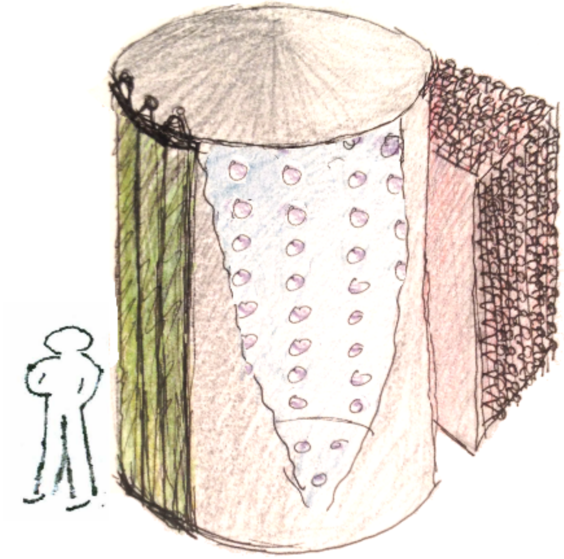
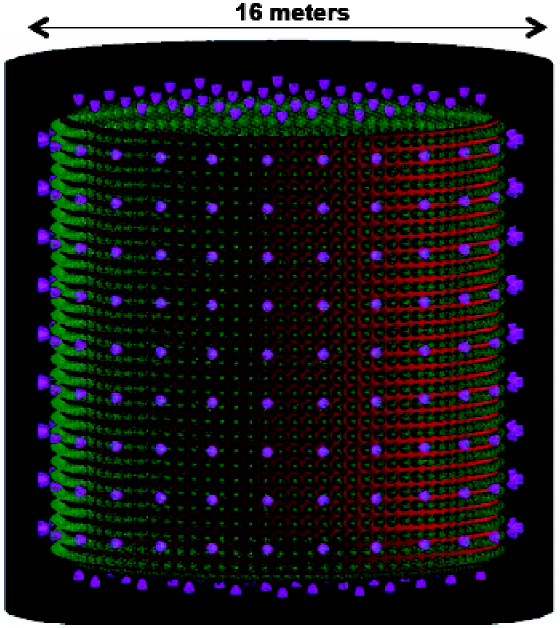
Water Cherenkov Neutrino Detectors for the 21st Century





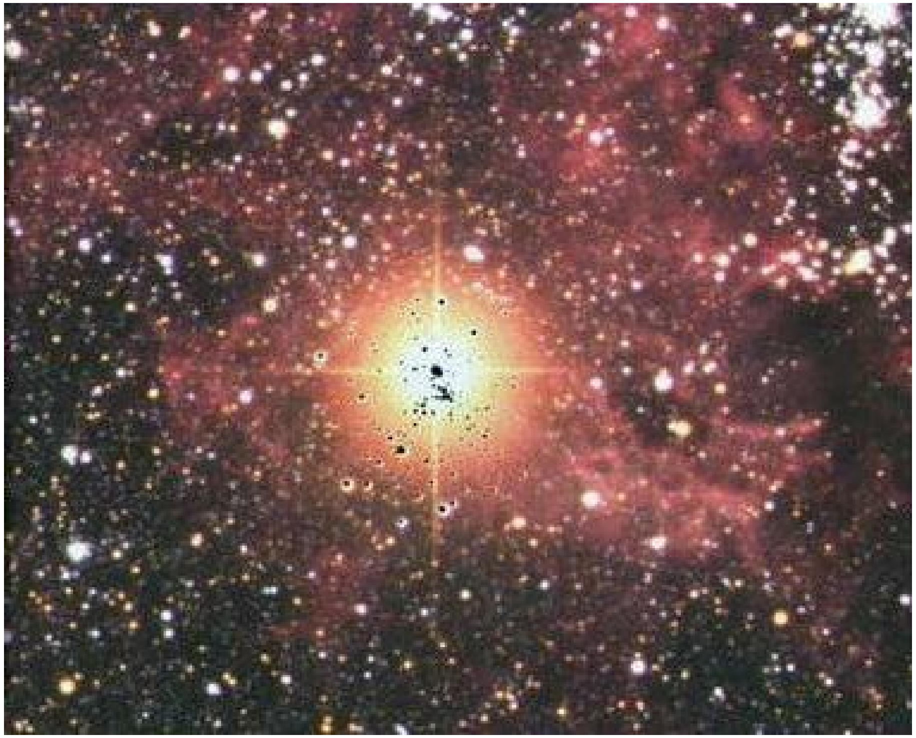
Matthew Malek
The University of Sheffield

University of Liverpool – HEP Seminar
07 November 2018

In the Beginning...

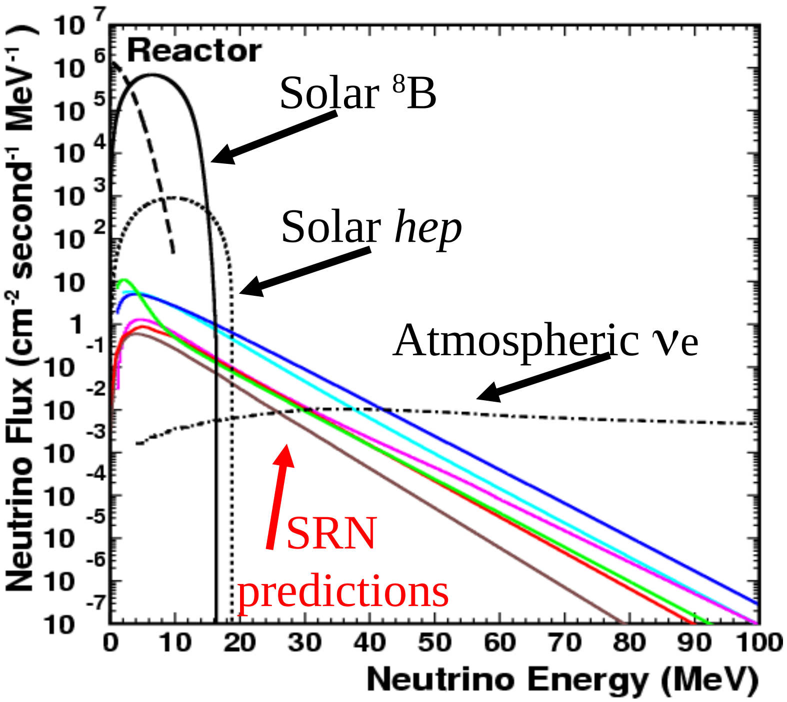
The University Of Sheffield.

Supernova Relic Neutrino (SRN) search at Super-Kamiokande:



Core-collapse supernova emits ~10^{46} J energy

99% is released as neutrinos (all 6 types); mainly from neutrino cooling (also ν_e from neutronisation burst).

