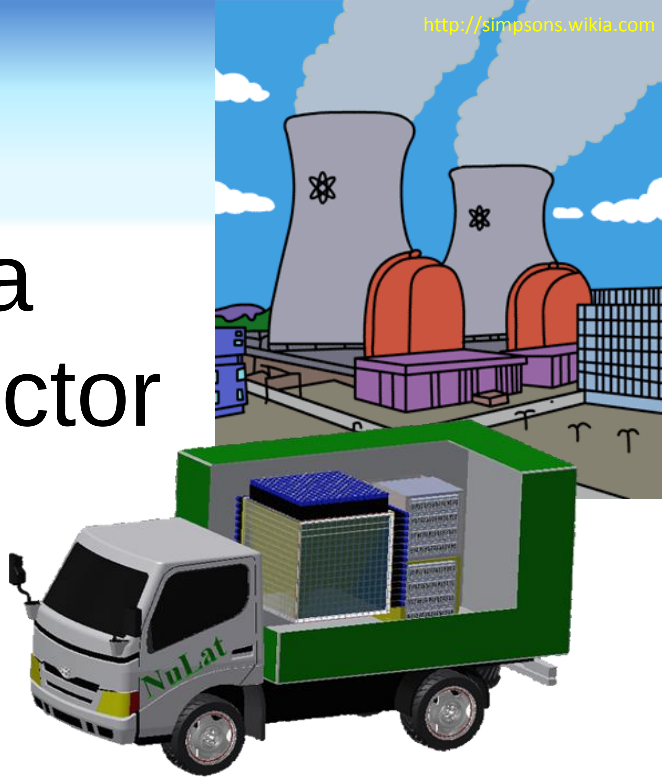
NuLat



NuLat: A Novel Design for a Reactor Anti-Neutrino Detector

Presented by S. Derek Rountree

For the NuLat Collaboration:

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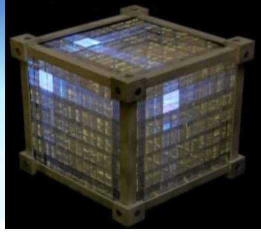
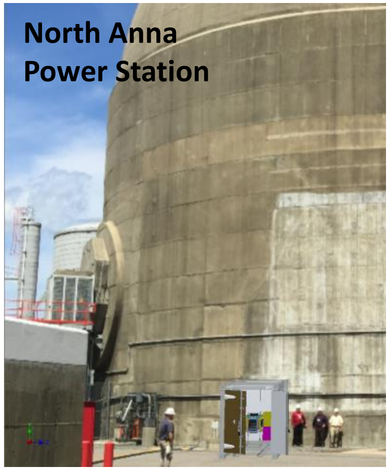
[1]*Drexel*, [2]*Johns Hopkins*, [3]*LSU*, [4]*NIST Gaithersburg*, [5]*NCCU*, [6]*Ultralytics LLC*, [7]*University of Hawaii*, [8]*Virginia Tech*

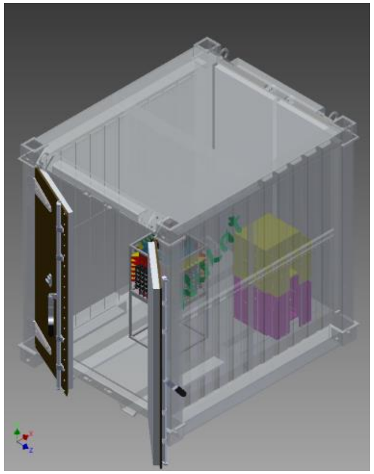
arXiv:1501.06935

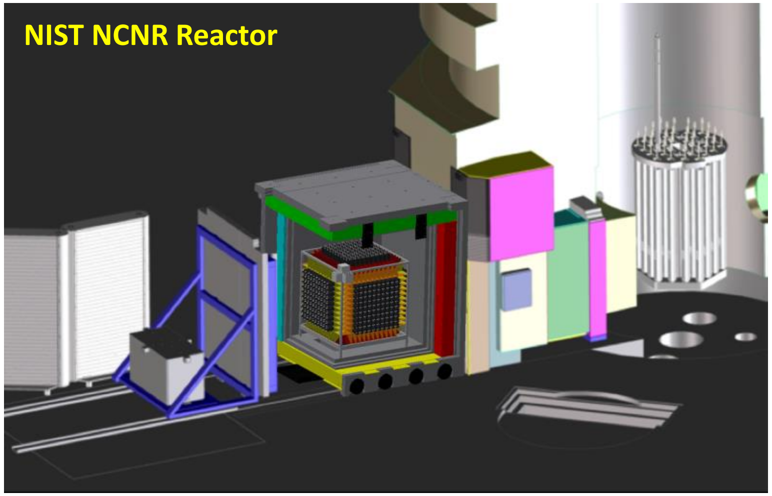
NuLat Motivation



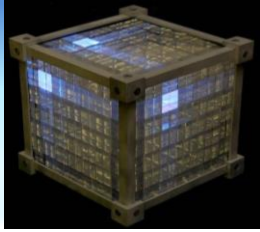
- **Demonstrate reactor monitoring capabilities**
  - Security monitoring
  - Commercial burnup monitoring
- **Determine fast neutron directionality capabilities**
  - Detection of special nuclear material
- **Probe reactor anomalies**
  - Sterile neutrino search
  - Precision ν_e energy spectrum measurment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





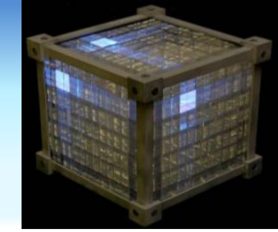


NuLat Features of Merit



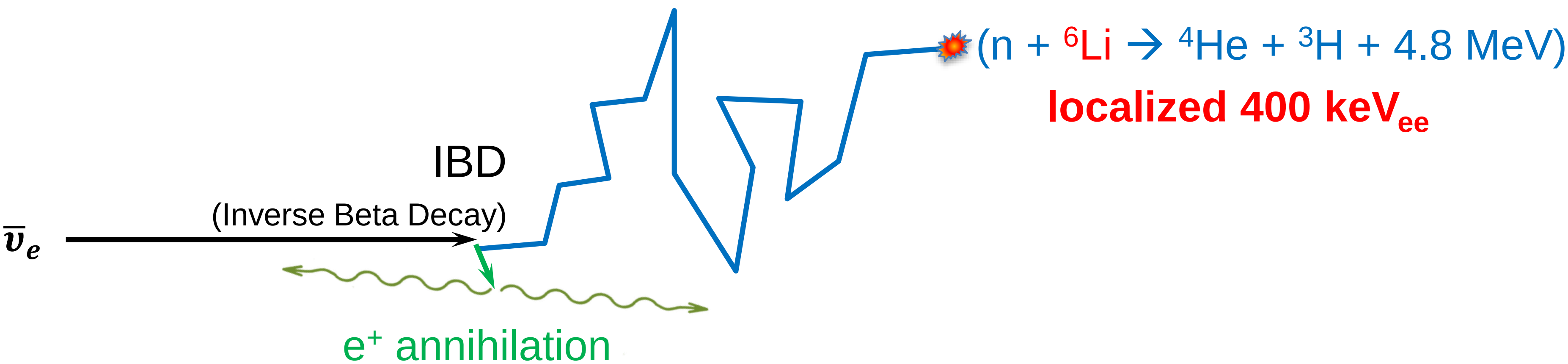
Feature	Rational
Excellent Energy Resolution	Precision Spectral Analysis – Distortions from prediction
Unique Start Signal	separate positrons from gammas, neutrons, and electrons
Unique Stop Signal	separate n-capture from backgrounds
Short Time Delay	improves real/random
Fine Segmentation	smaller improves 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 $\bar{\upsilon}_e$ Signature

