Sensitivity and Reactor Discovery Potential of the WATCHMAN Detector

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On behalf of the WATCHMAN Collaboration

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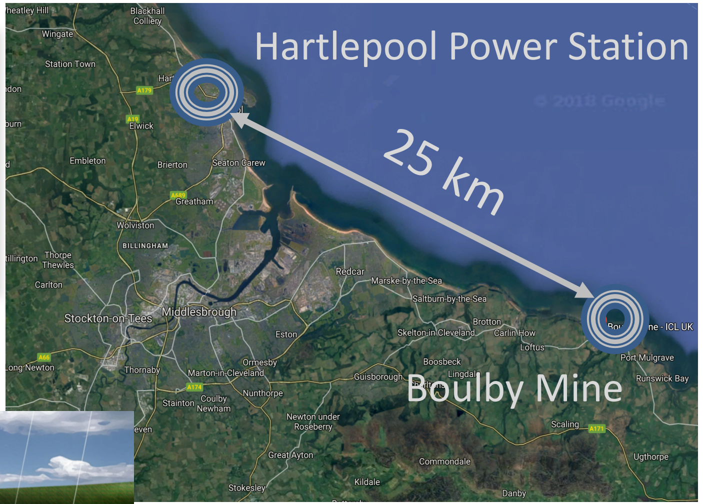
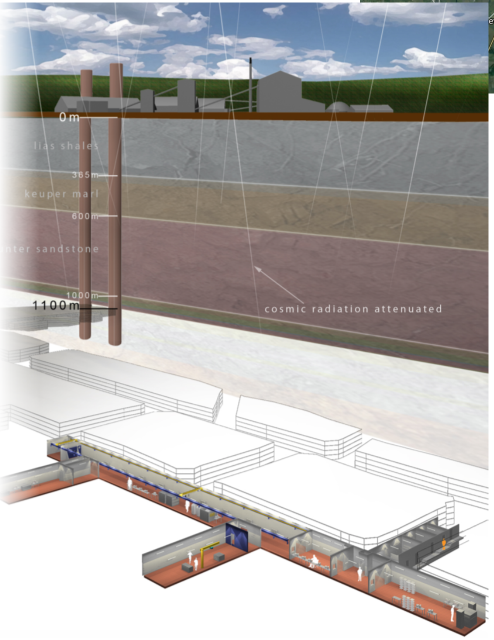
Use Cases for Far-Field Reactor Monitoring

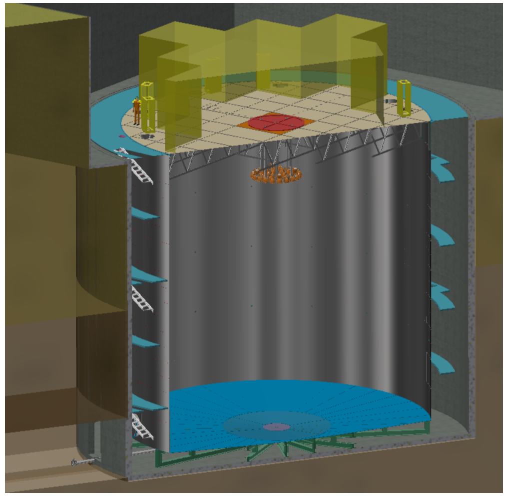
How well can WATCHMAN exclude the presence of a reactor?

How well can WATCHMAN verify the operating power of a reactor site?

The WATCHMAN Demonstration





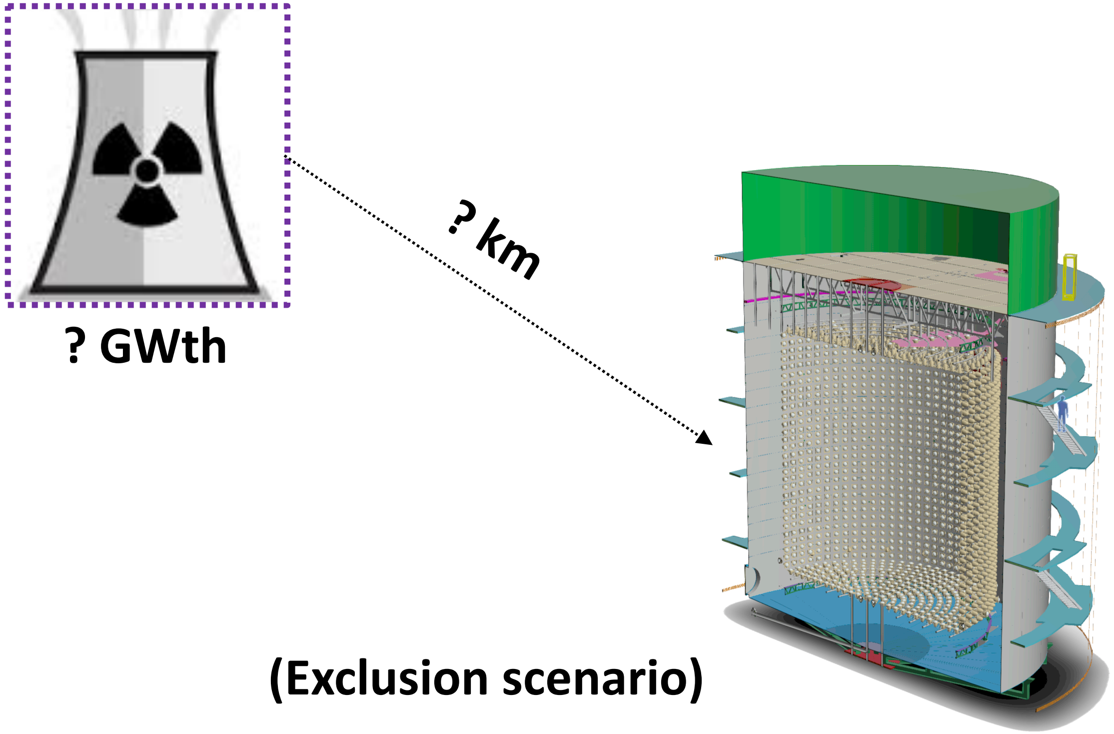


- WATCHMAN will be located on the Eastern Seaboard of the UK.
- Ambitious world reactor background.
- 20 meters by 20 meters Gadiated Water detector
- Demonstration of technology with the potential for scalability to large volumes.

Opportunities for upgrades and demonstration of scalability for specific use-cases!

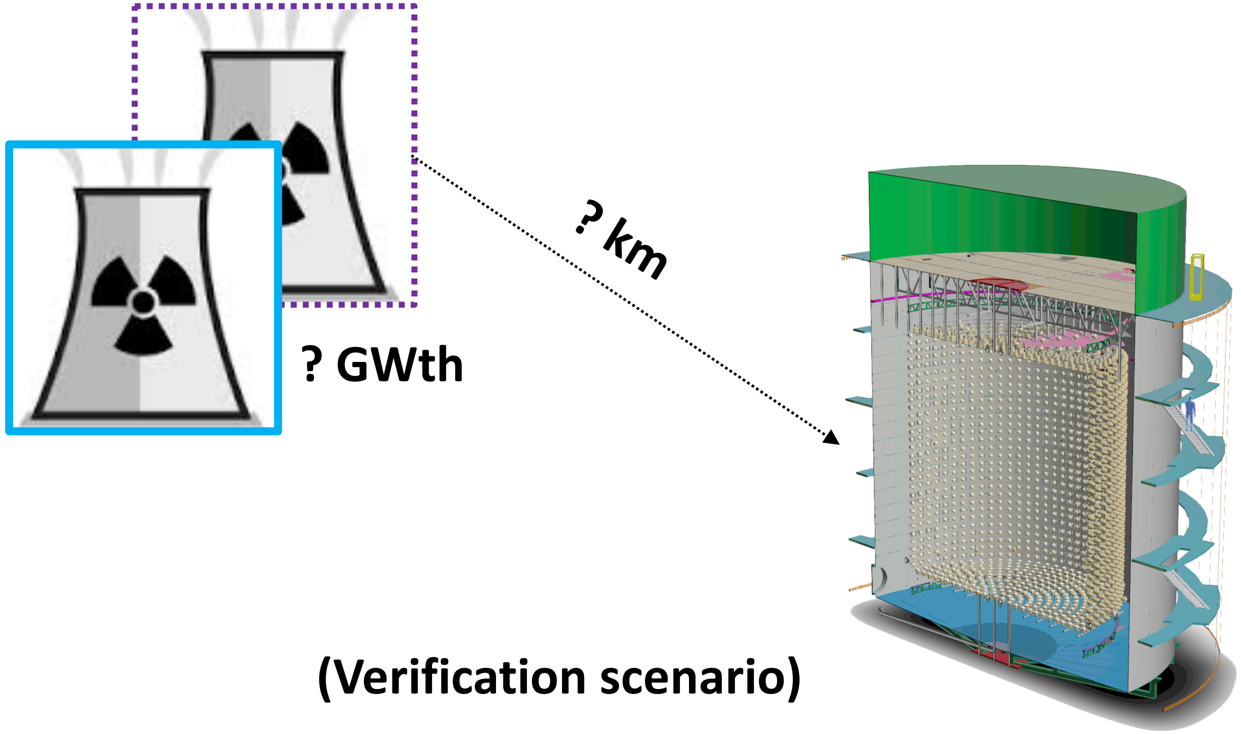
WATCHMAN Nonproliferation Goals

How well can WATCHMAN exclude the presence of a reactor?



(Exclusion scenario)

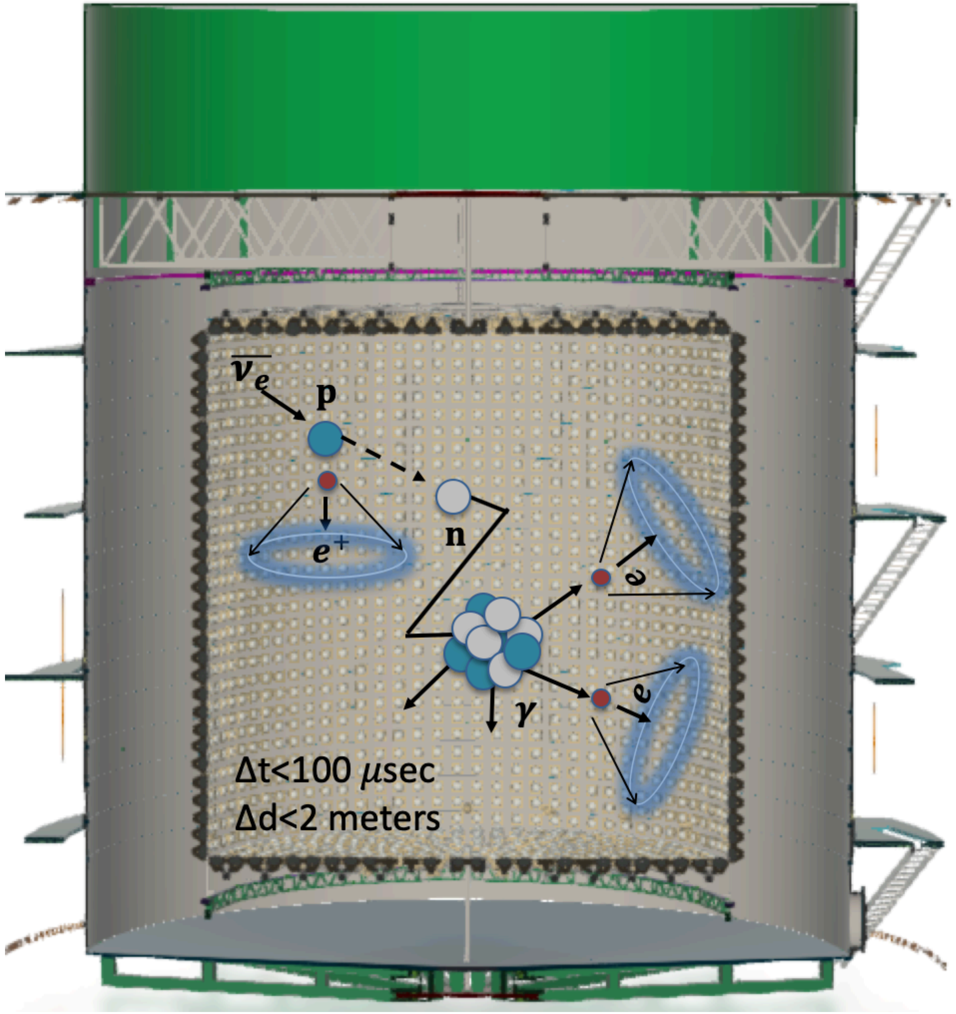
How well can WATCHMAN confirm the presence of a known reactor?



