THE WATCHMAN DEMONSTRATION:

REMOTE REACTOR MONITORING USING A GADOLINIUM-DOPED WATER CHERENKOV DETECTOR

TEAL PERSHING (UC DAVIS)

FOR THE WATCHMAN COLLABORATION

TAUP 2017

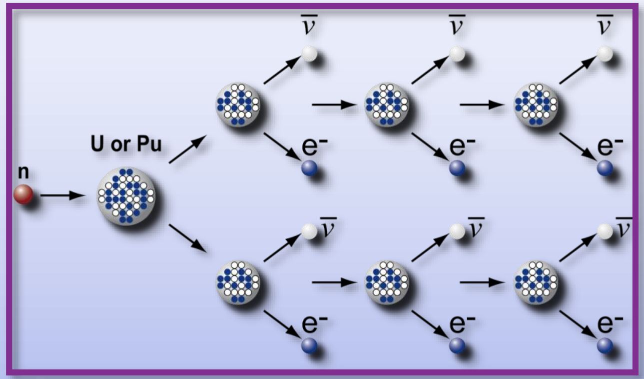
NEW TECHNOLOGIES PARALLEL

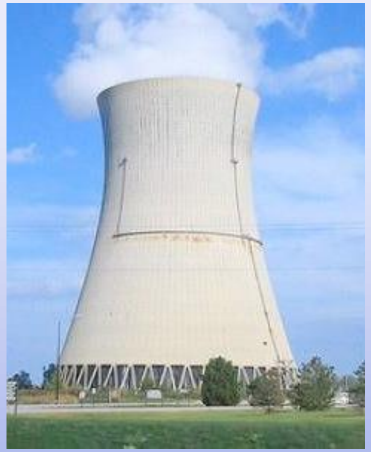
JULY 27TH, 2017

UCDAVIS
UNIVERSITY OF CALIFORNIA

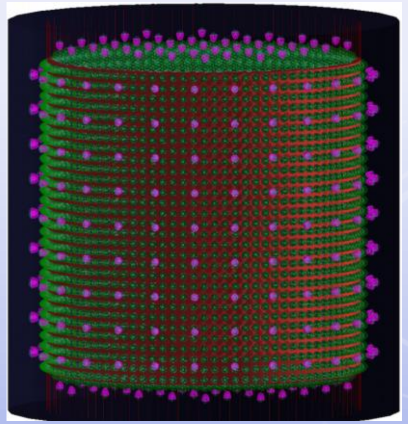
ANTINEUTRINOS FROM NUCLEAR REACTORS

~ 6	$\times$	10^{21}	$\rightarrow$	10^{22}	$\rightarrow$ Distance to detector, small interaction cross section	~ 3
Antineutrinos per nuclear fission		Fissions per second in a 3 GWt reactor		Antineutrinos per second from a 3 GWt reactor (all directions)		Antineutrino interactions per day (per 1 kton volume, at ~25 km standoff)





25 km

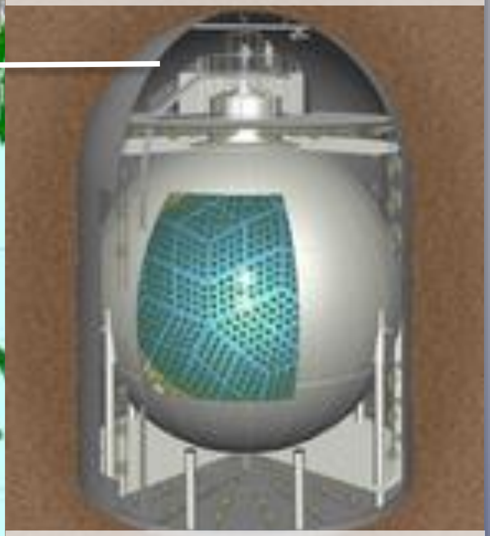


With the right detector configuration, antineutrinos could be used to monitor/exclude the existence of reactors at tens to hundred of kilometers

ANTINEUTRINO DETECTORS: AN EXAMPLE

- Already a scintillator-based detector measuring reactor antineutrino fluxes remotely
  - Detection made primarily measuring inverse beta decay (IBD) events
- Large standoff/single reactor monitoring and discovery presents additional requirements
  - Easily scalable & affordable
  - Low environmental impact
- <u>Gadolinium-doped water Cherenkov detectors meet the criteria for this end goal</u>

The KamLAND detector



1000 tonnes scintillator
1000 m depth

[1] Bernstein, A. For the WATCHMAN Collaboration, “WATCHMAN: a Demonstration of Remote Reactor Monitoring with Gadolinium Doped Water Detectors”, Presented Talk, The 2017 International Conference on Applications of Nuclear Techniques, Rare Event Detection Session, contribution ID 102

THE WATCHMAN COLLABORATION

The WATCHMAN Collaboration

Atomic Weapons Establishment	Lawrence Livermore National Laboratory	University of California, Berkeley	University of Hawaii	University of Sheffield
Brookhaven National Laboratory	Pennsylvania State University	University of California, Davis	University of Michigan	University of Tennessee
Iowa State University	Science Technology Facilities Council– Boulby	University of California, Irvine	University of Pennsylvania	

32 collaborators

10 Universities

4 National Laboratories

Co-spokespersons:

