Reactor Antineutrino Directionality via Elastic Electron Scattering in Gd-Doped Water Cherenkov Detectors

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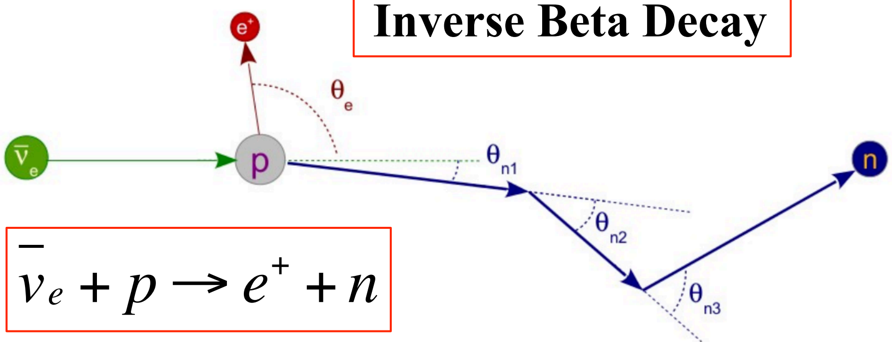
Outline

- Antineutrino interactions and directionality
- Reactor antineutrino energy spectrum
- Expected signal
- Backgrounds
- Sensitivity vs. radon, depth, and detector size
- Conclusions

Antineutrino Interactions

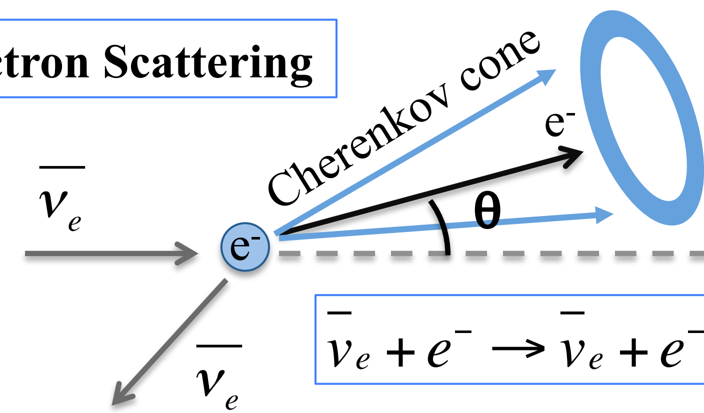
Inverse Beta Decay



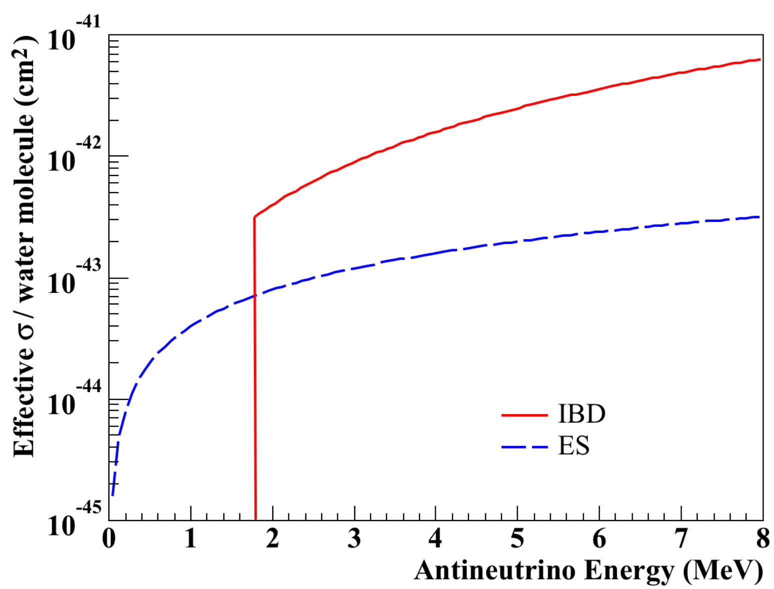
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

E. Caden (AAP, 2012)

Electron Scattering



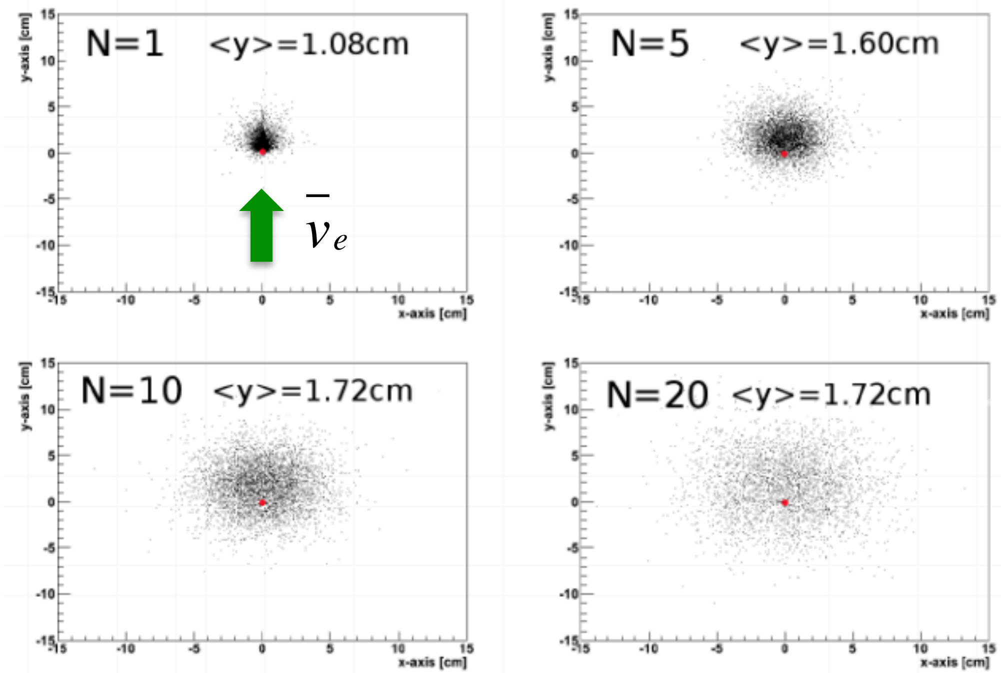
$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$



