WATCHMAN: Status and Prospects

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Outline

- Nonproliferation and anti-neutrinos
- Large-scale detectors for anti-neutrinos
- WATCHMAN
- Advanced Instrumentation Testbed
- Conclusions

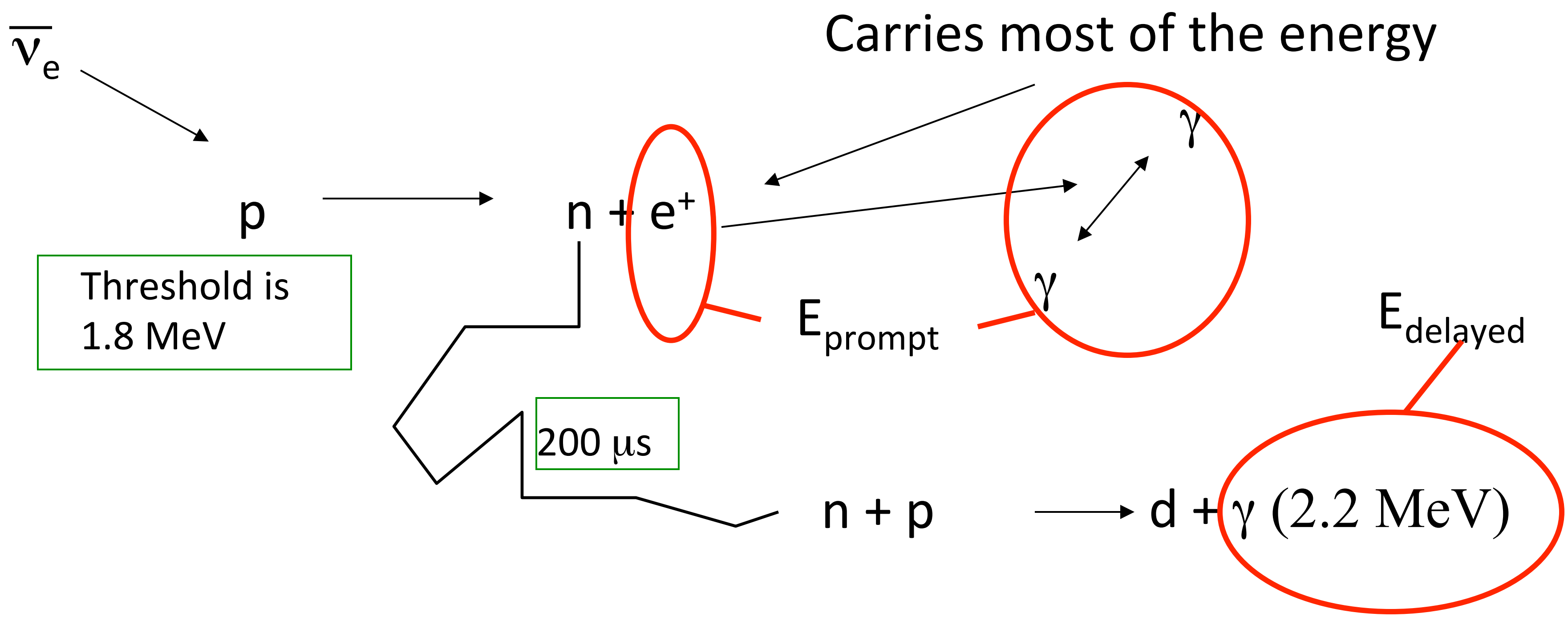
Nonproliferation and anti-neutrinos

- The International Atomic Energy Agency (IAEA) monitors fissile material in most countries of the world
  - Key goal: Detect/prevent the diversion of fissile material
  - Potential pathway for diversion of Pu: shutdowns of power reactors
  - Small undeclared reactors could be used to produce Pu for weapons
- Why is detection of anti-neutrinos potentially useful?
  - Fission reactors copiously produce electron anti-neutrinos
  - Cannot shield the anti-neutrinos, so their detection indicates a reactor is operating
  - Very few high-luminosity sources of electron anti-neutrinos, so long standoff detection is possible – 100's of kilometers – which in principle allows detection from outside the borders of a country
- Gd-doped water Cherenkov detector proposed by Bernstein, West and Gupta for this purpose: Science and global security v 9, 235 (2001).

Long history of anti-neutrino detection

- Discovery of neutrinos came from detection of inverse-beta decay of electron anti-neutrinos from a reactor
- KamLAND is the first long-baseline electron anti-neutrino experiment observing neutrinos from power reactors in Japan (and South Korea)

