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

Presented by Ryan Dorrill
for the NuLat Collaboration:

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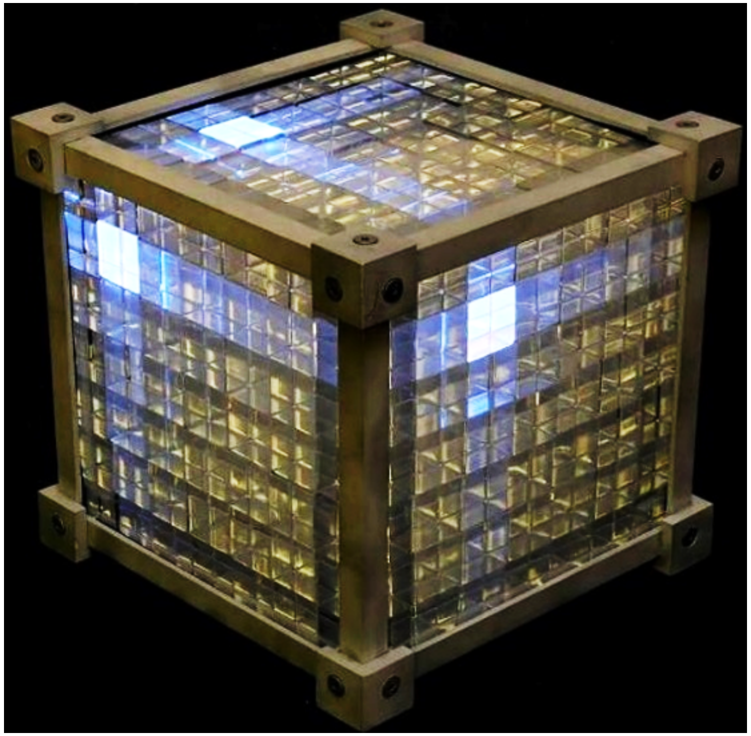
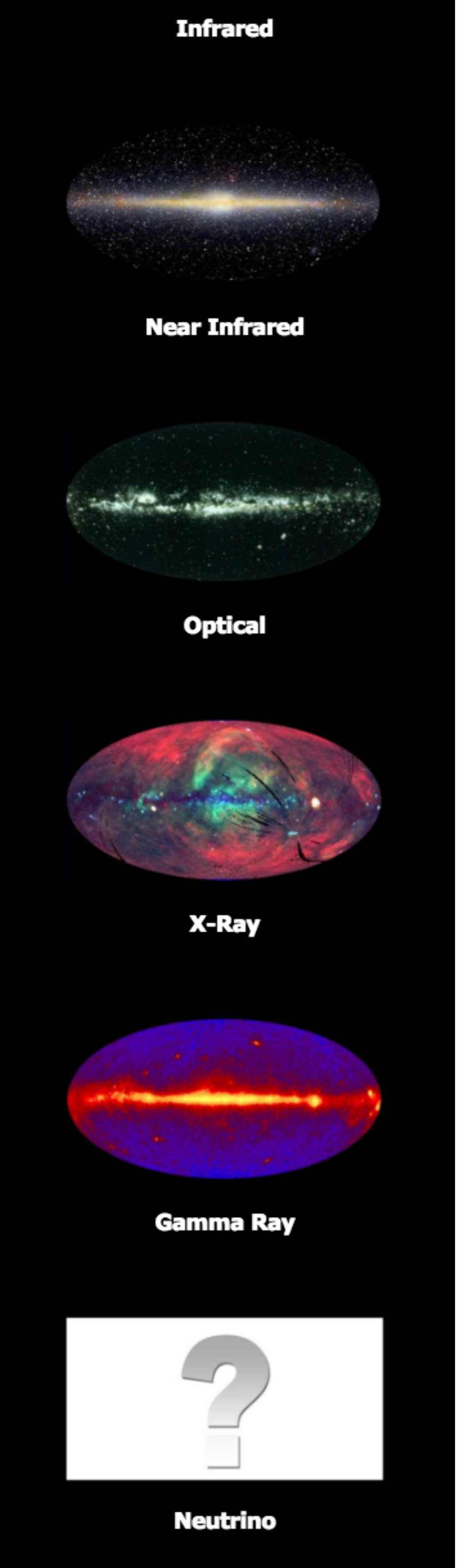
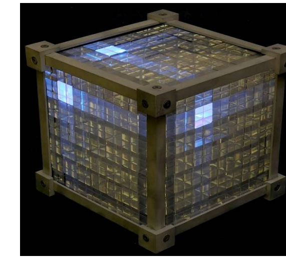
[1]*Drexel,* [2]*Johns Hopkins,* [3]*LSU,* [4]*NIST Gaithersburg,* [5]*NCCU,* [6]*Ultralytics LLC,* [7]*University of Hawaii,* [8]*Virginia Tech*





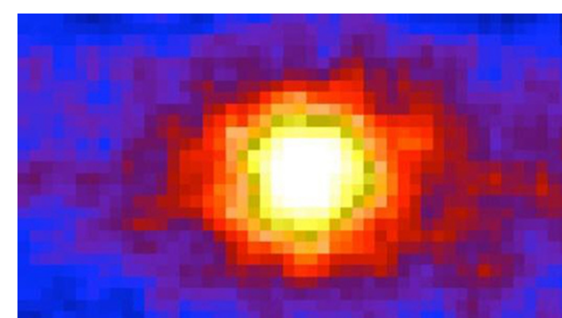
Why search for neutrinos?



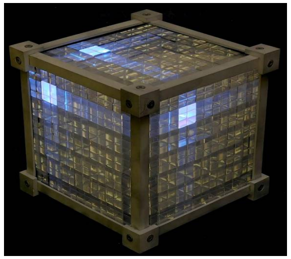
"They're ever so small, why they're almost nothing at all!"
- Dr. Seuss

- Neutrinos offer insights into nuclear and particle physics
- They pass through almost everything, but sometimes hit our detectors!
- They provide a unique window to the universe
- There's still much to learn

  about them

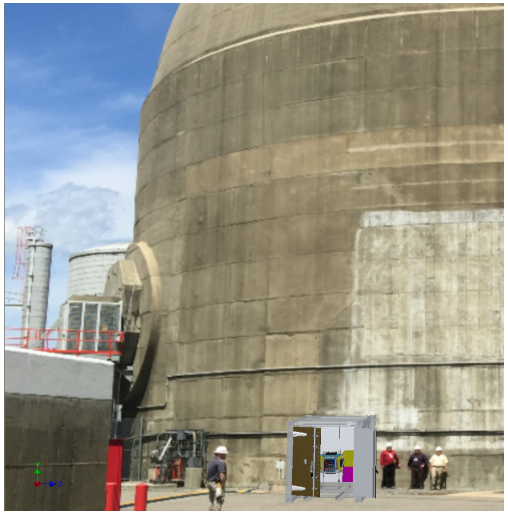


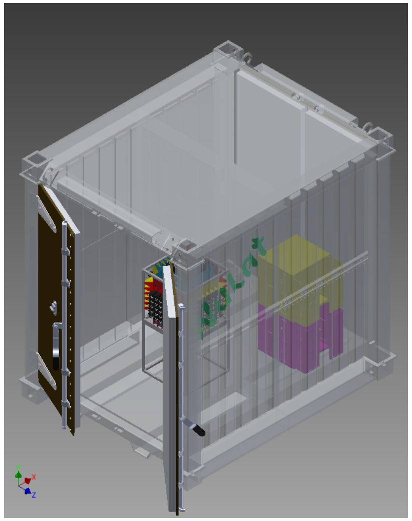
NuLat Motivation

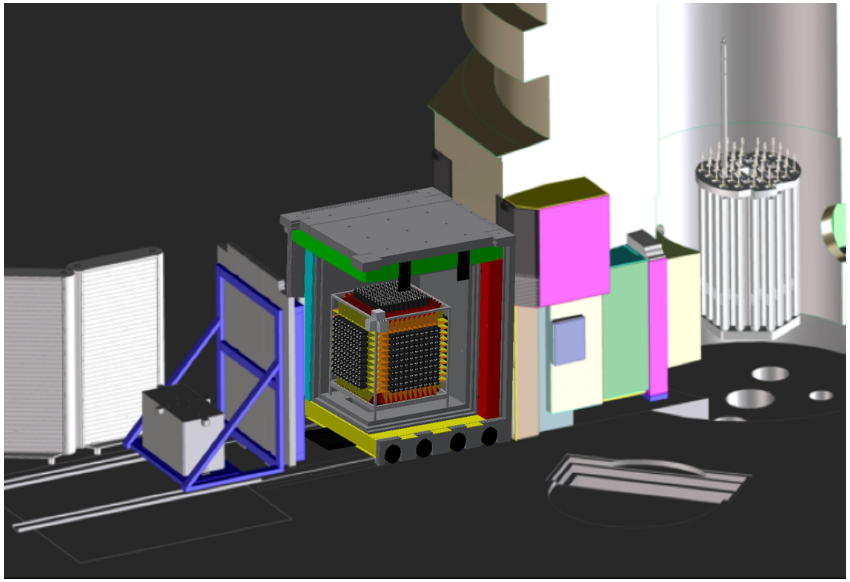


- **Demonstrate reactor monitoring capabilities**
  - Security monitoring
  - Commercial burn-up monitoring
- **Investigate fast neutron directionality capabilities**
  - Detection of special nuclear material
- **Probe reactor anomalies**
  - Sterile neutrino search
  - Precision ν_e energy spectrum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