Directionality

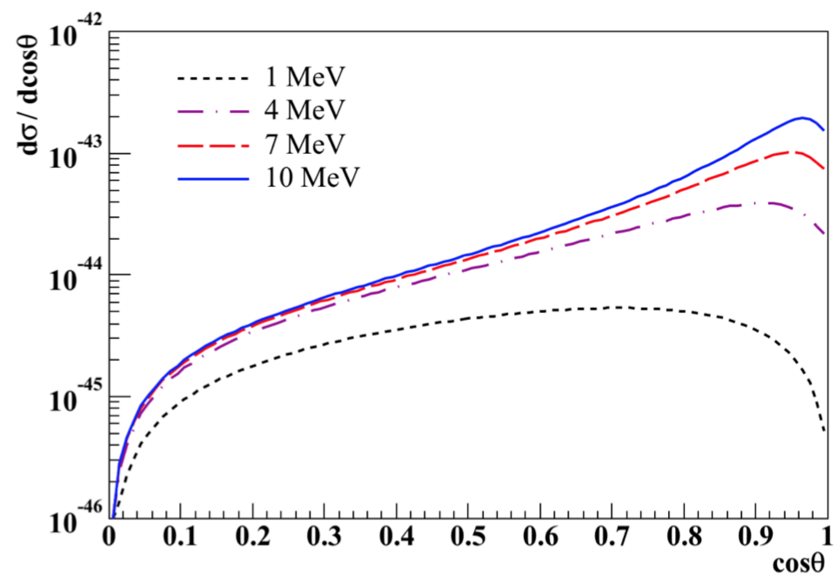
- Reduce background from multiple nearby reactors
- Search for clandestine reactors
- Supernova pointing