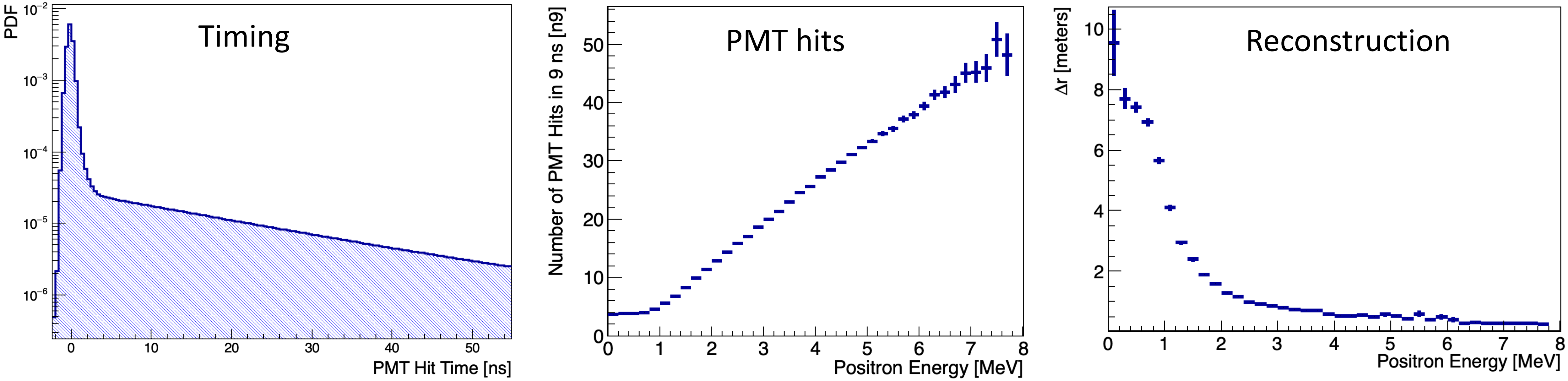
(Verification scenario)

WATCHMAN Detection Principles

- Antineutrinos detected through inverse beta decay.
  - **(IBD):** $\bar{\nu} + p \rightarrow e^{+} + n$
  - **(Q=-1.8 MeV,** $\sigma \sim 10^{-42} cm^2 E_{\bar{\nu}}^2$ **)**
- Events are simulated using Rat-Pac, a GEANT4 based simulations package.
- Reconstructed by evaluating the spatial, timing, and multiplicity of PMTs hits, using BONSAI (developed by Michael Smy at UCI).
- IBD events are determined by a timing window of 100 μsec, and a spatial separation of 2 meters in the detector.

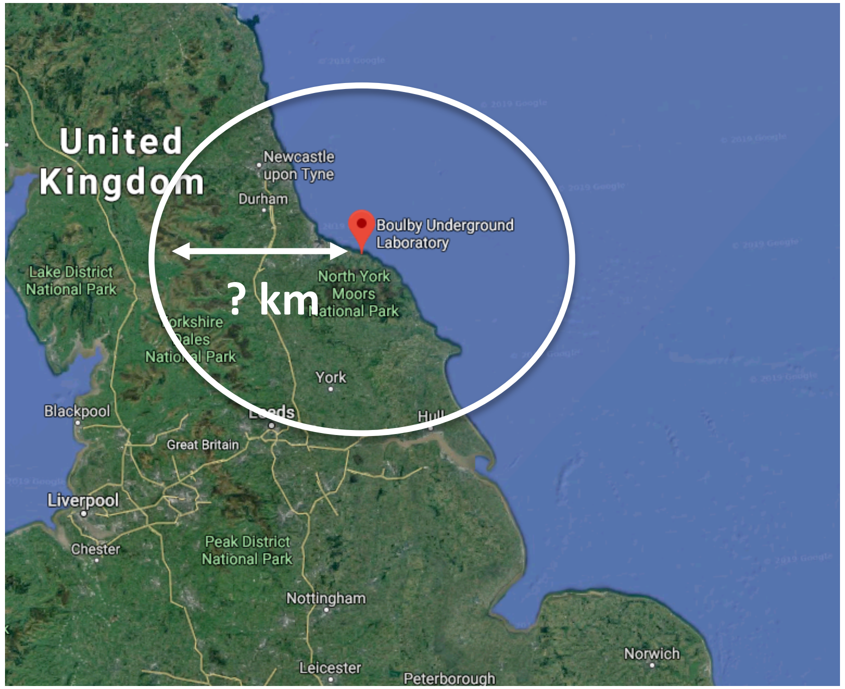


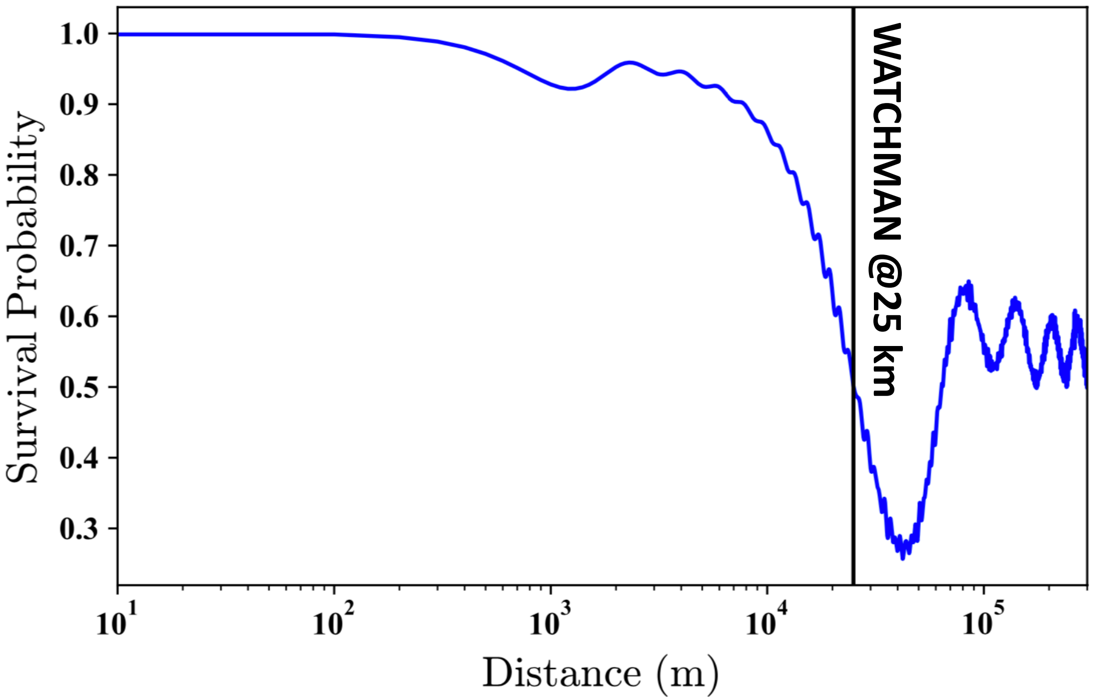
Positron Response



- Given the low light yield from IBD positrons (9 photoelectrons/MeV) we use the prompt light as our denotation for charge in the detector.
- Prompt light in our detector is denoted by how many PMTs fire within 9 ns, which we refer to as n9.
- Due to our energy cuts (n9>15) , we're more sensitive to the higher energy portion of the IBD spectra

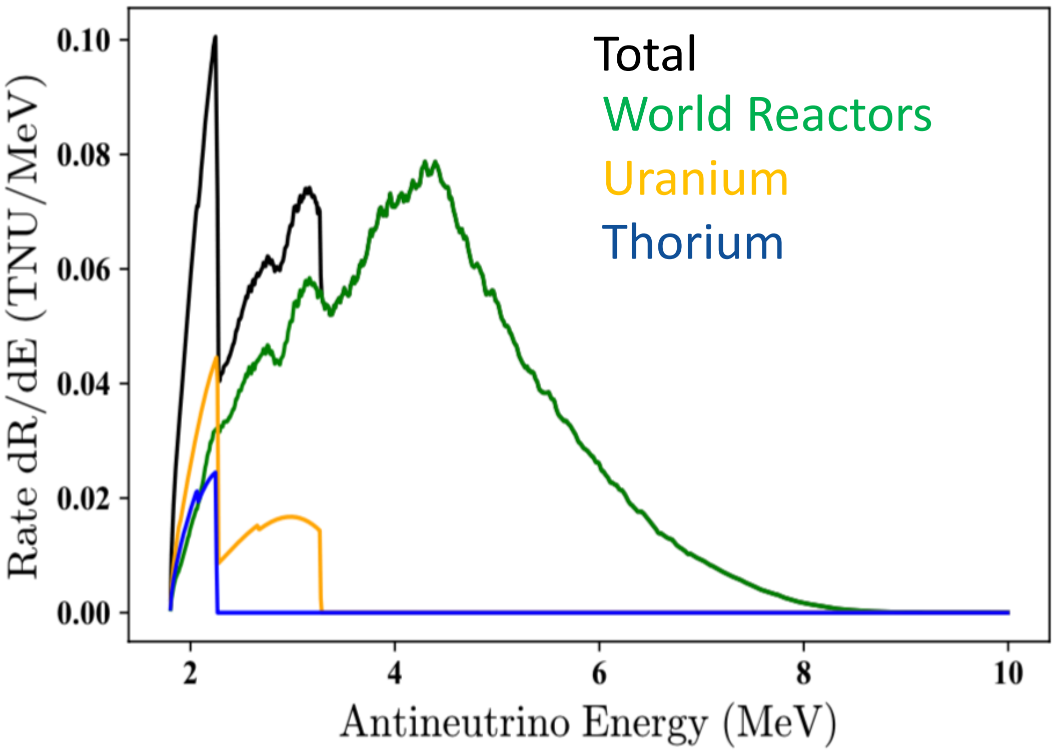
Reactor Antineutrino Signal

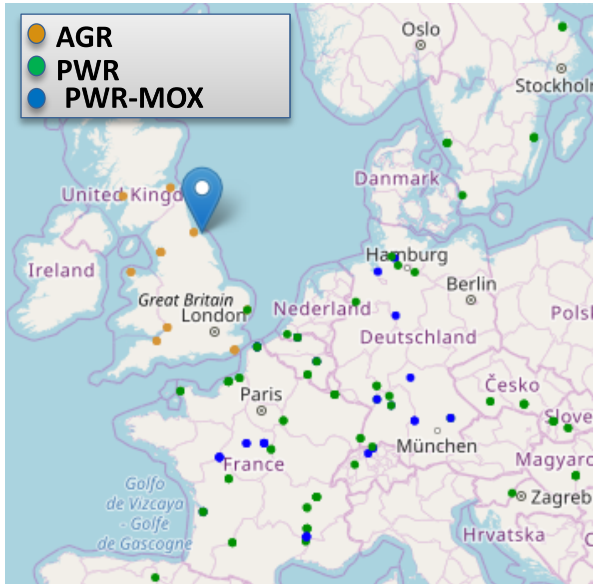




- To understand the WATCHMAN sensitivity we take the backgrounds from the Boulby, but vary the location and signal strength of the background.
- Given the relatively short refueling cycles of Advanced Gas Reactors (2 months), we use the average fissile composition for the antineutrino emission.