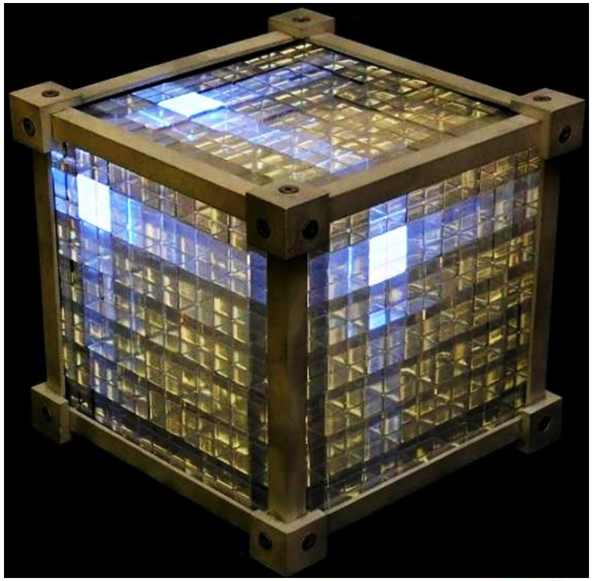


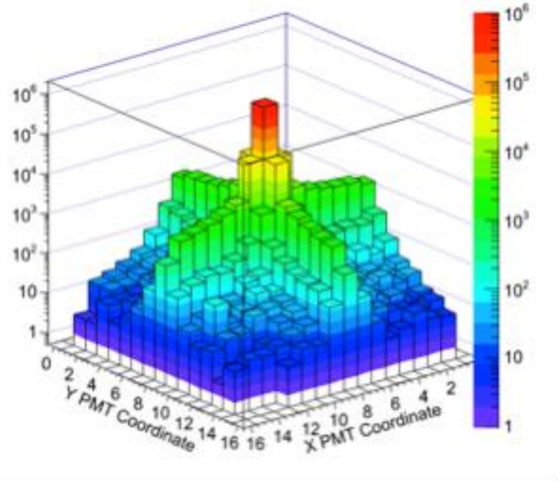
$$\overline{\nu_e} + p \rightarrow e^{+} + n$$

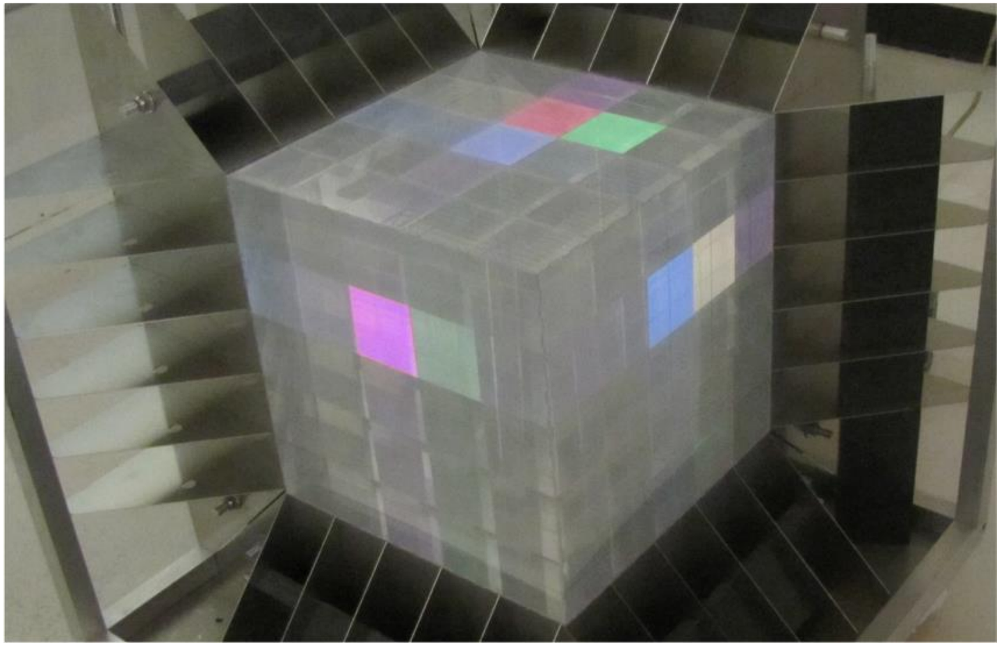
$$\xrightarrow[\tau\sim 7\mu s]{} n + {}^{6}Li \rightarrow \alpha + {}^{3}H$$



Raghavan Optical Lattice

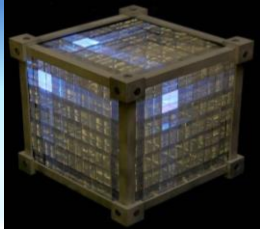




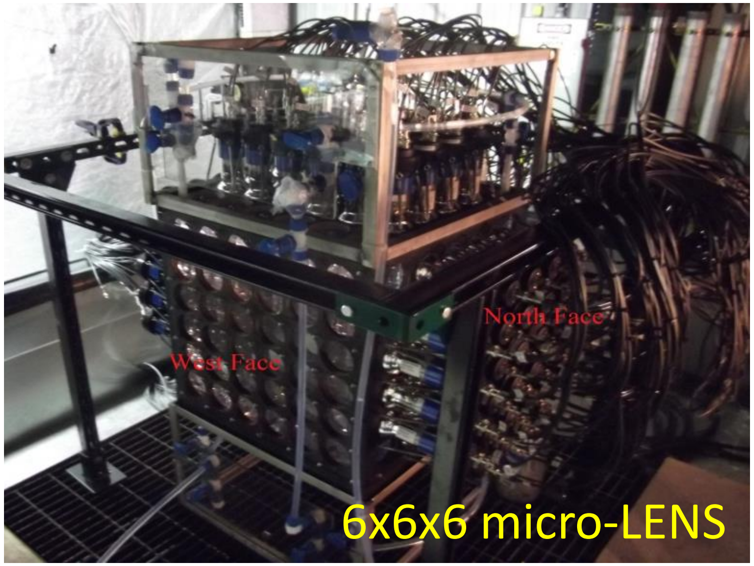


- light channeling via total internal reflection
- full 3D light collection along principle axes
  - Breaks degeneracies present in other detection schemes

Segmentation



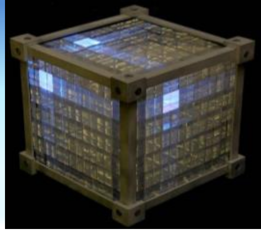
- proven technique: micro-LENS
  - operational liquid scintillator ROL detector located at KURF
  - Cell size = (3.25”)^3
  - thin Teflon walls (0.002”)
  - partial light channeling (n=1.34 and 1.49)