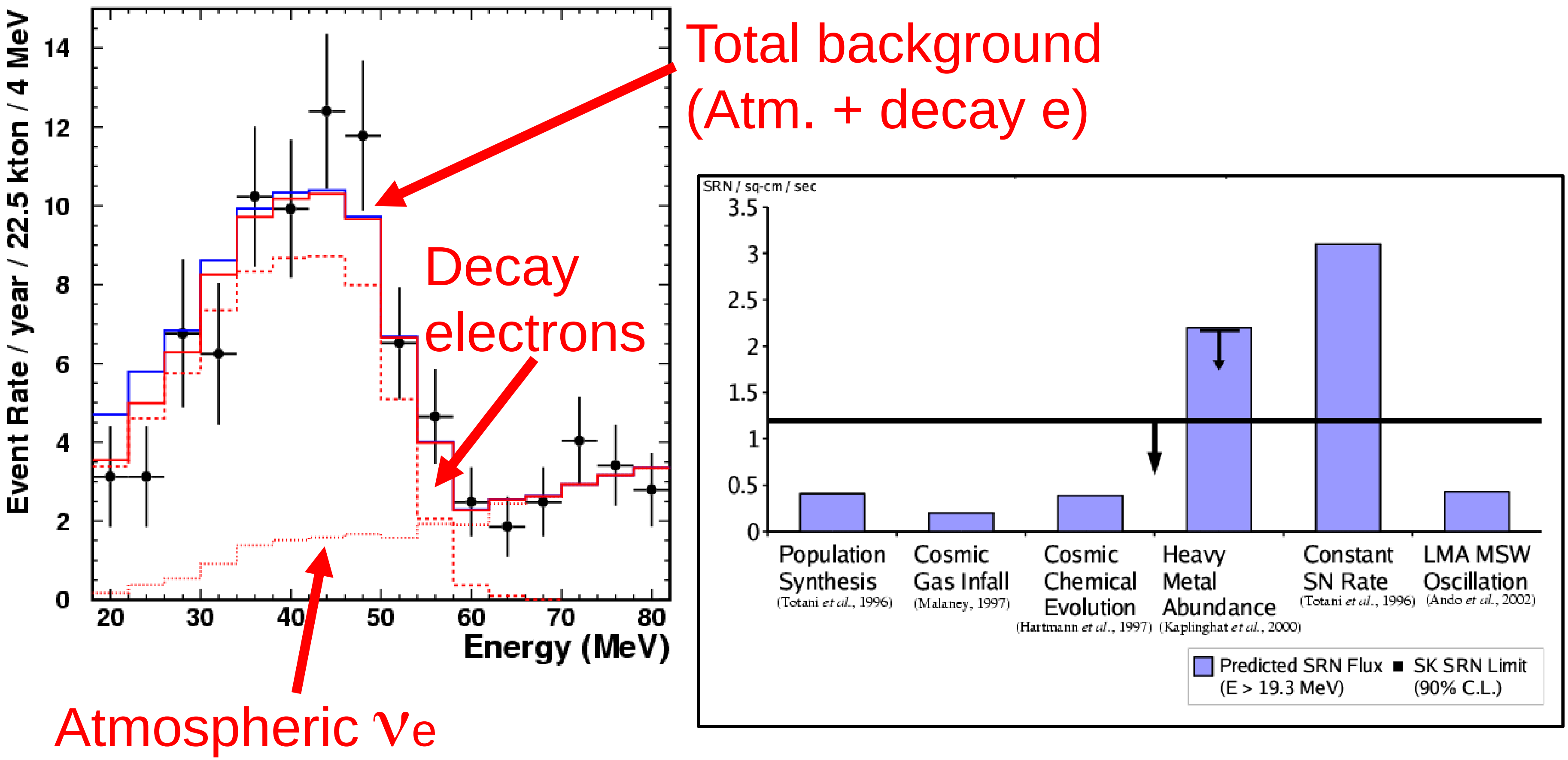


To date, only one observation (~25 neutrinos) on 24th February 1987 (SN1987A)

Diffuse background of SNν expected from <u>all</u> core-collapse supernovae that have ever exploded

SRN Search Results

The University Of Sheffield.

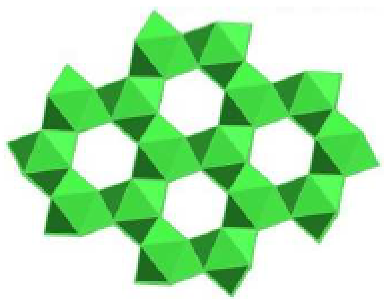


- SRN signal would manifest as distortion of BG
- No such signal seen yet → some models ruled out
- Background limitations form significant challenge!

M. Malek *et al.*, Phys.Rev.Lett. **90:061101** (2003)

Gadolinium & Water

Gadzooks!



[A Serious SK Upgrade Suggestion]

Mark Vagins
University of California, Irvine

Osawano
November 11, 2002

GADZOOKS! Antineutrino Spectroscopy with Large Water Čerenkov Detectors

John F. Beacom[1] and Mark R. Vagins[2]

[1]*NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500*
[2]*Department of Physics and Astronomy, 4129 Reines Hall, University of California, Irvine, CA 92697*
(Dated: 25 September 2003)

We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible for the first time in such detectors, allowing antineutrino tagging by the coincidence detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$). Taking Super-Kamiokande as a working example, dramatic consequences for reactor neutrino measurements, first observation of the diffuse supernova neutrino background, Galactic supernova detection, and other topics are discussed.

PACS numbers: 95.55.Vj, 95.85.Ry, 14.60.Pq FERMILAB-Pub-03/249-A

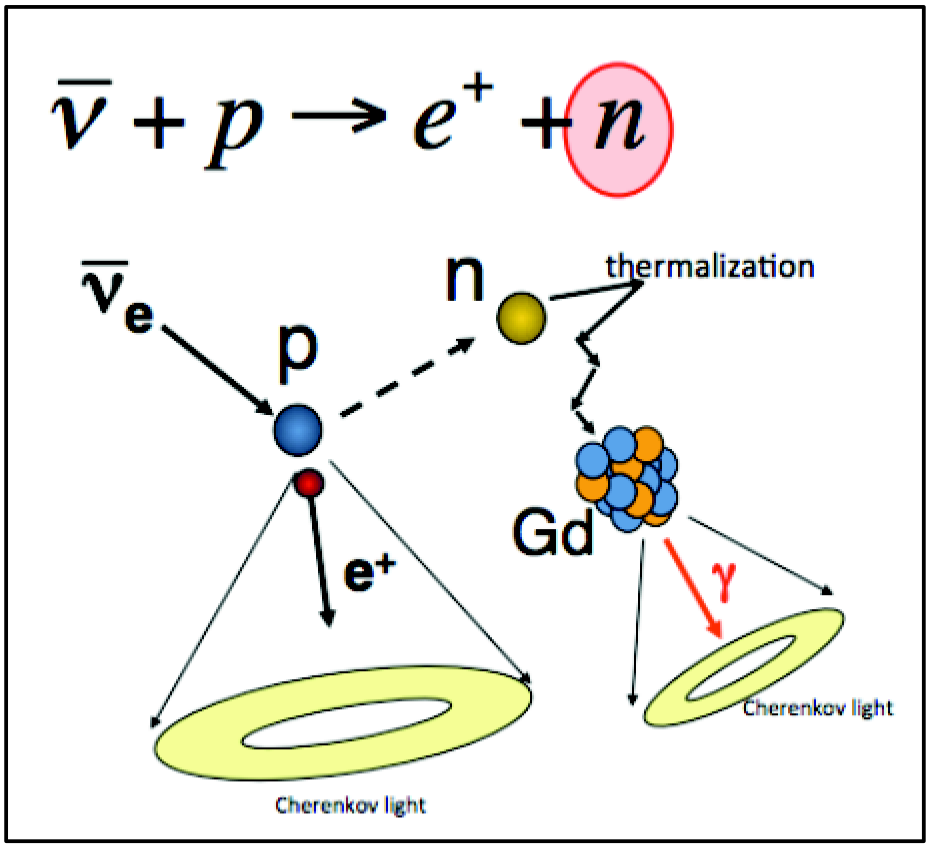
Beacom & Vagins, Phys.Rev.Lett. **93:171101** (2004)

Initial motivation for adding Gd to water Cherenkov detectors was background reduction for SRN experiments.