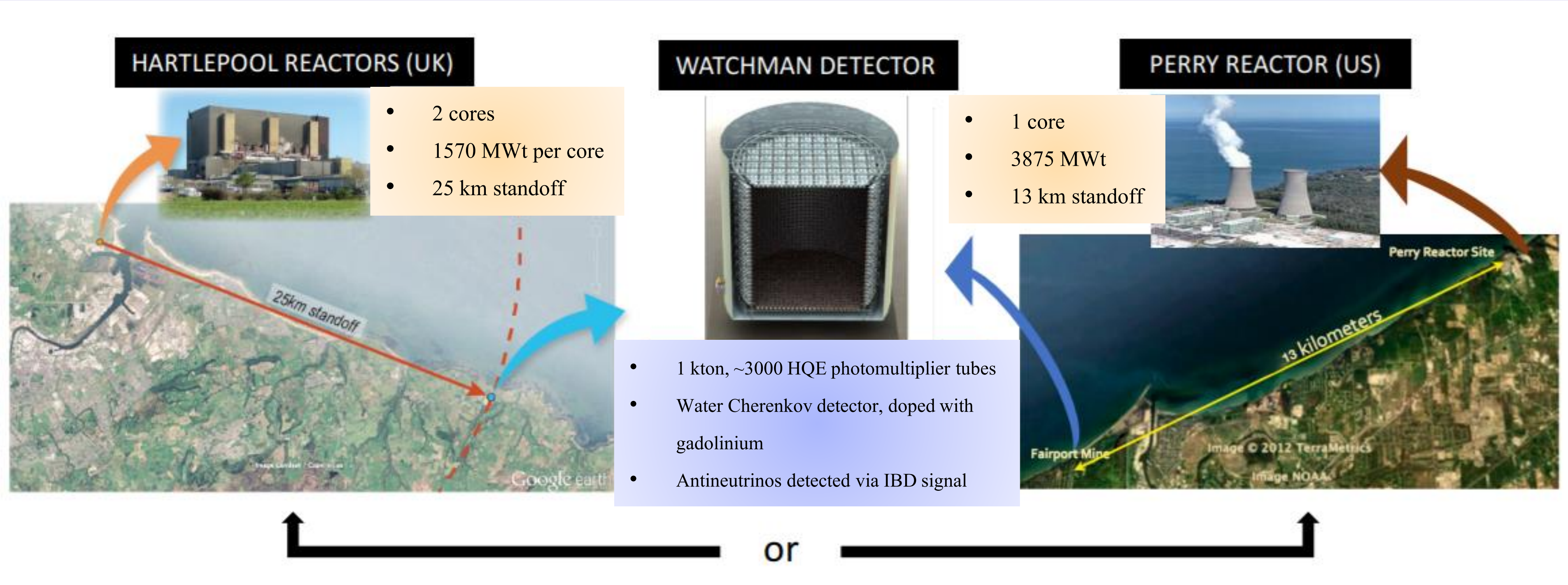
Adam Bernstein, LLNL

Mark Vagins, UC Irvine/Tokyo University

THE WATCHMAN DEMONSTRATION

- Primary goal: Actively monitor an operating reactor plant installation from 10-25 km standoff
  - Demonstrates the reactor monitoring capability of a ~kton volume Gd-water detector
  - Paves the path for operating 0.1-1 Mton volume Gd-doped detectors
    - Could actively monitor reactors at ~100 km standoffs

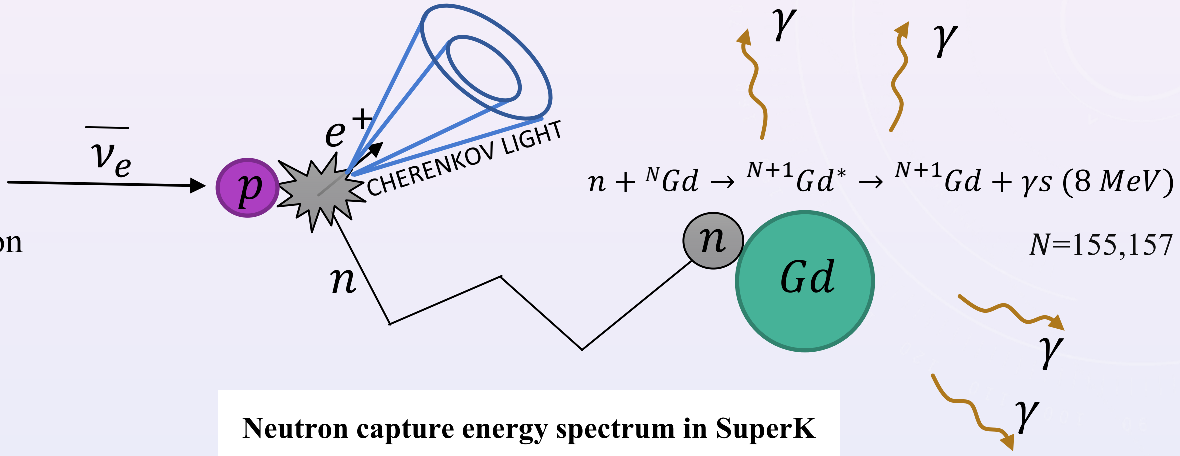
Potential upgrades:
- ~Installation of 100 fast photosensor units (i.e. Large area picosecond photodetectors)
- WbLS fill following Gd-$H_2$0



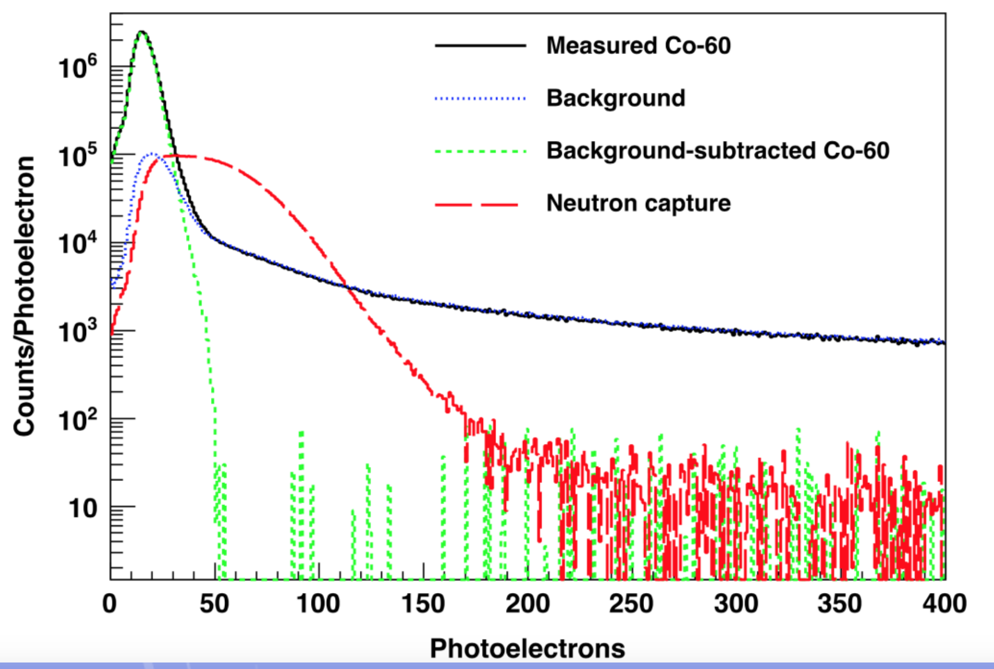
[4] M. Askins, M. Bergevin, A. Bernstein, S. Dazeley, S. T. Dye, et al. "The Physics and Nuclear Nonproliferation Goals of WATCHMAN: A WAter CHerenkov Monitor for Antineutrinos", **arXiv**:1502.01132v1 [physics.ins-det] 4 Feb 2015
[5] Bergevin, M. "Supernova detection capabilities of gadolinium doped water and water-based liquid scintillator detectors", Public Talk at WIN2017, Neutrino physics working group session, contribution ID 60