Antineutrino Backgrounds



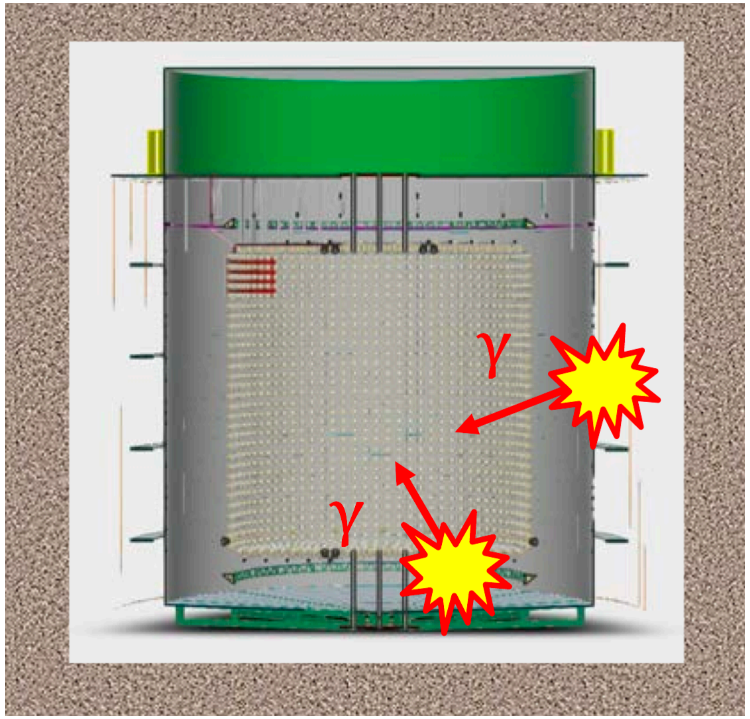


Reactors	Flux Contribution
Hartlepool	82.2%
Heysham	11.5%
Other UK Reactors	3.1%
French Reactors	4.9%
Belgium, Netherlands, and Germany	1.4%

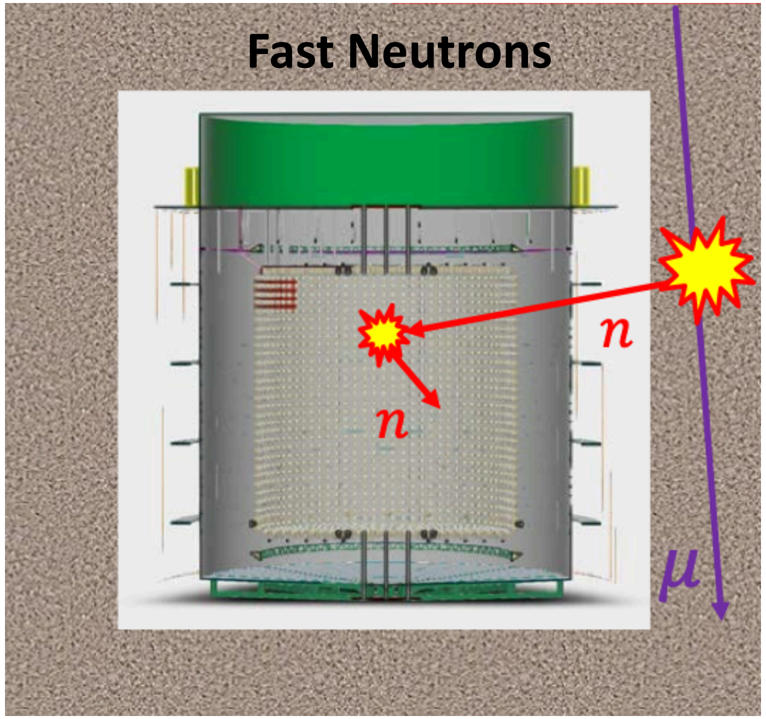
- The total reactor antineutrino background and geoneutrino spectra was taken from Geoneutrinos.org. for the Boulby mine location.
- To accommodate the variation in background due to reactor shut-downs, we associate a 5% systematic uncertainty to the antineutrino background flux.