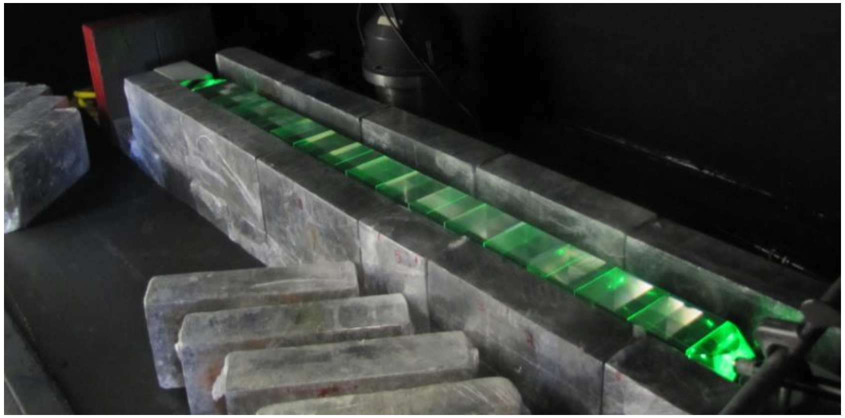


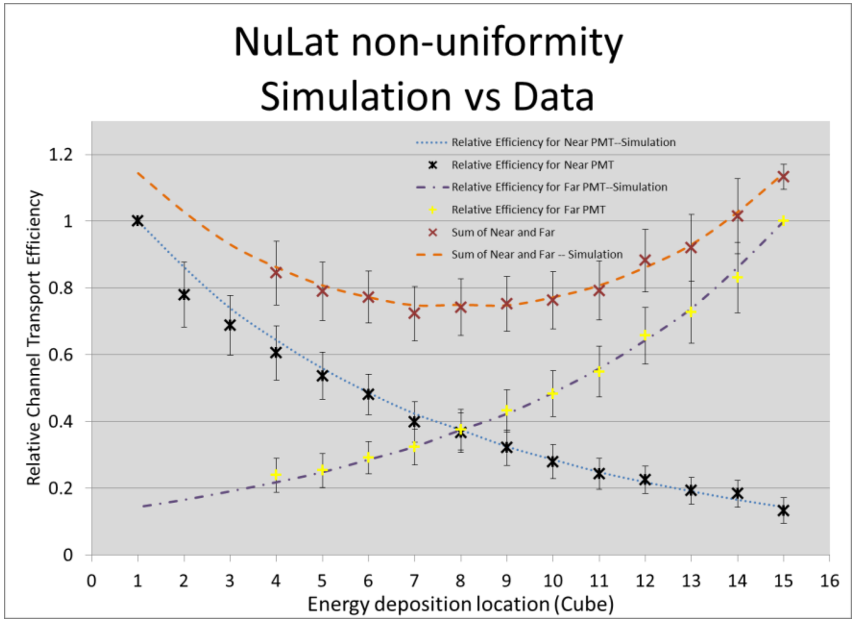
LENS 60x60x60

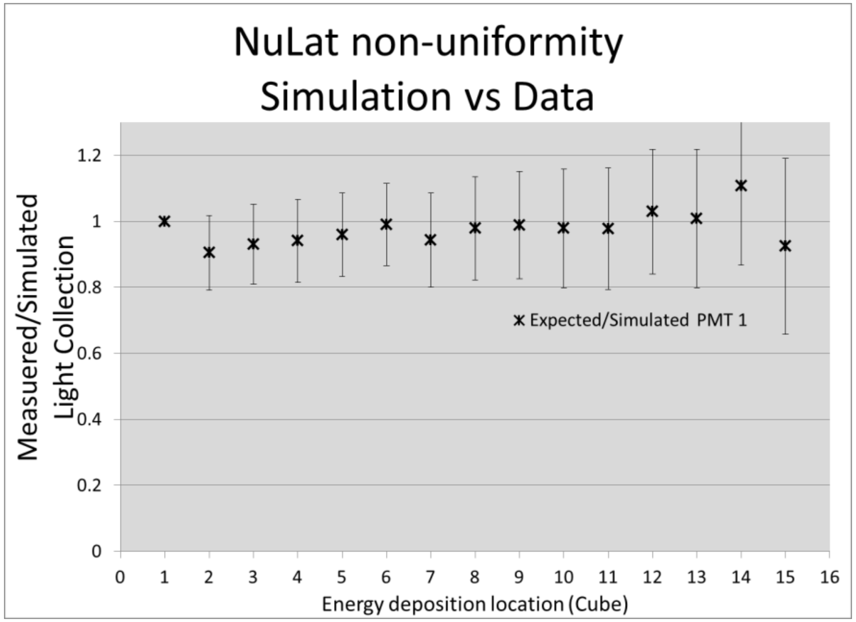
- NuLat (solid scintillator)
  - 10x10x10 cubes
    - effectively 1000 individual detectors
  - 2.5 inch polished plastic scintillator cubes
  - 0.5% ^{6}Li by wt. loading (Eljen)
  - VM2000 reflective film ‘dots’ to maintain air-gap
  - ***Total*** light channeling (n=1 and 1.54)
  - Easily scalable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