DETECTING IBDS WITH GD-DOPED WATER

- IBD interaction: $\bar{\nu}_e + p \rightarrow e^+ + n$
- Delayed coincidence signal
  - Prompt light from positron's Cherenkov light
  - Delayed signal (~30 μs) gamma cascade after Gadolinium capture of neutron
    - Average energy release of Gd capture above most natural backgrounds

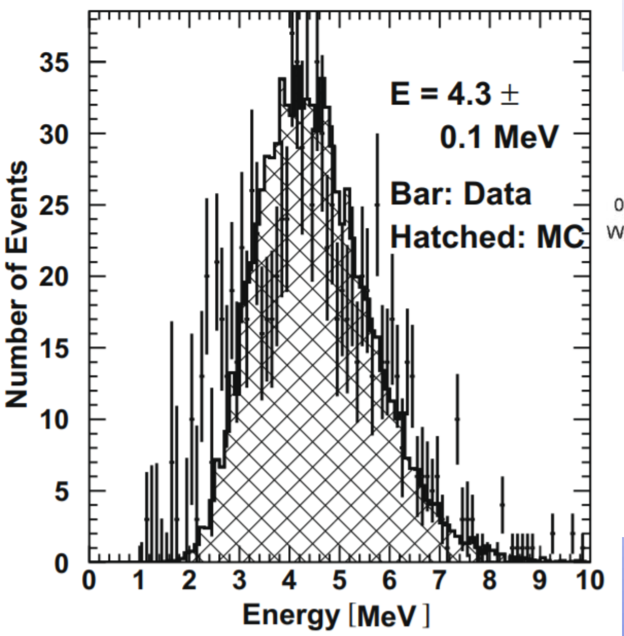


PE signal in LLNL well counter - 1 ton Gd-doped water

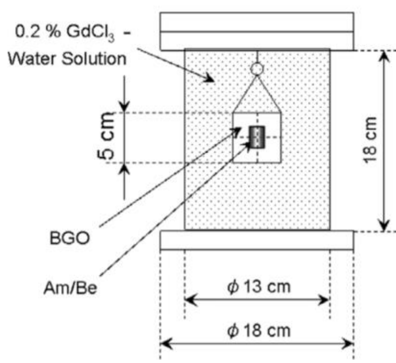


Well counter (top and schematic)

Neutron capture energy spectrum in SuperK



Gd signal source geometry (deployed in SuperK)