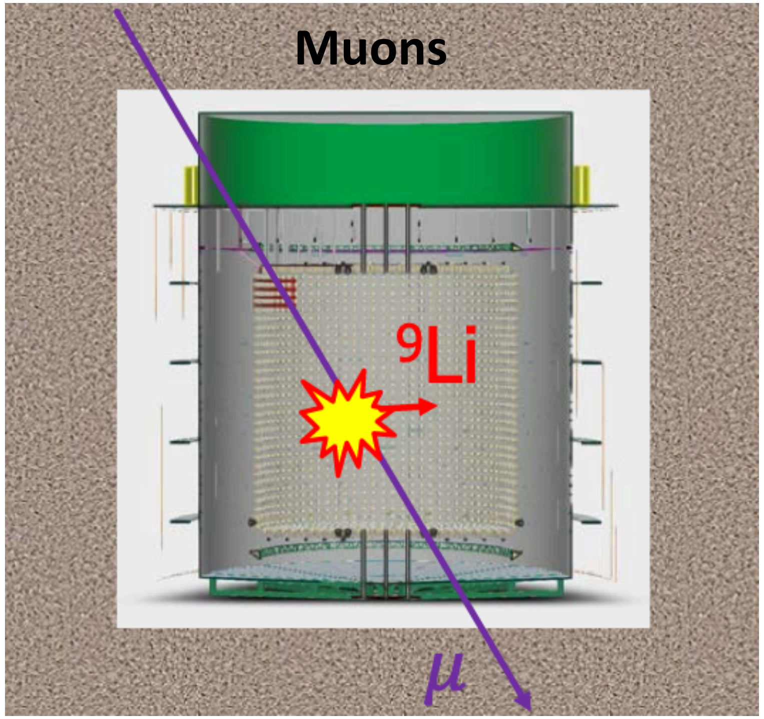
Classification of Backgrounds

Accidentals

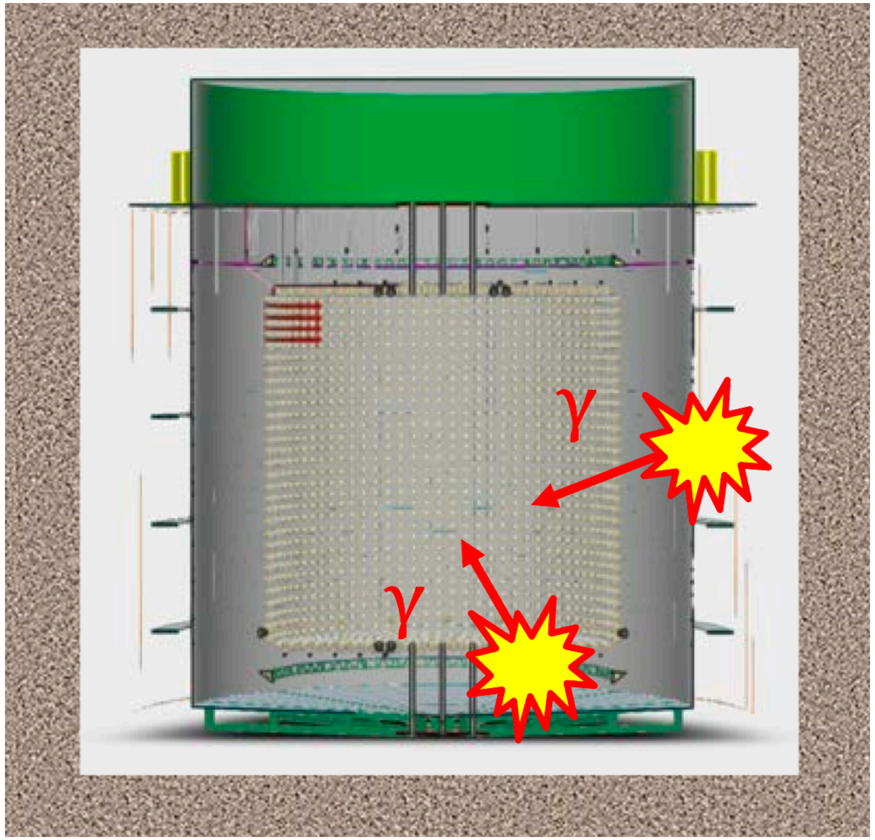


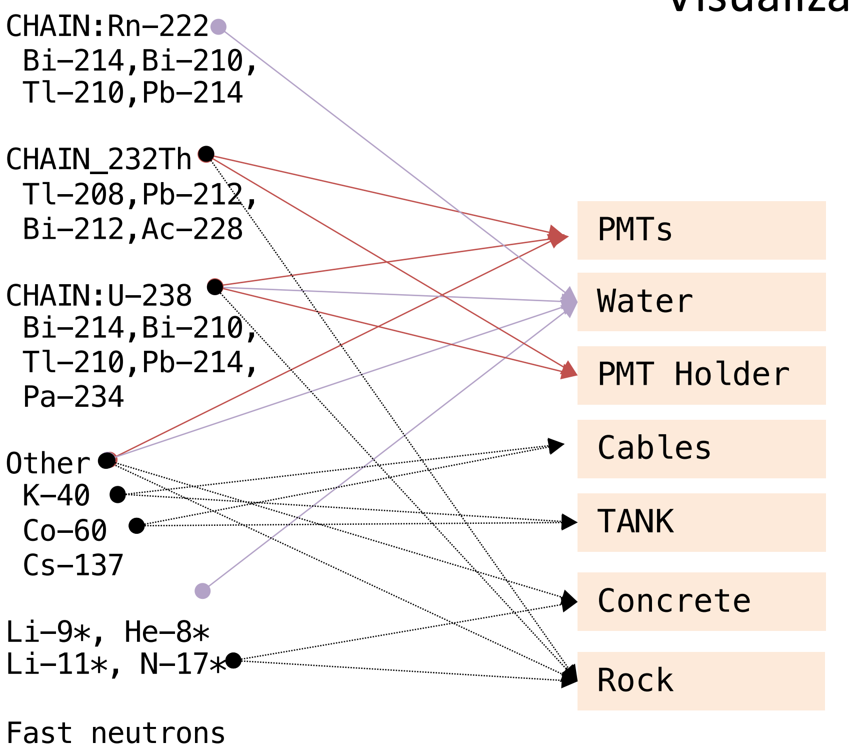
Correlated



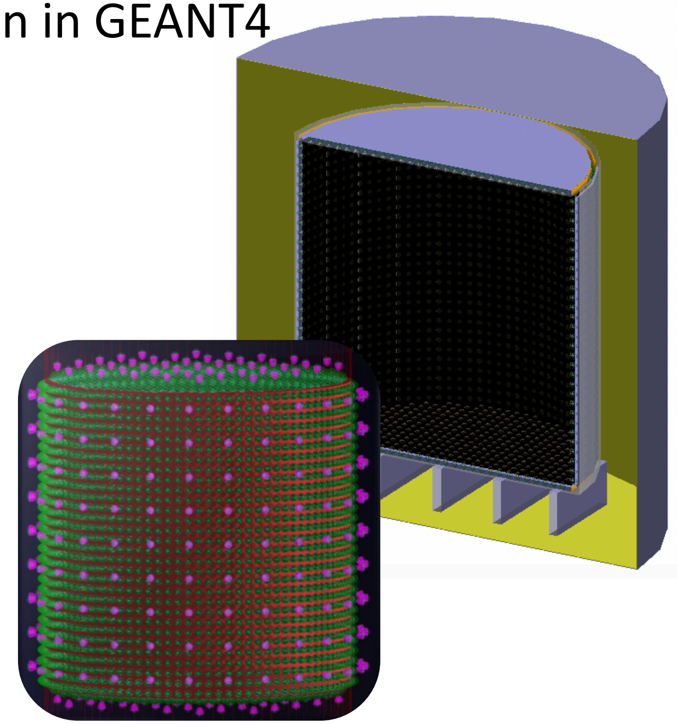


Accidentals



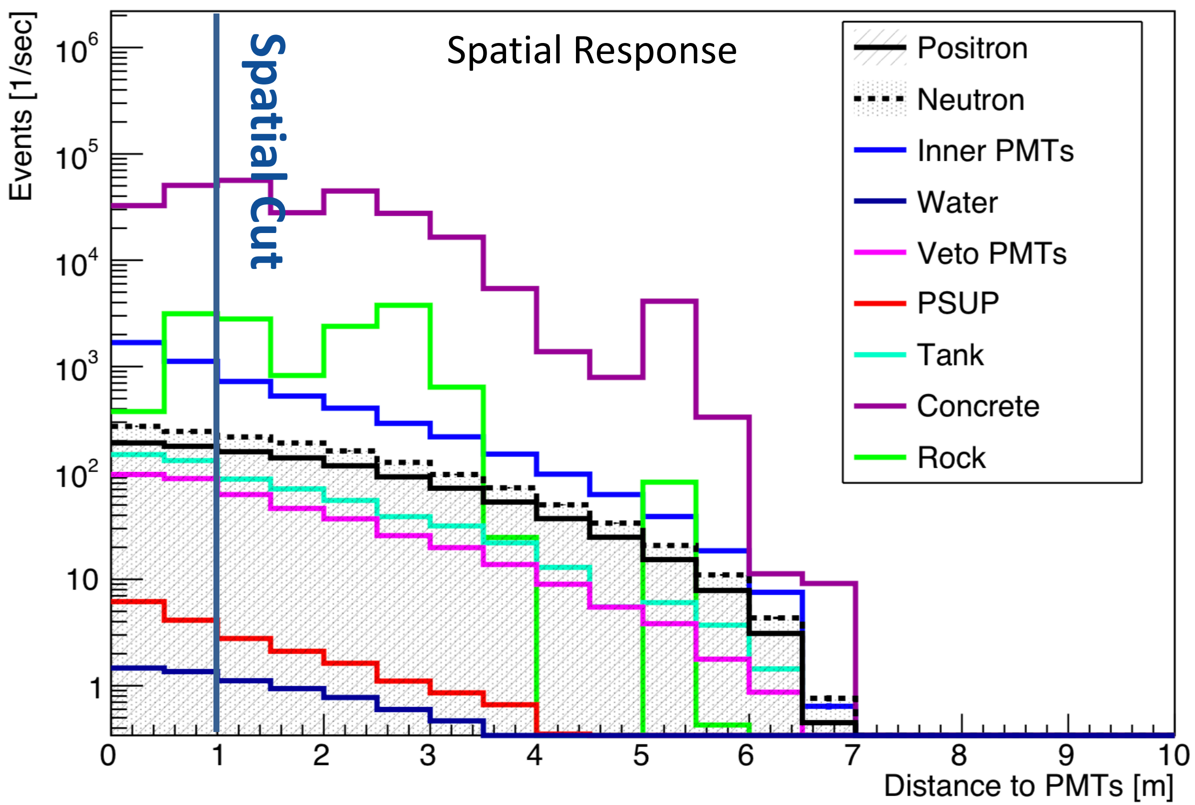


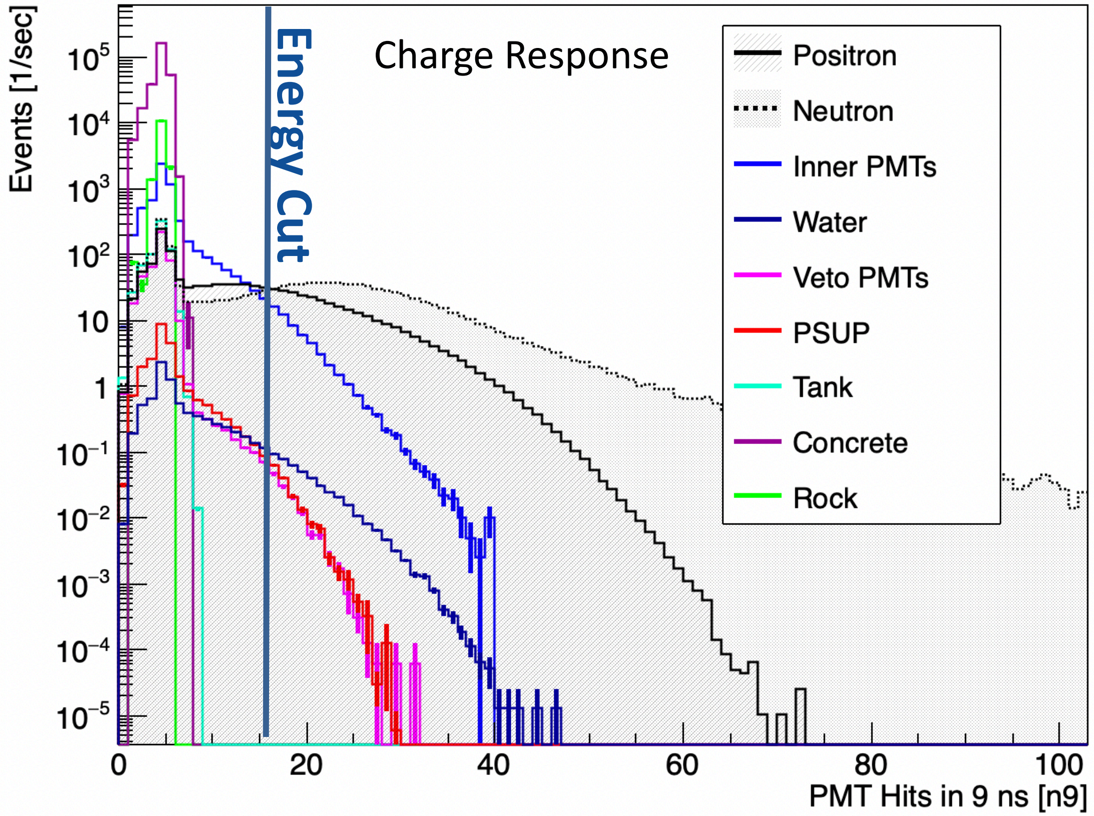
Visualization in GEANT4



- Events in the detector that can result in charge deposition are modeled in the detector using Rat-PAC, a GEANT4 simulation-based framework.
- We treat these backgrounds as uncorrelated, and result in IBD candidates when two events occur within our predetermined spatial and timing cuts.

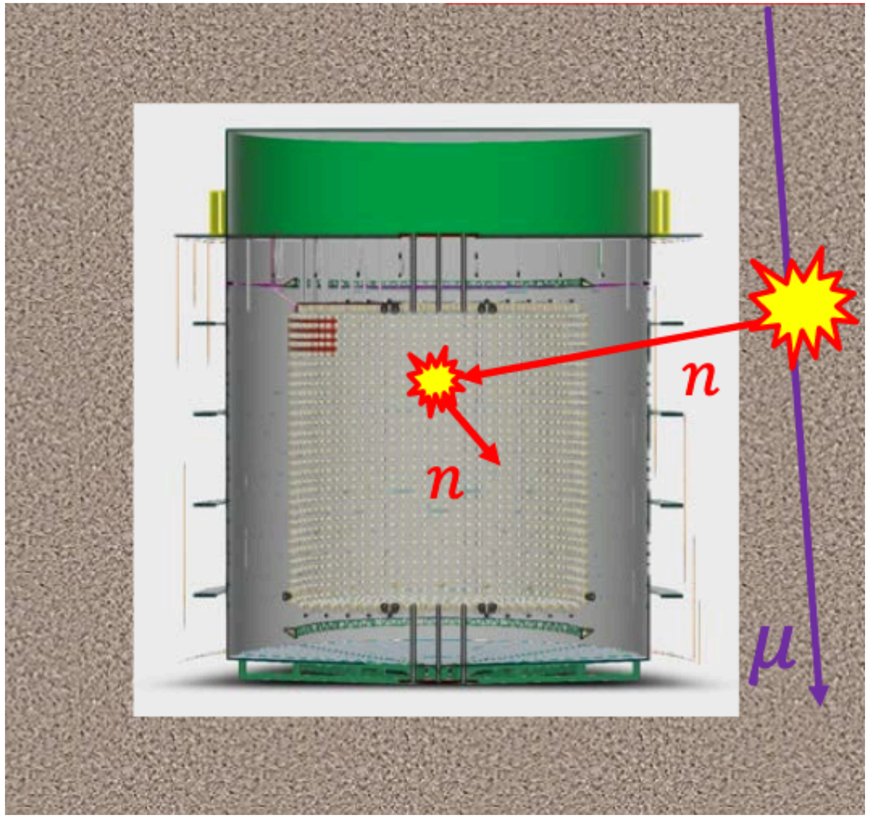
Accidentals



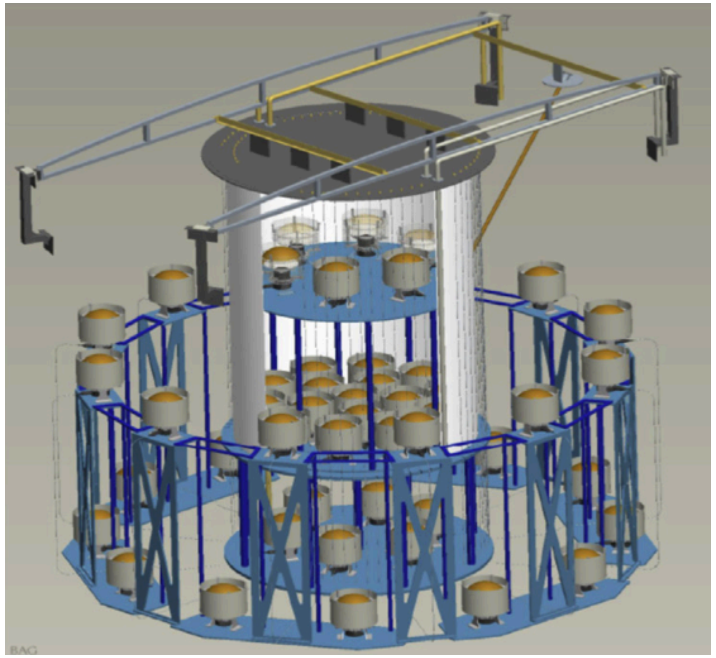


- The radiological contributions from the Rock and Concrete are the most prolific, however a low energy cut of n9>15 can remove these backgrounds.
- Above this cut the strongest contributor is the PMTs, which motivated a separate sensitivity analysis.

Correlated Backgrounds: Fast Neutrons

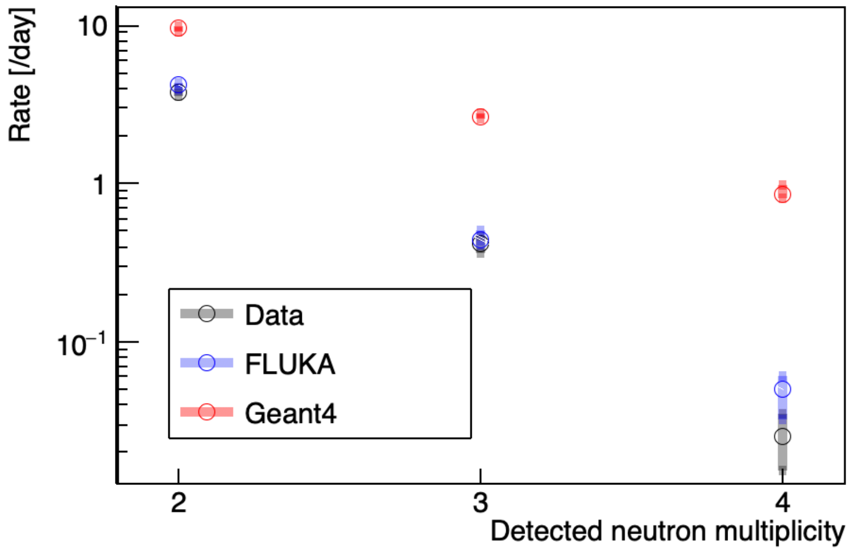


WATCHBOY Detector



- 400 m.w.e.
- 2 ton Gd-doped water Cherenkov target
- shielded by 40 ton pure water outer muon veto
- 16 target PMTs and 36 veto PMTs
- **S. Dazeley et al. NIMA 821 (2016) 151–159**

Fast Neutron Validation

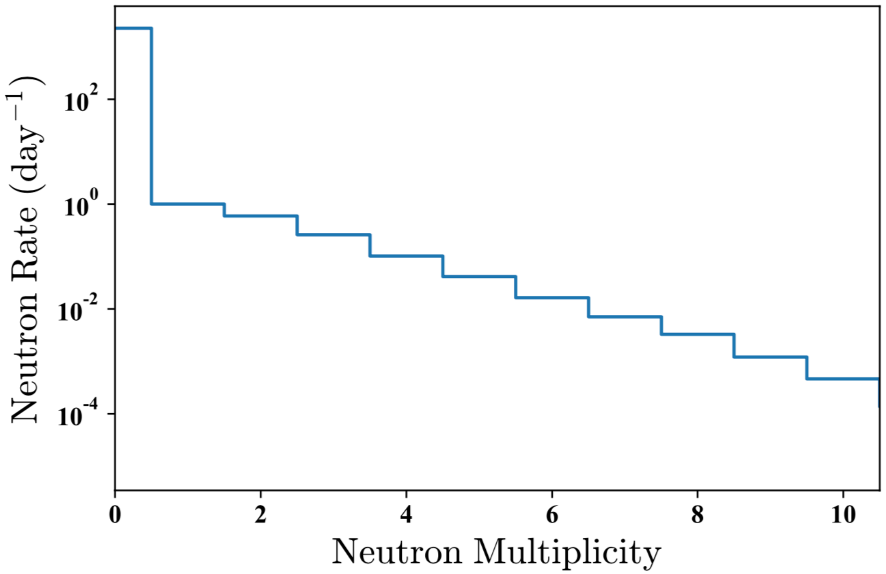


FLUKA-based neutron detection rates show a better agreement with the data in comparison with the Geant4-based neutron detection rates -Preliminary results by **Felicia Sutanto** (UMICH PhD Candidate).