Inverse Beta Decay

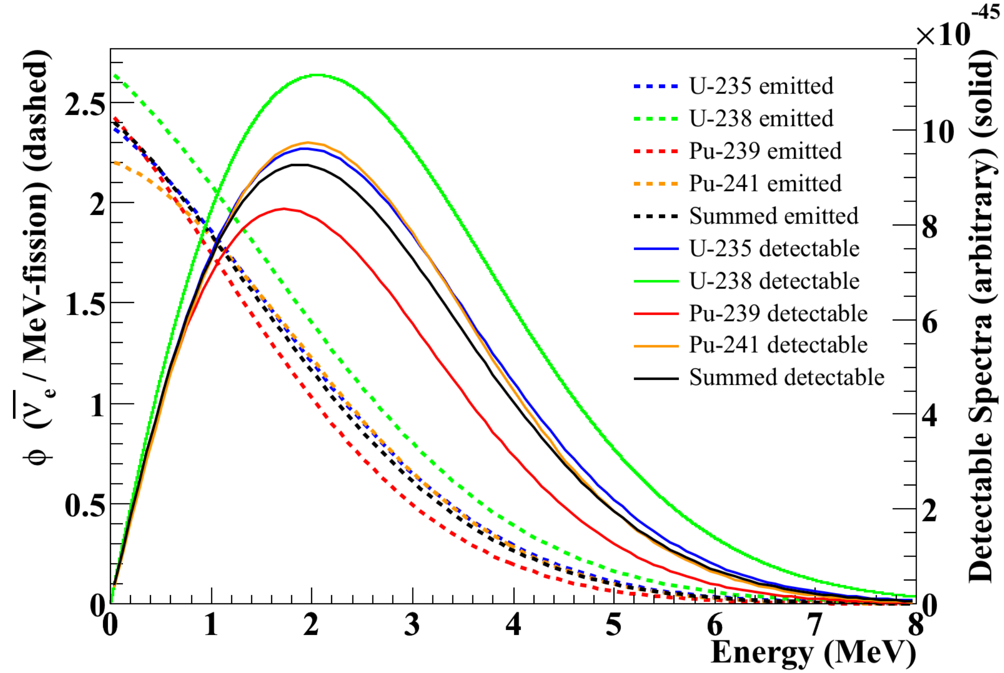


C. Langbrandtner (Ph.D. Thesis, 2011)

Electron Scattering



Reactor Energy Spectrum*



Detectable = folded with cross section

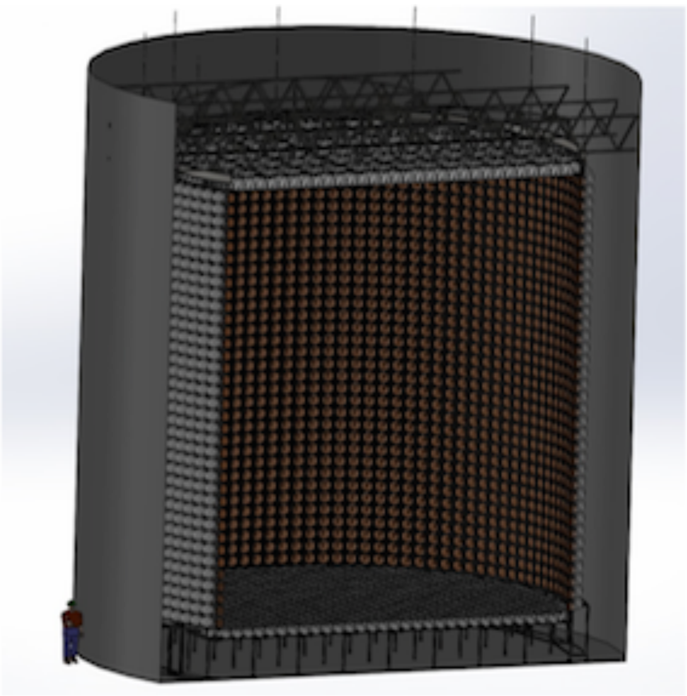
Summed = weighted sum using typical mid-cycle PWR fission fractions (49.6% ^{235}U, 35.1% ^{239}Pu, 8.7% ^{238}U, 6.6% ^{241}Pu)**

* *P. Vogel, J. Engel, Phys. Rev. D 39, 3378 (1989)*

** *G. Zacek et al., Phys. Rev. D 34, 2621 (1986)*

Baseline Detector Design

- Access to existing GEANT4 simulation of WATCHMAN detector



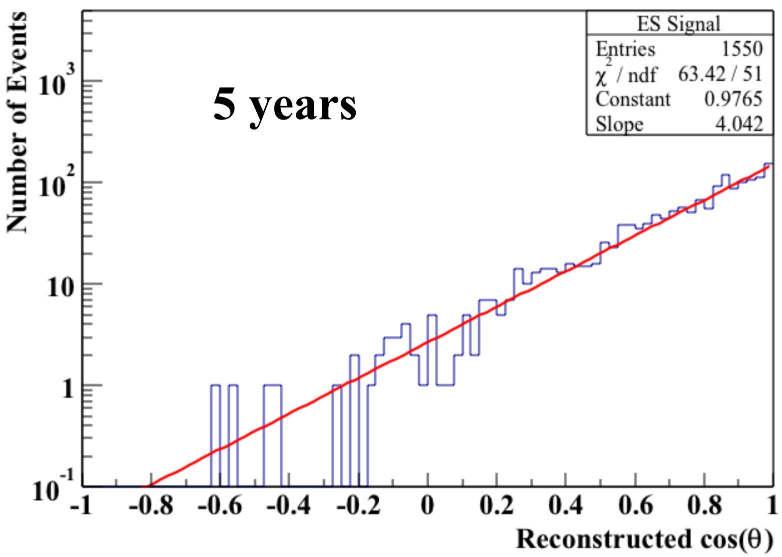
- 3.1 kilotons of Gd-doped water total
- 2.1 kiloton target
  - ~ 4300 12-inch PMTs facing target
- 1 kiloton veto
  - ~ 480 12-inch PMTs facing veto
- 1 kiloton fiducial
- 1.5 meter buffer
- Assume low-background PMTs
- 1500 m.w.e. overburden
- 13 km standoff from 3.758 GWth LWR

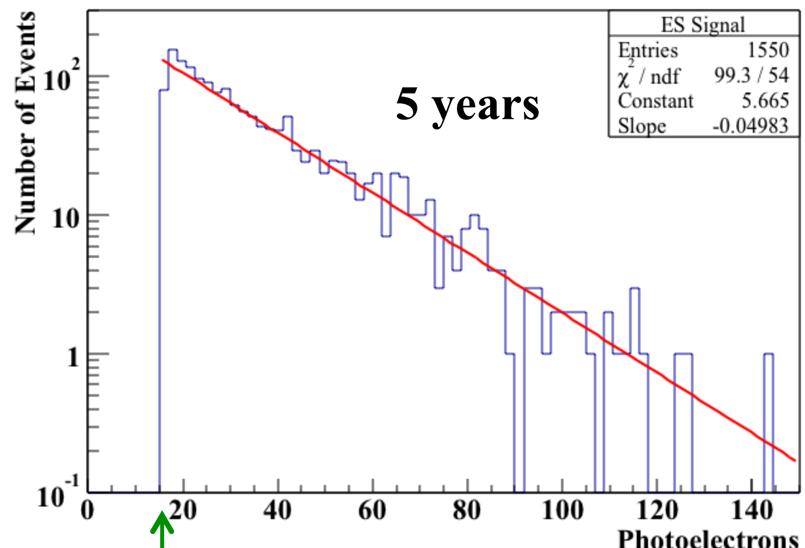
Note: WATCHMAN not originally designed for directionality