Delayed coincidence $\overline{\nu}_e$ detection method

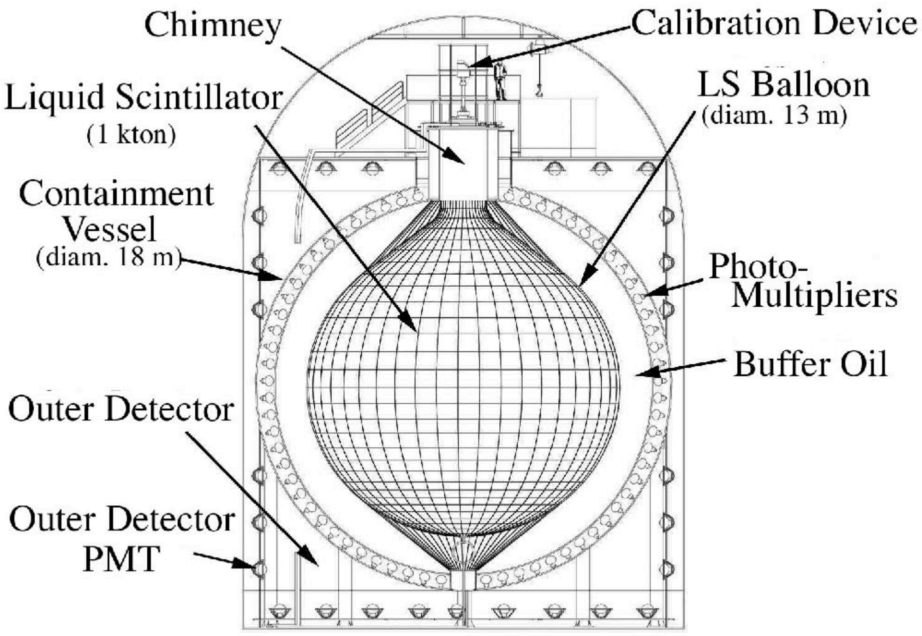


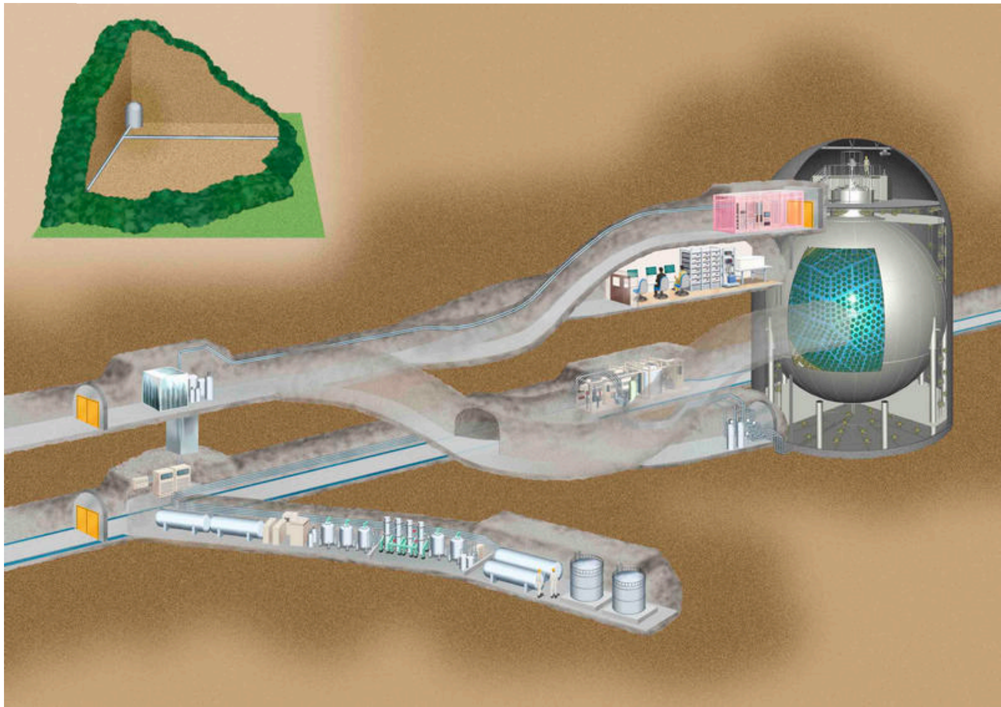
$$E_{prompt} = E_{\nu} - 0.8\ \text{MeV}$$

Inverse-β decay – Same method as employed by Reines and Cowan to discover neutrinos in the late 1950's