Correlated Backgrounds: Fast Neutrons

WATCHMAN Neutron Production Rate

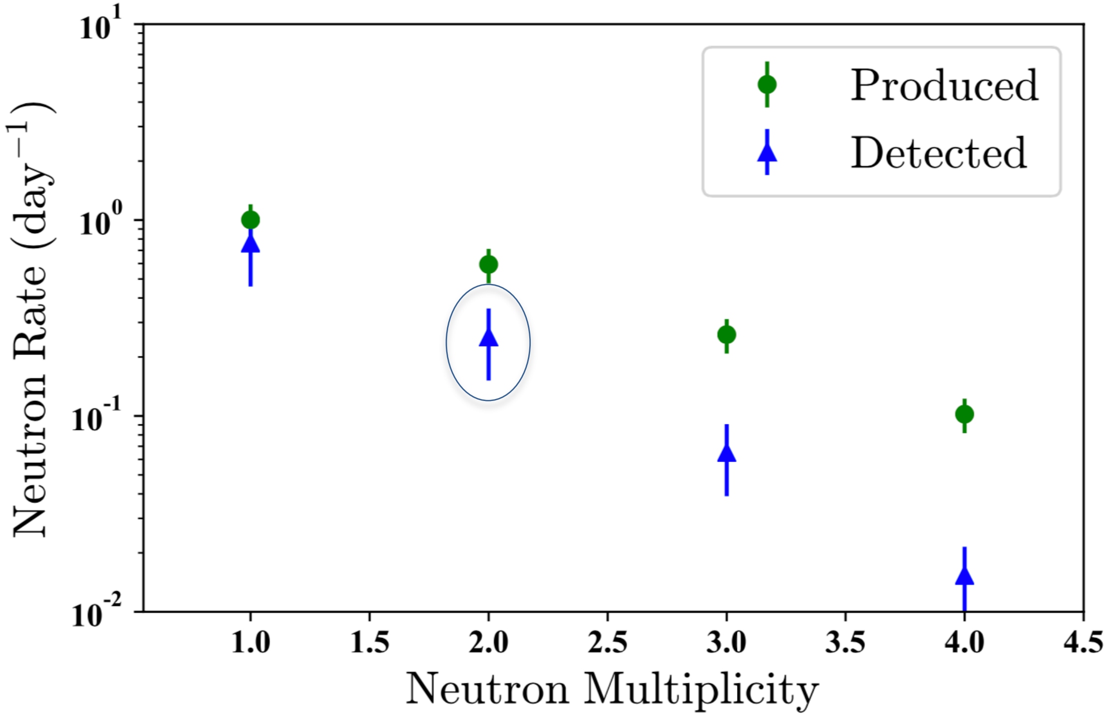
FLUKA was used to simulate the fast neutron production rate in WATCHMAN using the same methodology as the WATCHBOY neutron production confirmation.



The di-neutron detection rate is determined assuming a binomial distribution with a neutron detection efficiency of 58.63%:

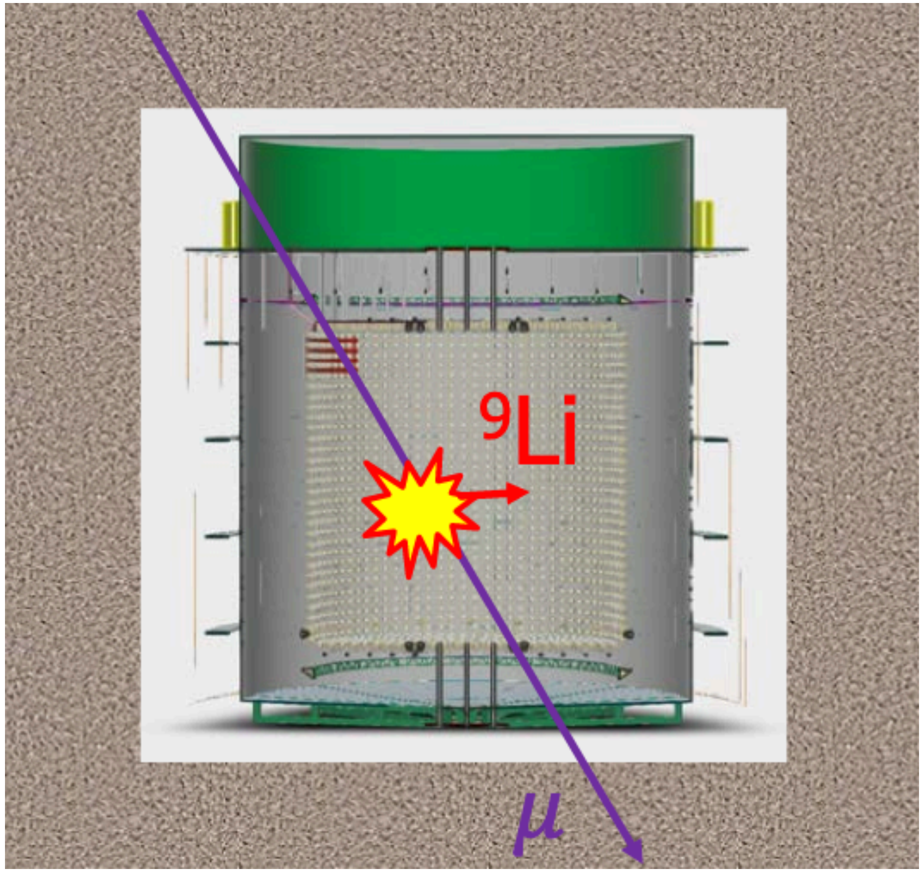
$$P(k=2) = \sum \binom{n}{2} \varepsilon^2 (1-\varepsilon)^{n-2}$$

WATCHMAN Neutron Detection Rate

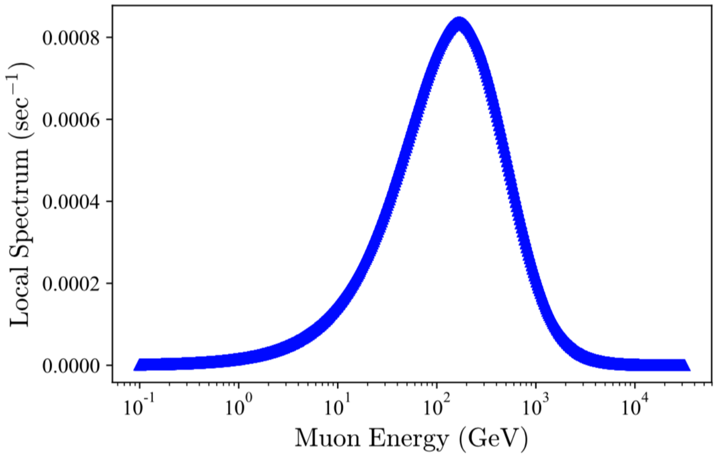


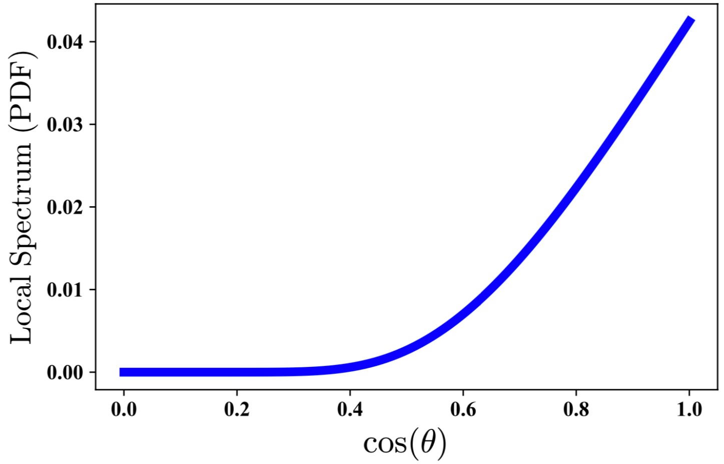
The neutron detection rate in WATCHMAN's fiducial is expected to be **0.0252 +/- 0.0106 events/day**

Muogenic Response



D. M. Mei, A. Hime



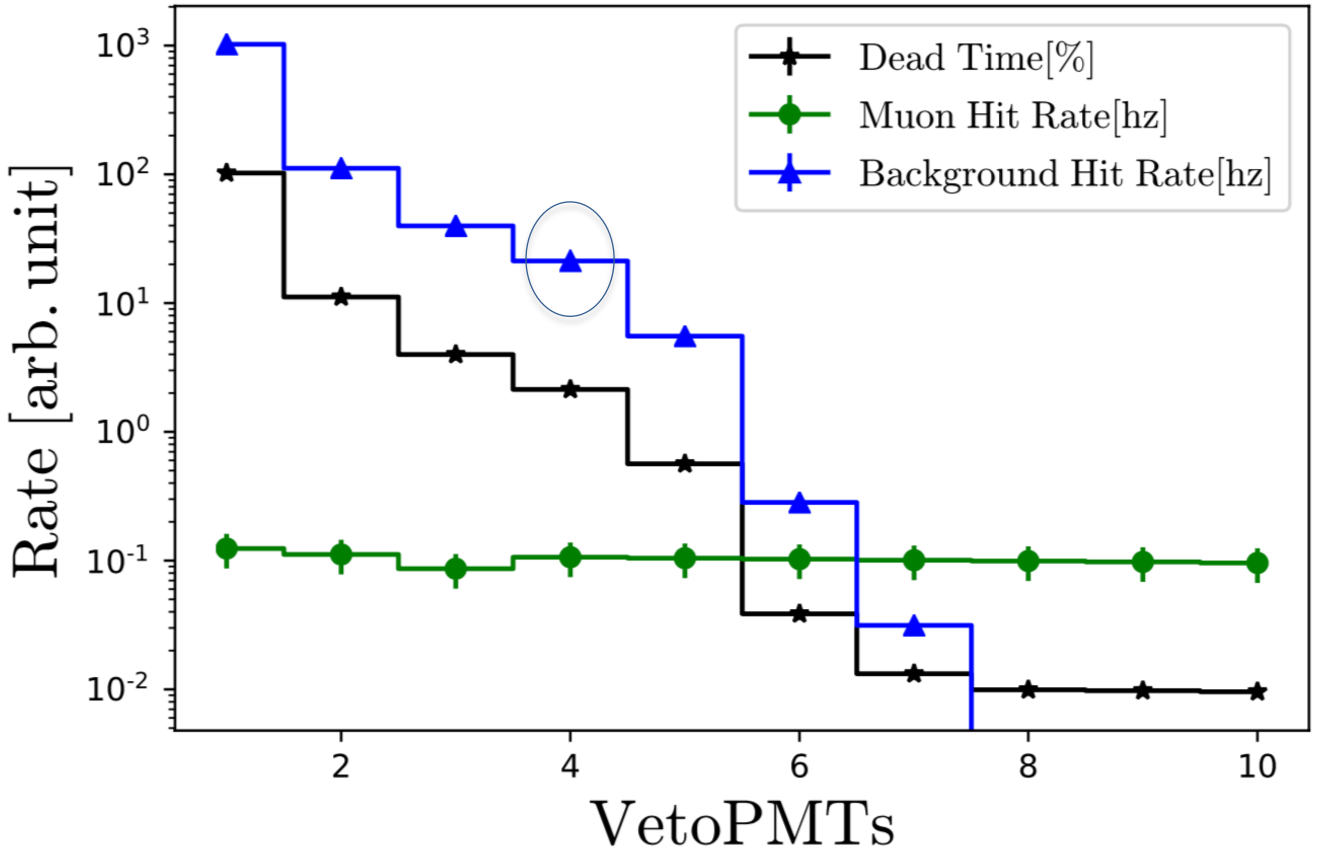


- Muons are modeled using the energy and directionality described in **PhysRevD.73.053004.** The muon rate in WATCHMAN is expected to be **0.116±0.004 hz**

- WATCHMAN will have 236 Veto PMTs to trigger a deadtime in the event that muons pass through the detector.

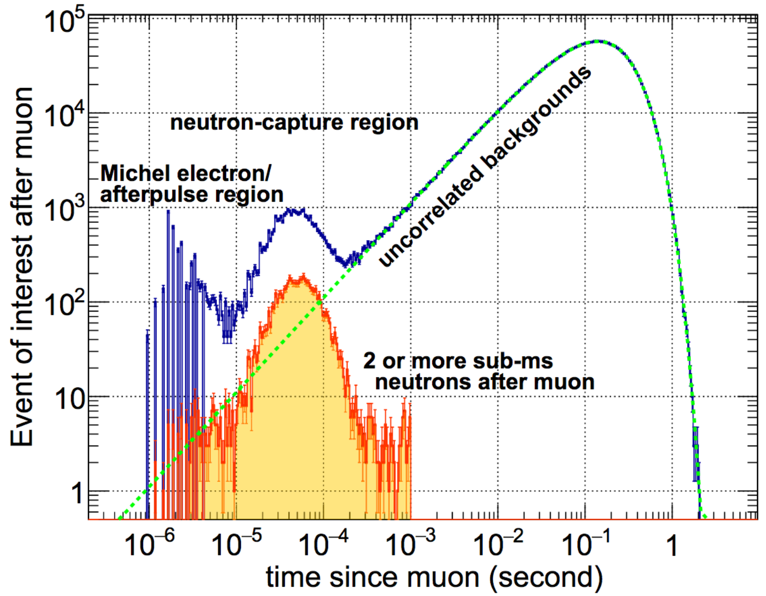
- Additionally, muons passing through the detector can cause radionuclide production of ^{9}Li and ^{8}He which decay with the emission of a beta and neutron pair.