NuLat 15 Cube
Full Channel Module Testing

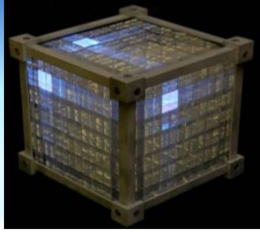


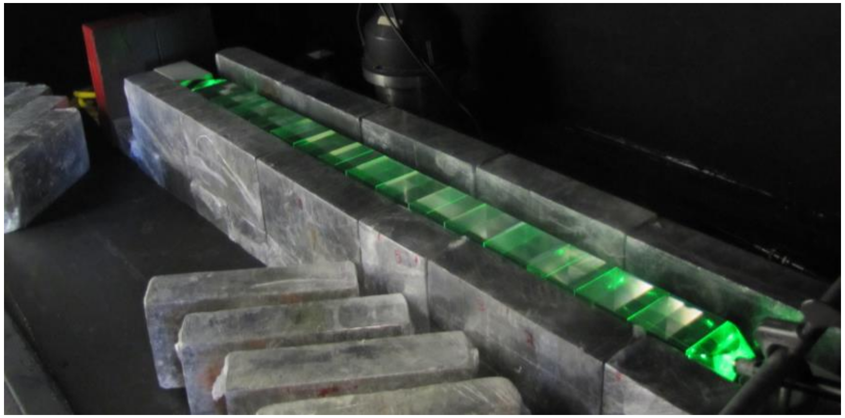


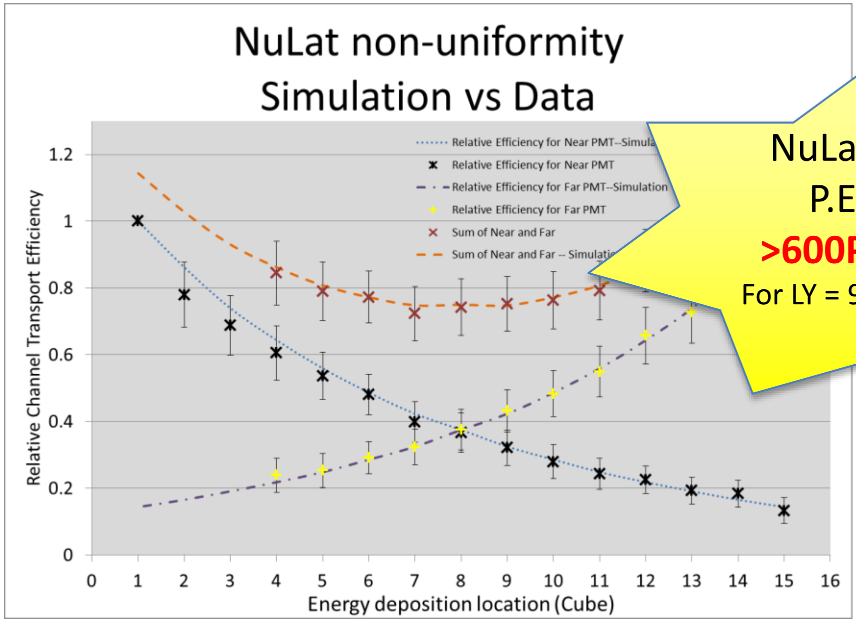




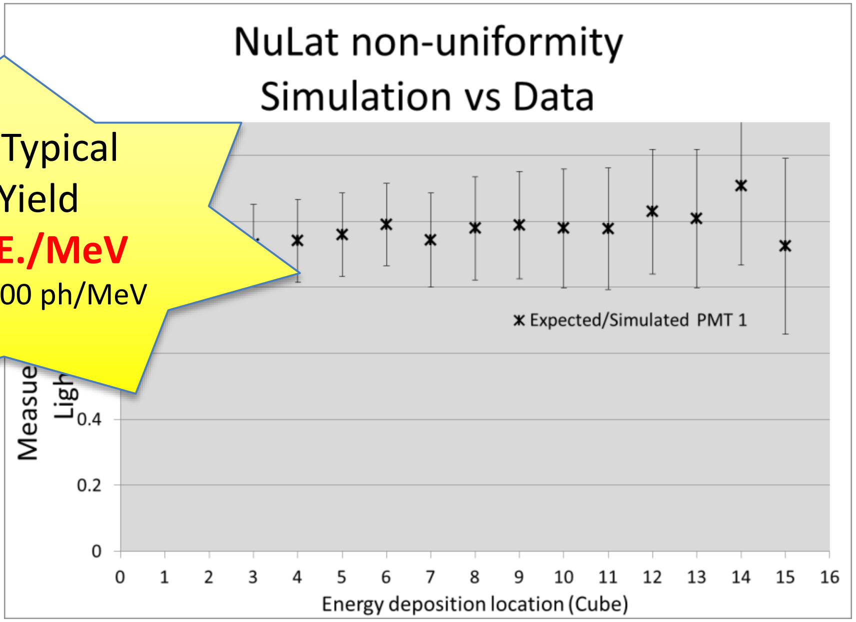
NuLat 15 Cube
Full Channel Module Testing



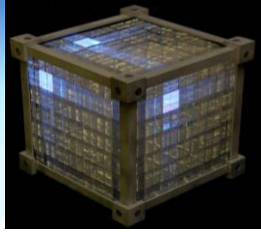




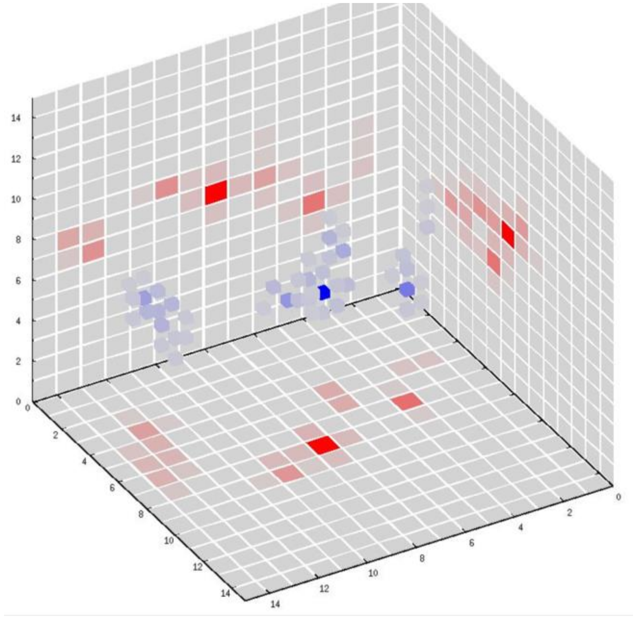
NuLat Typical
P.E. Yield
>600P.E./MeV
For LY = 9200 ph/MeV



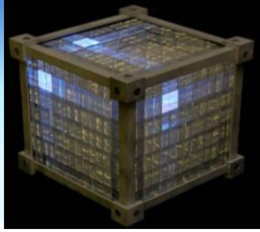
Unique Start Signal



- Positron plus annihilation
  - 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 halo
  - pair production reduced by primary shielding



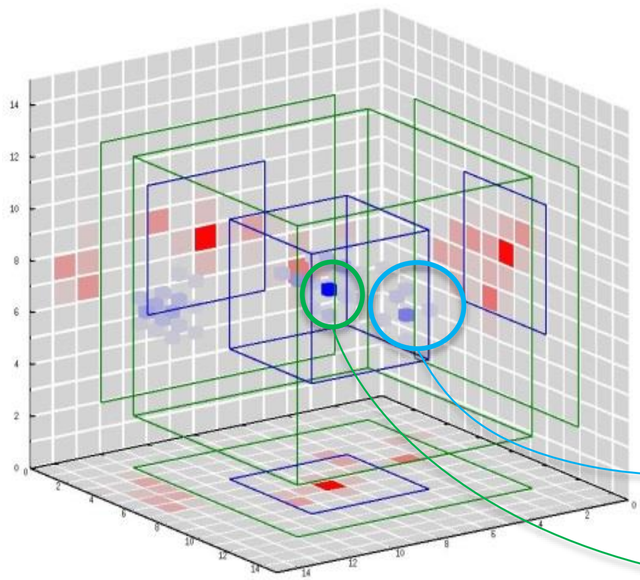
Event Topology

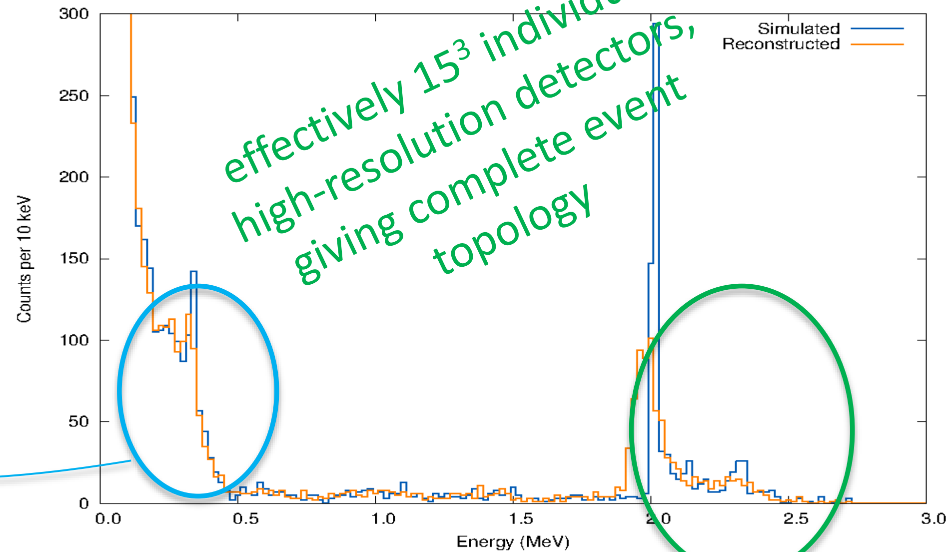


$$\overline{\nu}_e + p \rightarrow e^+ + n$$

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

4%/$\sqrt{E}$ (600 p.e. /MeV)
single cell position (< 3 cm w timing)