Idea has now spread to many other uses, for both physics and impact applications

Basic Idea

Tag antineutrinos via coincidence between positron and neutron from inverse beta decay:



- In ordinary water:

  Neutron thermalizes, then is captured on a free proton

  - Capture time is ~200 μsec
  - 2.2 MeV gamma emitted
  - Detection efficiency @ SK (40% coverage) is ~20%

- When n captured on Gd:
  - Capture time ~25 μsec
  - ~8 MeV gamma cascade
  - 4 - 5 MeV visible energy
  - > 70% detection efficiency

Gd Capture X-Sections

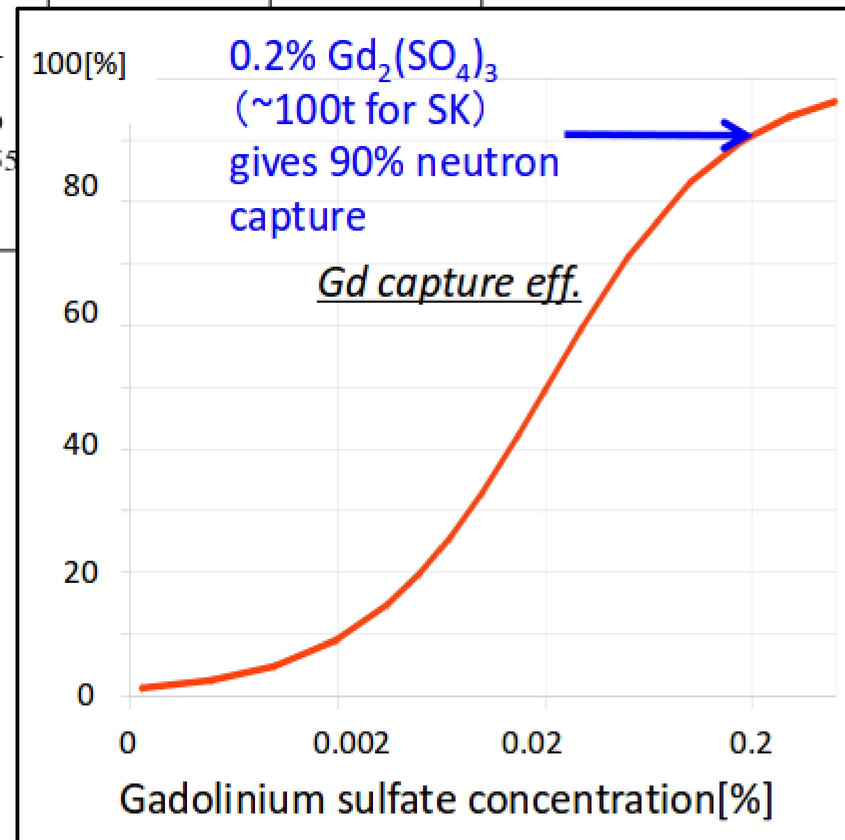
The University Of Sheffield.

Thermal Capture Cross Sections: A Comparison of ENDF/B-VI to RPI Results*

Thermal Capture Cross Sections							
		ENDF			RPI		
Isotope	Abundance	Thermal Capture	Contribution to Elemental	Percent	Thermal Capture	Contribution to Elemental	Percent
^{152}Gd	0.200	1 050	2.10	0.00430	1 050	2.10	0.00430
^{154}Gd	2.18	85.0	1.85	0.00379	85.8	1.87	0.00422
^{155}Gd	14.80	60 700	8 980	18.4	60 200		
^{156}Gd	20.47	1.71	0.350	0.000717	1.74		
^{157}Gd	15.65	254 000	39 800	81.6	226 000		
^{158}Gd	24.84	2.01	0.499	0.00102	2.19		
^{160}Gd	21.86	0.765	0.167	0.000342	0.755		
Gd	—		48 800	100.0			

*The units of all cross sections are barns. The units of abundance are percent.

G. Leinweber *et al*., Nucl.Sci.Eng. **154:261** (2006)



Cross-section for neutron capture is:

- ~49,000 barns for natural Gd
- 0.3 barns for H

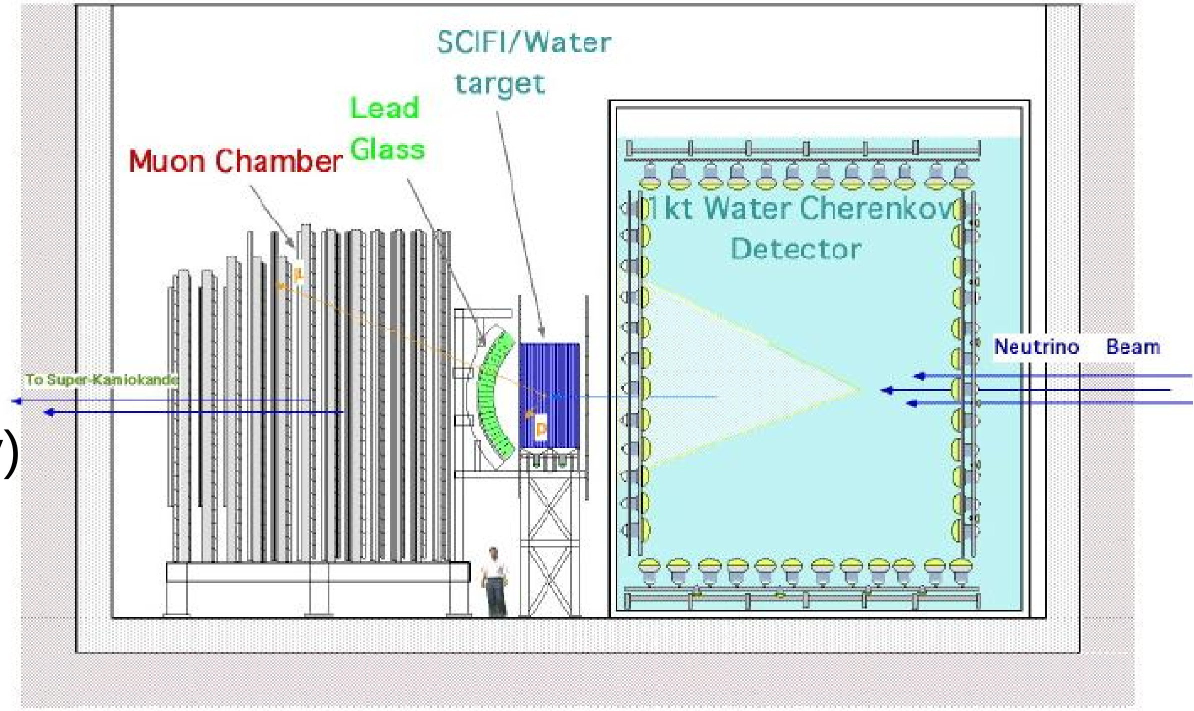
0.1% Gd concentration results in ~90% of neutrons capturing on Gd