Muogenic Response: Veto Response



WATCHBOY Result:

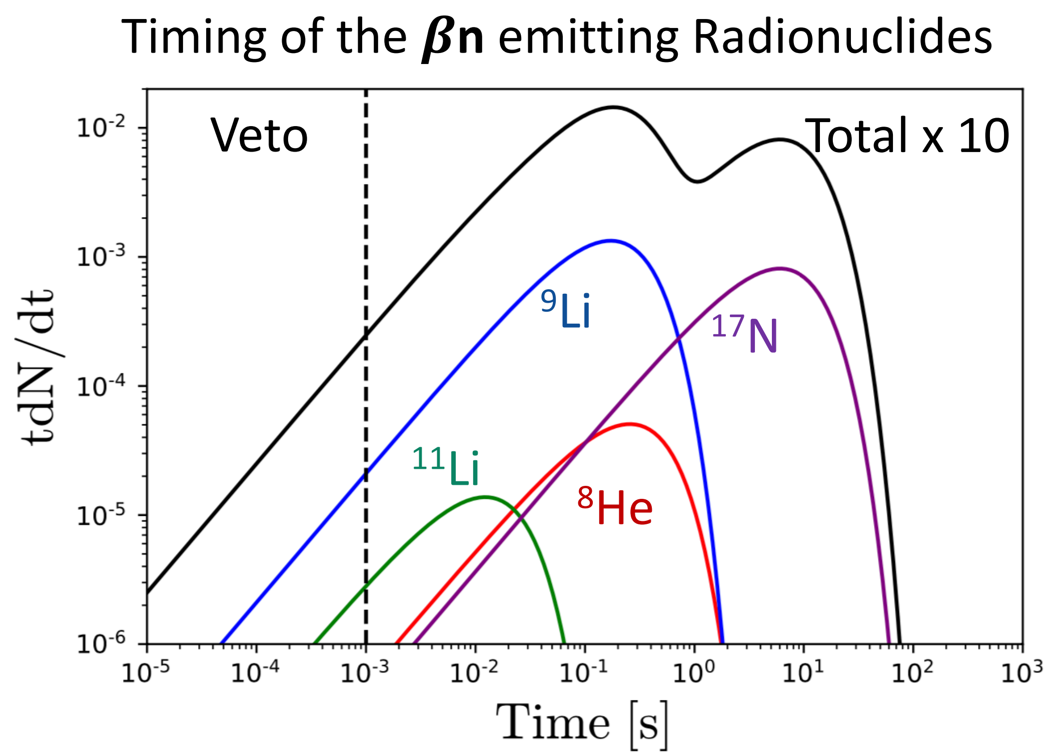
S. Dazeley et al. NIMA 821 (2016) 151–159

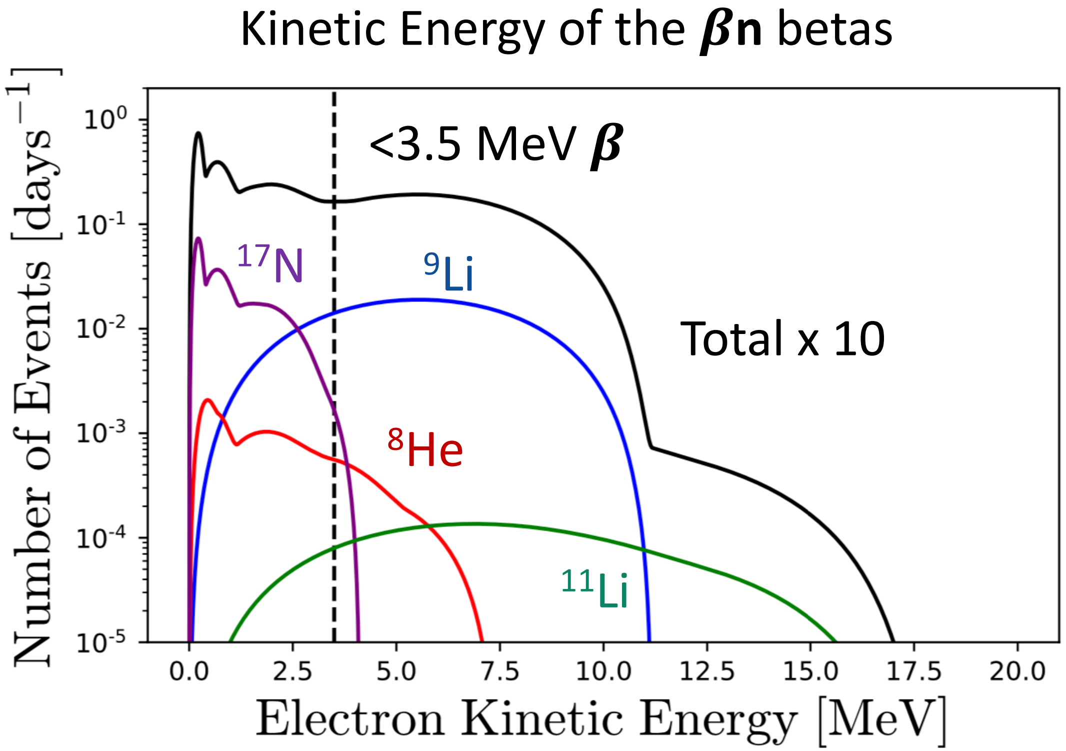


- Based on the WATCHBOY results, a 1 ms deadtime is imposed on the detector following a muon event (4 Veto PMT hits). The deadtime for the detector is expected to be **2.13%** while the efficiency for detecting muon events is **91.4%**.

- The single largest contributor to veto triggers is the radiation signature from the structural and surrounding detector material. Additionally, the most pernicious muons are the sub 5 GeV muons that capture in the detector.

Muogenic Response: Radionuclides

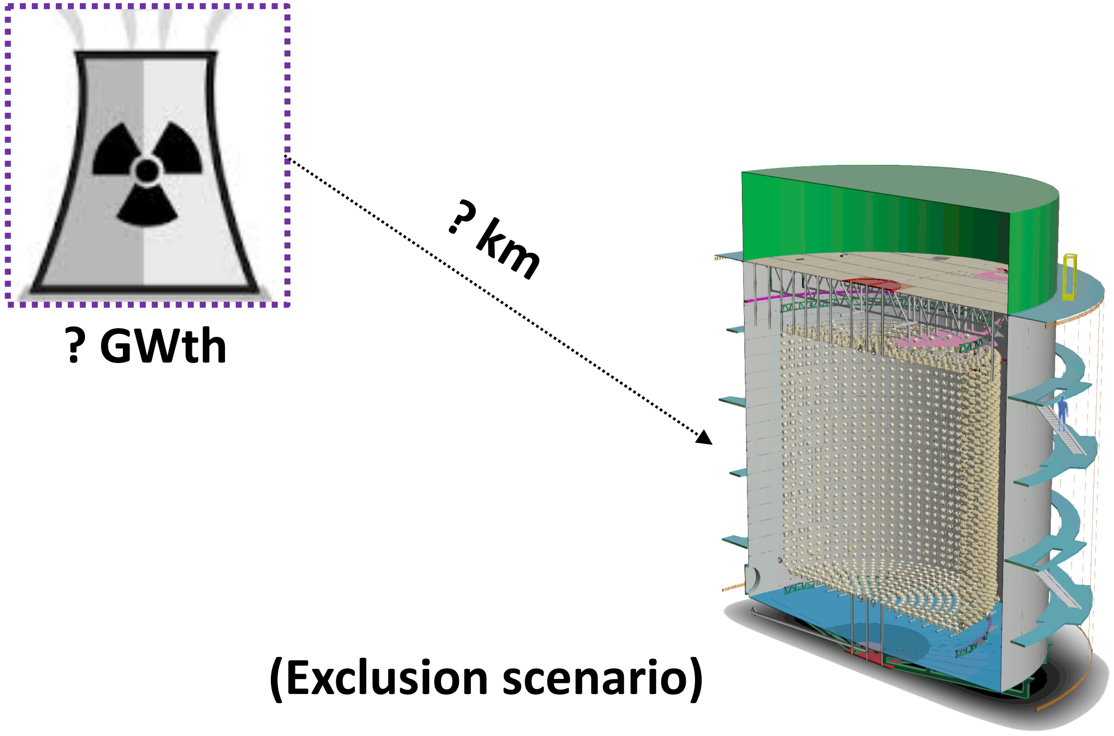




- WATCHBOY set a limit for **^{9}Li** in the detector, the intent is to scale this rate from the Super Kamiokande results (**PhysRevD.93.012004**) and the Li & Beacom Analysis (**PhysRevC.89.045801**). *Note this background is not fully enfolded into the sensitivity analysis.
- In addition to ^{9}Li, βn emitters include ^{11}Li, ^{17}N, ^{8}He. Theoretically, contributions from ^{16}C are possible, however WATCHMAN would not be sensitive to its rate.

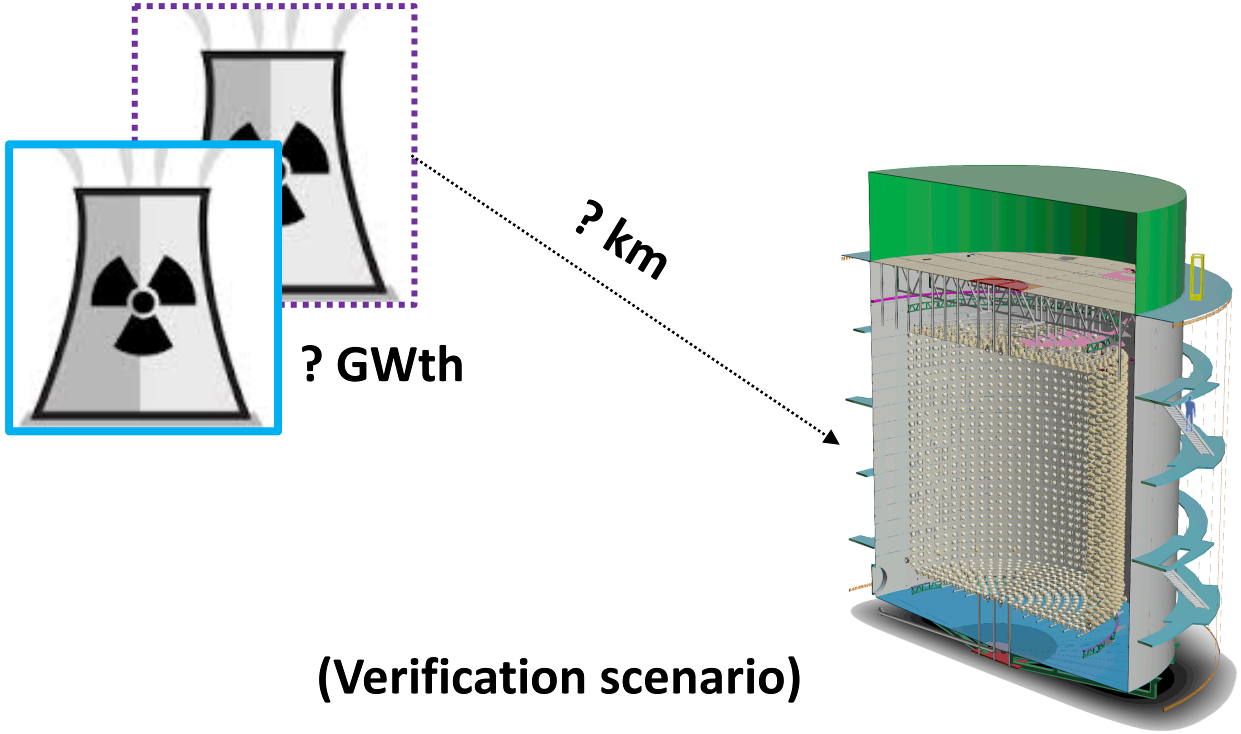
WATCHMAN Nonproliferation Goals

How well can WATCHMAN exclude the presence of a reactor?