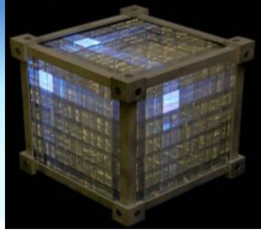


effectively 15^3 individual high-resolution detectors, giving complete event topology

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

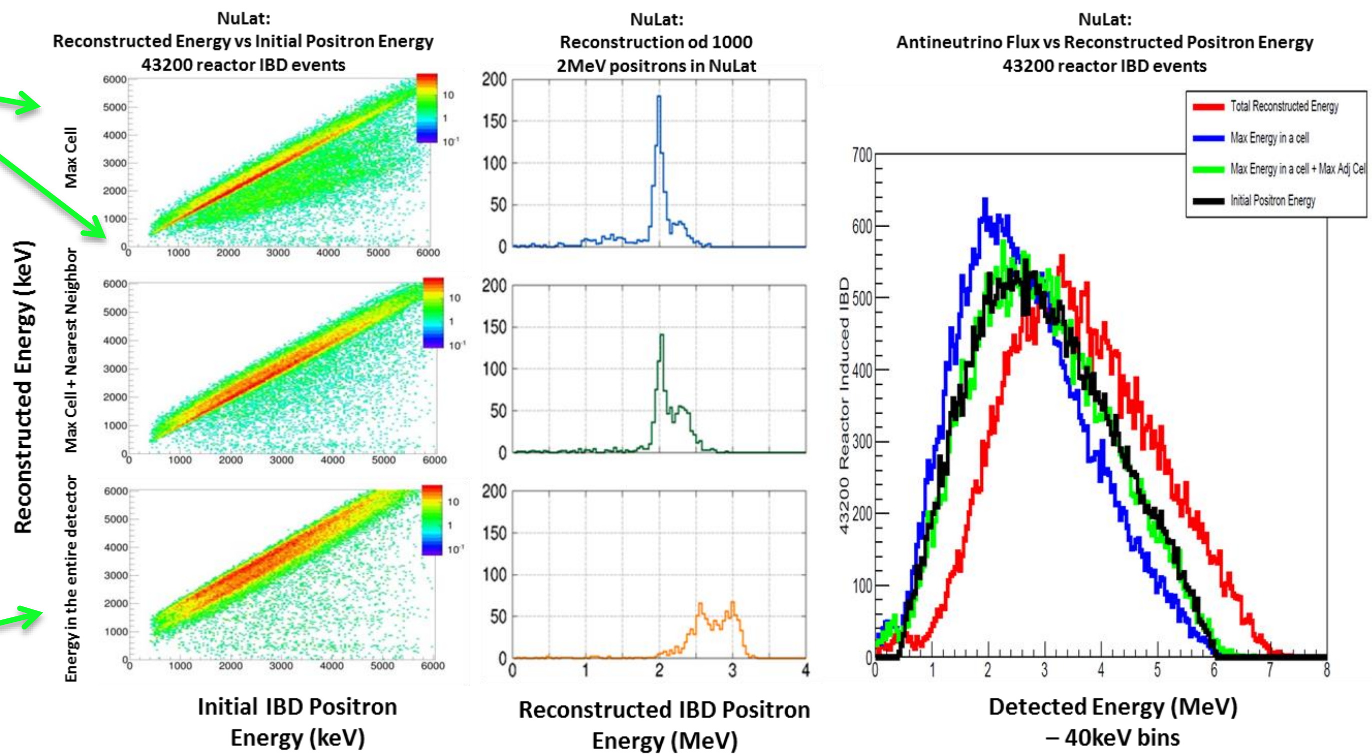
Energy Resolution



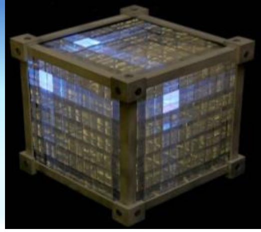
→ $E_{\nu}=E_{e+}$ + 1.8 MeV
→ full positron energy in one cell or at most two (vertex cell)
→ minimal contamination by annihilation gammas in vertex cell
→ allows excellent neutrino energy resolution throughout the *complete* detector

unique to NuLat

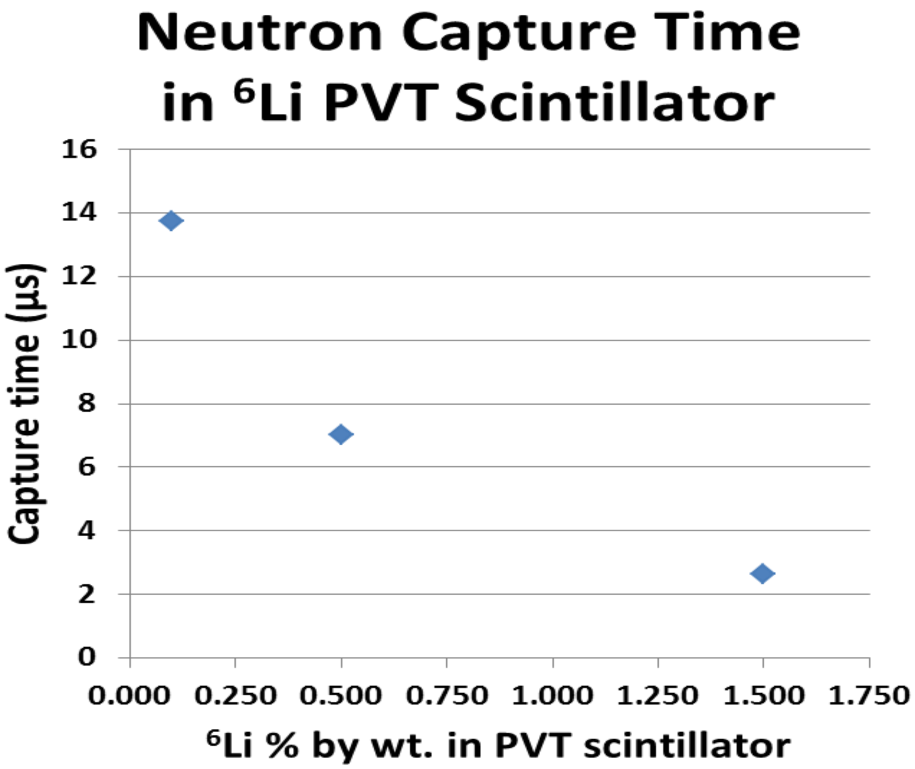
available to all integrating small detectors



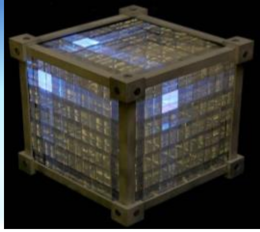
Unique Stop Signal



- Lithium-6 PVT
  - $^{6}Li + n \rightarrow \; ^{3}H + \alpha$
  - 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