Expected ES Signal

$$R_{\bar{\nu}_e/e^-} = \frac{N_e}{4\pi d^2} \sum_i f_i \int \phi_i(E_{\bar{\nu}_e})\sigma(E_{\bar{\nu}_e})dE_{\bar{\nu}_e} \quad (\sim 9270 \text{ events/5 years})$$

- Simulations done with GEANT4 simulation **RMSim**
- Event reconstruction done with **BONSAI**

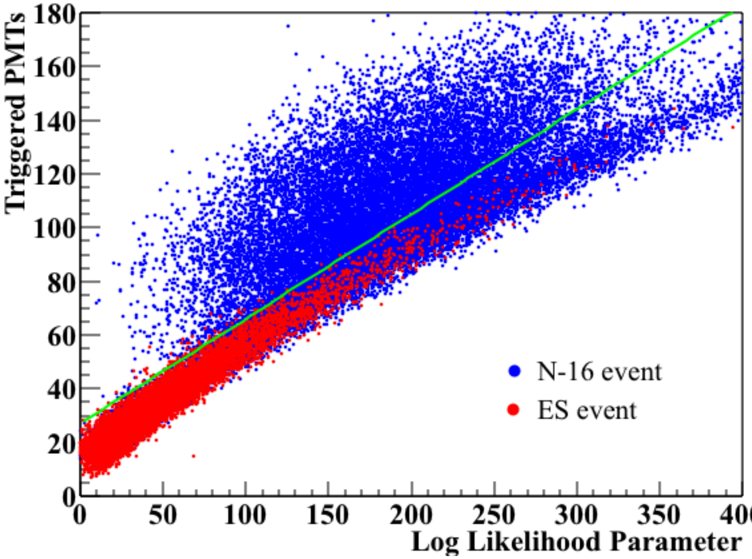




RMSim imposes 16 PE trigger threshold
→ 17% detection efficiency

Cosmogenic Radionuclides

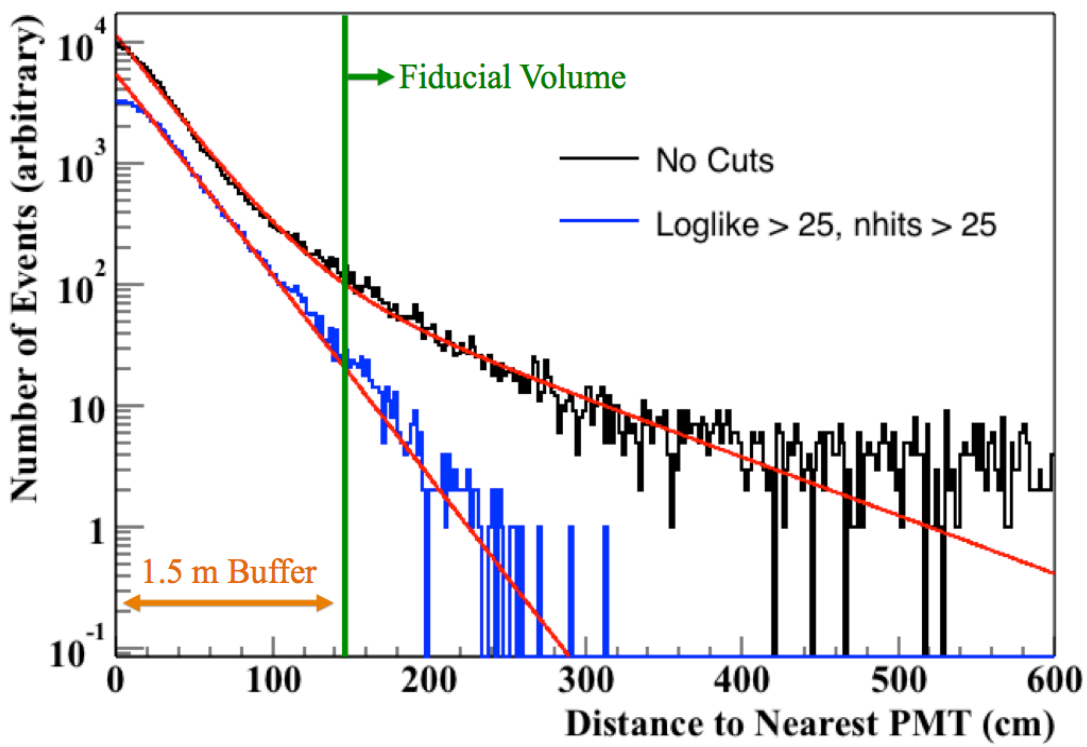
- $\beta^{+/-}$ decay of ^{16}N, ^{15}C, ^{11}Be, ^{8}B, ^{8}Li
  - Utilize yields from Super-K FLUKA study*
- Muon rates (relative to KamLAND) obtained from GEANT4 simulation of muons as a function of depth
  - provided by David Reyna (SNL)**
- Impose a 10 sec position sensitive veto
  - 1 meter tube for non-showering muons
  - 2 meter tube for showering muons
    - Results in 67% livetime
- Remove events that reconstruct as more than one Cherenkov cone
  - evidence of coincident β and γ