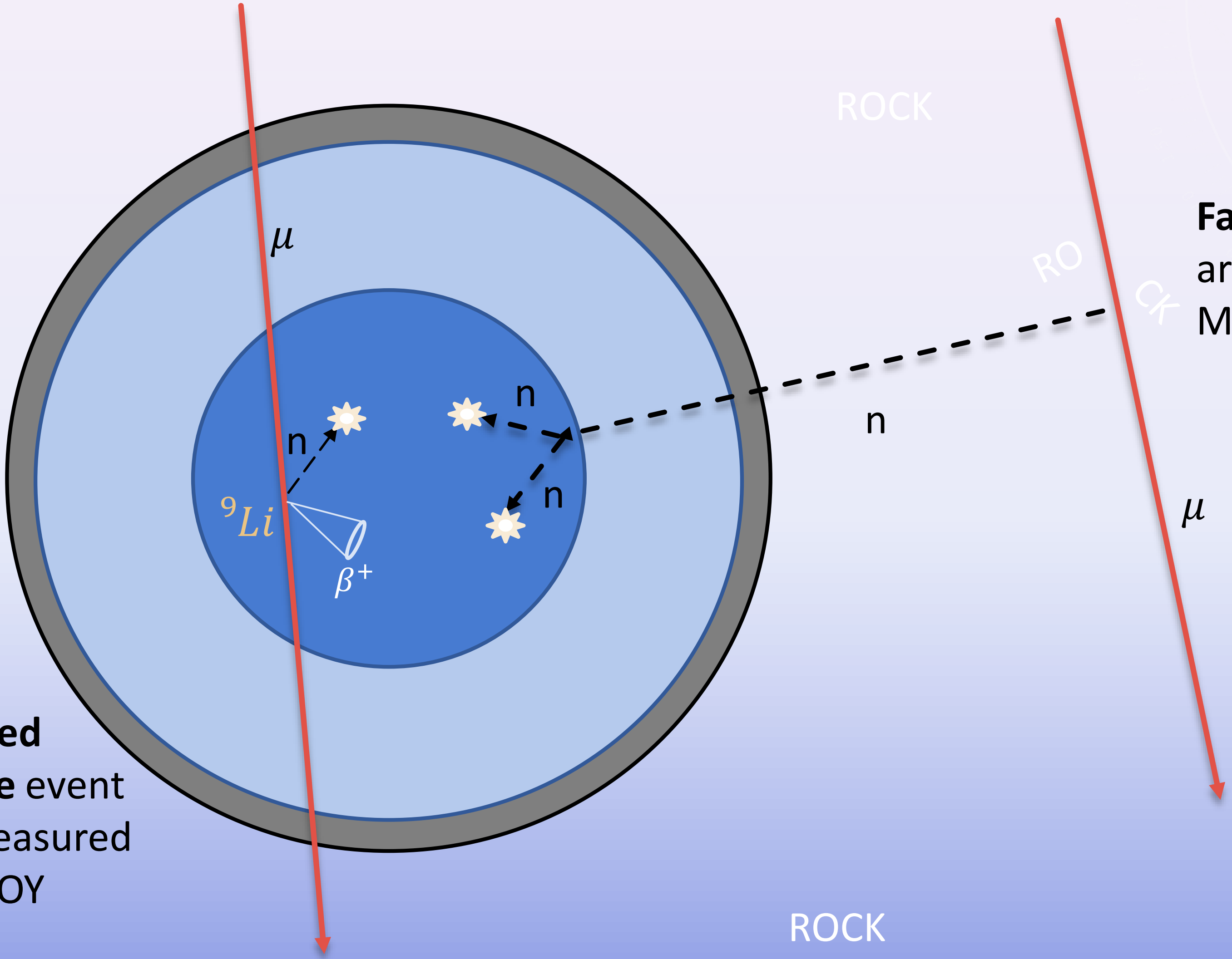


[2] S. Dazeley, A. Asghari, A. Bernstein, N.S. Bowden, V. Mozin, "A water-based neutron detector as a well multiplicity counter", **Nuclear Instruments and Methods in Physics Research A** 771 (2015) 32–38

[3] H. Watanabe, et al. (The SuperKamiokande Collaboration), "First study of neutron tagging with a water cherenkov detector," Astroparticle Physics, vol. 31, no. 4,pp. 320 – 328, 2009.

WATCHMAN – DOMINANT BACKGROUNDS

1: long lived radionuclides
2: fast neutrons
3: coincidences of:
single gamma-rays,
neutrons,
muons,
radon…



Fast neutron rates are measured by MARS

ROCK

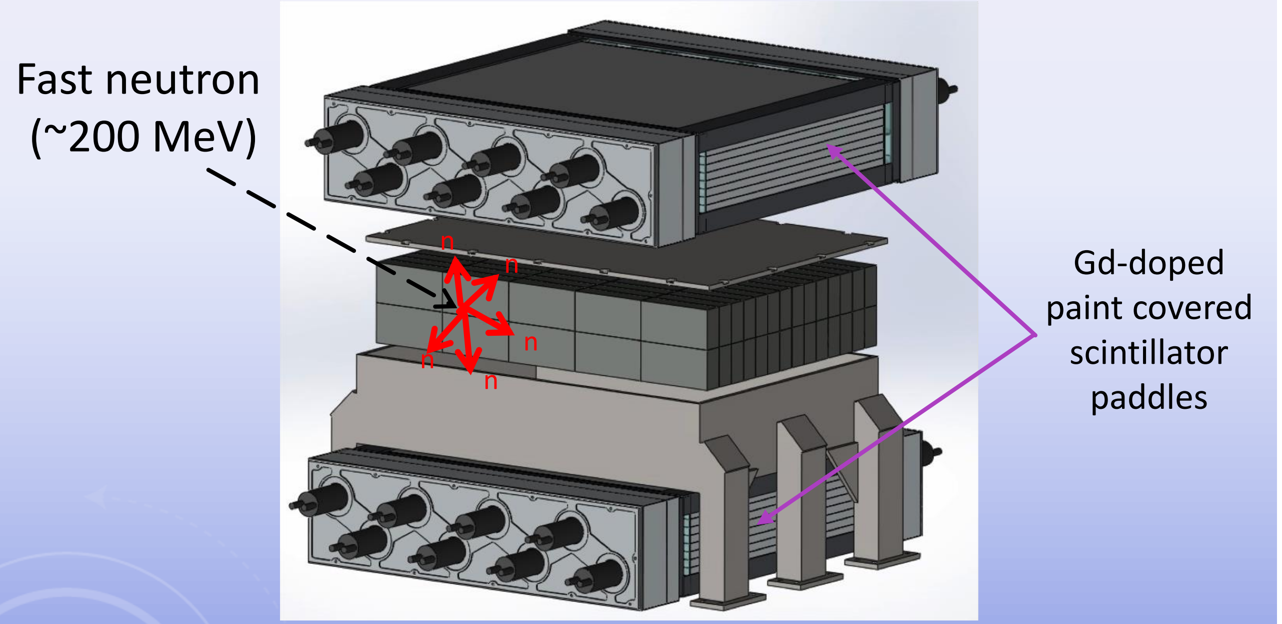
The **long lived radionuclide** event rates are measured by WATCHBOY

