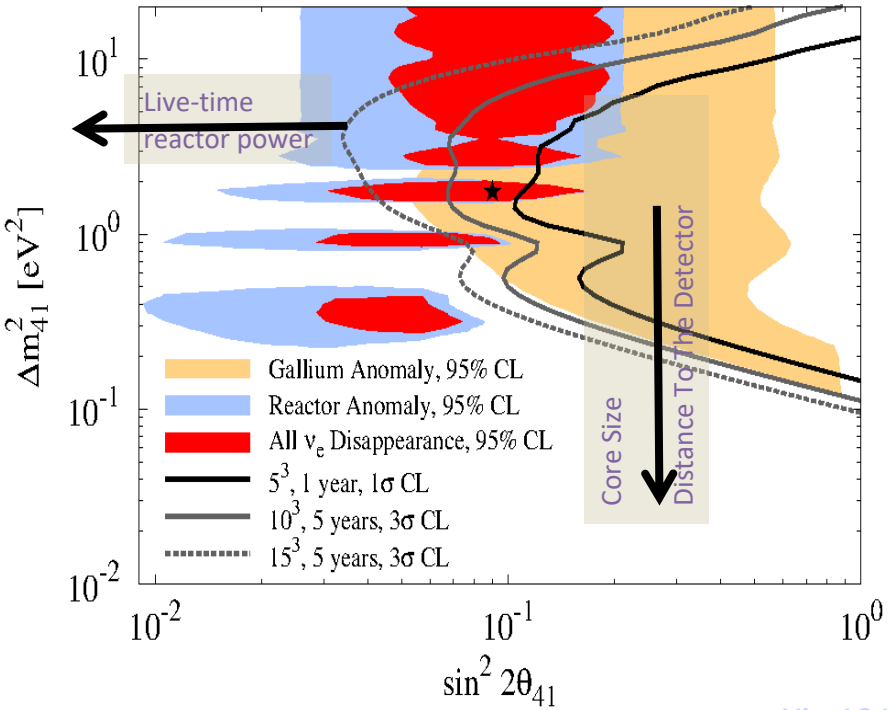


Sterile ν Search Performance



- **S/B = 3**
- **Time is calendar time at NIST**
- **NuLat is expected to have better S/B, even in higher-flux environments (10/1)**

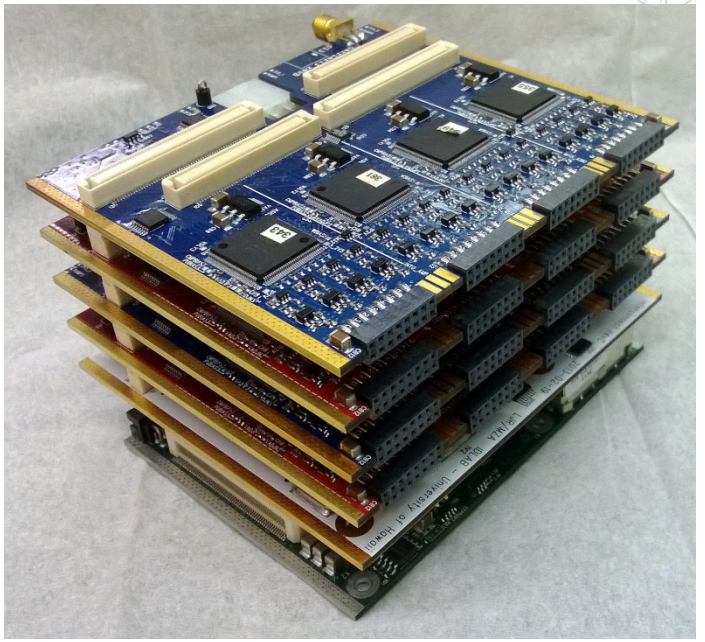


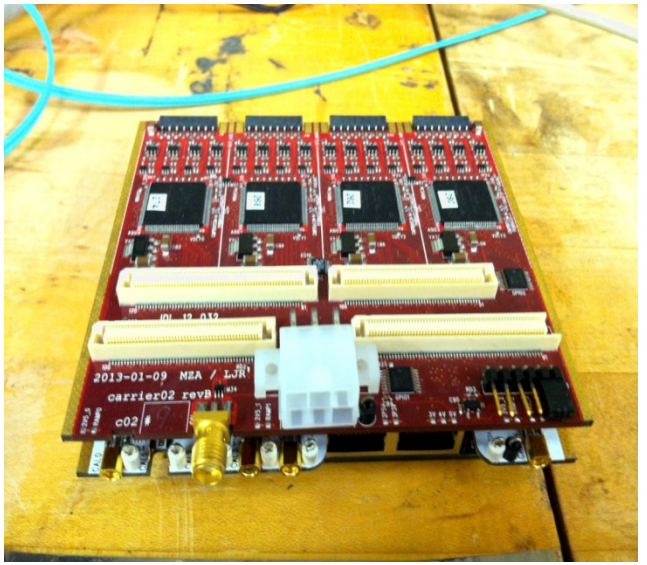


arXiv:1212.2182
arXiv:1501.06935

IRS: Custom Digitizers

- 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
- 192 chips per cube (1536 chan)
- 8 channels per chip, 2-4 Gigasamples / s
- 32,768 sample analog storage
- (per channel)





Additional System Electronics

- Clock and Triggering Board
  - Provides a low-jitter clock to front-end modules ($\sigma_t < 2$ ps)
  - Issues system triggers to all boardstacks based on parameters set by the user
  - Can distribute pulses for testing and calibration
- Weiner HV power supply
- 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