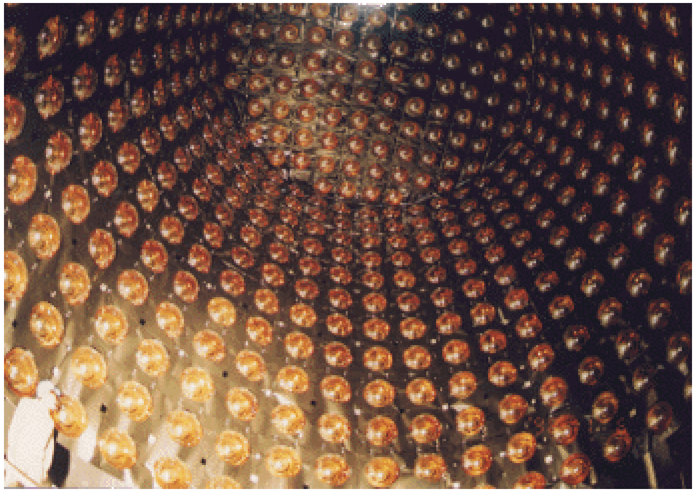
First Attempt: KEK

About 10 years ago, $GdCl_3$ tested in 1kt tank from KEK experiment.

Results **not** good
→ Severe rusting!

Lesson learned:
Only use **stainless** steel (high quality)





Second Attempt: EGADS

The University Of Sheffield.

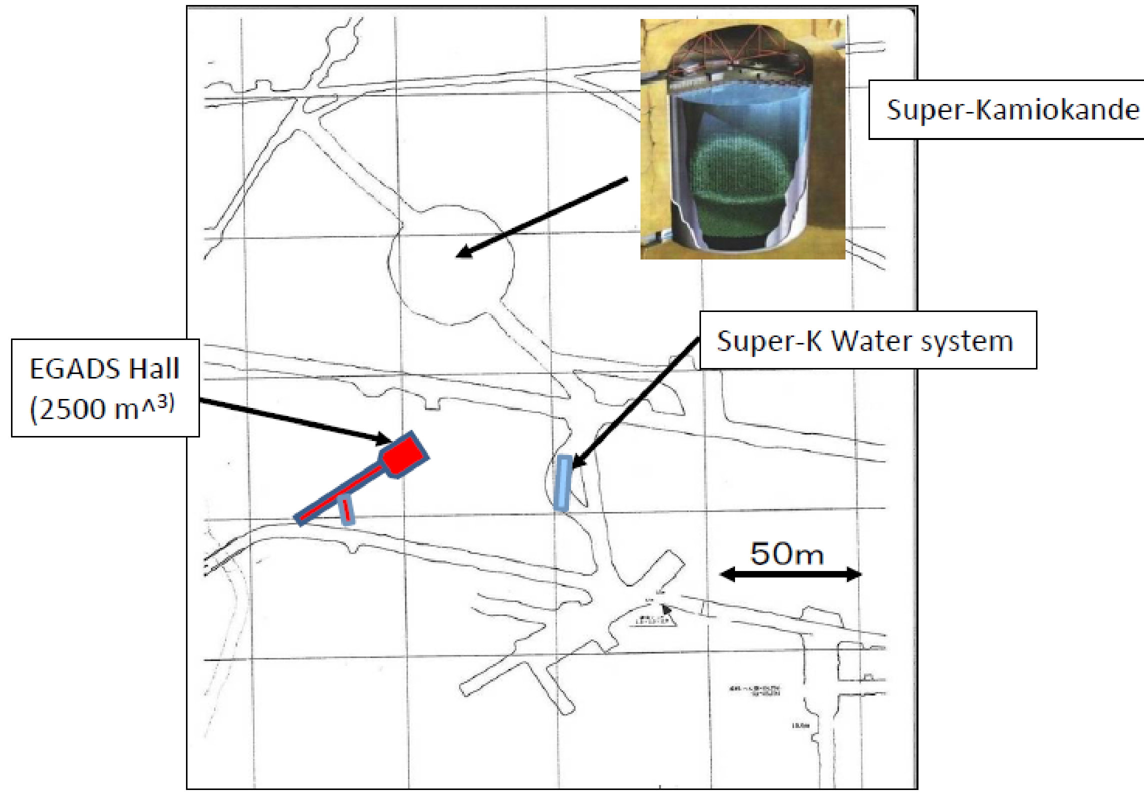
EGADS = Evaluating Gadolinium's Action on Detector Systems

After KEK debacle, shift from $GdCl_3$ to $Gd_2[SO_4]_3$ (Gadolinium Sulphate) to reduce environmental risks