Key features

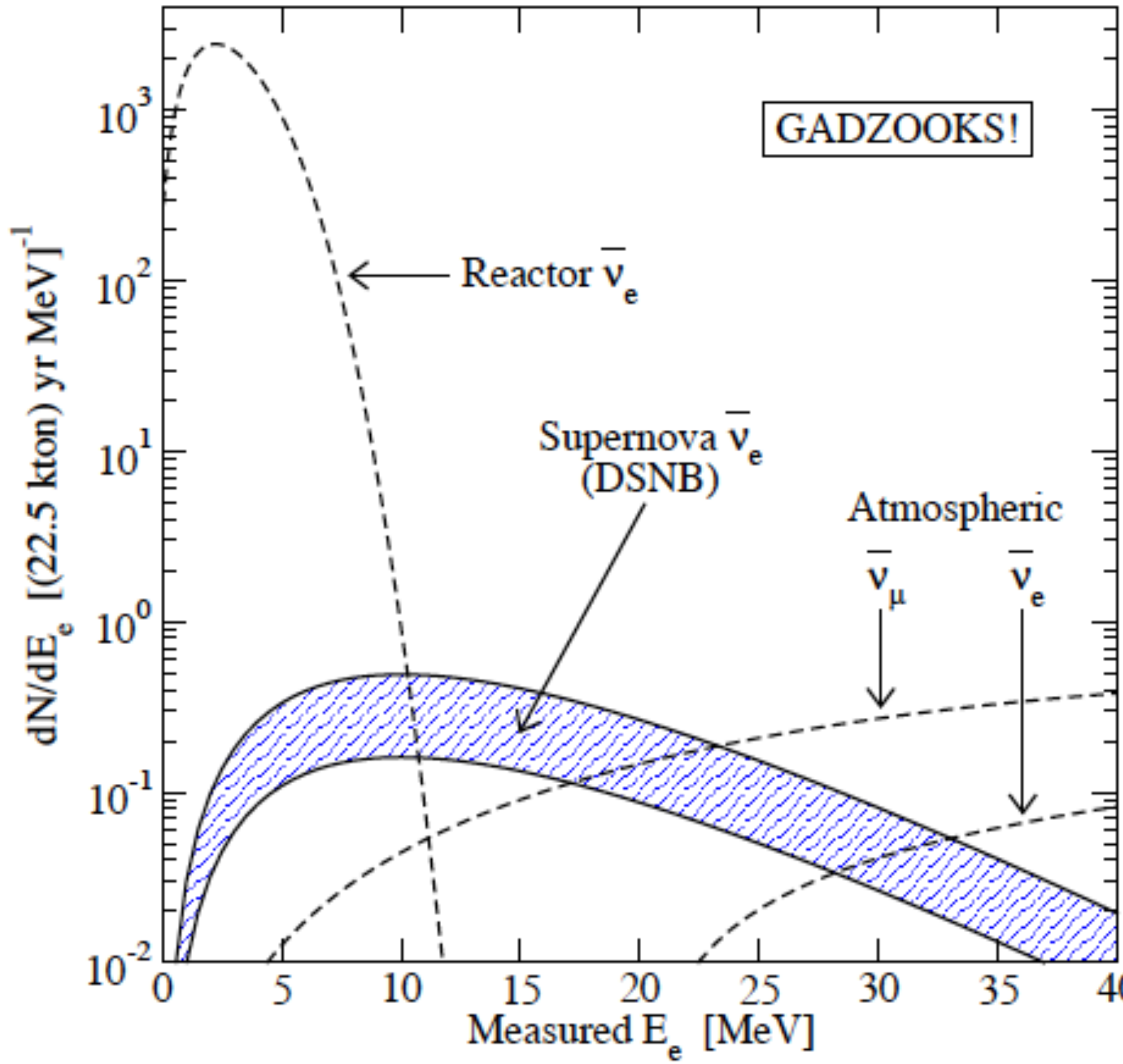
- Delayed coincidence reduces background from radioactive materials in the detector
- Large overburden to reduce cosmogenic backgrounds – KamLAND at 2700 mwe (see Gando's talk yesterday)
- Good energy resolution for the prompt and delayed signal
- Kiloton-scale detector due to small neutrino cross-section
- Organic liquid scintillator is expensive – hard to scale to the megaton, JUNO will go to 20 kilotons (see Garfagnini's talk yesterday)





Beacom and Vagins propose Gd for Super-Kamiokande

- Proposed for detection of diffuse supernova neutrino background
- Gd has a large neutron-capture cross-section and 8 MeV in gamma-rays from the capture
- Makes high-efficiency neutron detection possible in water Cherenkov detectors
- Useful for a variety of other physics
- Scalable to megaton-detectors
- See talk by Michael Smy yesterday



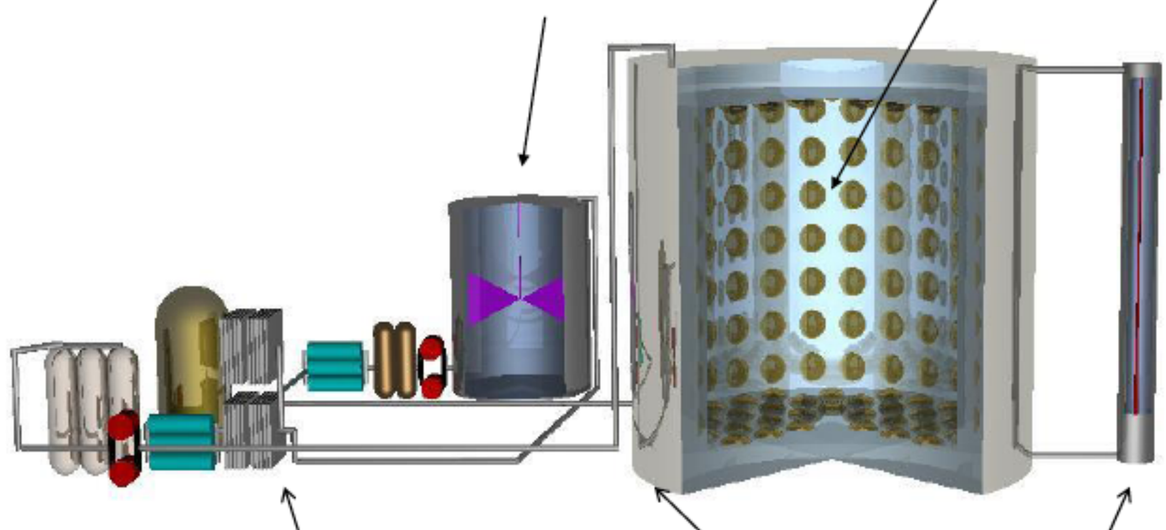
Phys.Rev.Lett. 93 (2004) 171101

Extensive R&D program demonstrates its viability

- Extensive development associated with Super-Kamiokande – preparing for deployment (see Smy's talk yesterday)
- R&D also conducted for nonproliferation purposes in the U.S. associated with the WATCHMAN program