* *S. Li, J. Beacom, Phys. Rev. C 89, 045801 (2014)*
** *D. Reyna, arXiv:0604145v2 (2006)*

PMT Backgrounds

- Mostly interact in buffer, however uncertainty in reconstruction can place them in the fiducial volume



→ Use exponential behavior to estimate backgrounds

^{222}Rn / ^{214}Bi

- Presence of radon gas in detector medium
  - Trace amounts of naturally occurring ^{238}U
  - Radon gas migrating out of PMT glass
  - Radon gas leaking into detector from mine air
- Estimate with radon contamination of 10^{-14} gU/gD_2O published by SNO*
  - Including 67% livetime and 20% detection efficiency results in **1350 events/day** (~ 2.5 x 10^6 events/5 years)

→ Progress must be made in radon removal

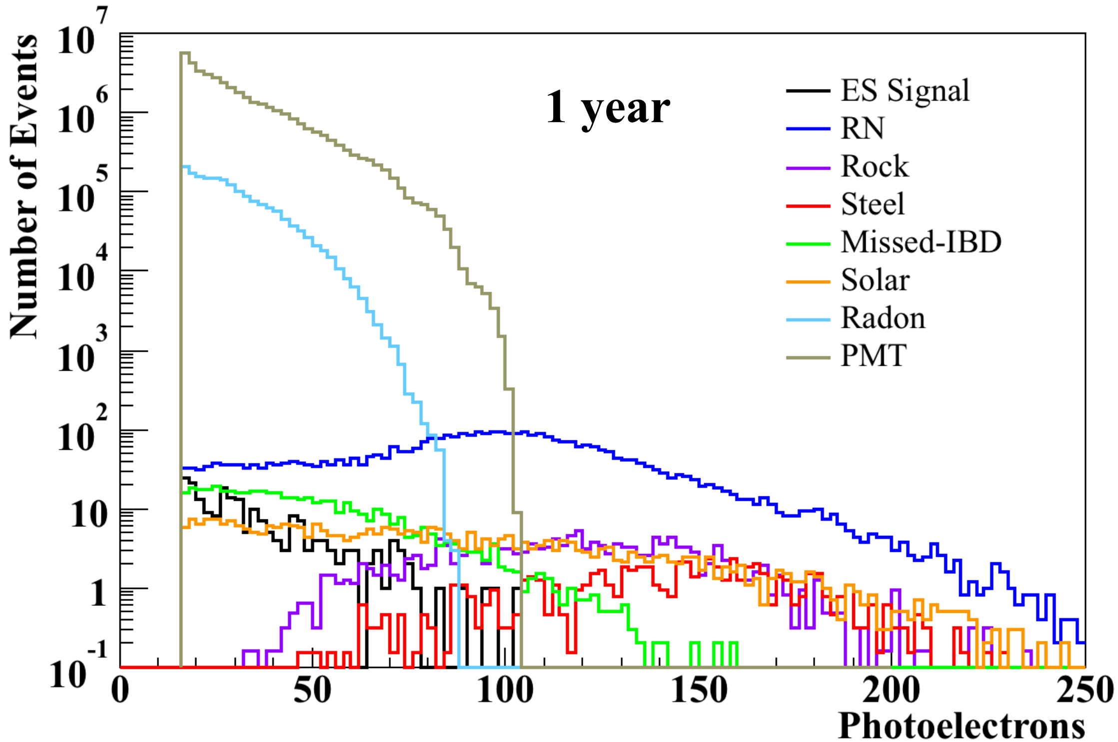
- Radon free air
- Uranium removal
- Directed clean water flow (permeable acrylic barrier)

→ Beginning to investigate these methods

* *I. Belvis et al., Nucl. Instrum. Methods A 517, 139 (2004)*

Other Backgrounds

- Steel/rock γ's and solar ν scaled from IsoDAR study on KamLAND*
  - Take into account larger fiducial volume and different livetime
- Misidentified IBD interactions estimated assuming an event rate of 20 events/day and a 20% missed neutron rate