Dedicated test facility commissioned at Kamioka Observatory

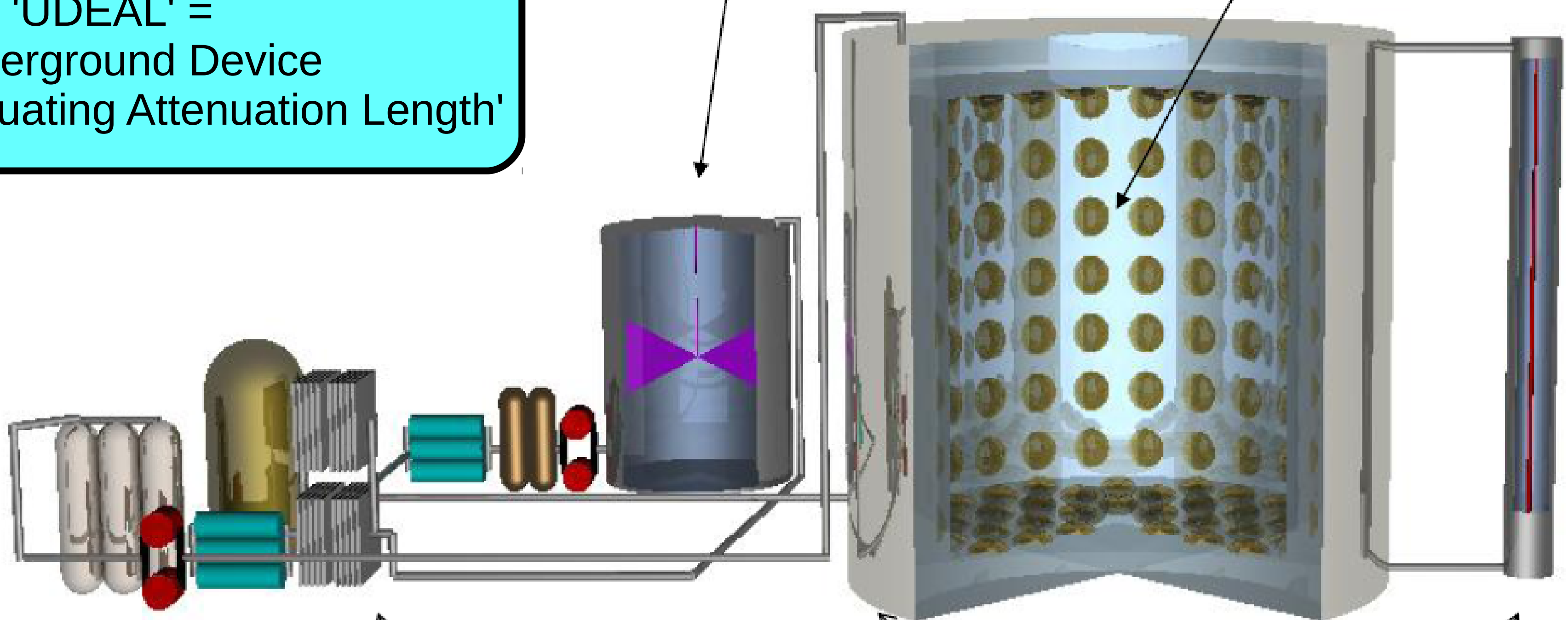
EGADS is a:

- 200 tonne R&D project, charged with establishing the technical viability of loading Gd into water Cherenkov detectors
- Dedicated test facility, with its own water filtration system, 50cm PMTs, DAQ, etc.



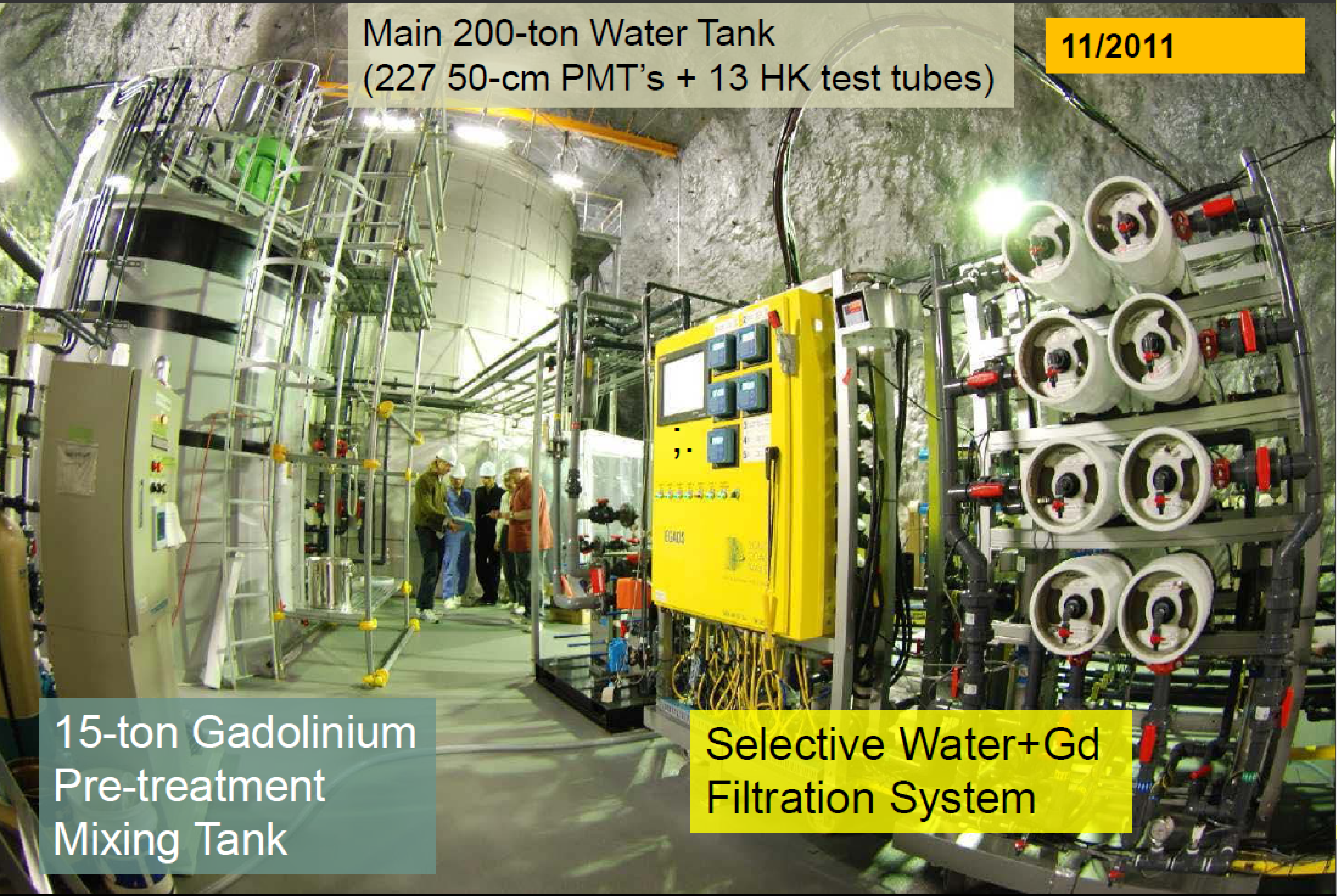
EGADS Facility

N.B. 'UDEAL' =
'Underground Device Evaluating Attenuation Length'



EGADS Facility

The University Of Sheffield.