North Anna Power Station

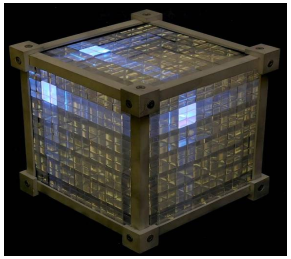






NIST NCNR Reactor

NuLat Features

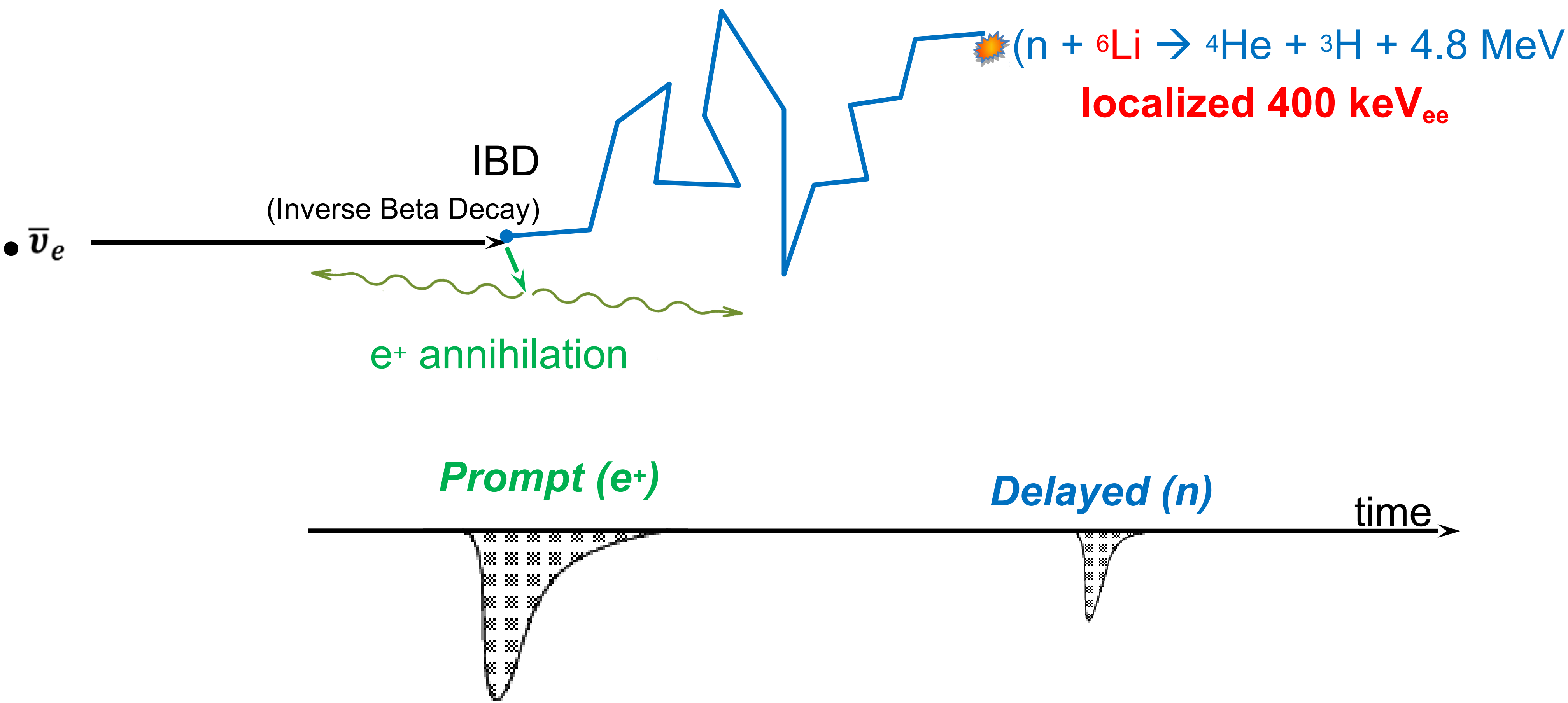


Feature	Rational
Excellent Energy Resolution	Precision Spectral Analysis – Distortions from prediction
Unique Start Signal	separate positrons from gammas, neutrons, and electrons
Unique Stop Signal	separate n-capture from backgrounds
Short Time Delay	improves real/random
Fine Segmentation	smaller improves 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
Minimal R&D required	Short time-scale and cost for early science

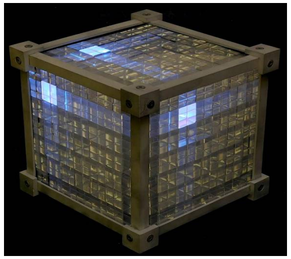
Classic $\overline{\upsilon}_e$ Signature

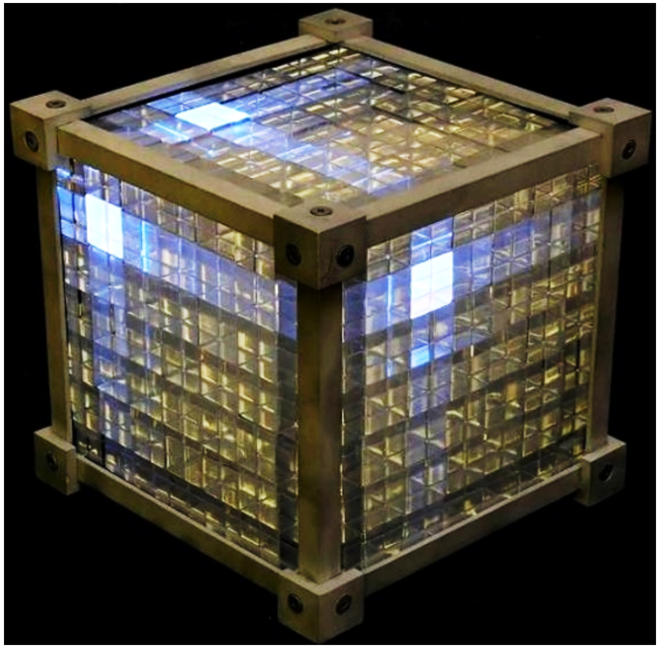
$$\overline{\nu}_e + p \rightarrow e^{+} + n$$

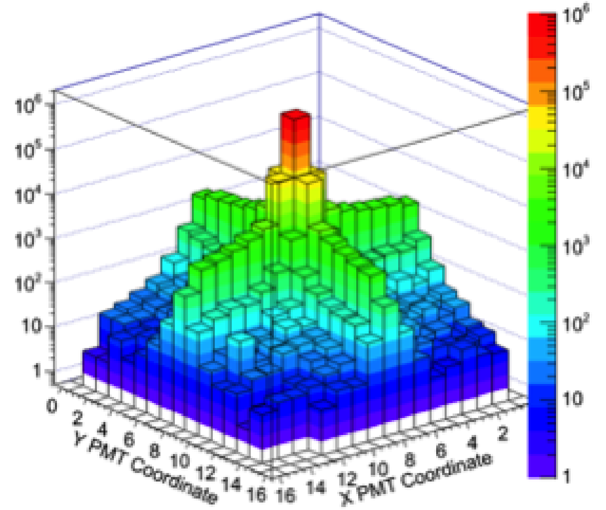
$$\xrightarrow[\tau\sim 7\mu s]{} n + {}^{6}Li \rightarrow \alpha + {}^{3}H$$

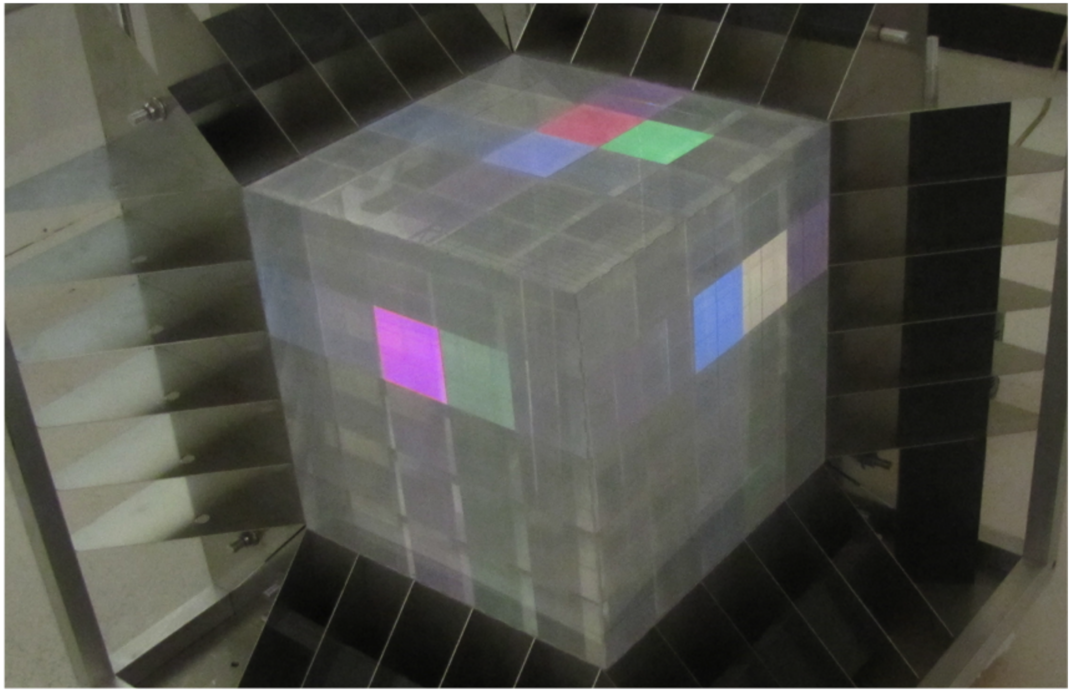


Raghavan Optical Lattice



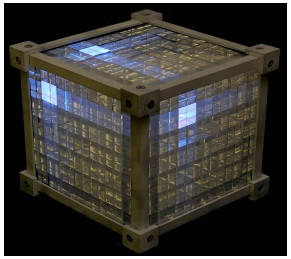




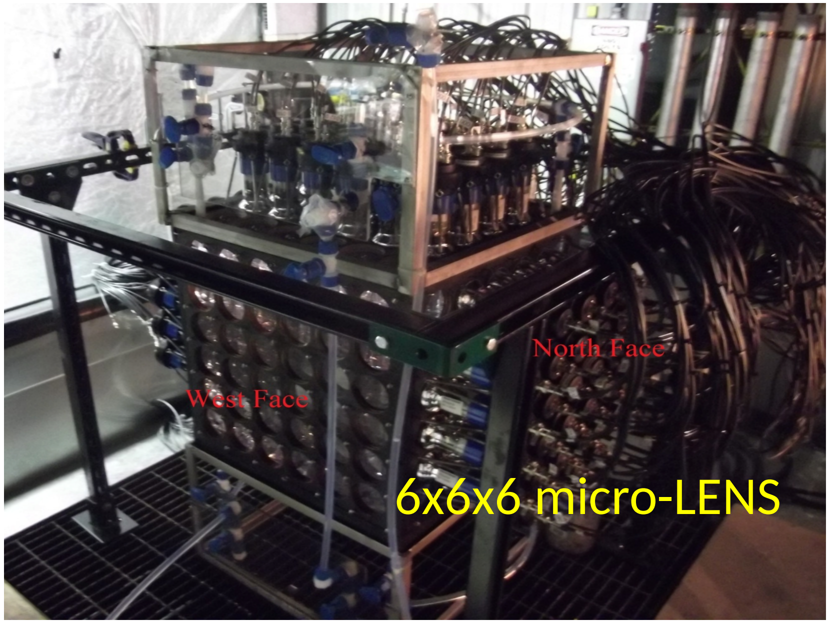


- light channeling via total internal reflection
- full 3D light collection along principle axes
  - Breaks degeneracies present in other detection schemes