ROCK

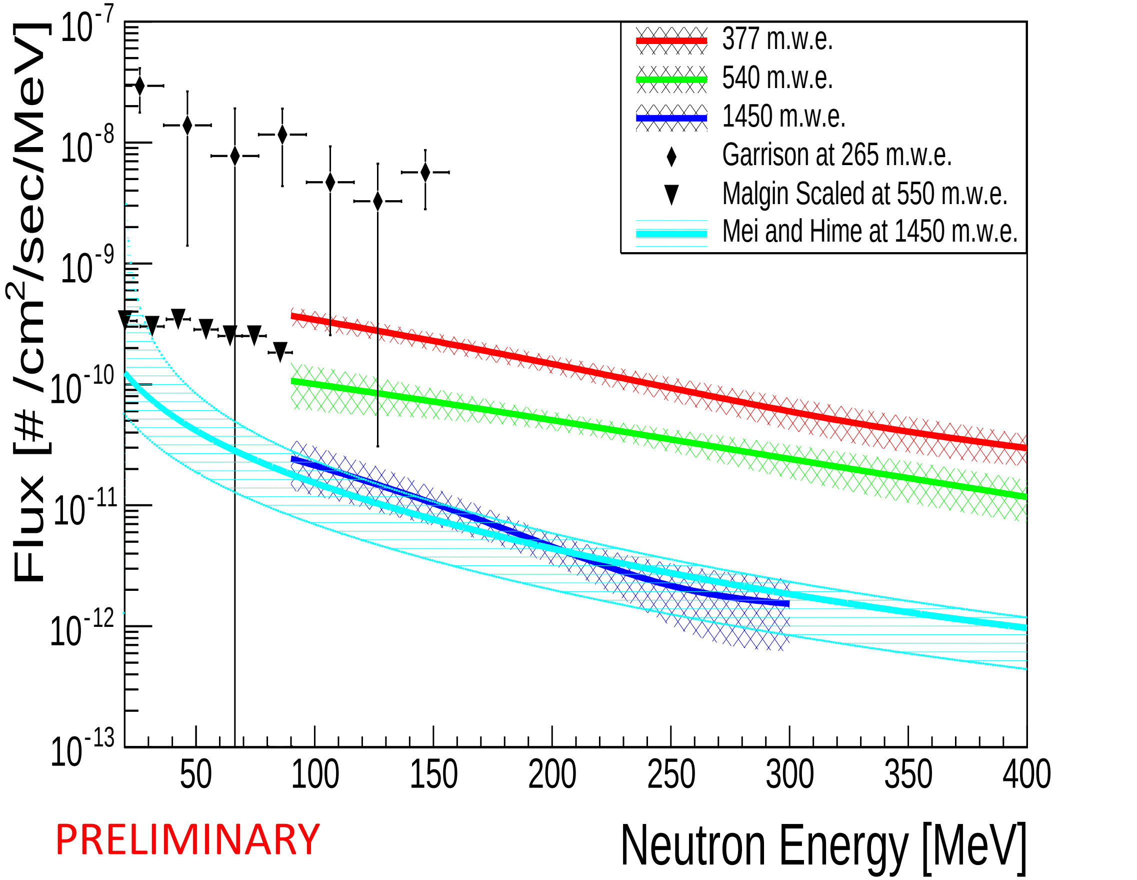
ROCK

FAST NEUTRON MEASUREMENT - MARS

- Multiplicity and Recoil Spectrometer (MARS)
- Fast neutrons incident on lead target induce multiple neutron products
  - Fast neutron incident energy determined with neutron multiplicity
- First variable depth measurement made with one detector
  - Paper submitted to PRL May 2017