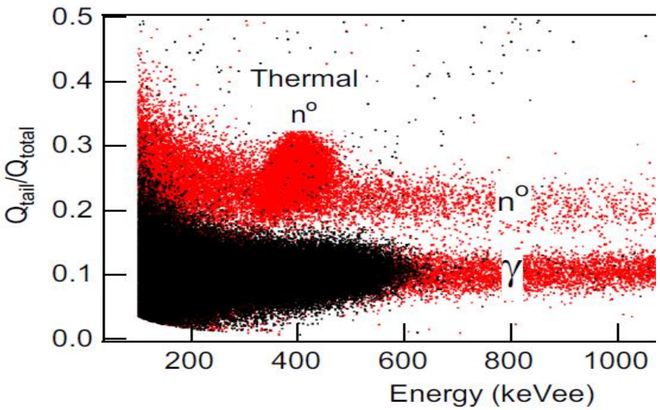


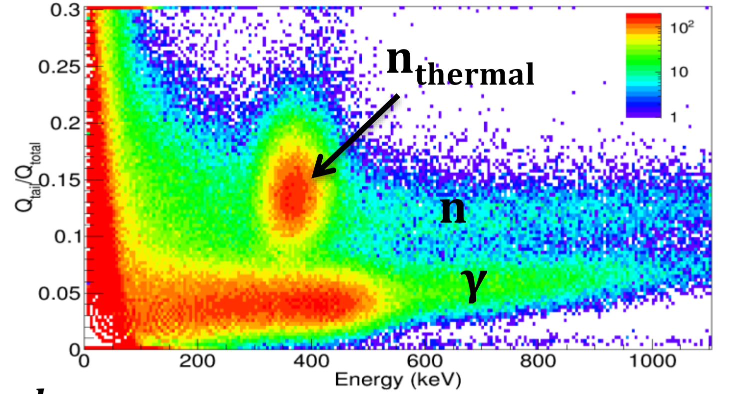
PSD in ^{6}Li Plastic



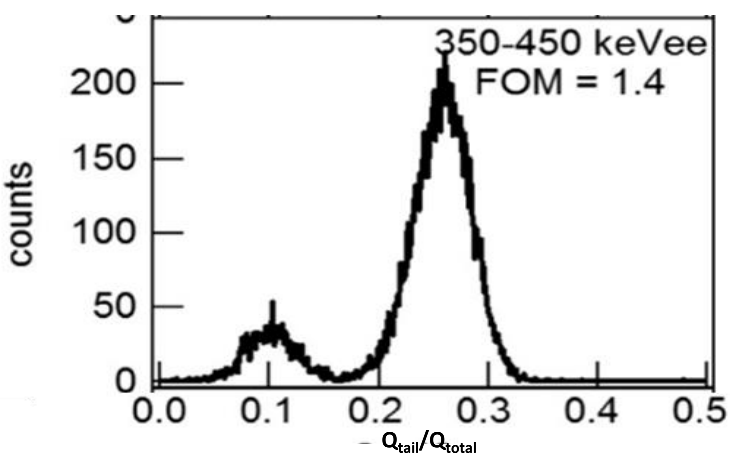
Eljen LLNL based EJ-200 ^{6}Li PSD characterization as measured at Virginia Tech

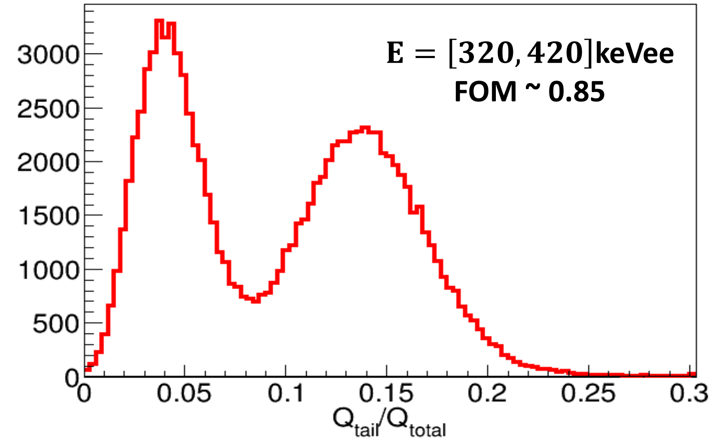
Cherepy NIM A778 2015





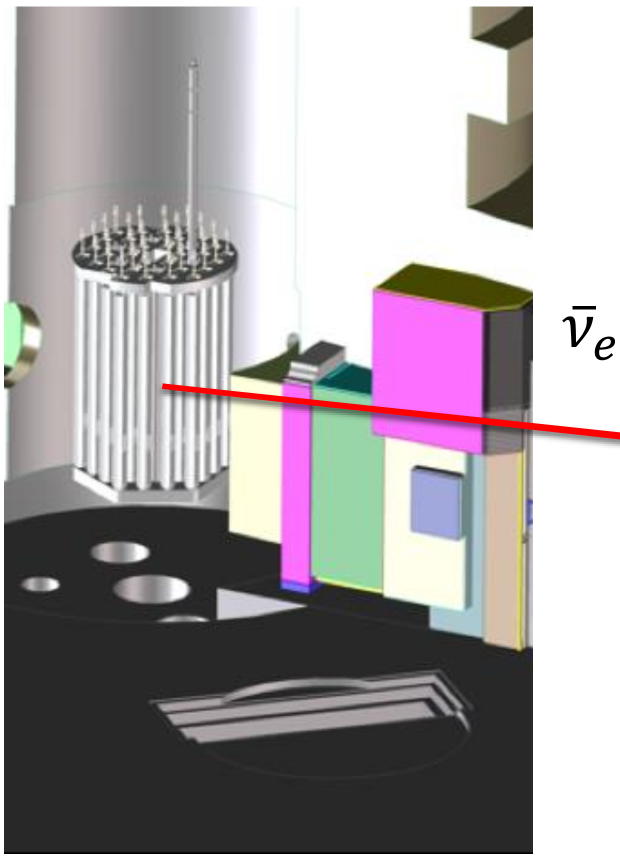
$$FOM = \frac{d}{FWHM_{\gamma} + FWHM_{n}}$$



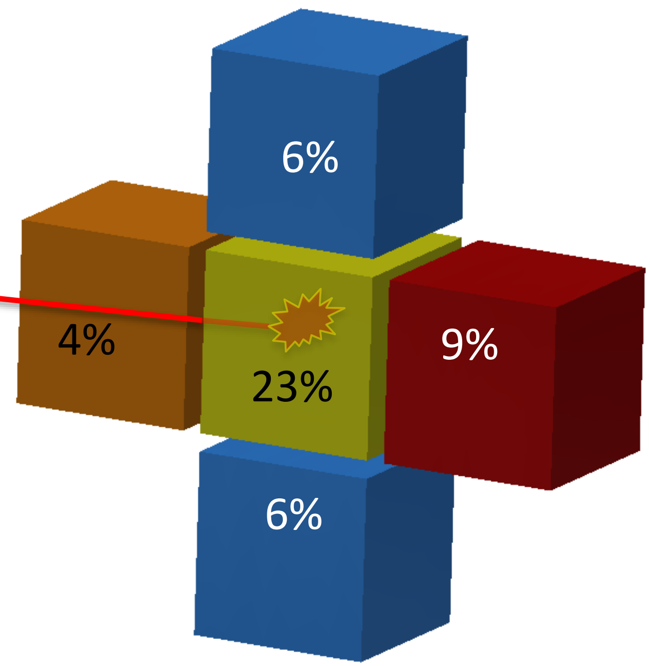


Better energy resolution results in better background rejection.