Segmentation



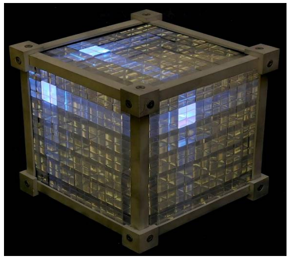
- proven technique: micro-LENS
  - operational liquid scintillator ROL detector located at KURF
  - Cell size = (3.25")^3
  - thin Teflon walls (0.002")
  - partial light channeling (n=1.34 and 1.49)

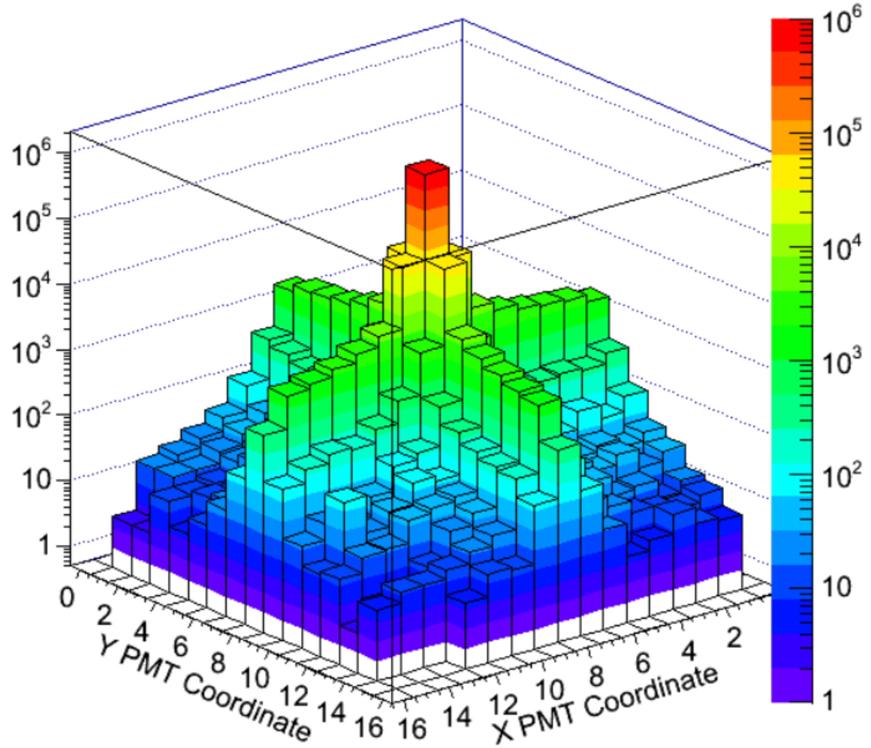


LENS 60x60x60

- NuLat (solid scintillator)
  - 10x10x10 cubes
    - effectively 1000 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

Segmentation 2

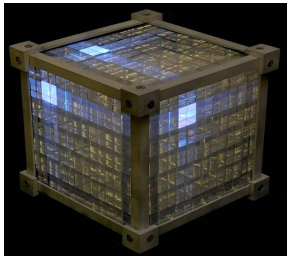


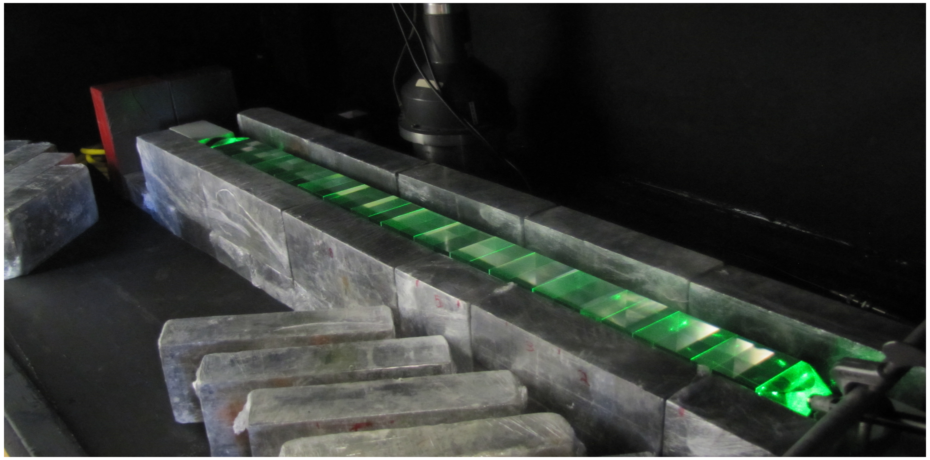


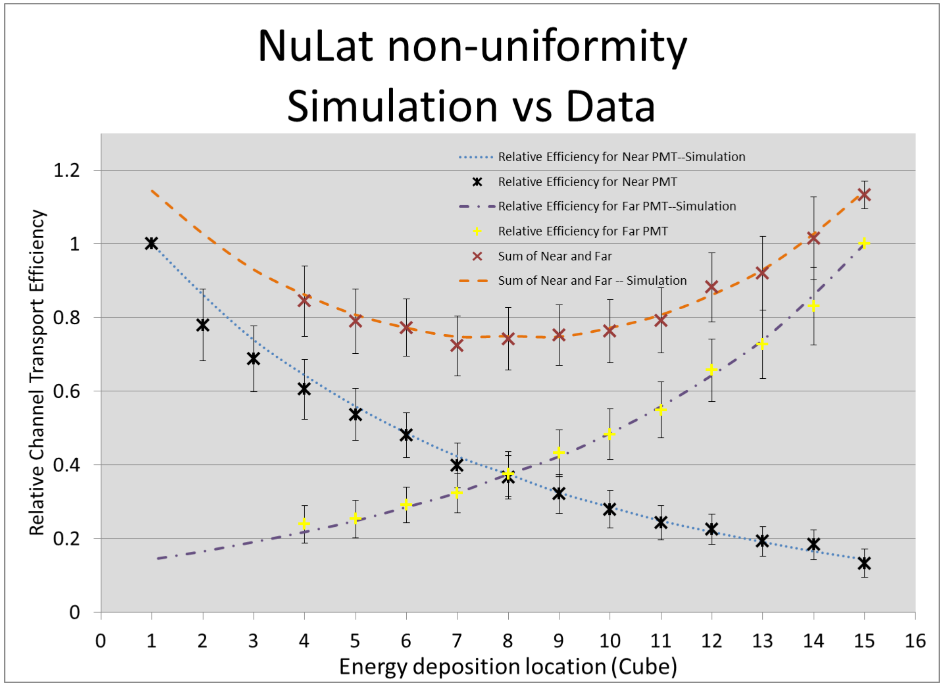
Log plot of light output on the (X-Y) face of a mirrored NuLat design via deposition of 2 MeV in the central cell

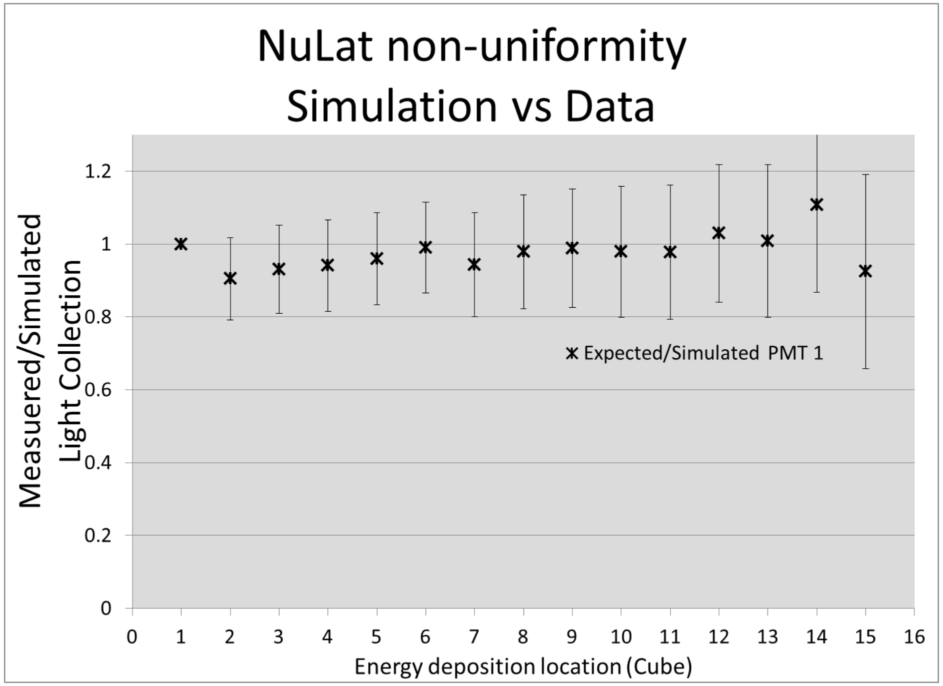
- The amount of light detected in the plane that is not directly facing the cell with the energy deposit is at the level of < 5%
- This pattern is seen in all 3 projections
- The cube containing the energy deposit is identified uniquely by amplitude alone
- Detected light may further be identified by signal timing, permitted location (such as the gammas from positron annihilation must be on average in opposite directions)