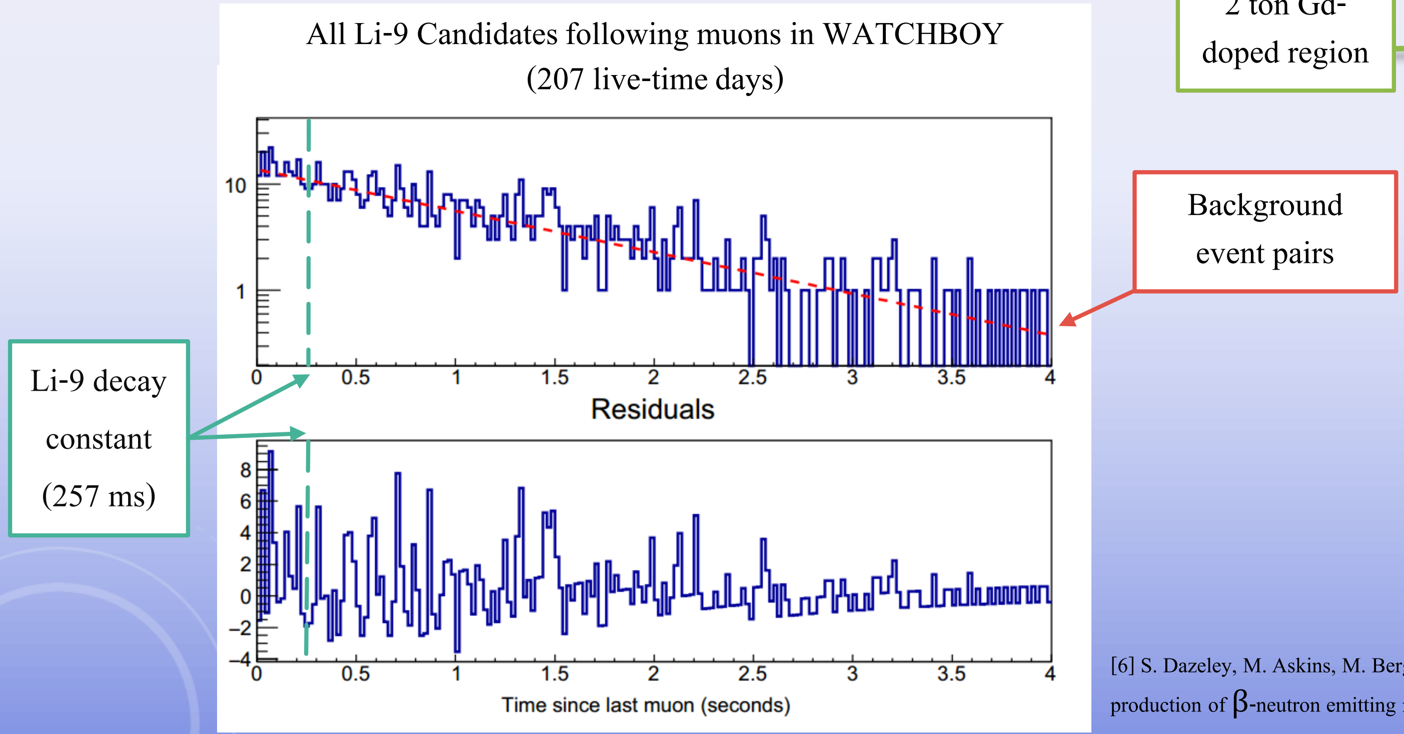


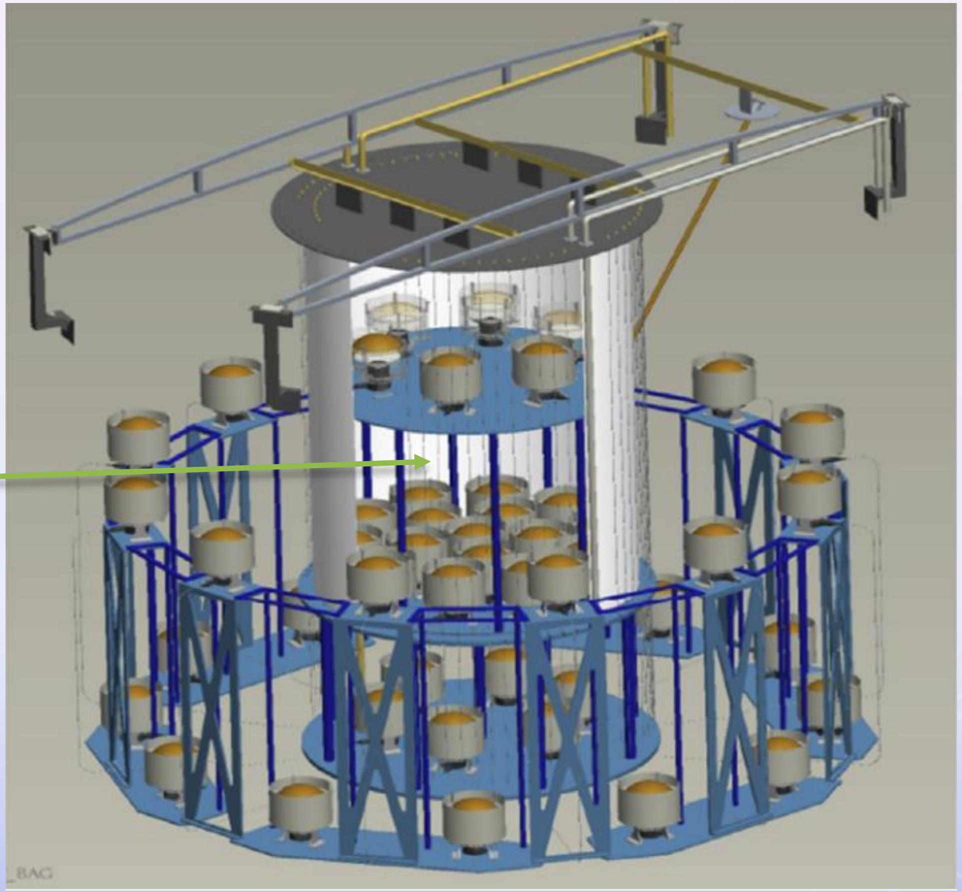
Fast Neutron Flux vs. Energy, measured at the Kimballton Underground Research Facility (KURF)



LONG-LIVED RADIONUCLIDES WITH WATCHBOY

- WATCHBOY – Gd-doped water detector designed to measure the ^9Li production rate following cosmic muons
  - ^9Li signal: two flashes (prompt beta and delayed neutron) following a muon event
- Set a limit on ^9Li production rate at 400 m.w.e. depth at KURF
  - 90% CL: $1.9 \times 10^{-7} \mu^{-1} g^{-1} cm^2$
  - Determined radionuclide production is a subdominant background
- Results published in NIM Phys. R. A in June 2016





- 36 10” outer volume PMTs in a water volume for muon ID
- 16 10” PMTs in Gd-doped water region

[6] S. Dazeley, M. Askins, M. Bergevin, A. Bernstein, N.S. Bowden, T.M. Shokair, P. Jaffke, S.D. Rountree, M. Sweany, “A search for cosmogenic production of β-neutron emitting radionuclides in water”, **Nuclear Instruments and Methods in Physics Research A** 821 (2016) 151–159

MONITORING OF REACTOR STATES - STUDY

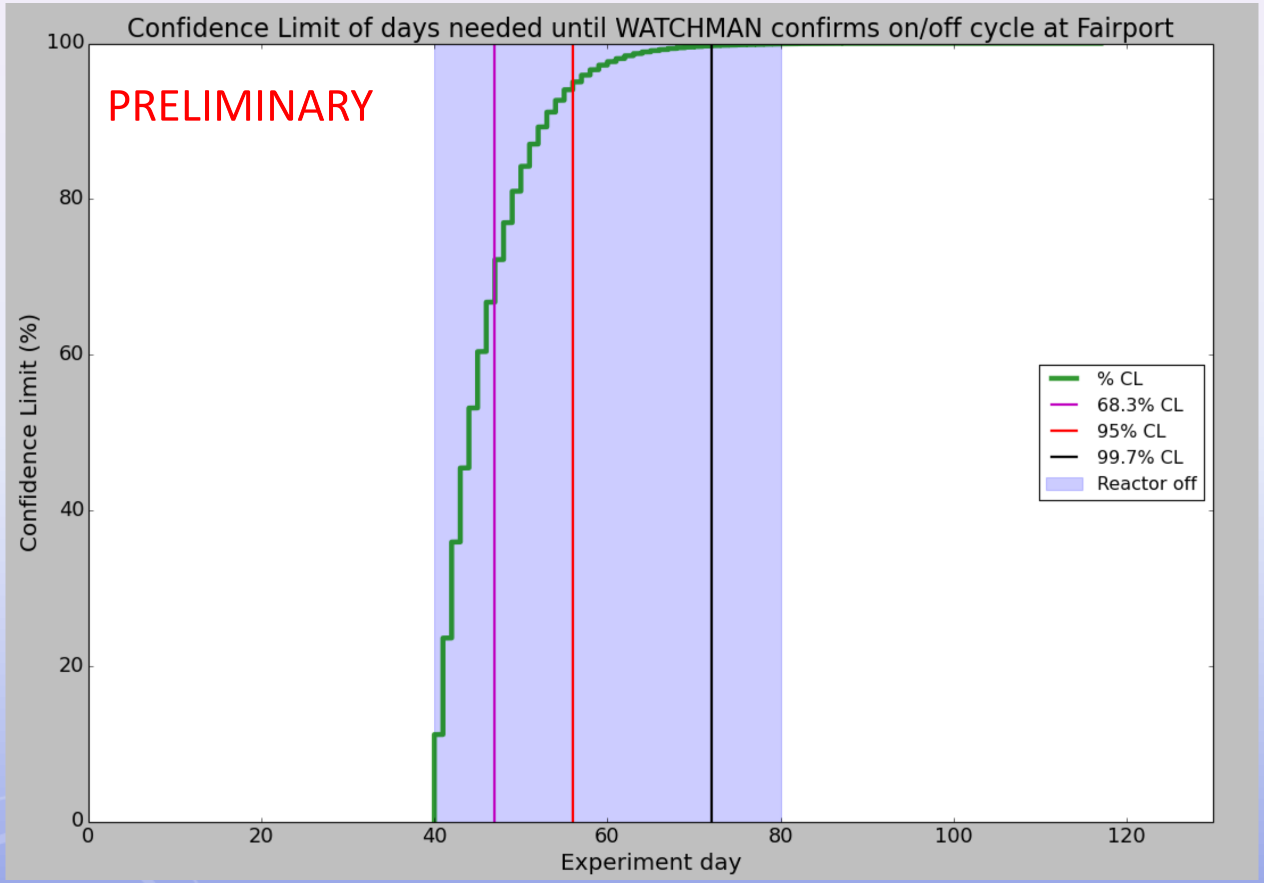
- Boulby Mine (UK) and Fairport (USA) two main potential sites for WATCHMAN Gd-doped water Cherenkov detector