EGADS Facility in the Kamioka Mine

From Mark Vagins



WATCHMAN (Water Cherenkov Monitor for Anti-neutrinos)

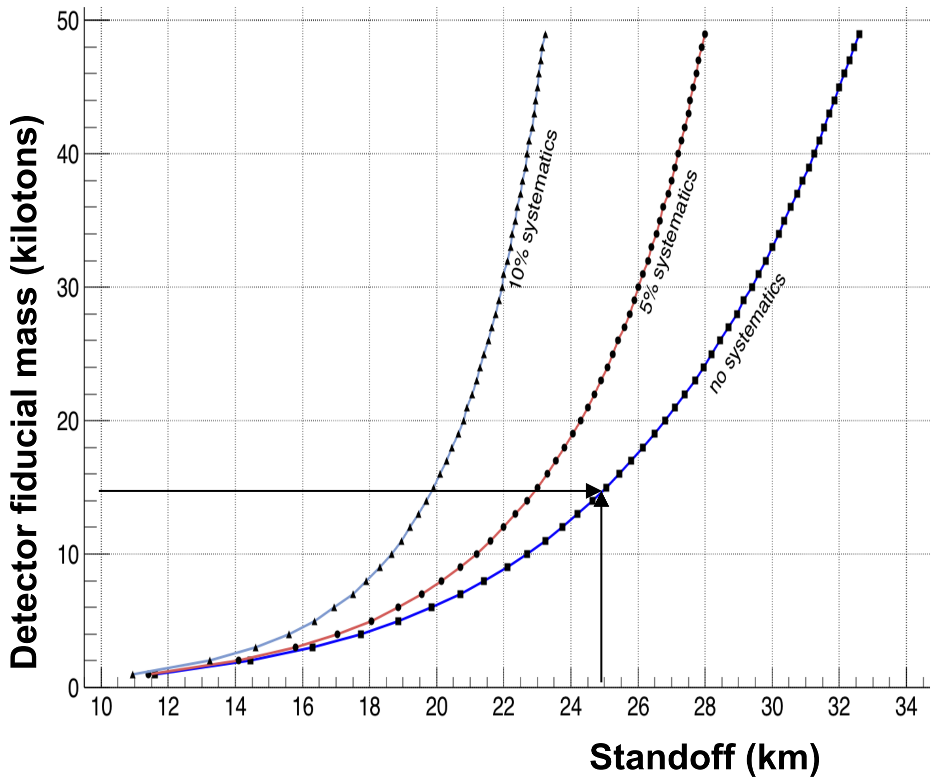
- WATCHMAN will demonstrate the ability to detect electron anti-neutrinos from a reactor from a significant standoff by the deployment of a 1 kiloton fiducial mass Gd-doped water Cherenkov detector in the Boulby mine – 25 km from the Hartlepool reactor complex in NE England.

WATCHMAN Collaboration

- Atomic Weapons Establishment, Boston University, Brookhaven National Laboratory, Iowa State University, Lawrence Livermore National Laboratory, Middlebury Institute of International Studies, Pacific Northwest National Laboratory, Pennsylvania State University, STFC-Boulby, UC-Berkeley/LBNL, UC-Davis, UC-Irvine, U Edinburgh, U Hawaii, U Liverpool, U Michigan, U Pennsylvania, U Sheffield, U Wisconsin (PSL)
- LLNL – lead institution
- 80+ collaborators, 19 institutions

15 kton water detector confirms the absence of operating reactors in a wide geographical region

- A **15 kton** fiducial WATCHMAN-like detector:
- excludes **a 40 MWt reactor**, in **6 months,** with **2 sigma confidence**
- at a standoff of up to **25 kilometers**



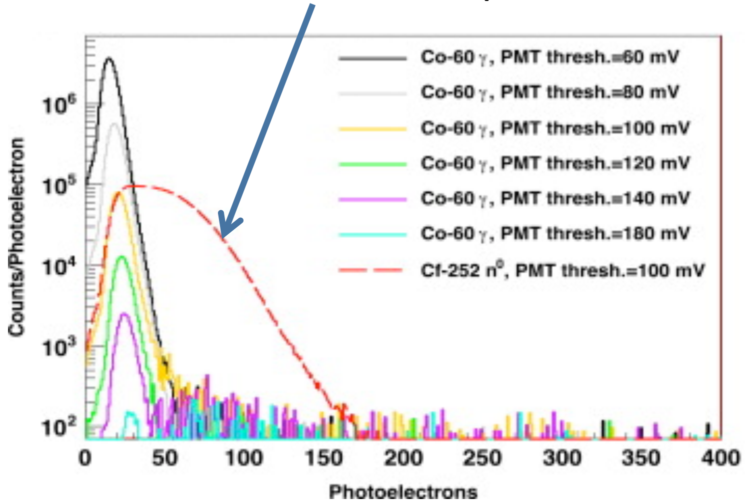
- based on a detailed Monte Carlo simulation including known backgrounds
- includes oscillations from the reactor of interest
- other reactor backgrounds are negligible for this assumed location