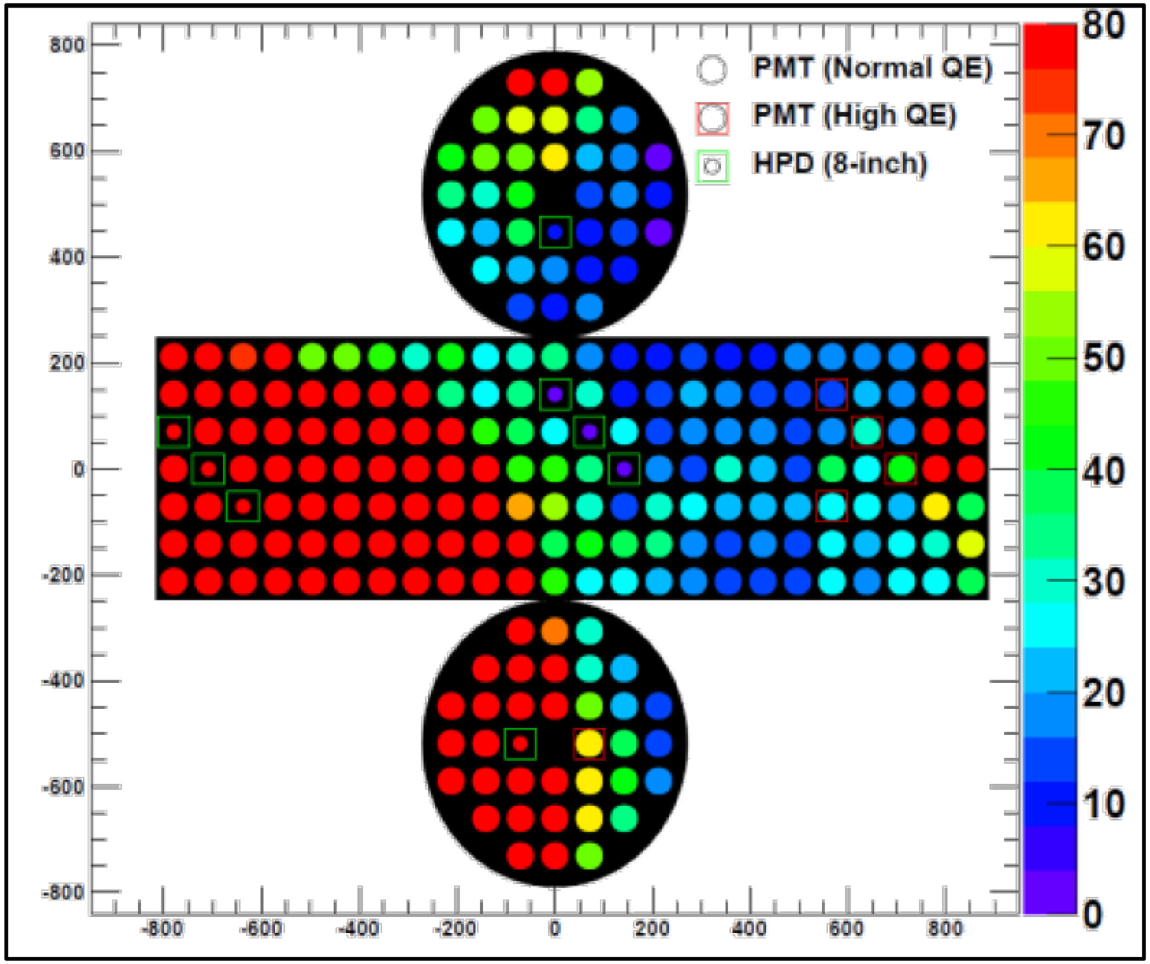
EGADS Facility

The University Of Sheffield.

EGADS Data Taking

The University Of Sheffield.

Muon event in EGADS tank (June 2015)



Since April 2015, EGADS has been fully loaded with the target goal of 0.2% $Gd_2[SO_4]_3$ (390.6 kg)

No problems encountered in this time period

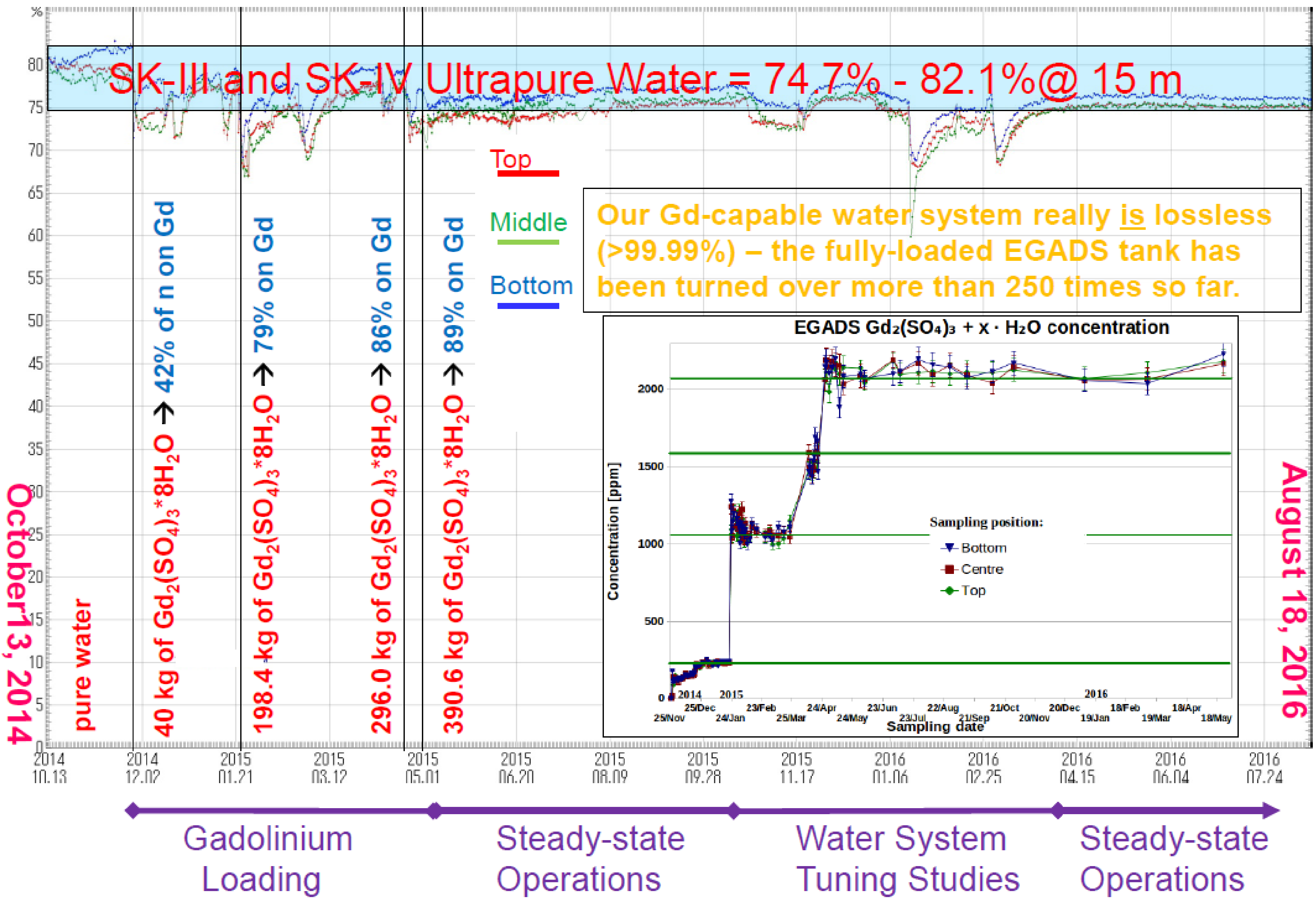
Also, no loss of Gd during continuous filtration process (> 250 complete turnovers to date)

High quality water purity is demonstrated (see next slide), allowing use in larger experiments

The EGADS project has demonstrated the technical feasibility of gadolinium-loading for water Cherenkov detectors

EGADS Water Attenuation

The University Of Sheffield.