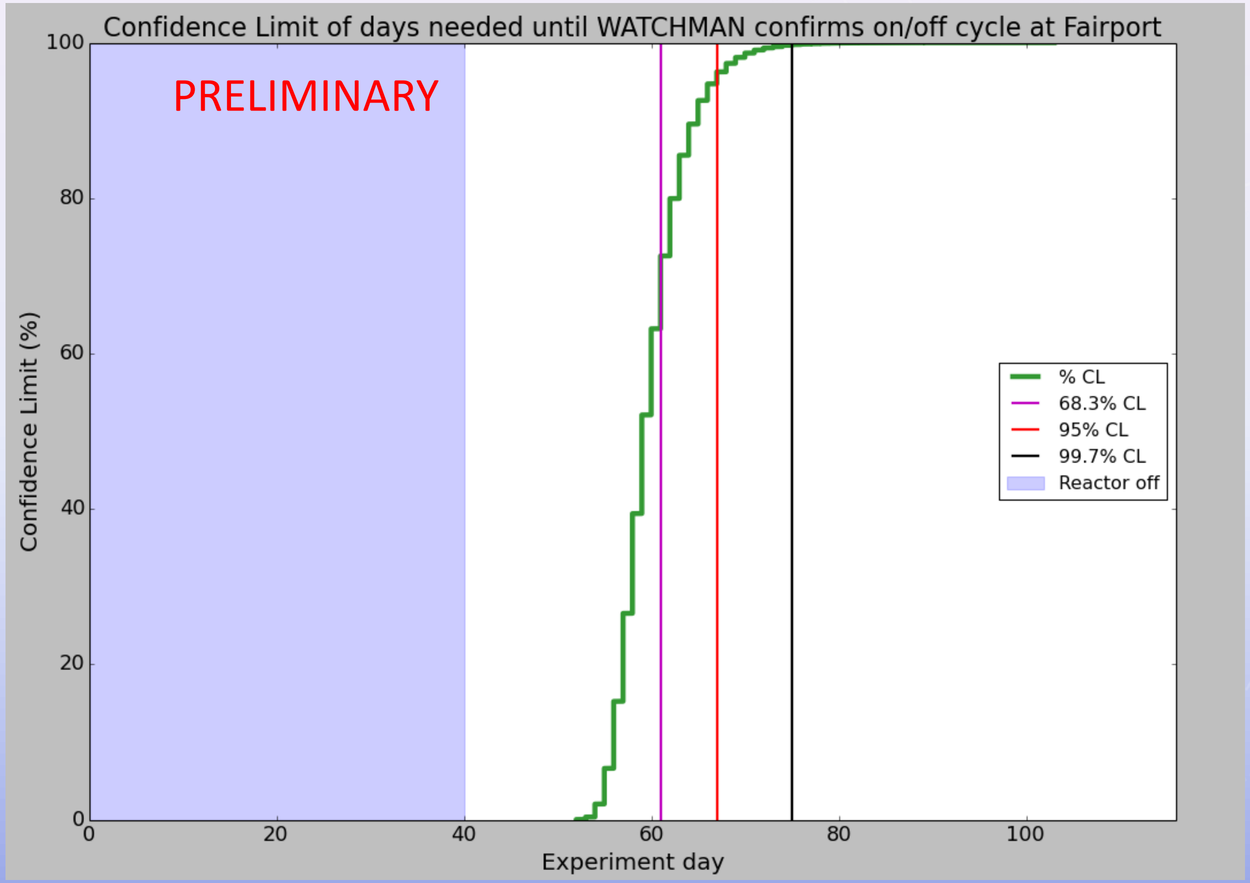
	Option 1	Option 2
Reactor Location	Perry, Ohio, United States	Hartlepool, England, United Kingdom
Thermal Power (MWt)	1 x 3875	2 x 1500
		
Detector Location	Morton Salt/IMB mine Painesville, Ohio	Boulby underground science lab, Boulby, England
Standoff	~13 km	~25 km
Overburden (mwe)	~1500	~3000
Signal Events	110 per month	11 per month
Background Events	50 per month	20 per month

- **For Fairport's expected signal vs. background rates, how many days would WATCHMAN need to run to see a clear 3-sigma deviation between the "reactor on" data set and "reactor off" data set?**
  - Assume we have the proposed reactor operation schedule at either site
  - WATCHMAN detector performance simulated using RAT-PAC
- Boulby study still ongoing

REACTOR ON/OFF TRANSITIONS - FAIRPORT

- At the Fairport site, WATCHMAN would observe the Perry power plant's on/off cycle in less than 3 months
  - Statistically generated 100,000 experiments to set confidence levels on the day of observation
  - Fairport assumed schedule: Core off for 40 days, on for 700 days





- Blind confirmation studies (i.e. no prior knowledge of the schedule) the next task

CONCLUSION

- Gadolinium-doped water Cherenkov detectors are a competitive detection medium for reactor monitoring
  - High IBD detection efficiency
  - Scalability to 100 kton – 1Mton scales
- Potential testbed for additional detector technologies in a ~kton scale detector
  - Fast photosensors
  - Water-based liquid scintillators
- New physics measurements already made on the path to the WATCHMAN demonstration
  - Fast neutron flux vs. depth
  - First Gd-water demonstration at ~ton scale
- Sensitivity to confirming a reactor plant's given operation schedule at Fairport site investigated
  - Studies on measuring deviations from a given schedule upcoming
  - Boulby study and optimization underway
- Currently proposed to start WATCHMAN in 2018