From Adam Bernstein

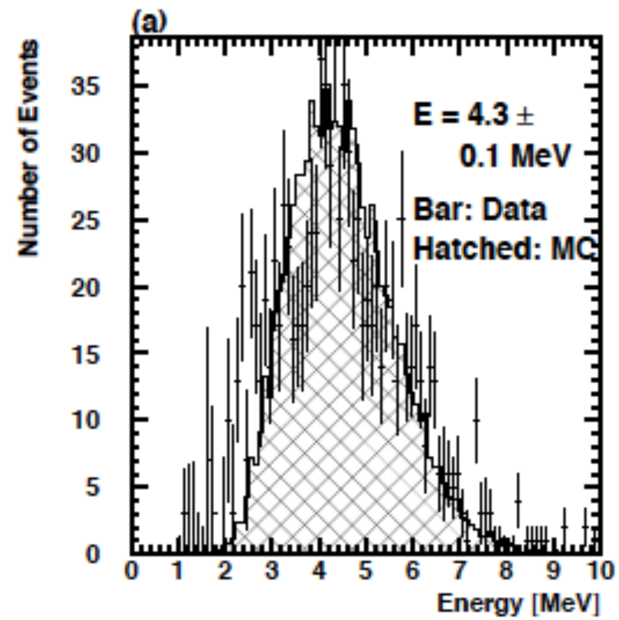
Neutron Capture Signal Clearly Visible

- Neutron captures studied in Super-Kamiokande (lower right) and the WATCHBOY detector (lower left) demonstrate high-efficiency detection of neutrons from capture on Gd in water Cherenkov detectors

Neutron signal in
4 tons of Gd-doped water



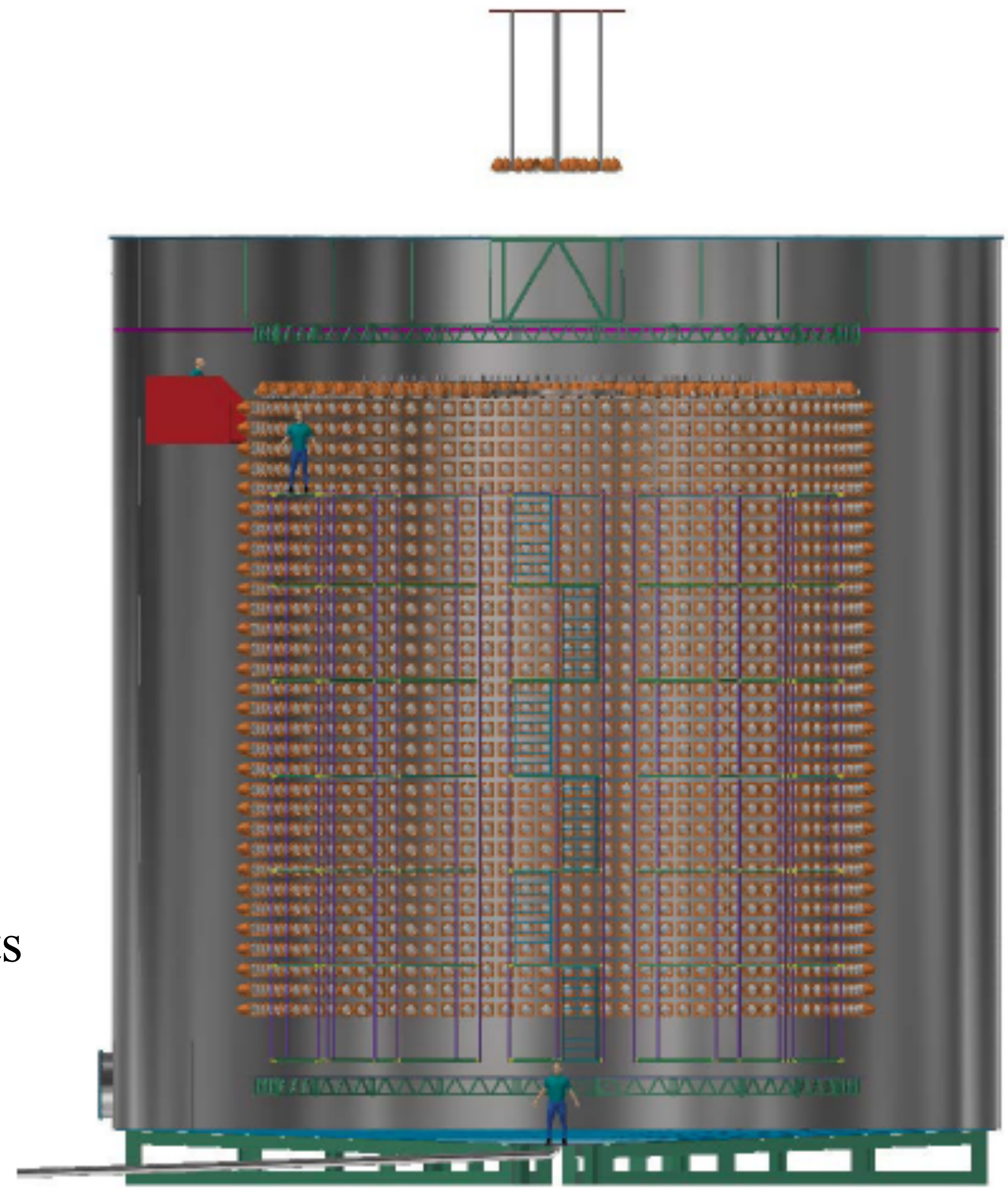
Nucl. Instrum. Meth., A607:616–619.



Astropart. Phys., 31:320–328.