NuLat 15 Cube
Full Channel Module Testing

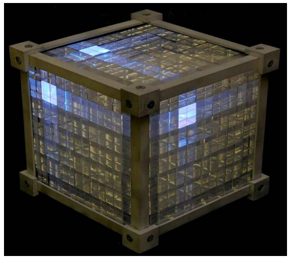




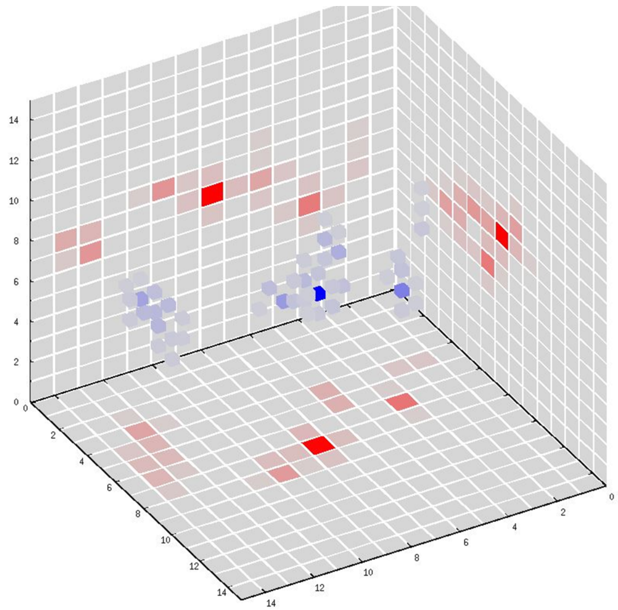




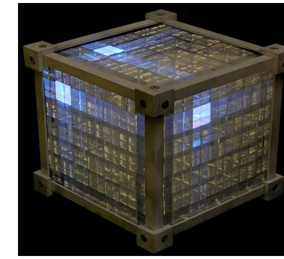
Unique Start Signal



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



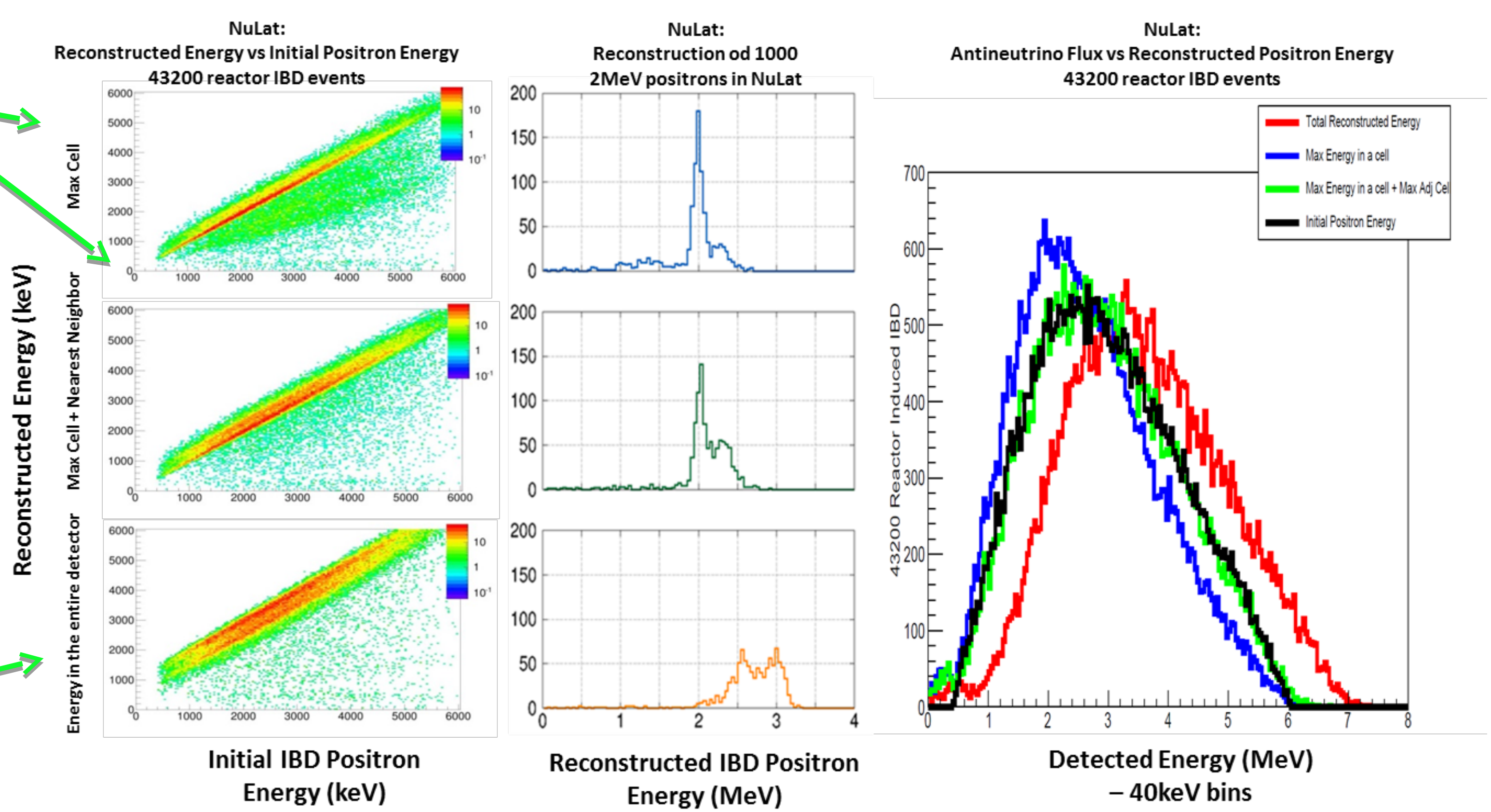
Energy Resolution



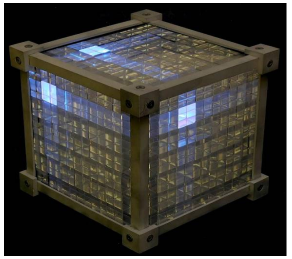
- → $E_\nu = E_{e+} + 1.8$ MeV
- → full positron energy in one cell or at most two (vertex cell)
- → minimal contamination by annihilation gammas in vertex cell
- → allows excellent neutrino energy resolution throughout the *complete* detector

unique to NuLat

available to all integrating small detectors



Event Topology

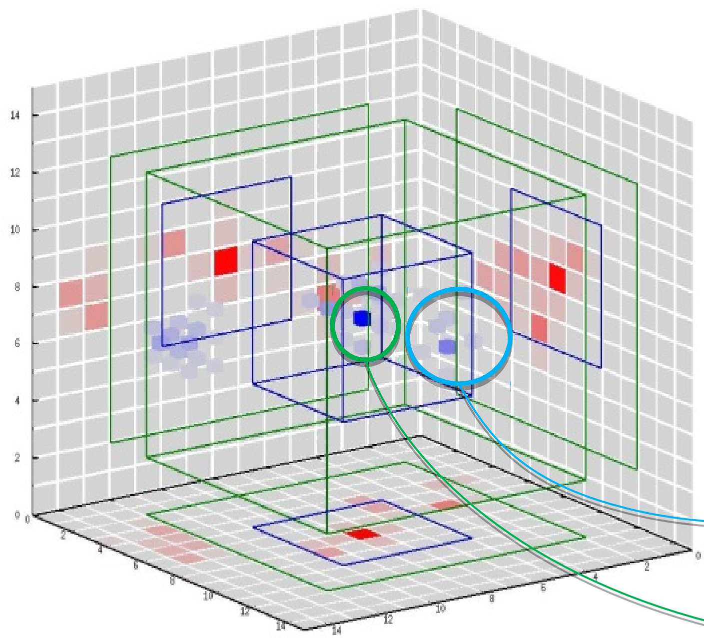


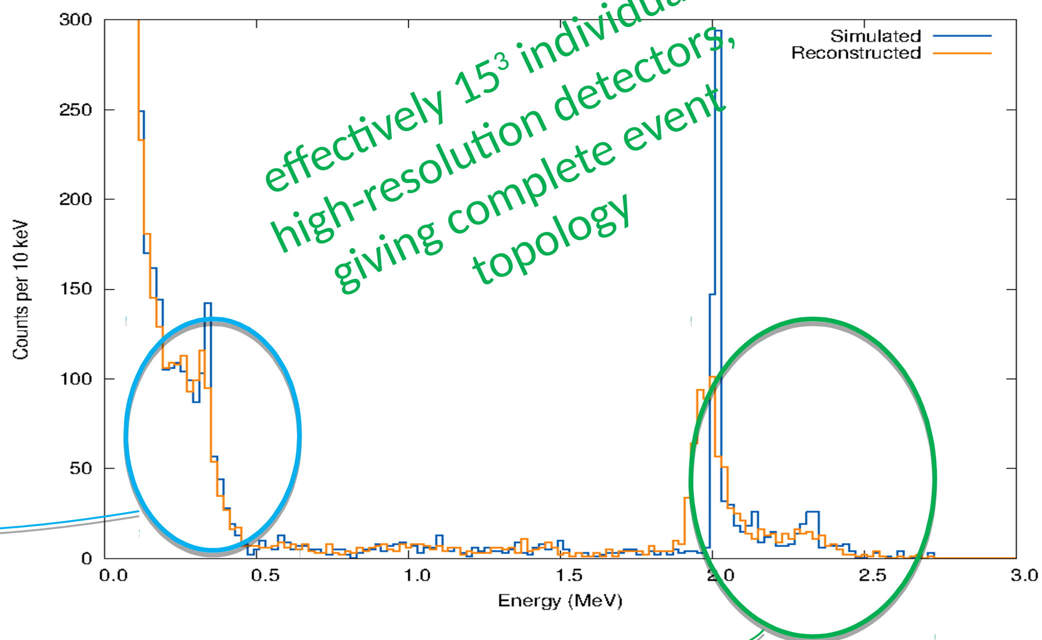
$$\overline{\nu_e} + p \rightarrow e^+ + n$$

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

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

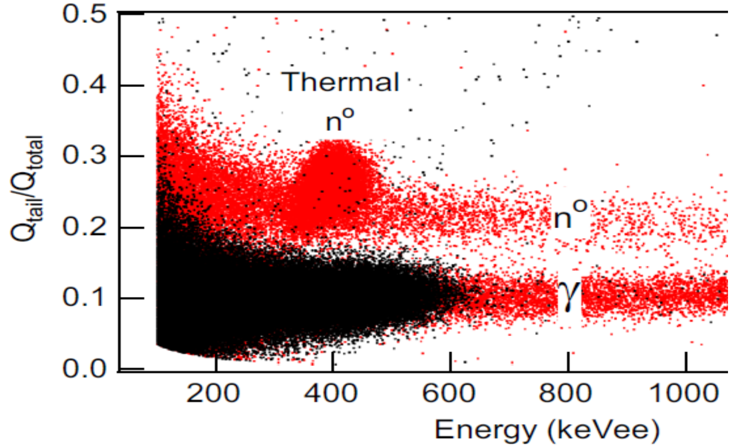
Average single-cell prompt response to a uniform 3.8 MeV anti-neutrino flux.