Upcoming Experiments:

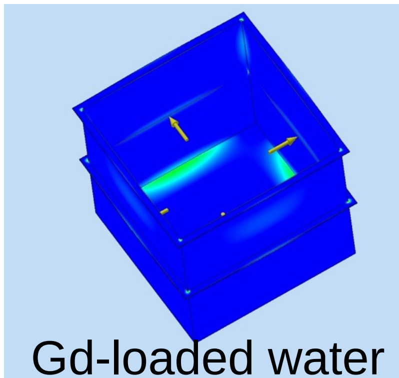
Now that the **concept** of Gd-loaded water Cherenkov experiments has been demonstrated and shown to be technically feasible, there are a host of upcoming experiments that plan to exploit it.

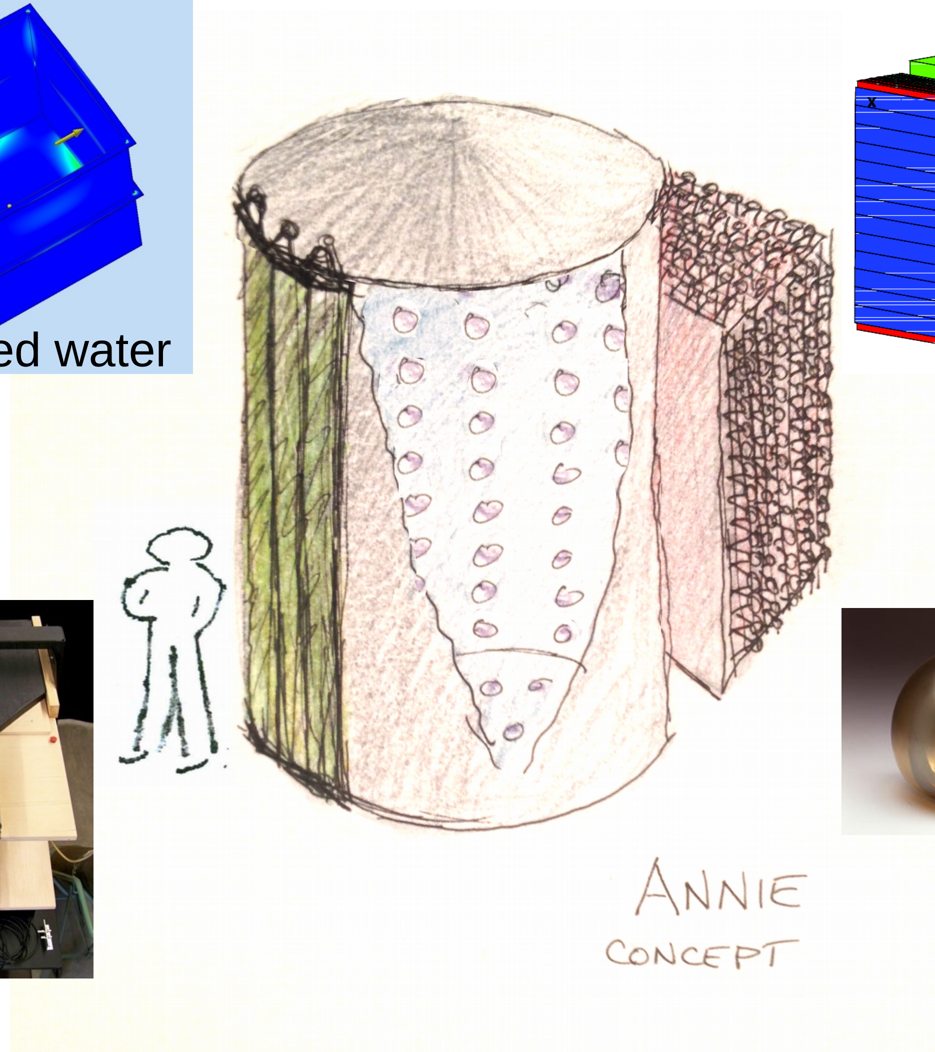
These include.....

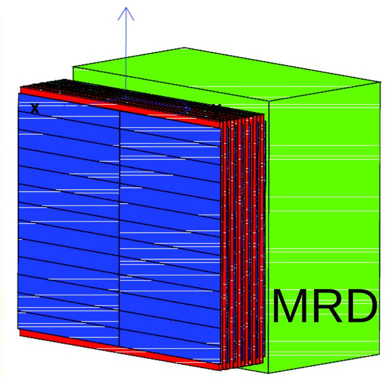
[*] "The Tempest", by William Shakespeare (Act II, Scene 1)

The ANNIE Experiment

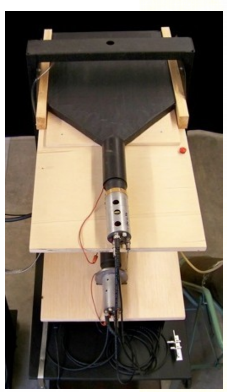
ANNIE: **A**ccelerator **N**eutrino-**N**ucleus **I**nteraction **E**xperiment