***Reference Design*: Tank and PMT Arrangement**

- Tank height and diameter are 20m
- PMTs arranged facing inward with a veto region
- Similarity to Super-Kamiokande and LBNE water Cherenkov detector designs
- Central plug for ease of construction, future upgrade paths
- Designing multiple ports for calibration deployments
- Anticipate two calibration glove-boxes – one stationary, one mobile

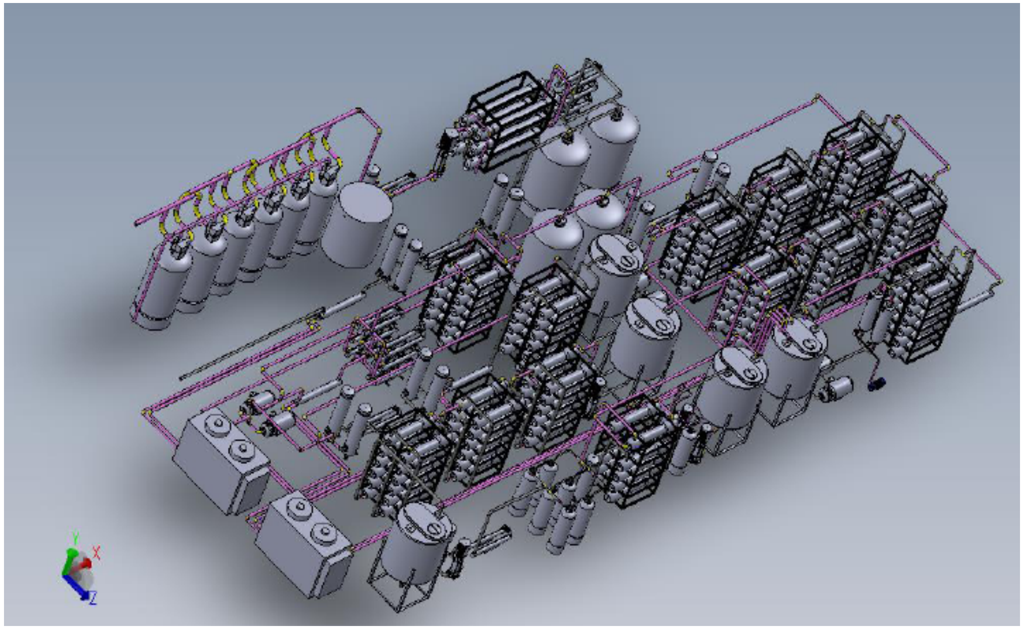


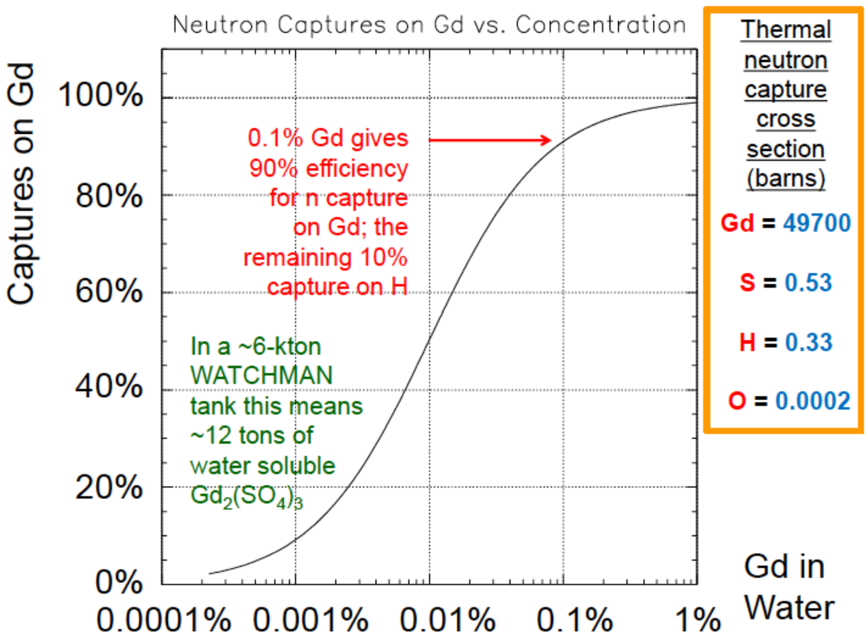
PMTs and Housing

- Housing reference design based on LBNE-Water Cherenkov by the Physical Sciences Laboratory (Wisconsin)
- PMTs are high QE, low radioactivity glass
- Acquired 125 10-inch PMTs from Hamamatsu that are undergoing detailed characterization now
- Approximately 4000 PMTs required

Water System Reference Design

- Based on systems designed for EGADS and SK-Gd
- Extensive validation of molecular bandpass approach allowing Gd to pass through the system and impurities to be removed
- System validated by EGADS (see M. Smy's talk) shows water transparency to be excellent and stable
- Load 0.1% Gd for 90% of neutron captures to take place on Gd





Cleanliness and Materials Compatibility

- Important for the Gd-phase
- Crucial for any upgrade path that includes scintillator
- Active working group interfacing with all other subsystems to ensure appropriate attention

HV, Electronics, DAQ

- Several systems under consideration will employ waveform digitization for triggerless data-taking
- No major technical challenges anticipated – seeking best approach for keeping costs low