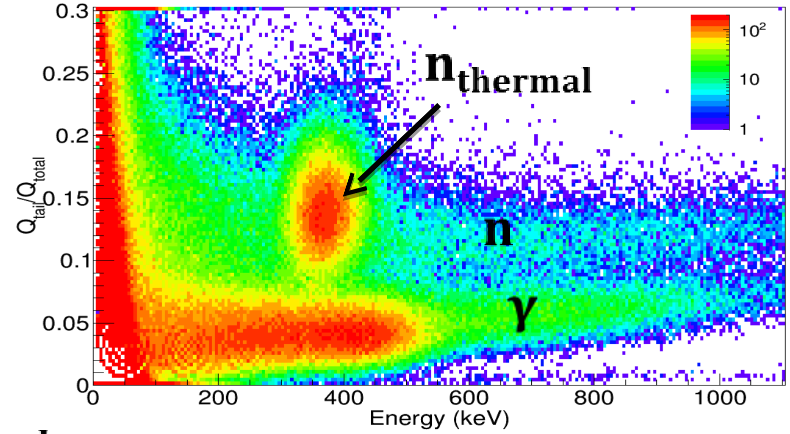
no fiducial cut

PSD in ^{6}Li Plastic

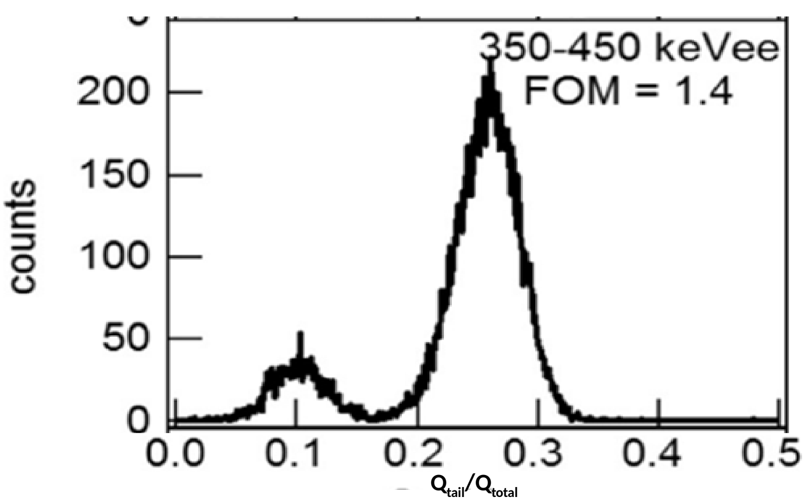
Eljen LLNL based EJ-200 ^{6}Li PSD characterization as measured at Virginia Tech

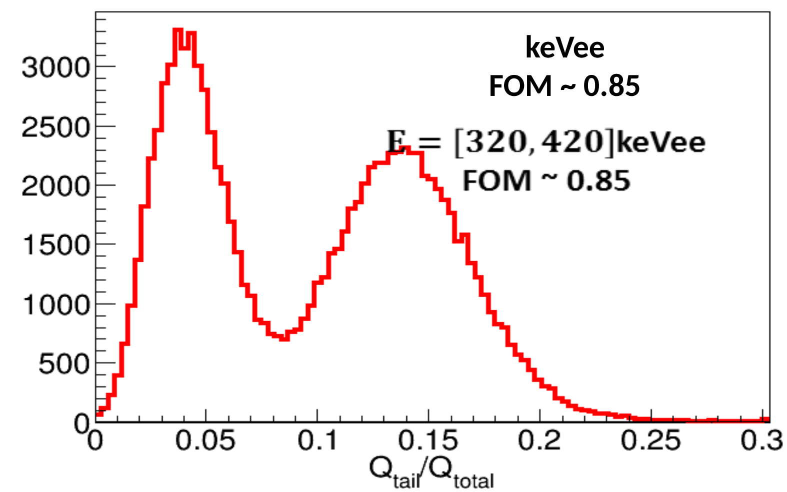
Cherepy NIM A778 2015





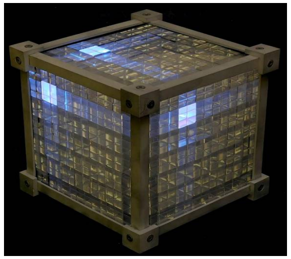
$$FOM = \frac{d}{FWHM_\gamma + FWHM_n}$$



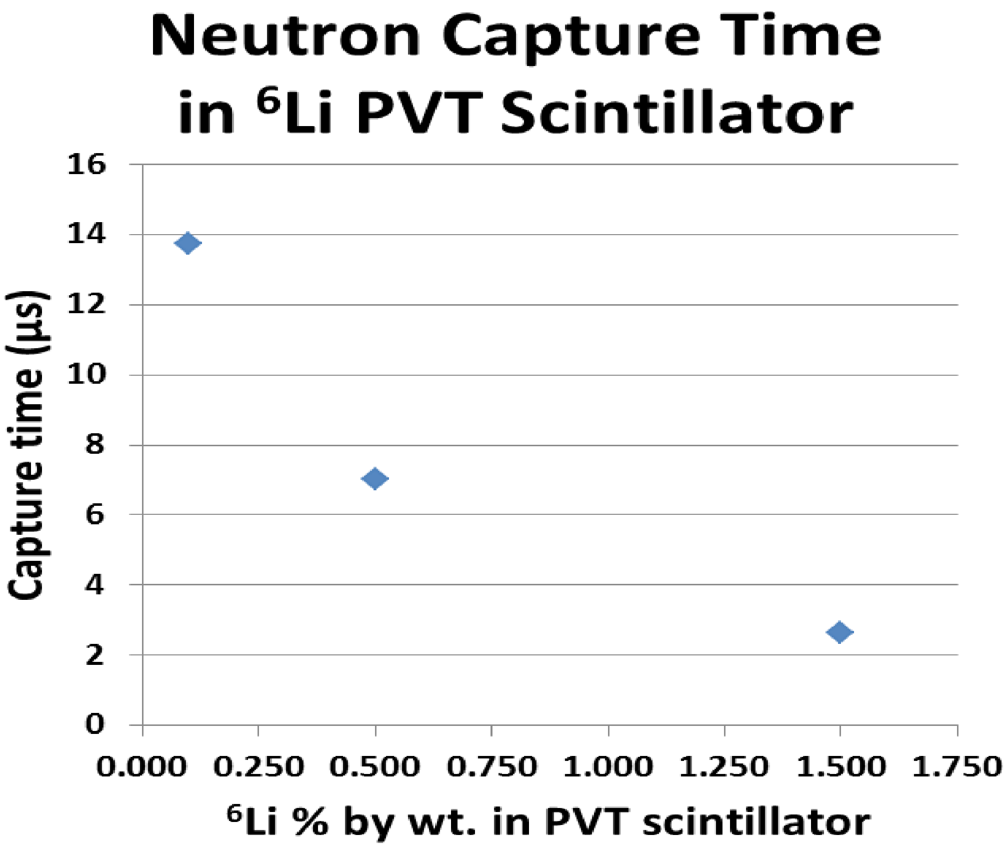


Better energy resolution results in better background rejection.

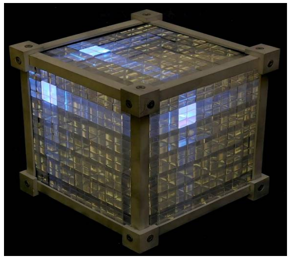
Unique Stop Signal

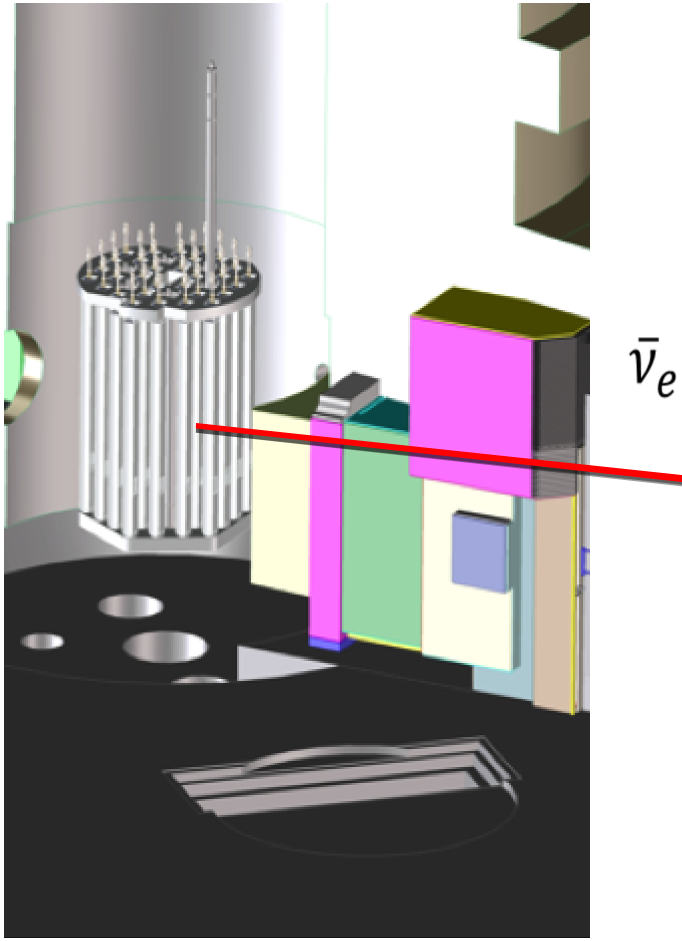


- Lithium-6 PVT
  - 7 μs time correlation
    0.5% by wt. ^{6}Li PVT
  - mono-energetic ~400 keV_{ee}
  - single cell stop tag
  - n/gamma PSD separation
  - 23% n capture in same cell as positron
  - 60% n capture in same cell as positron plus the six facing cells
  - 940 barns

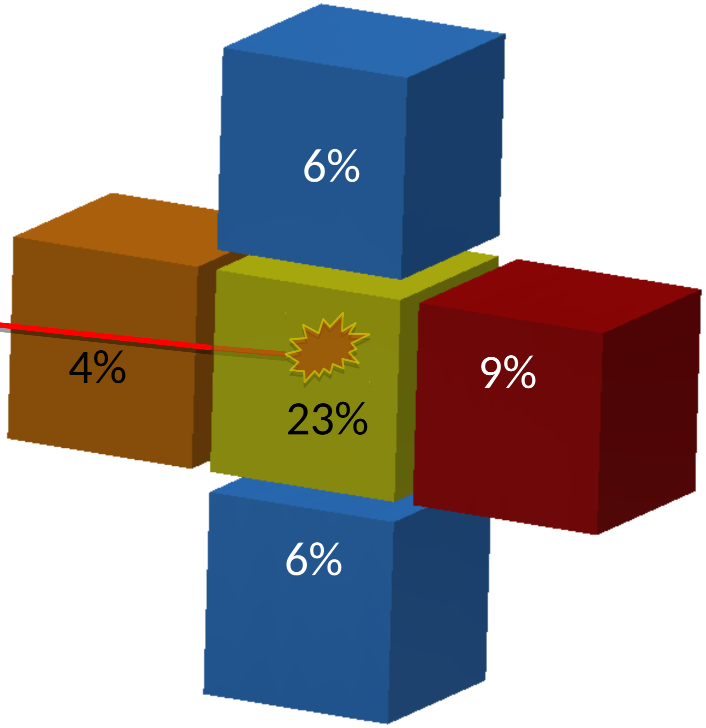


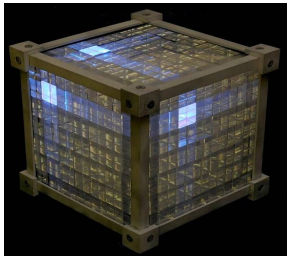
Unique Topology for the Ensemble of IBD Events