(Exclusion scenario)

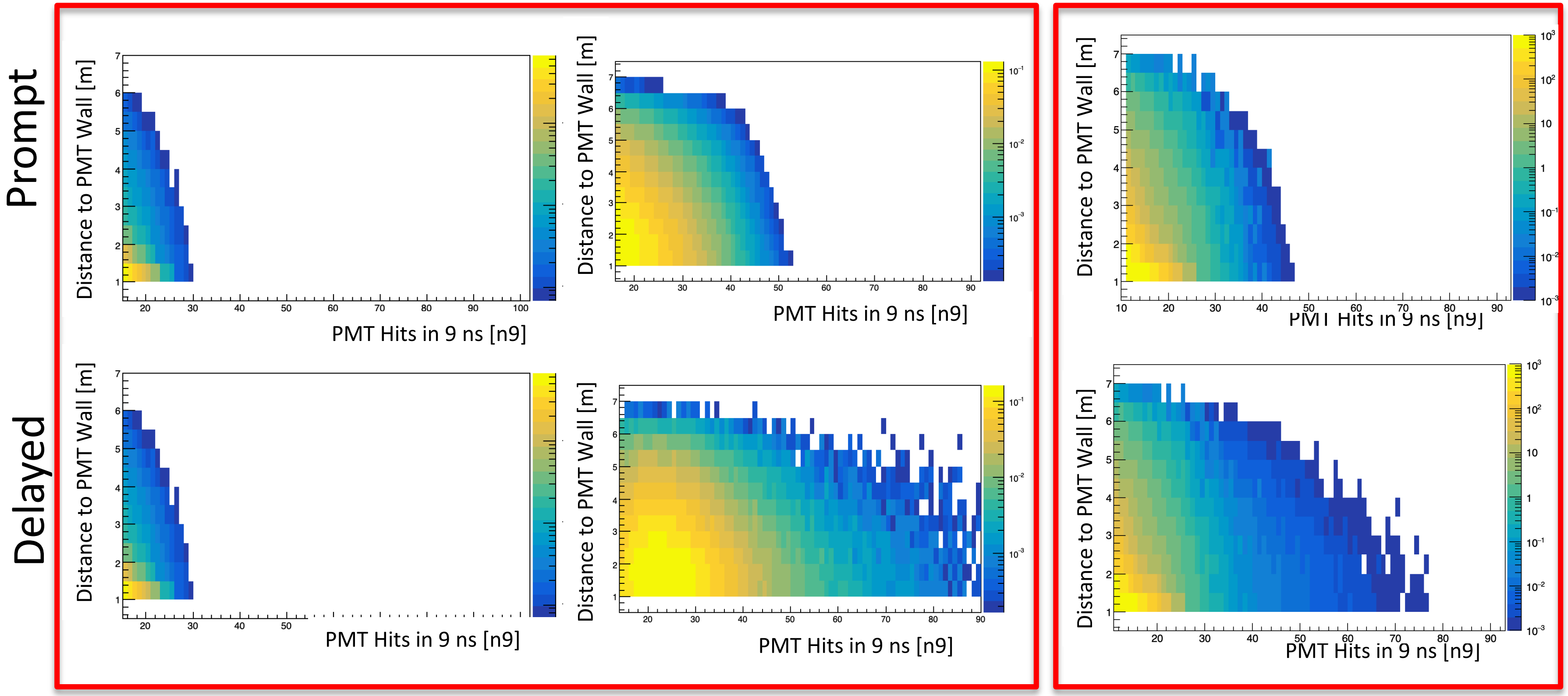
How well can WATCHMAN confirm the presence of a known reactor?



(Verification scenario)

Sensitivity Methodology

- A Feldman-Cousins based confidence intervals for reactor searches for a one year dwell time.
- Templates of the signal and background spatial and charge distribution in the detector are generated based on if they are correlated or random events.
- A different template is generated for variable dwell time, detector standoff, and thermal power of the facility.



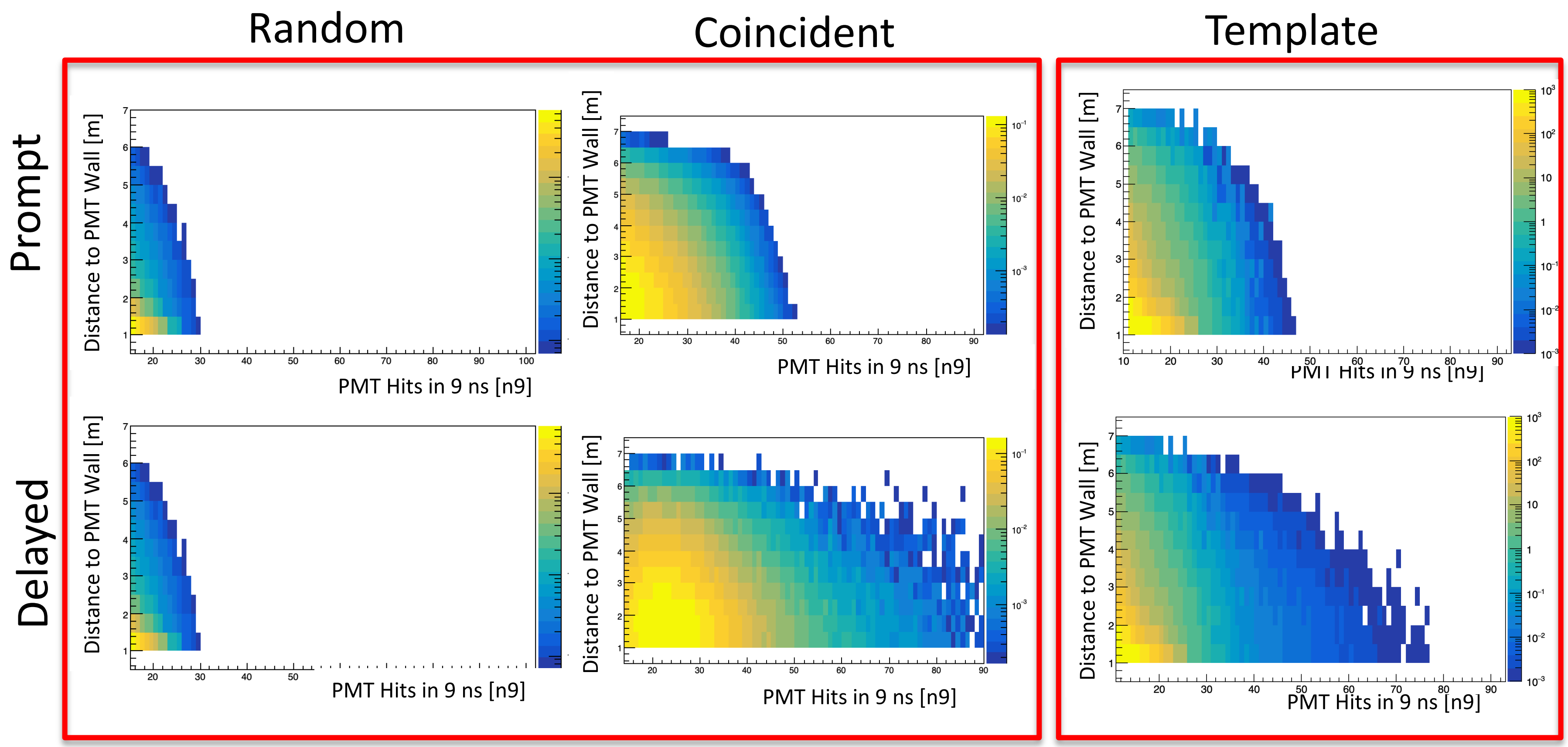
Random:
Accidentals

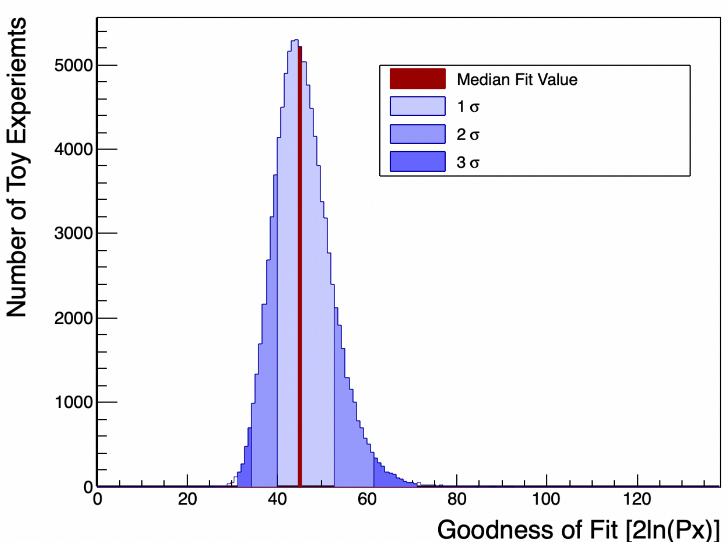
Coincident:
IBD,IBD (background),Fast Neutrons, and Radionuclides*

Template

Our covariance matrix is diagonalized in this study as systematics causing correlations have not been fully realized.

Sensitivity Methodology



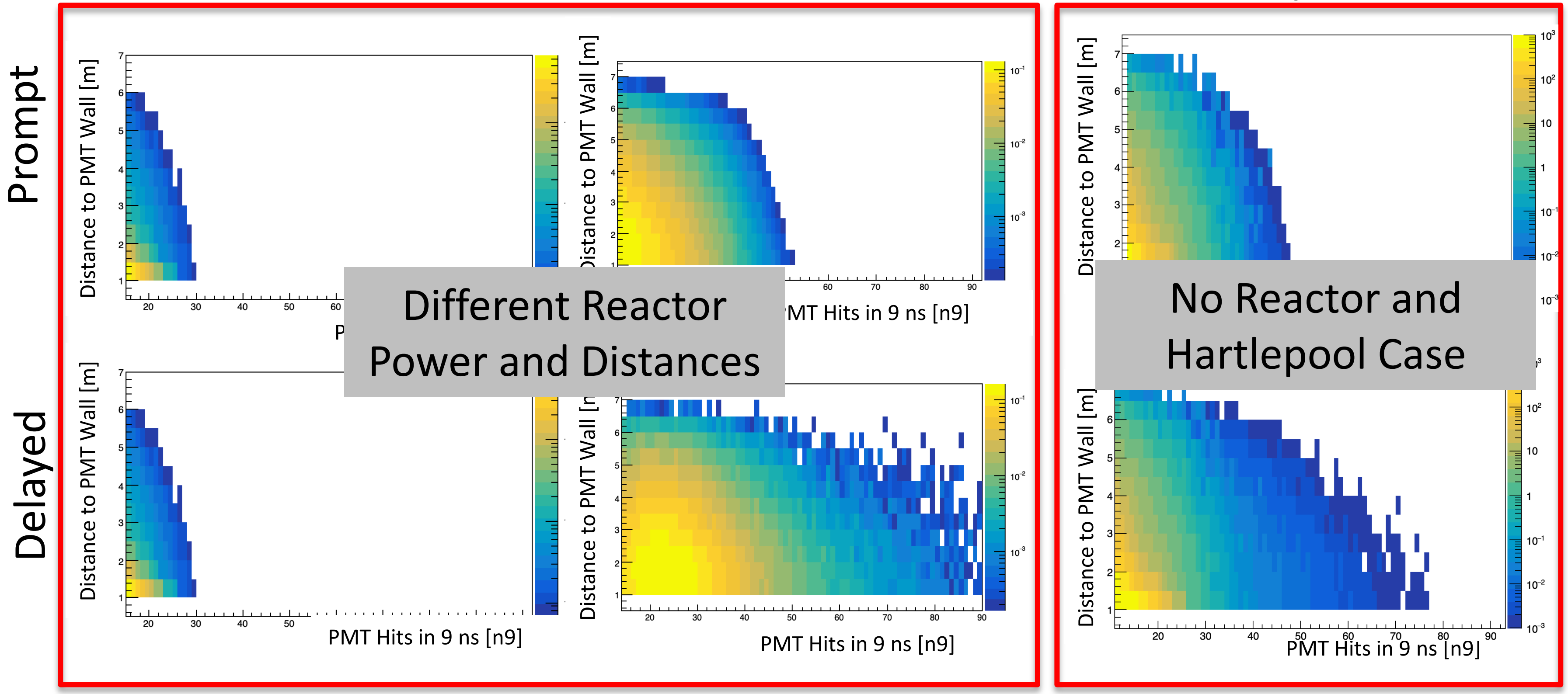


Generate confidence intervals for each configuration and time by making a histogram of the results of the fit.