WATCHMAN Analysis Goals

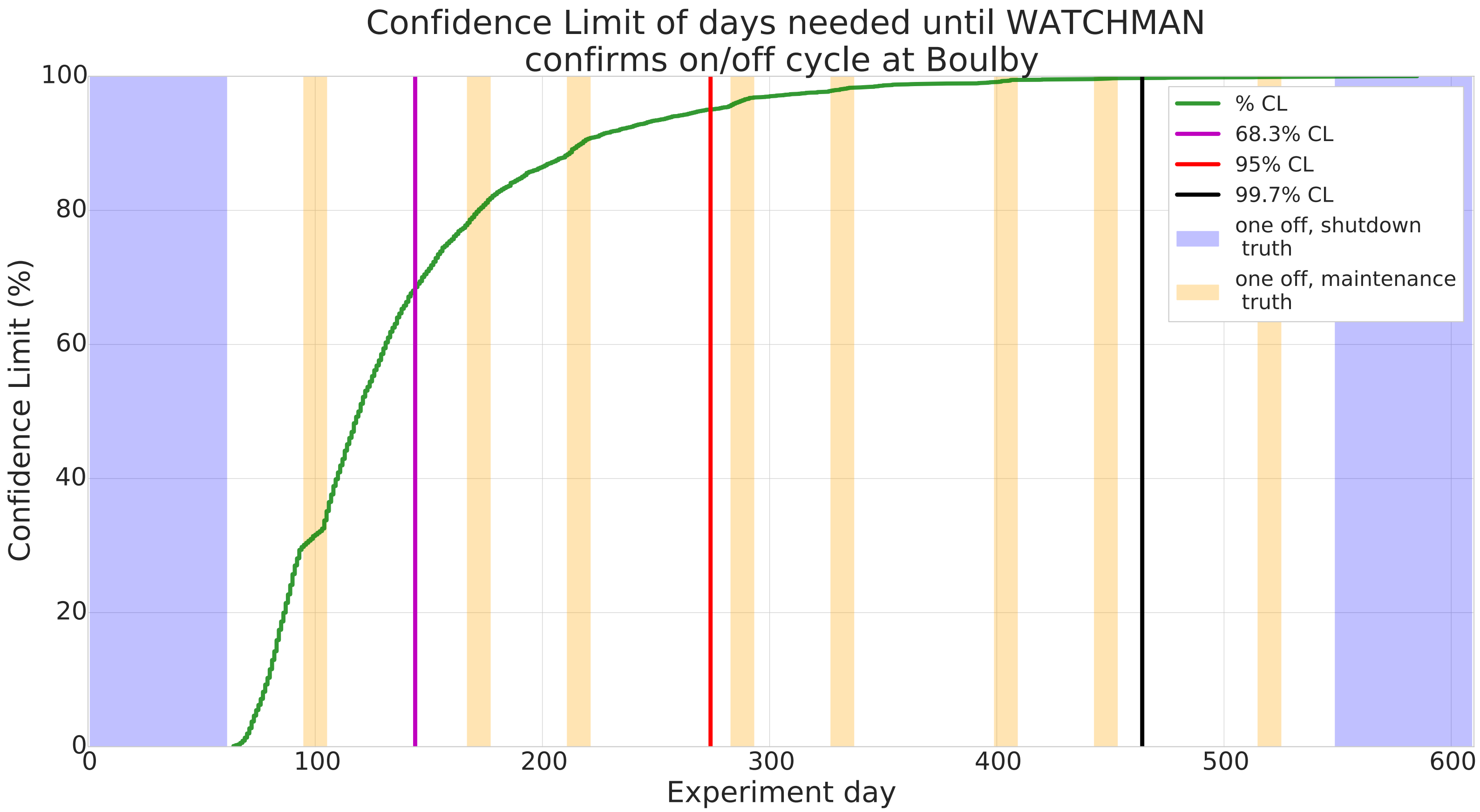
1. Perform the experiment with full knowledge of both reactors' ON/OFF status (unblinded).
2. Perform the experiment with knowledge of a single reactor as a background, with a remaining unknown reactor.
3. Perform the experiment with no knowledge of either reactor (fully blinded).

Signal and Background at Boulby

Component	Events/week
Core 1 (signal)	4.8
Core 2 (background)	4.8
World Reactors	1.5
Cosmogenic radionuclides	0.1
Fast neutrons	0.6
Accidentals	0.6