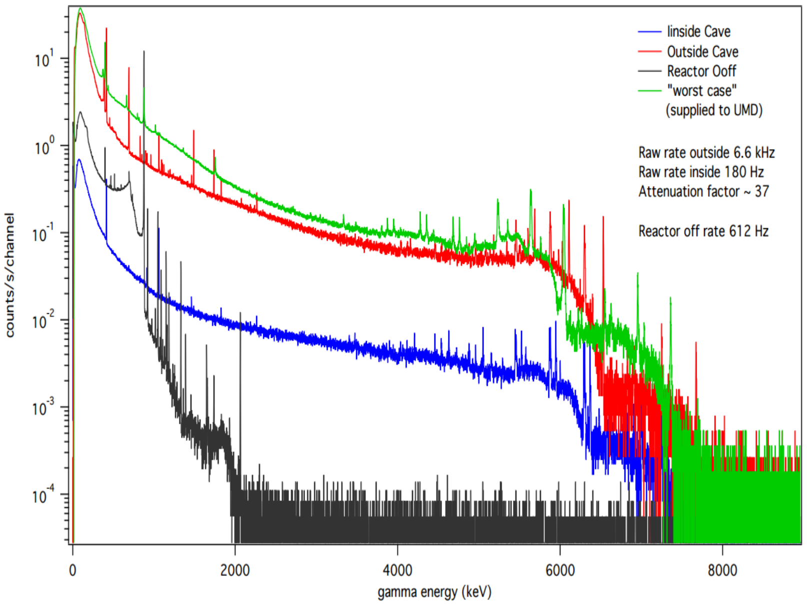
Relative location of neutron capture to IBD positron production

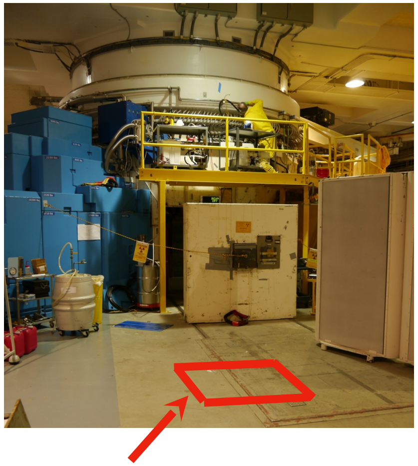




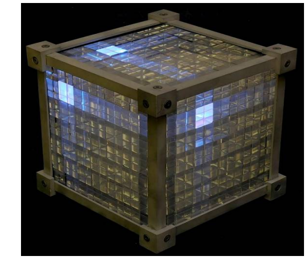
NIST Background Studies

- 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

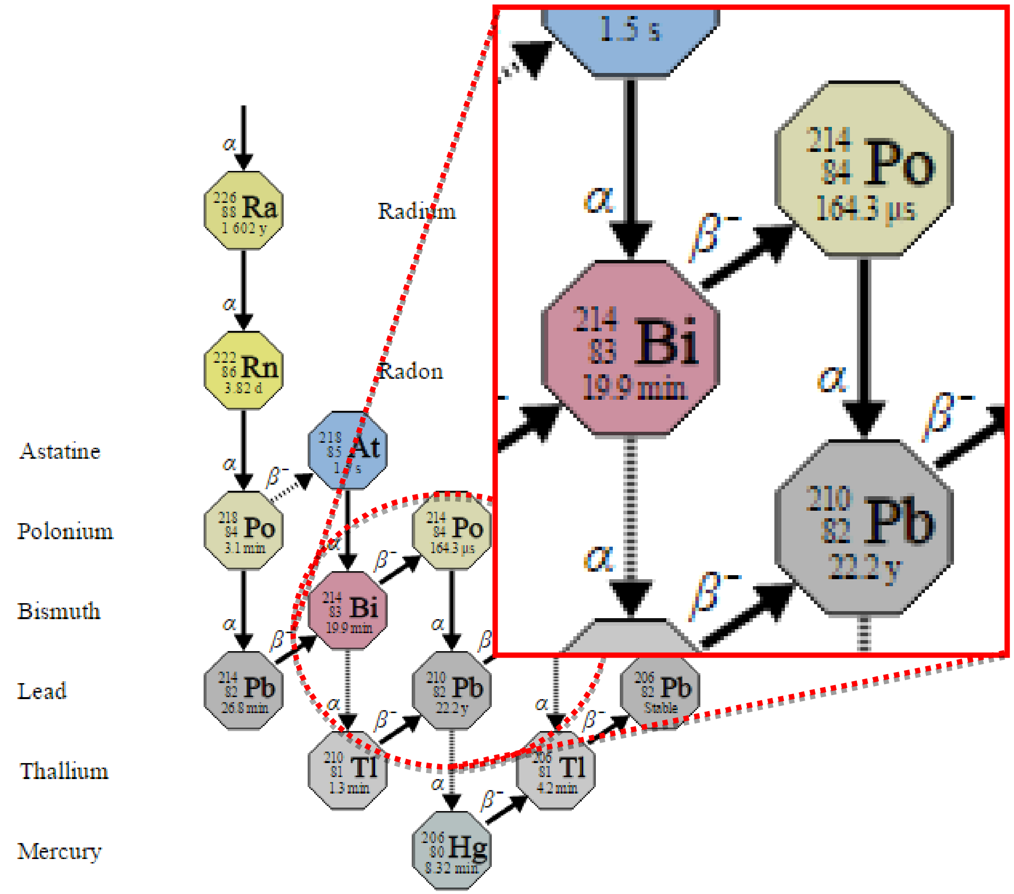


- ^{226}Ra ^{222}Rn-Generator
- Fill airgaps with ^{222}Rn rich gas
- Same/adjacent cell

  $^{214}\mathrm{Bi} \rightarrow \beta- + {}^{214}\mathrm{Po}$

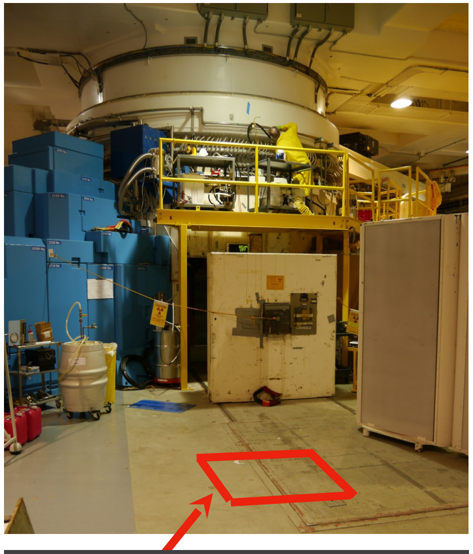
  followed by (τ=164μs)

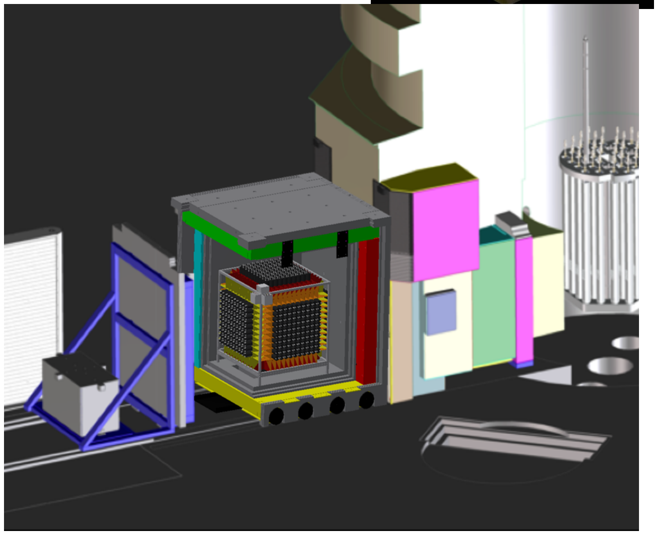
  $^{214}\mathrm{Po} \rightarrow \alpha + {}^{210}\mathrm{Pb}$
- Close temporal and spatial structure to that of a antineutrino capture
- Provides PSD stop tag
- Mean $\beta-$ E = 642keV
- Mean α E ~ 700keVee
- Characterize surface scintillation affects

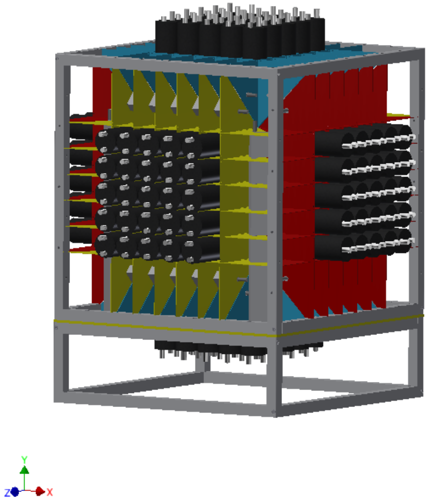


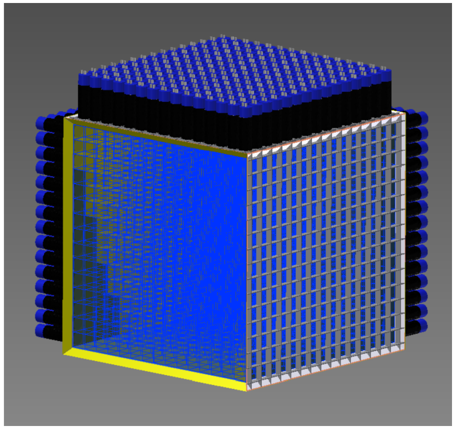
ROL 5^3 Antineutrino Detector

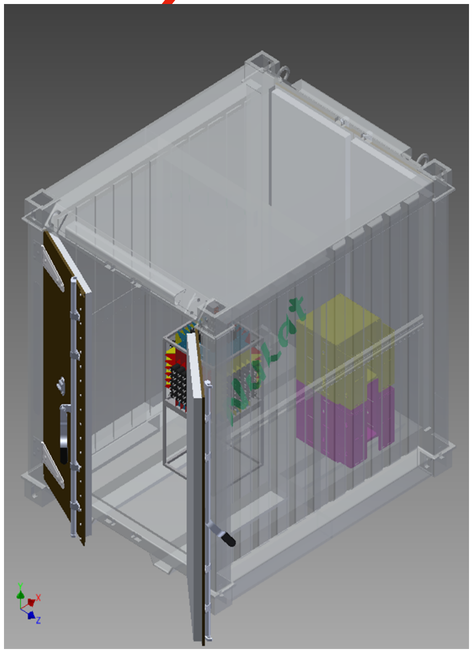
- Design Finalized
- All major material has been ordered
- Construction to be completed ~early 2017
- Deployment:
  - North Anna (L ≈24m)
    - P = 2x900 MW
  - NIST (L ≈ 4.7m)
    - P = 20 MW