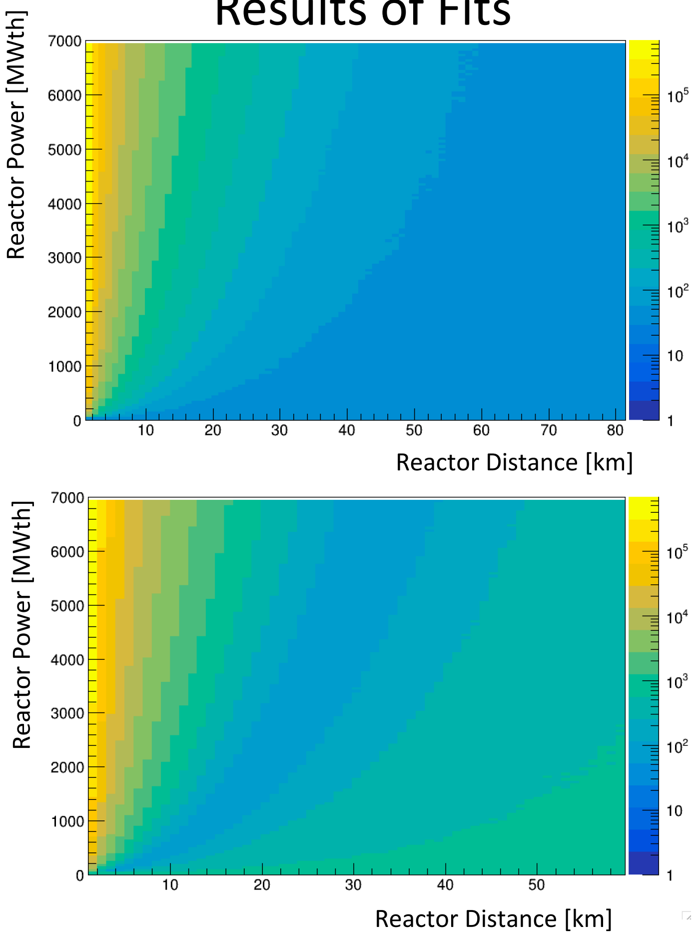
- Sample the Charge and Spatial response and weather the event is a coincident or accidental event 100,000 times.
- A log-liklihood fit to the template response is made to determine the confidence intervals.

Sensitivity Methodology

Random | Coincident | Template

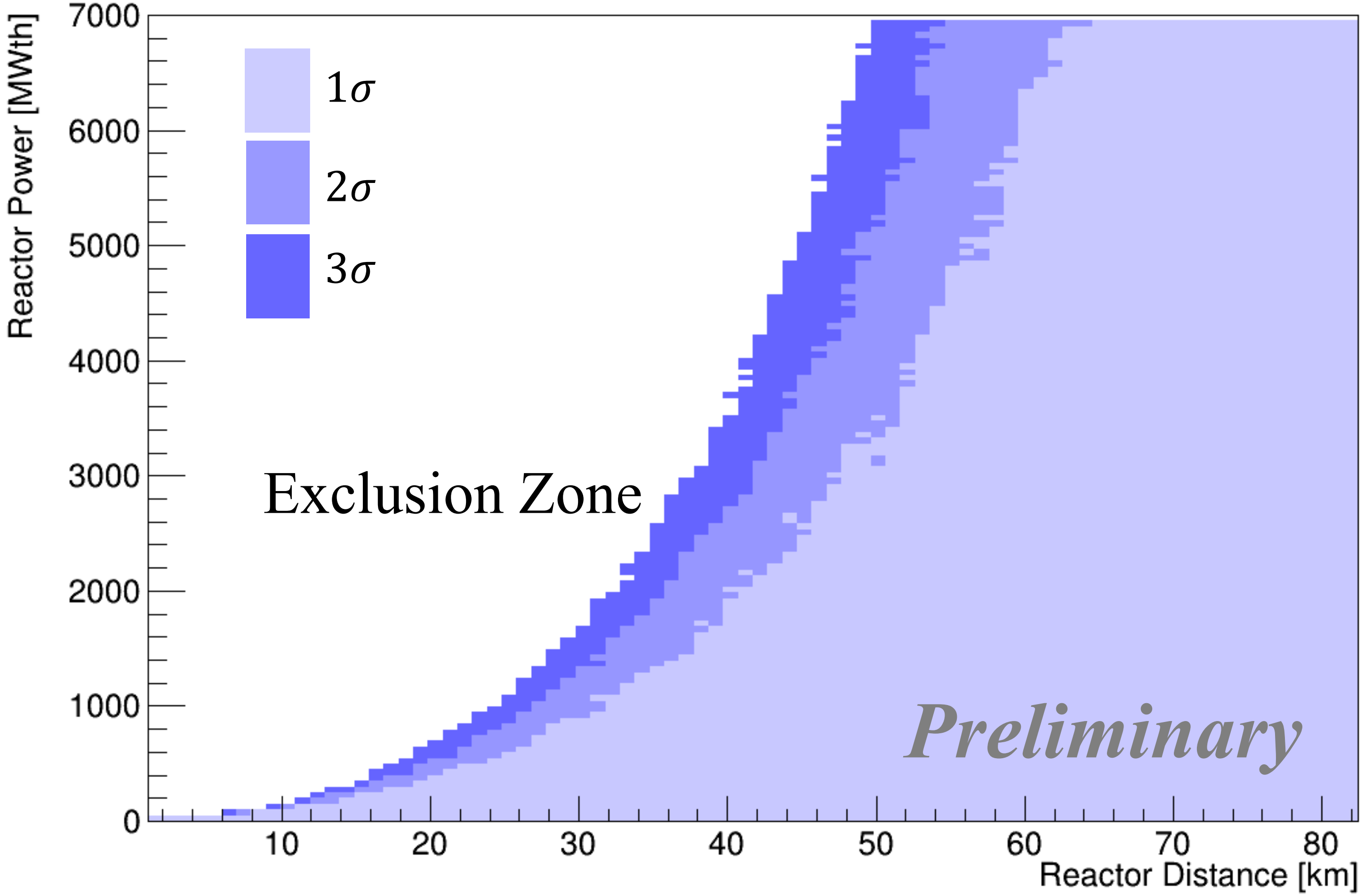


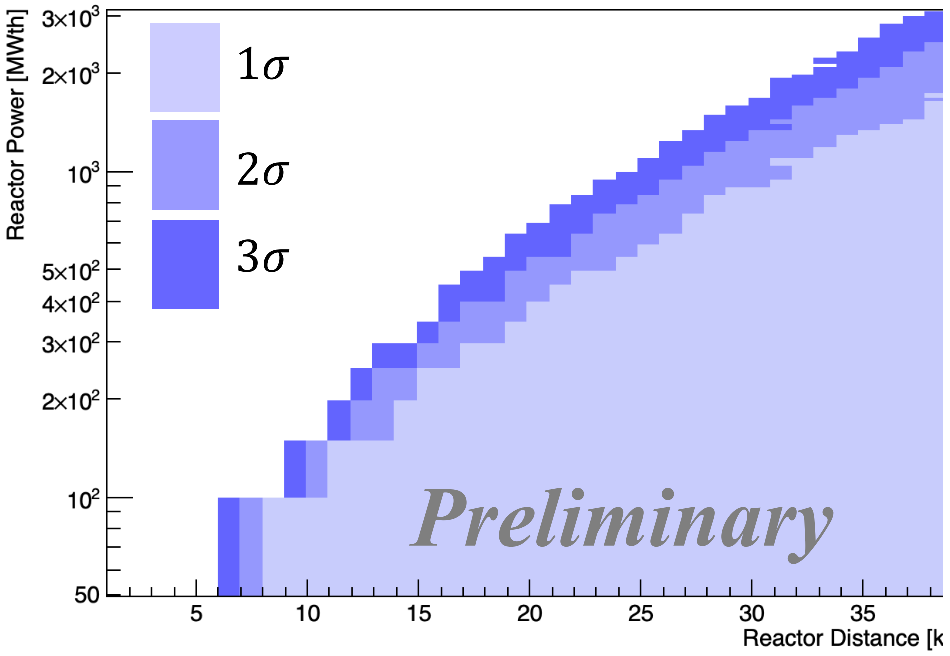
Results of Fits



- Sample the Charge and Spatial response and weather the event is a coincident or accidental event 100,000 times.
- A log-liklihood fit to the template response is made to determine the confidence intervals.

0 MWth Reactor Power 1-Year Dwell Time

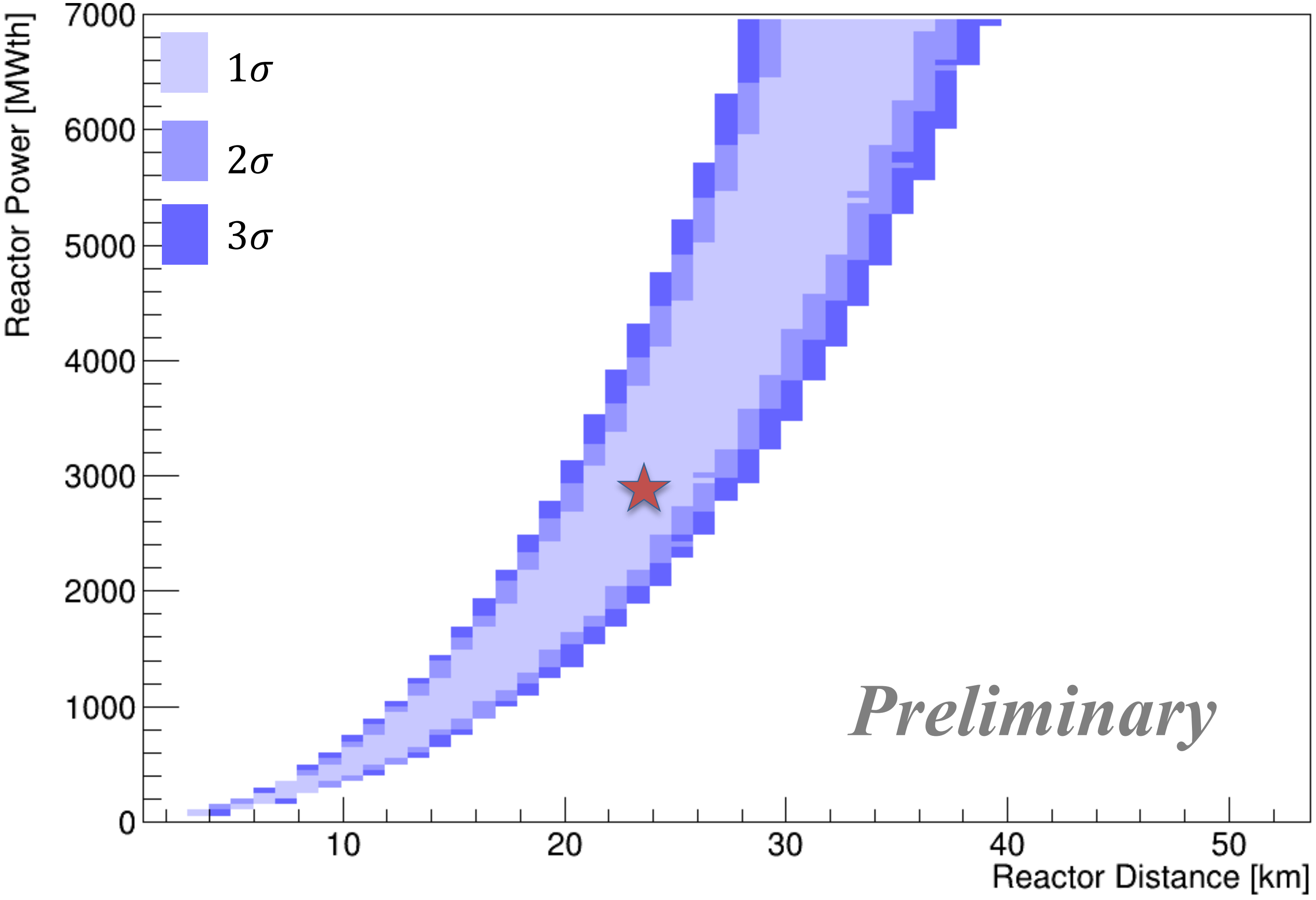




- The exclusion of variable reactor sizes and distances are shown in linear and log plots. However WATCHMAN will only be able to confirm the 1500 MWth and 3000MWth at 25 km standoff.
- For a low power reactor, 50 MWth, can be excluded with greater than 3 sigma at 5 km standoff.

3 GWth Reactor Power 1-year Dwell Time

- When observing the 3GWth reactor at a 25km standoff (Hartlepool Case), we can not delineate between a large reactor core at a far standoff, and a low power reactor at a short standoff distance.
- The combination of low-energy resolution, relatively low statistics, and sensitivity to the higher energy region of the spectra strongly reduces the capability for reactor ranging without prior information.



Conclusion

- WATCHMAN is a kiloton scale detector deployed in the Eastern UK to detector antineutrinos using Gd-doped water.
- The sensitivity metric of which reactor powers and standoffs can be excluded was determined however, the WATCHMAN detector will monitor the two-core reactor complex at Hartlepool from a 25 km standoff and can confirm specific scenarios .
- The Advanced Instrumentation Testbed (AIT) has beyond WATCHMAN aim to facilitate non-proliferation using far-field monitoring with new detection tools and materials, along with the analysis tools to focus on variable use-case scenarios.
- Design and Construction Underway!!

THANK YOU!

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Questions?

Lawrence Livermore National Laboratory