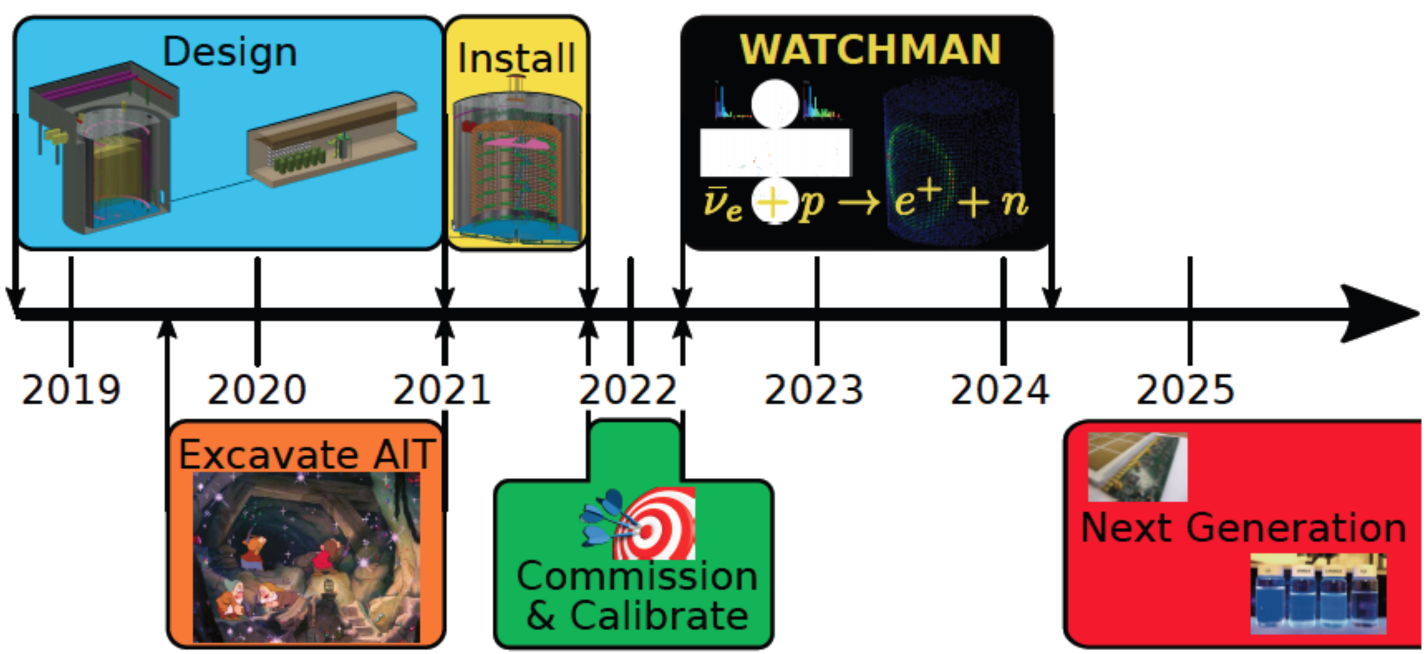
Boulby site – 2805 mwe (roughly factor of 10 lower muon rate than Kamioka)

Dwell time to determine reactor on/off



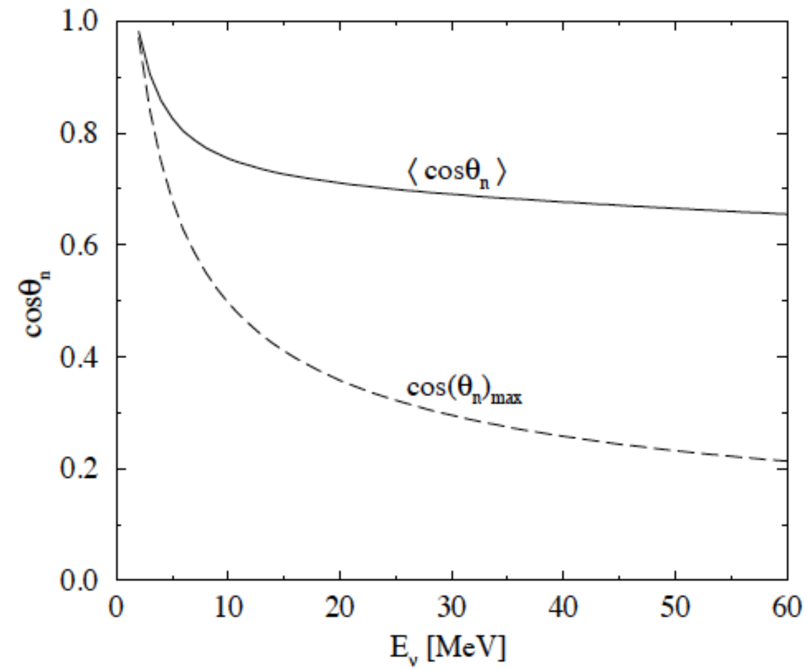
Project Organization and Plan

- WATCHMAN is a U.S.-U.K. collaboration supported by MOD and STFC in the U.K., and DOE-NNSA and DOE Office of Science in the U.S.
- Anticipate a conceptual design review early in the next calendar year
- Designs in this talk are *reference*, not even conceptual, yet
- Focus will be on the site excavation and construction and tank construction – designs for the detector systems can be finalized later
- Early PMT acquisition is essential



Advanced Instrumentation Test-bed (AIT)

- WATCHMAN is the first phase of a broader program (AIT) designed to develop technologies and methods for nonproliferation purposes:
  - improve scalability of the detectors
  - enhance detection efficiency
  - improve background rejection – especially at shallower depths
  - directionality
- Directionality would be a game-changer for nonproliferation and would be useful for neutrino oscillation studies
  - Improved timing or light collection could allow observation of neutron capture position relative to positron
- Large Area Picosecond Photodetectors (LAPPDs) could improve timing
- Water-based liquid scintillator could improve energy resolution and be scalable to large masses (see THEIA talk)



Vogel and Beacom
Phys.Rev. D60 (1999) 053003

Conclusions

- WATCHMAN is undergoing detailed design and preparing for construction
- Data-taking expected to commence in 2022
- The Advanced Instrumentation Test-bed will provide opportunities to study ideas for future large-scale detectors relevant for nonproliferation, particle physics, and the goals of NNN