→ Look to higher energies
→ Reduce fiducial volume
→ Reduce radon

→ More overburden

* *M. Toups et al., Phys. Rev. D 89, 072010 (2014)*

WATCHMAN vs. Radon

*5 years

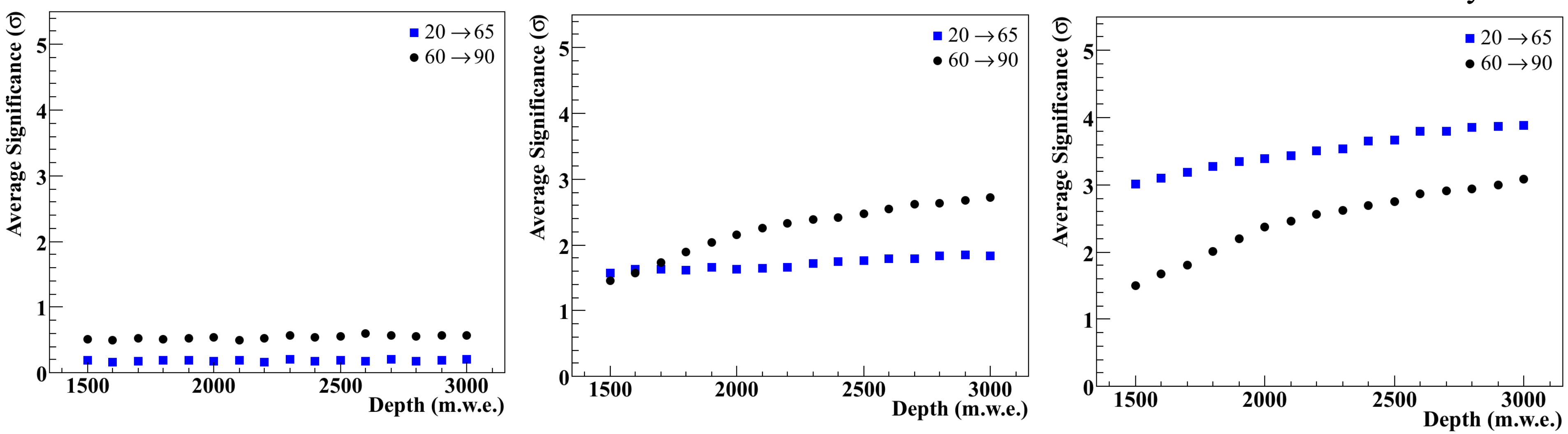
PMT Triggers	FV (m^3)	ES	Exp. Slope		RN	PMTs	Other	Radon (x SNO)		
								1	10^{-2}	10^{-4}
$25 \rightarrow 65$	187	**80**	4.6		741	1212	438	638670	6387	64
				Total BG				**641061**	**8778**	**2455**
				Significance				$\mathbf{0.2\sigma}$	$\mathbf{1.6\sigma}$	$\mathbf{2.9\sigma}$
$50 \rightarrow 80$	400 - 500	**48**	6.0		1717	906	735	125430	1254	13
				Total BG				**128788**	**4612**	**3371**
				Significance				$\mathbf{0.3\sigma}$	$\mathbf{1.5\sigma}$	$\mathbf{1.8\sigma}$
$60 \rightarrow 90$	500 - 1000	**43**	6.7		3947	227	1171	34390	344	3
				Total BG				**39735**	**5689**	**5348**
				Significance				$\mathbf{0.5\sigma}$	$\mathbf{1.3\sigma}$	$\mathbf{1.4\sigma}$

- Low energy slice only relevant with significant fiducialization and radon reduction
- Without radon reduction, high energy cuts must be used
  - But radionuclides begin to dominate

Sensitivity vs. Depth

- Determine RN background as function of depth
- Recalculate significance for each depth and various radon levels

*5 years



$1 \times$ SNO radon

$10^{-2} \times$ SNO radon

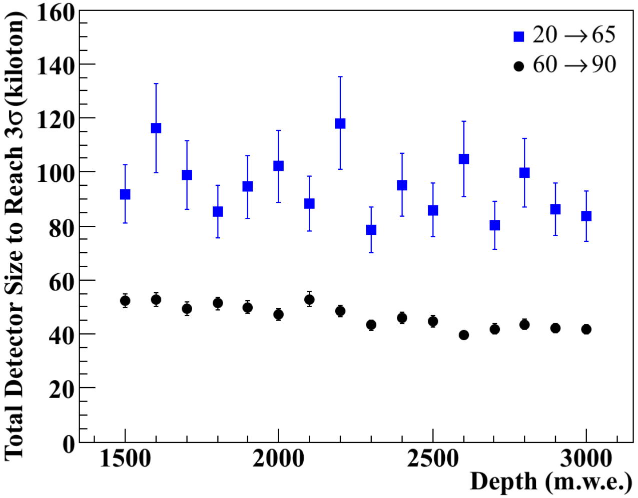
$10^{-4} \times$ SNO radon

*Data represents mean value of multiple repeated experiments

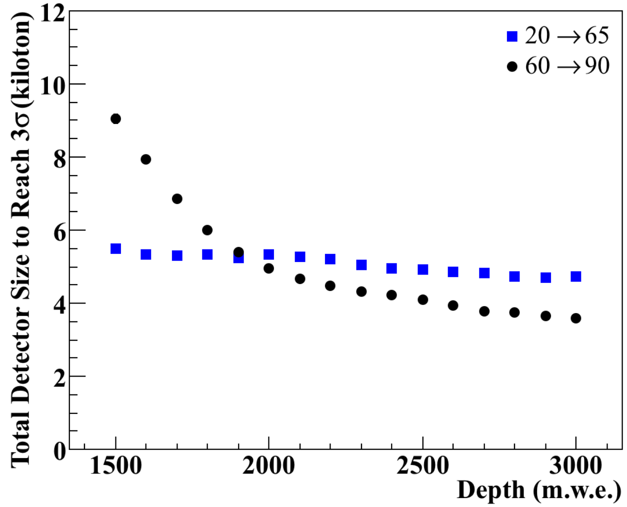
Sensitivity vs. Depth vs. Size

- Now determine the detector size required for 3σ
- Scale signal with volume, scale significance with signal to noise ratio