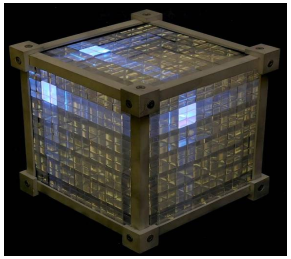






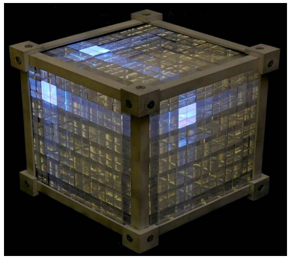


NuLat Preliminary Schedule Detector Tasks

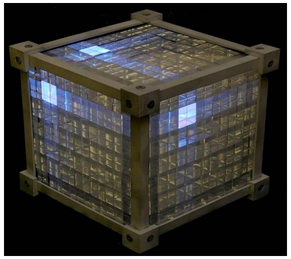


	Expected Completion
Detector Construction	
Order 125 pre-cut 6Li-Loaded Scintillating cubes	CY 2017 Q1
Demonstrate lattice construction	CY 2017 Q1
Construct 6Li-Loaded ROL 5^3 Detector	CY 2017 Q2
Electronics	
Demonstrate 5x5-6sided DAQ and trigger (150 channels)	CY 2017 Q2
Demonstrate gain and timing calibration	CY 2017 Q2
DAQ, Simulation, and Analysis	
Reconstruct 'positron' event topology and energy via $\gamma \dashrightarrow e^+ + e^-$	CY 2017 Q2
Demonstrate neutron tagging	CY 2017 Q2
Demonstate timing topology to show time-ordering	CY 2017 Q2
Evaluate the performance difference between 3 and 6 sided instrumentation	CY 2017 Q3
Deployment	
Deploy at commercial reactor	CY 2017 Q3
measure neutrino rate & signal/background	
Deploy at NIST	CY 2017 Q4
Other studies towards *full* NuLat	
Determine the amount of passive shielding required	CY 2017 Q4
Evaluated the ability and need to adjust detector reactor baseline	CY 2017 Q4

Conclusion

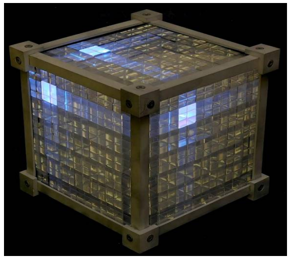


- NuLat design:
  - Precision topology capabilities E(x,y,z,t)
  - Short mean time for coincident signal
  - Pulse shape discrimination for both start and stop signals
  - Several methods of evaluating systematics
- NuLat addresses
  - Reactor neutrino physics
  - Reactor monitoring
  - Special nuclear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

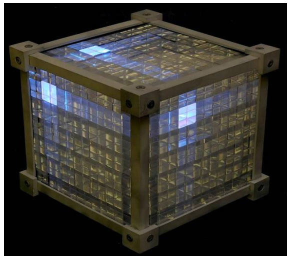


Questions?

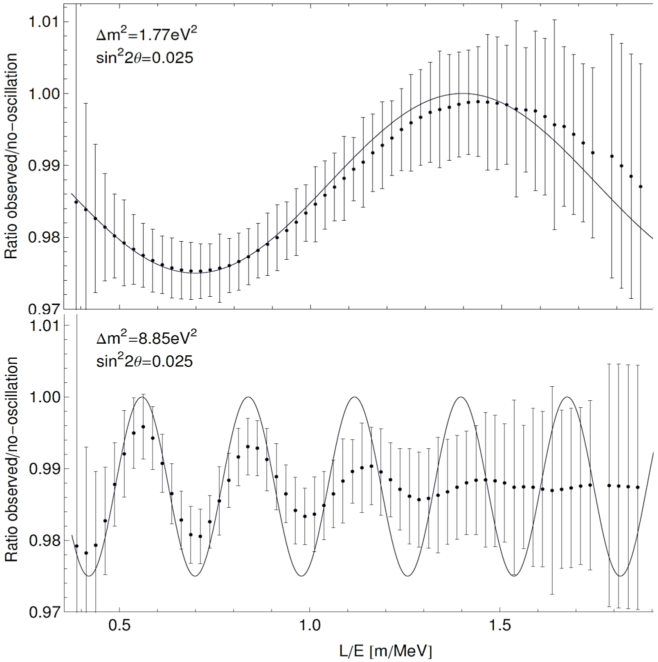
Backup Slides

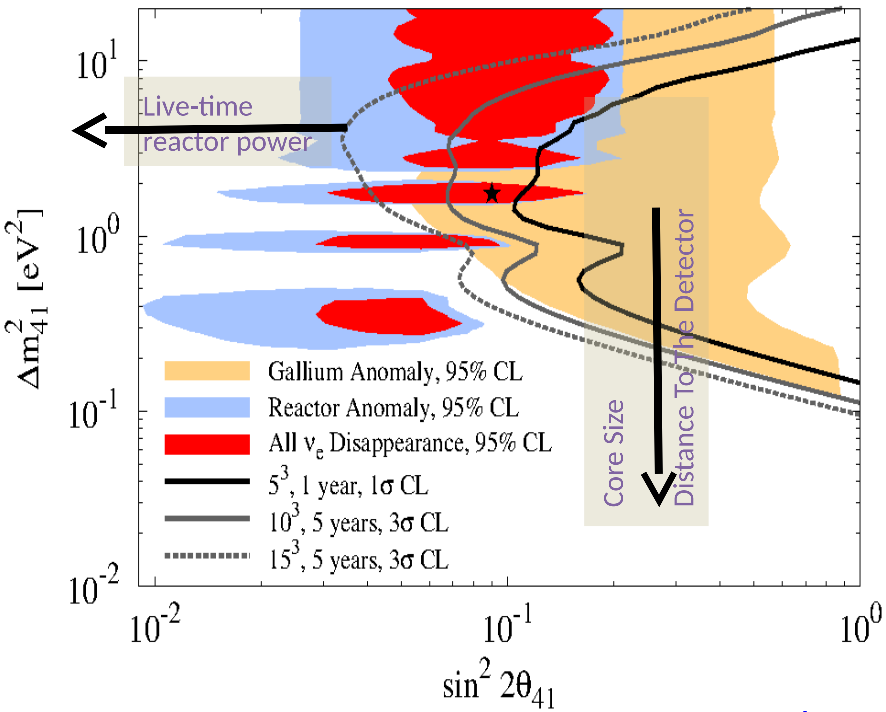


Sterile ν Search Performance



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

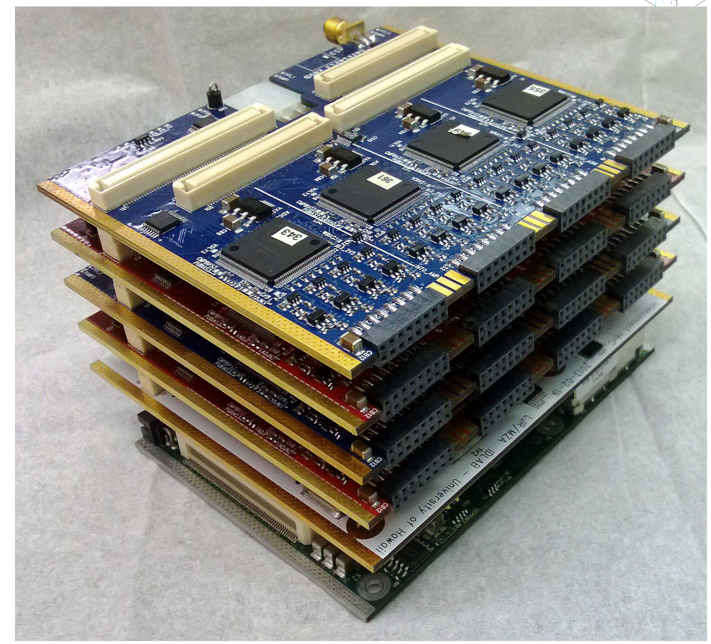


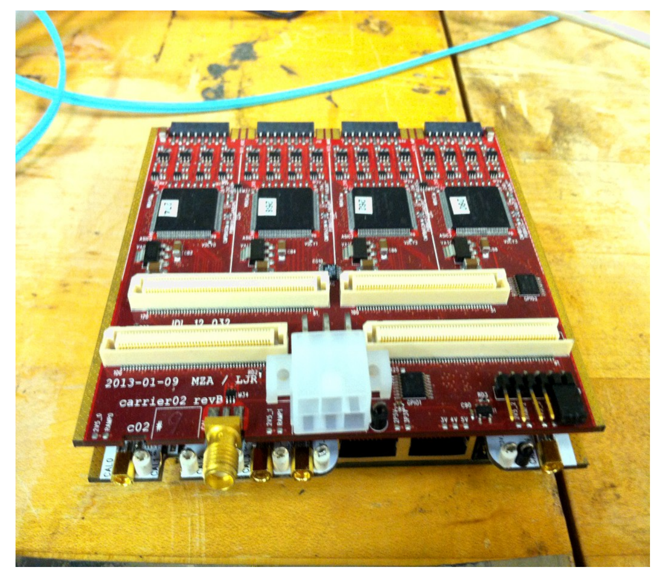


arXiv:1212.2182
arXiv:1501.06935

IRS: Custom Digitizers

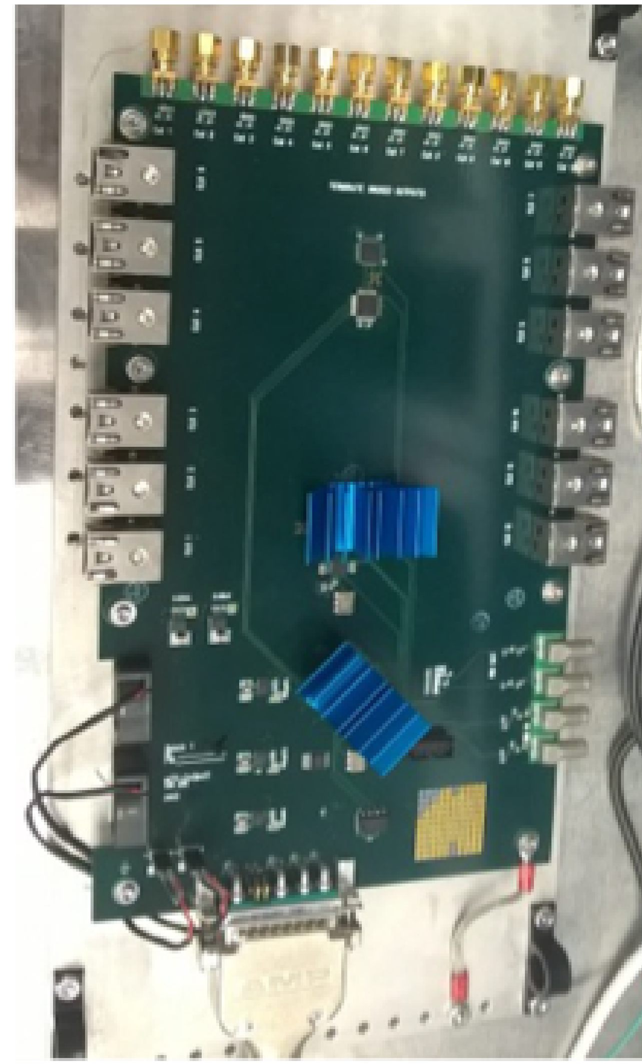
- SCROD - board stack with IRS3d chips similar to those used in Belle – 100 ps timing resolution
- Separate Data and triggering paths
- 16 chips per board stack -> seen at right
- 192 chips per cube (1536 chan)
- 8 channels per chip, 2-4 Gigasamples / s
- 32,768 sample analog storage
- (per channel)