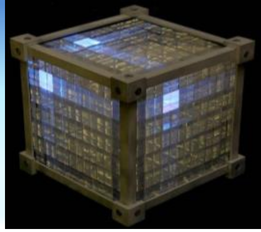
Unique Topology for the Ensemble of IBD Events



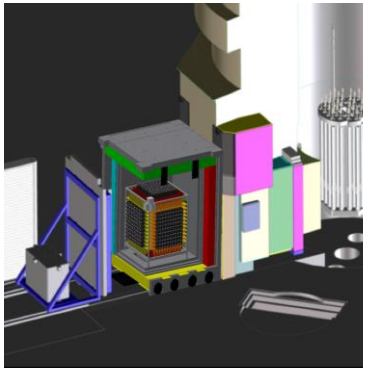
Relative location of neutron capture to IBD positron production

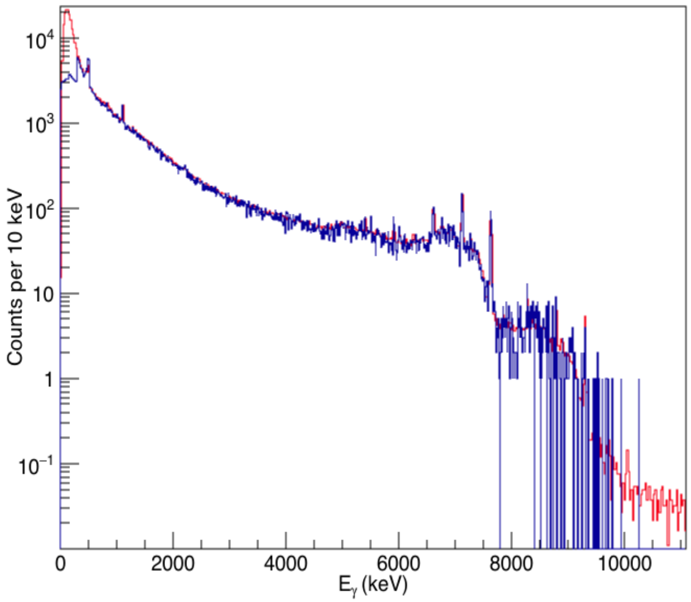


NIST Background Studies

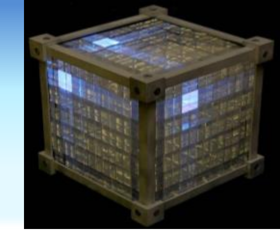


- Gamma spectrum surveyed via germanium detector (red)
- Germanium detector response to gamma model developed (blue)
- Gamma model allows for detailed simulation studies inside mTC Cave





^{222}Rn Internal Calibration

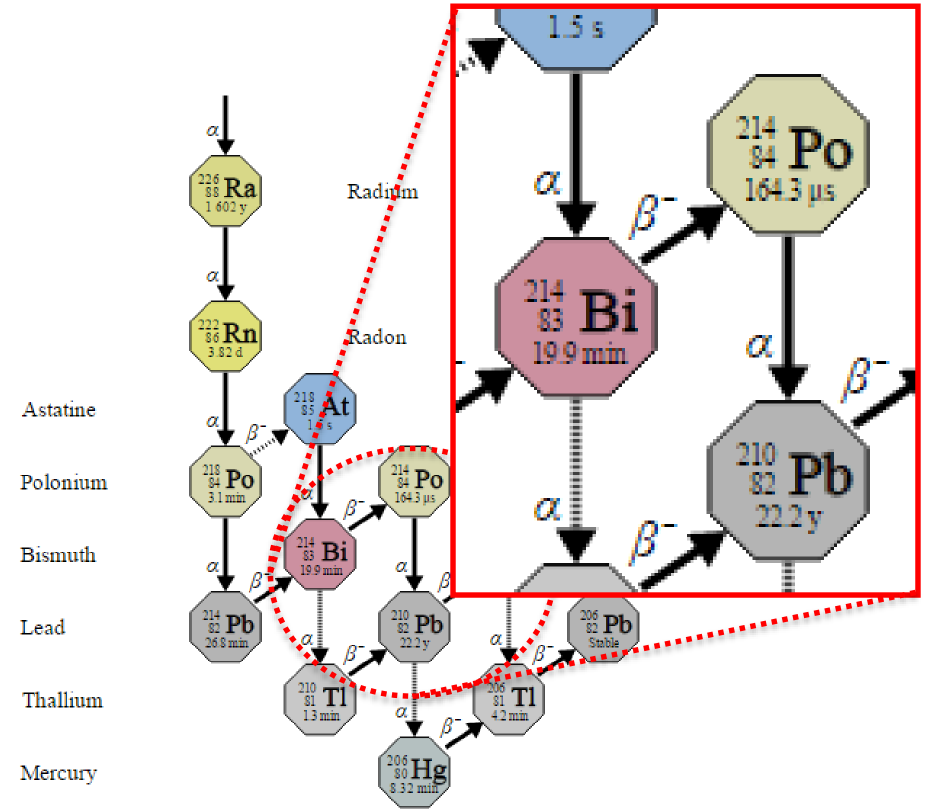


- ^{226}Ra ^{222}Rn-Generator
- Fill airgaps with ^{222}Rn rich gas
- Same/adjacent cell

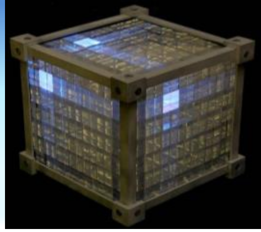
  $^{214}\mathrm{Bi} \rightarrow \beta- + {}^{214}\mathrm{Po}$

  followed by (τ=164μs)

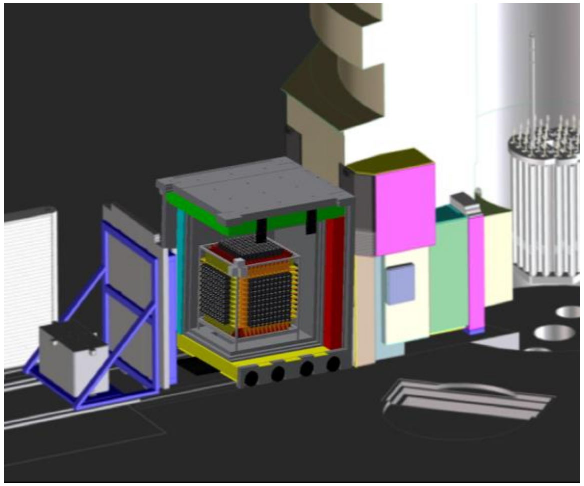
  $^{214}\mathrm{Po} \rightarrow \alpha + {}^{210}\mathrm{Pb}$
- Close temporal and spatial structure to that of a antineutrino capture
- Provides PSD stop tag
- Mean $\beta-$ E = 642keV
- Mean α E ~ 700keVee
- Characterize surface scintillation affects