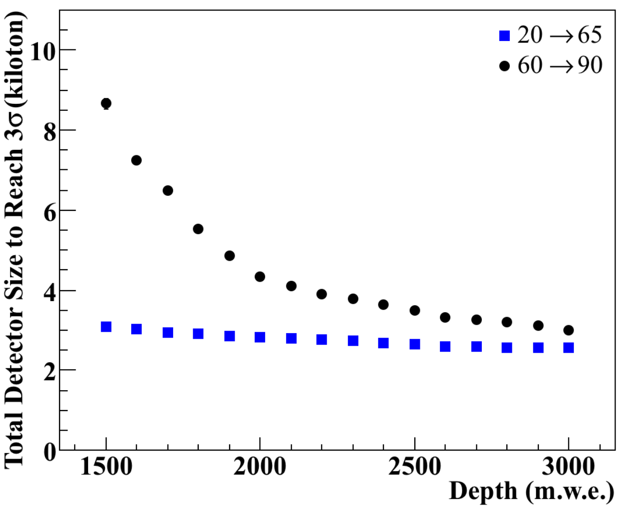
*5 years



1 × SNO Radon



10^{-2} × SNO Radon



10^{-4} × SNO Radon

*Data represents mean value of multiple repeated experiments

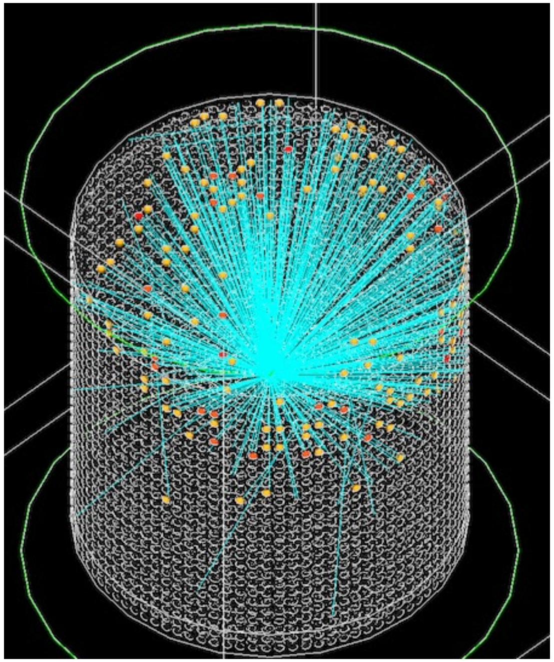
Conclusions

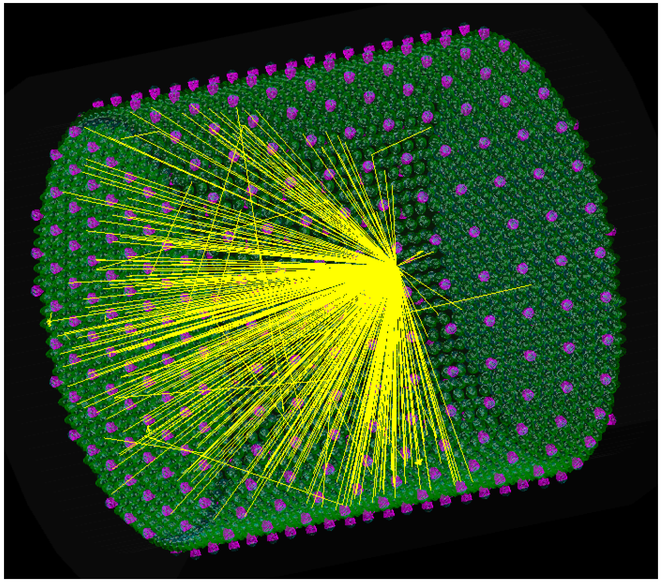
- Similar radon contamination as SNO → need much larger detector (> 40 ktons)
- ×100 reduction in radon → need combination of a larger and deeper detector
- ×10,000 reduction in radon → 3 kton detector at 1500 m.w.e. (WATCHMAN) should be directionally sensitive

- Assumes full power reactor operation with no shutdown periods
- Fission fractions are constant in time (no burnup)
- Technically the directional sensitivity with respect to an assumed direction
  - Need statistical penalty for testing in multiple directions

- **Paper being submitted to journal soon**
- **Currently at arXiv:1512.00527**

Questions?





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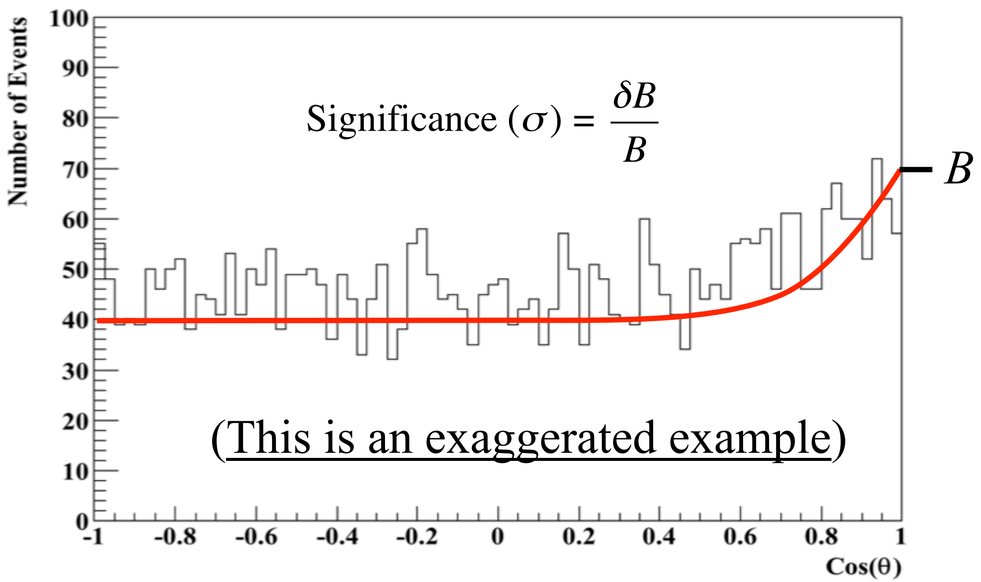
Supplementary Slides