RESOURCE SLIDES

AVERAGE IBDS/DAY FOR EACH SITE AS SIMULATED IN WATCHMAN

Values used in preliminary study shown
Values generated using WATCHMAN's RAT-PAC as of June 2017

Boulby Site Values


```
{
   "Photocoverage_Cases": [
    { "Photocoverage": 0.25,
    "Signal_Contributions": {
        "Core_1" : 0.3699,
        "Core_2" : 0.3699,
        "Other_Reacs": 0.1073,
        "Accidentals": 0.0996,
        "Fast_N": 0.0832,
        "Radionuclides": 0.0145
        }
    }]
}
```


Fairport Site Values


```
{
   "Photocoverage_Cases": [
    { "Photocoverage": 0.20,
    "Signal_Contributions": {
        "Core_1" : 3.69,
        "Other_Reacs": 0.1845,
        "Accidentals": 0.4333,
        "Fast_N": 0.8554,
        "Radionuclides": 0.1896
        }
    }]
}
```

UNCERTAINTIES FOR ON/OFF CYCLE CONFIRMATION

For either the "both cores on" or "one core off" data set…

$$\Gamma_{IBDs}(t) = \frac{N_{IBDs}}{t}$$

Γ_{IBDs} – Average IBDs/Day according to all data taken up to that day (cores + background)

t – time in days of data collected for this data set

At any day in the experiment, the uncertainty in this average is:

$$\sigma_\Gamma = \Gamma_{IBDs}\sqrt{\left(\frac{\sigma_N}{N}\right)^2 + \left(\frac{\sigma_t}{t}\right)^2}$$

$$\sigma_\Gamma = \Gamma_{IBDs}\left(\frac{\sigma_N}{N}\right) = \Gamma_{IBDs}\left(\frac{\sqrt{N_{IBDs}}}{\Gamma_{IBDs} * t}\right)$$

$$\sigma_\Gamma = \frac{\sqrt{N_{IBDs}}}{t}$$

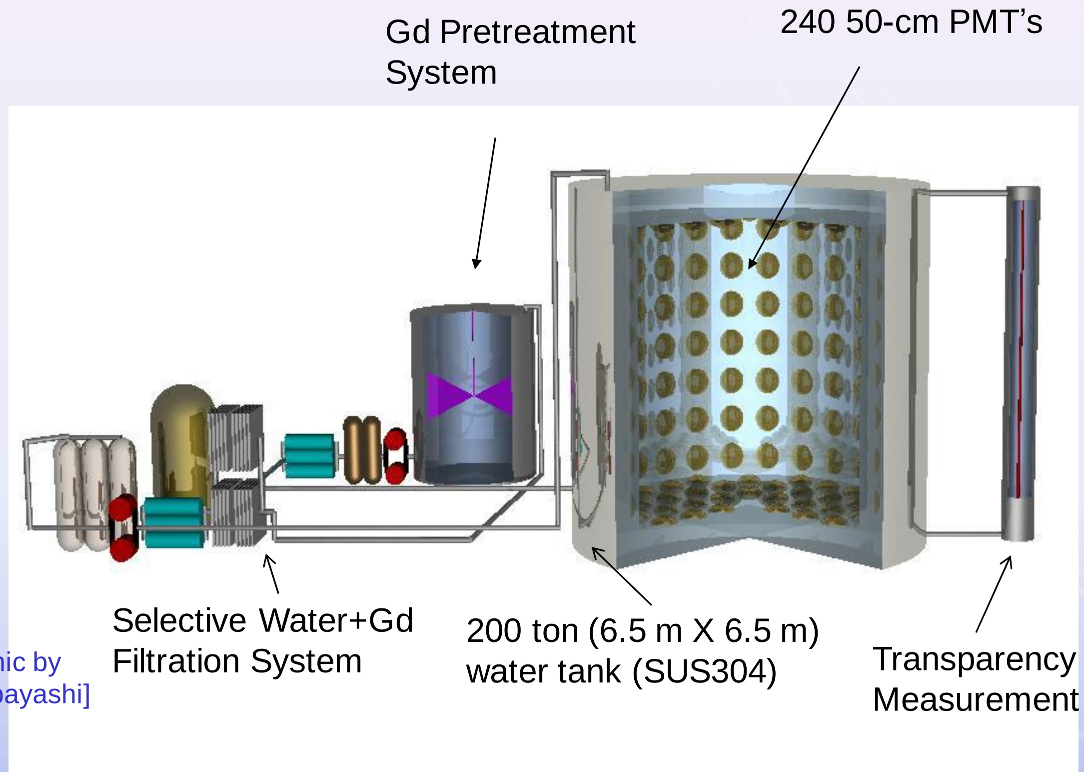
"Confirmation" of the reactor cycle is claimed when:

$$\Gamma_{ON} - \Gamma_{OFF} > 3\sigma_{TOT}$$

is true for 14 days in a row. σ_{TOT} is the "ON" and "OFF" data set average undertainties added in quadrature

GADOLINIUM PURIFICATION USING EGADS

- Gadolinium-doped water has been investigated for potential addition to Superkamiokande
- Evaluation of Gadolinium Action on Detector Systems (EGADS) developed in Kamioka mine
  - 200 ton Gd-doped water Cherenkov detector
  - $Gd_2(SO_4)_3$ diluted in DI water
  - Gd-compound + water purification system
- Separation of gadolinium compound and DI water for purification of water performed
  - 99.9% recovery of Gadolinium compound achieved in system
- Continuous operation and purification of Gd-doped water system ongoing
  - Will give a final benchmark on purification performance on longer timescales



[graphic by A. Kibayashi]

[A1] Mori, Takaaki (for the SuperKamiokande Collaboration), "Status of the Super-Kamiokande gadolinium project", Nuclear **Instruments and Methods in Physics Research A** 732 (2013) 316–319

THE IBD SIGNAL, NO GADOLINIUM

- Delayed coincidence signal
  - Prompt light from positron Cherenkov radiation
  - Delayed (~100 μs later) 2.2 MeV signal from neutron capture
    - For water Cherenkov detectors, this energy range has numerous natural backgrounds