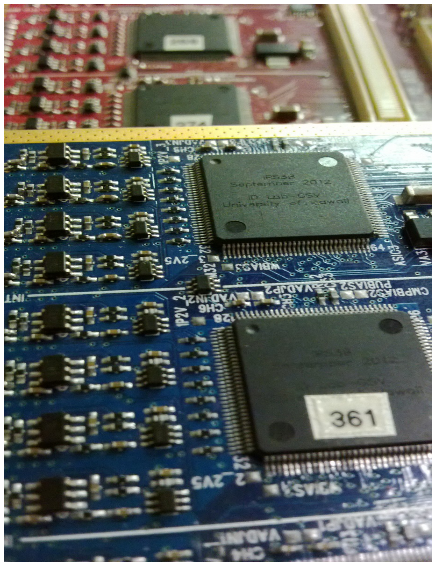
Additional System Electronics

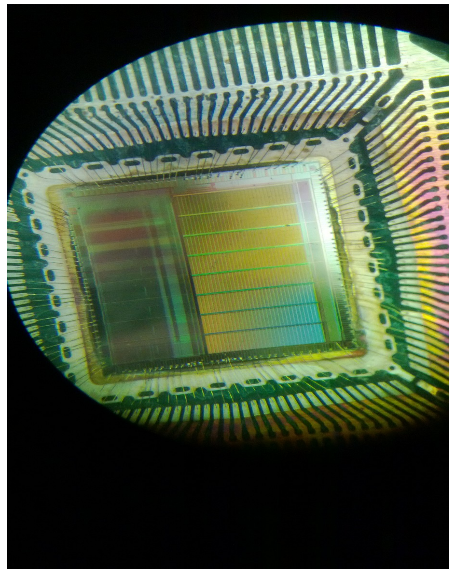
- Clock and Triggering Board
  - Provides a low-jitter clock to front-end modules ($\sigma_t < 2$ ps)
  - Issues system triggers to all boardstacks based on parameters set by the user
  - Can distribute pulses for testing and calibration
- Weiner HV power supply
- Dell server and other computers for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



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

Keeping it Cool



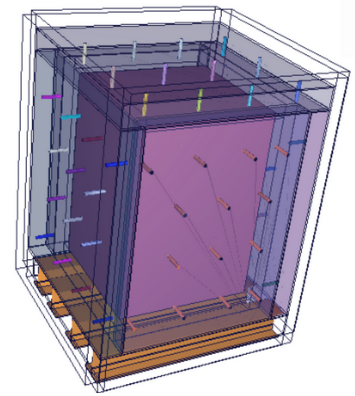


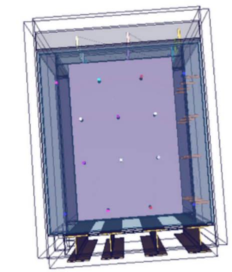
- 84 boards total, 192 IRS chips, along with amplifiers, PMTs, etc. produce ~ 400 W heat
- The mTC's cover and shielding restrict air flow, making cooling more difficult
- Fans / air flow isn't enough!
-

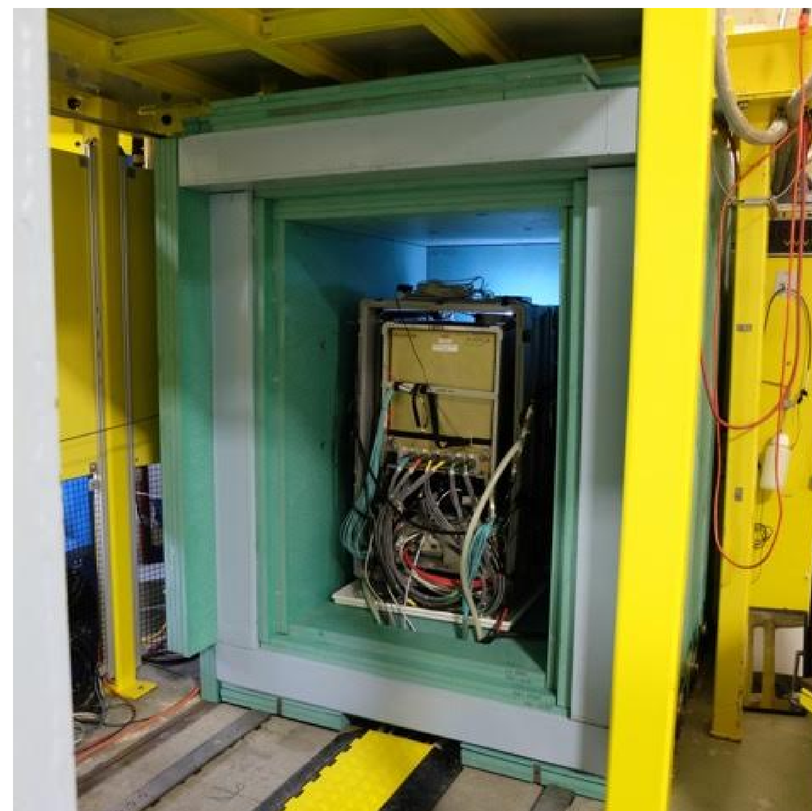
- We use the following:
  - Koolance hard drive chiller plates
  - An "Advantage" water chiller unit - 16 °C, 2 gallon per min
- $T_{inside} \rightarrow$ 20-35 °C
- $T_{chips} \rightarrow$ 35-55 °C

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





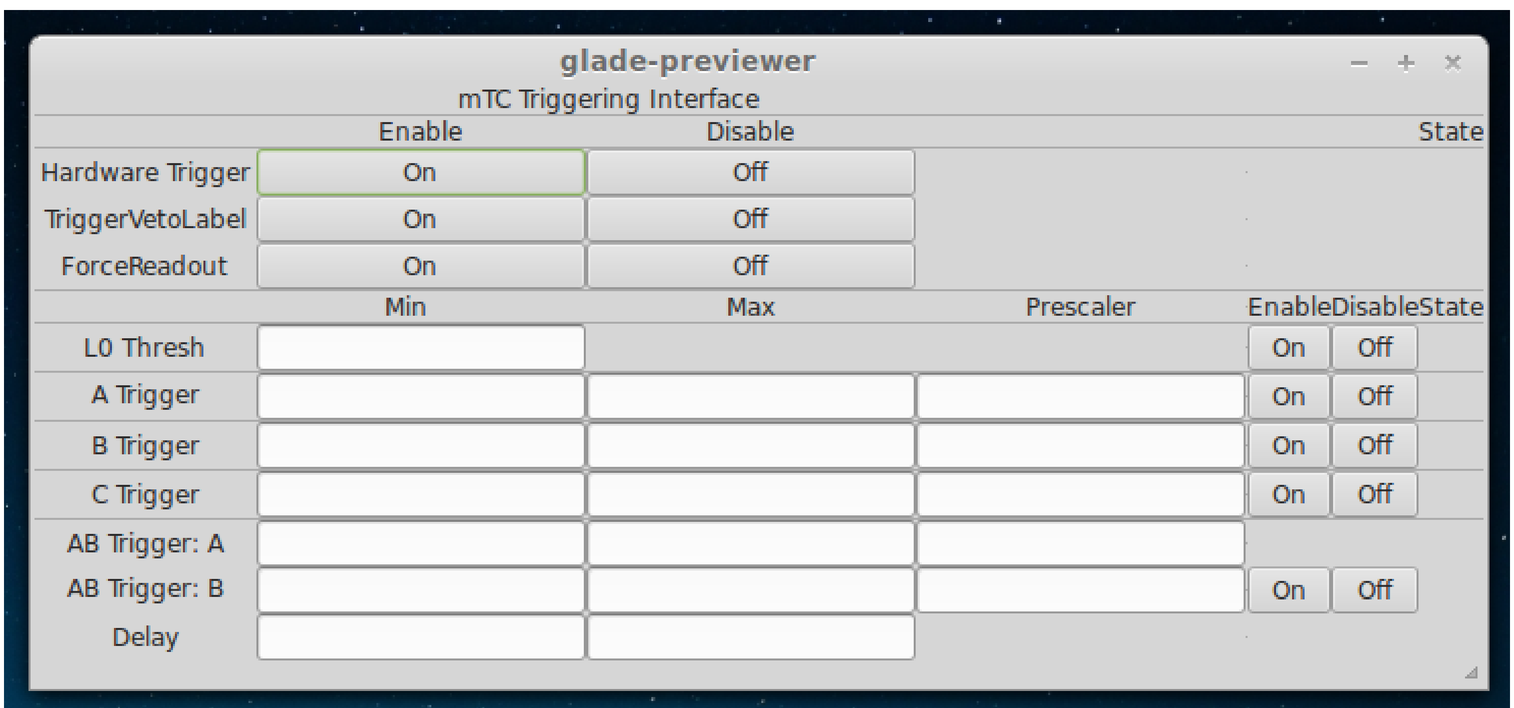


	normal	shielded	normal	shielded	attenuation
Type	#/mTC/s		#/cm^2/s		%
Muon	15	1.72	.017	2.0×10^{-3}	88.2%
Neutron	10151	0.082	12	9.7×10^{-5}	99.9%
Gamma	860	9.03	1.0	1.1×10^{-2}	98.9%

How we identify Neutrino Signals

Step 1: smart triggering

- The mTC has several triggering “modes”:
  - Muon trigger (C): based on minimum and maximum number of hits
  - Forced readout and self-triggers: trigger based on external signals, or signals from the clock and timing board
  - **Neutrino Trigger (AB type in interface)**: looks for a prompt, then a delayed signal after a set delay.
-



- Main Trigger Types
- AB trigger: (neutrino trigger)
- C Trigger: simple trigger (muons)