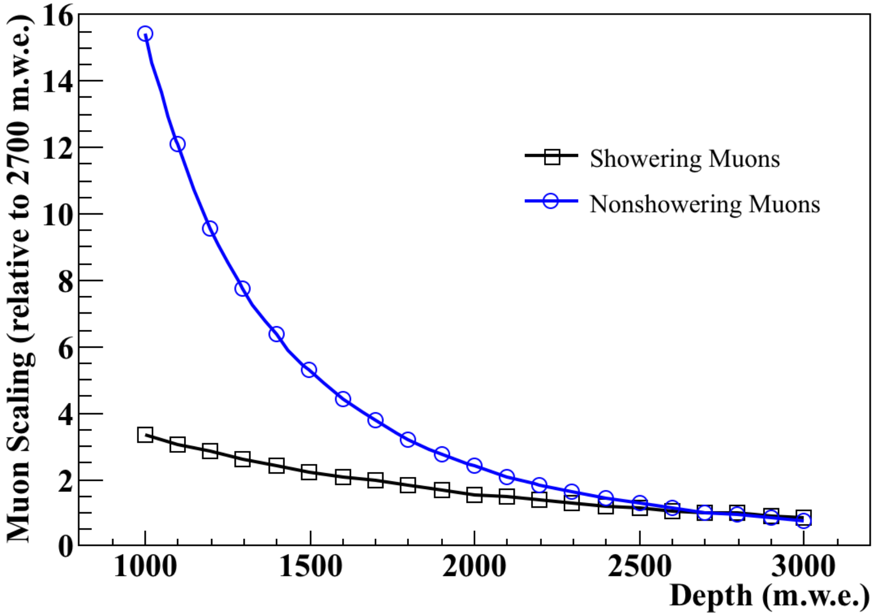
Significance Calculation

- Background assumed to be isotropic (ignore solar anisotropy)
- Fit signal with constant + exponential ($A + Be^{Cx}$)
- Use calibration source to predetermine exponential slope, C
- Use uncertainty in exponential normalization B to determine signal significance

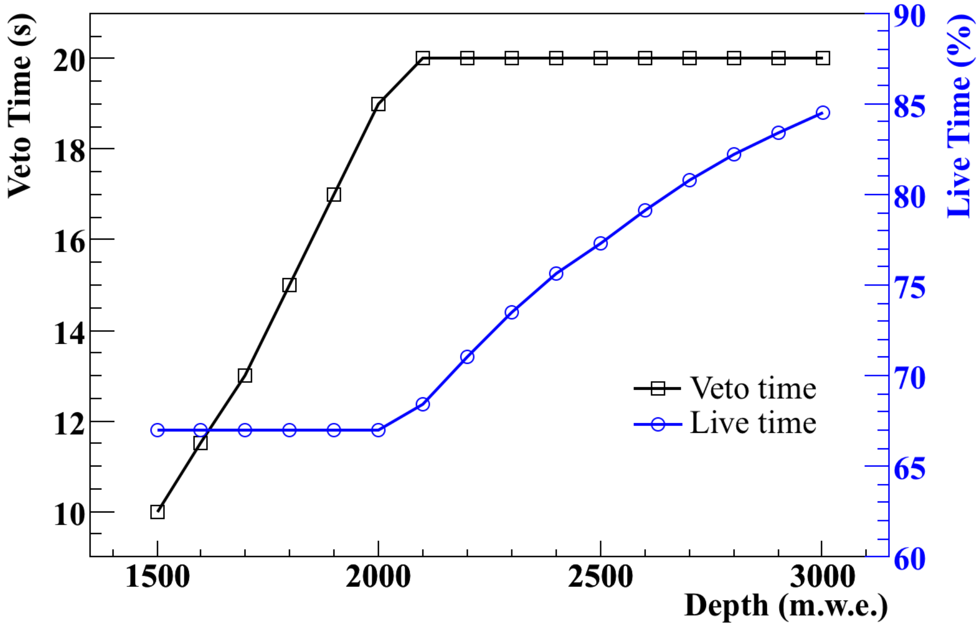


Sensitivity vs. Depth

Muon rate scaling with depth
(relative to KamLAND)



Adjust veto time to reduce more
RN with depth



→ As we increase the depth, we can increase veto time without sacrificing livetime

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