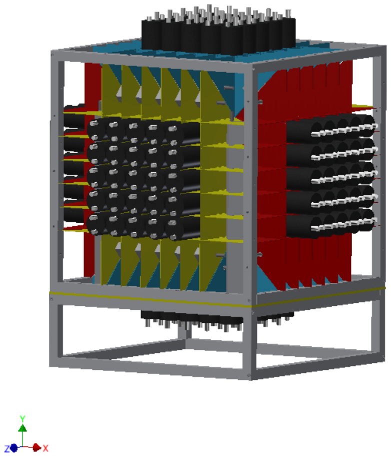


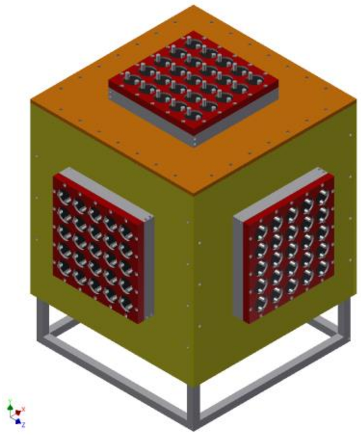
ROL 5^3 Antineutrino Detector

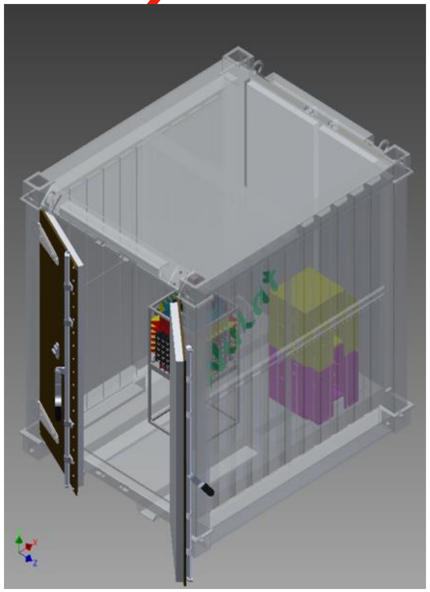


- Design Finalized
- All major material has been ordered
- Construction to be completed ~March 2016
- Deployment:
    - North Anna (L ≈24m)
    - NIST (L ≈ 4.7m)

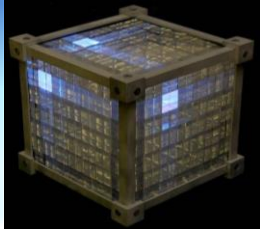




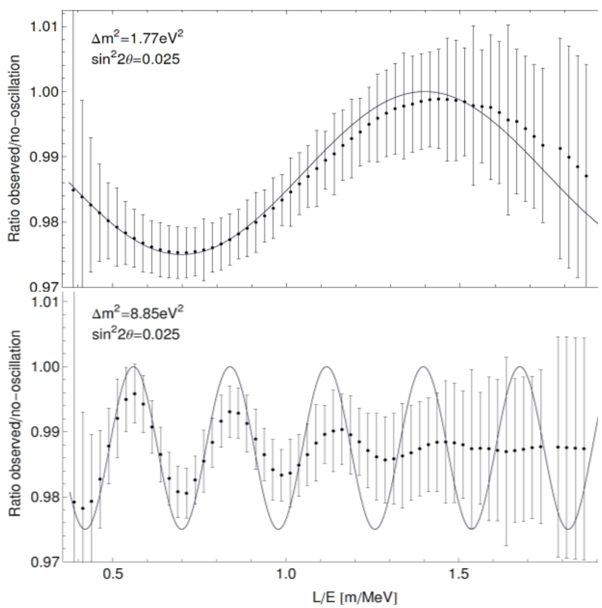


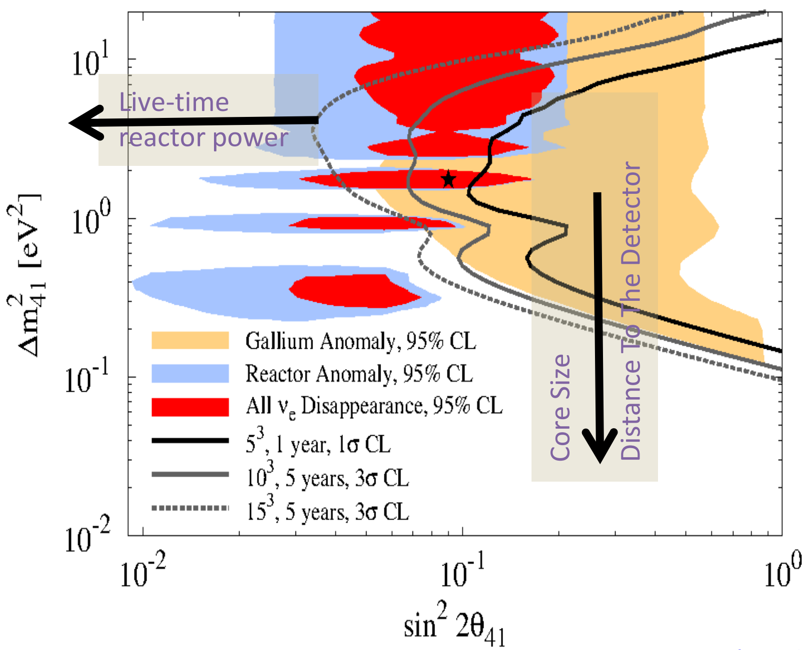


Sterile ν Search Performance



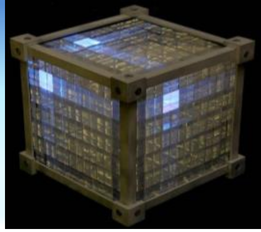
- **S/B = 3**
- **Time is calendar time at NIST**
- **NuLat is expected to have better S/B, even in higher-flux environments (10/1)**





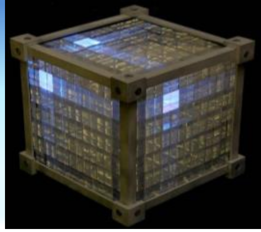
arXiv:1212.2182
arXiv:1501.06935

NuLat Features of Merit



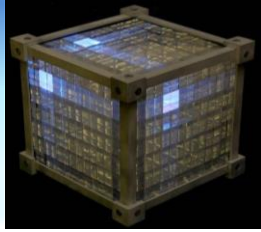
	Feature	Rational
✓	Excellent Energy Resolution	Precision Spectral Analysis – Distortions from prediction
✓	Unique Start Signal	separate positrons from gammas, neutrons, and electrons
✓	Unique Stop Signal	separate n-capture from backgrounds
✓	Short Time Delay	improves real/random
✓	Fine Segmentation	smaller 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
✓	Sub Nanosecond Timing	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

ROL 5^3 Antineutrino Detector Tasks



	Expected Completion
Detector Construction	
Order 125 pre-cut 6Li-Loaded Scintillating cubes	FY 2015 Q3 (CY Q2)
Demonstrate lattice construction	FY 2015 Q4 (CY Q3)
Construct 6Li-Loaded ROL 5^3 Detector	FY 2016 Q2 (CY Q1)
Electronics	
Demonstrate 5x5-6sided DAQ and trigger (150 channels)	FY 2016 Q2 (CY Q1)
Demonstrate gain and timing calibration	FY 2016 Q2 (CY Q1)
DAQ, Simulation, and Analysis	
Reconstruct 'positron' event topology and energy via $\gamma \rightarrow e^+ + e^-$	FY 2016 Q2 (CY Q1)
Demonstrate neutron tagging	FY 2016 Q2 (CY Q1)
Demonstate timing topology to show time-ordering	FY 2016 Q2 (CY Q1)
Evaluate the performance difference between 3 and 6 sided instrumentation	FY 2016 Q3 (CY Q2)
Deployment	
Deploy at commercial reactor	FY 2016 Q3 (CY Q2)
measure neutrino rate & signal/background	
Deploy at NIST	FY 2016 Q4 (CY Q3)
Other studies towards *full* NuLat	
Determine the amount of passive shielding required	FY 2016 Q4 (CY Q3)
Evaluated the ability and need to adjust detector reactor baseline	FY 2016 Q4 (CY Q3)

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