Upstream
μ veto

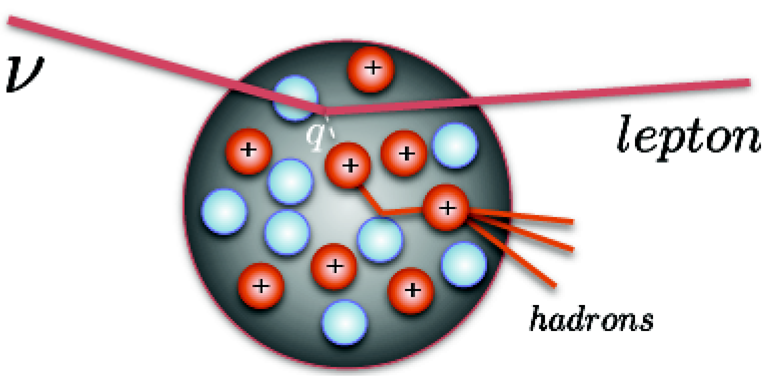


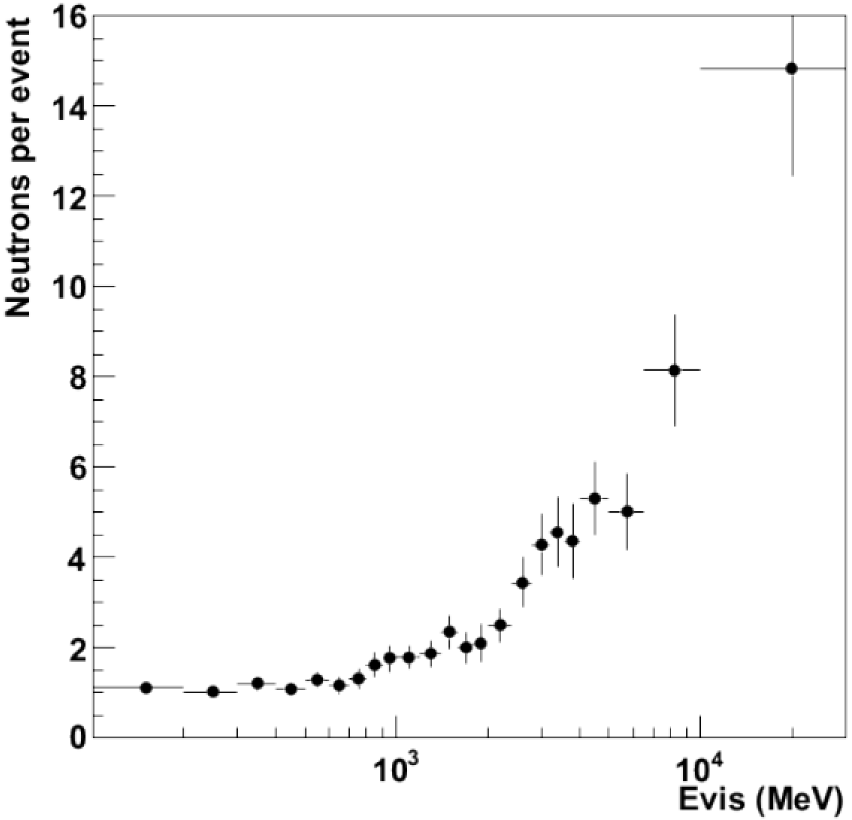
Primary physics objectives:

1) A measurement of the abundance of final state neutrons ("neutron yield") from neutrino interactions in water, as a function of energy.

Performed in Super-K using atmospheric neutrinos and capture on H

- ~20% tagging efficiency
- Combined statistics for ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$
- Significant room for improvement!



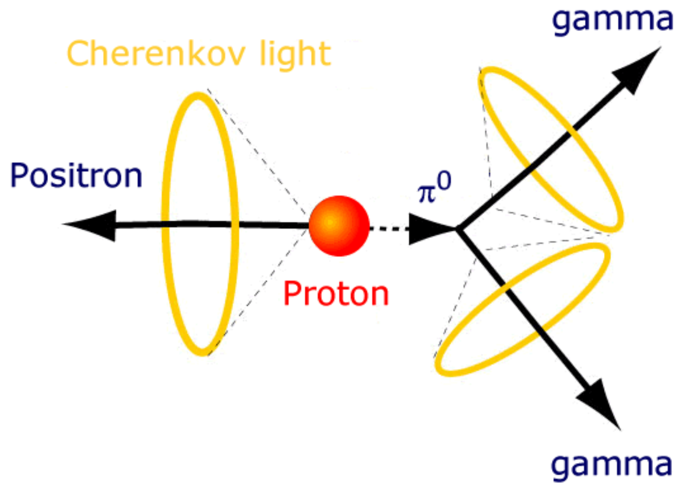


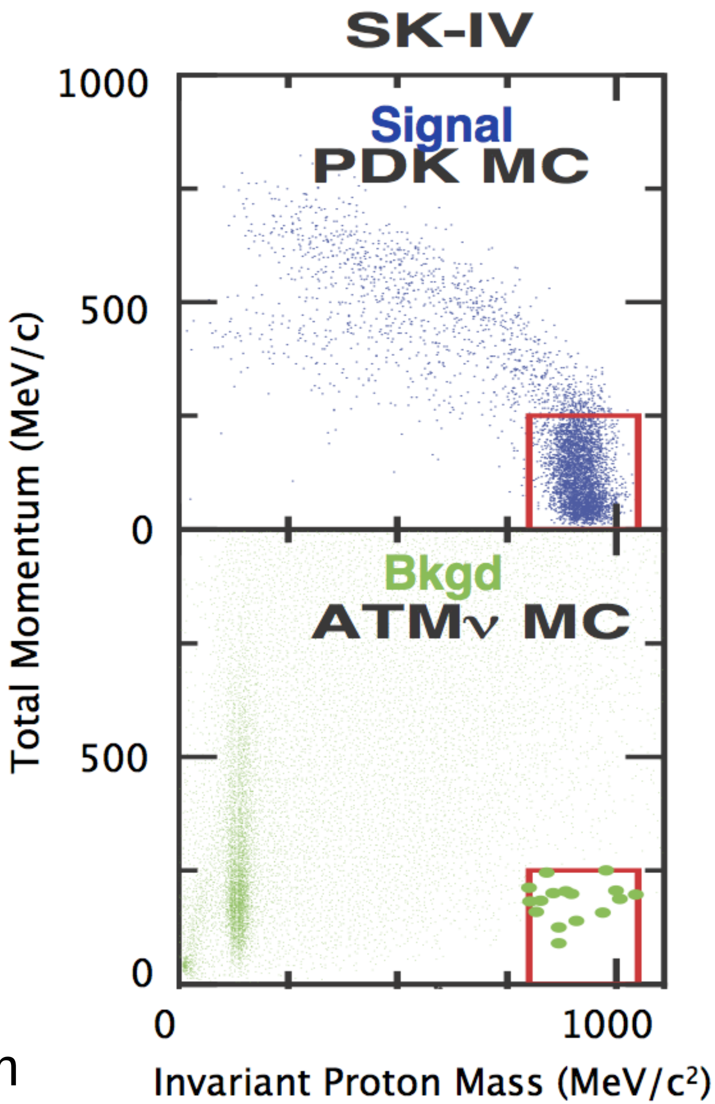
Proton Decay

In a water Cherenkov detector, a typical signal looks like:

- Three rings (all electron-like)
- Total energy close to M_p
- Unbalanced momentum close to 0.

$$p \longrightarrow e^{+} + \pi^{0}$$





Modern GUTs predict lifetimes of 10^{35-36} years.

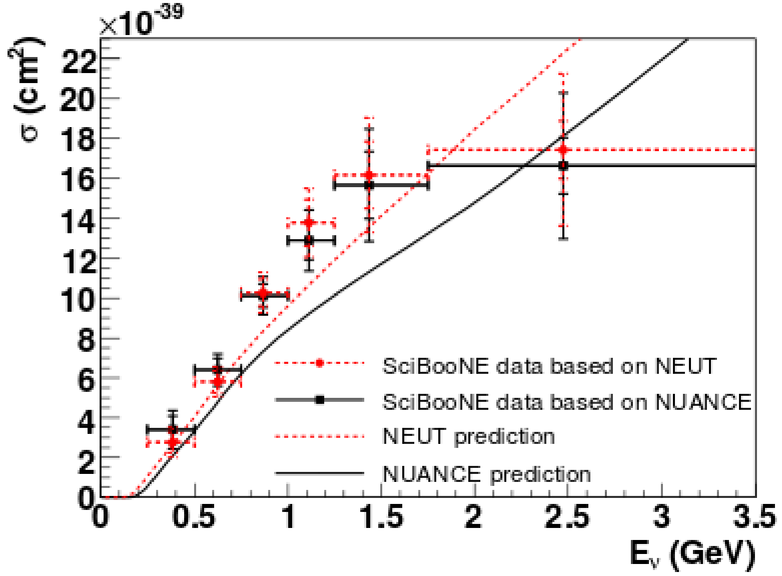
→ Larger detectors needed to probe this region

At this scale, previously negligible backgrounds from atmospheric neutrinos start to limit sensitivity.

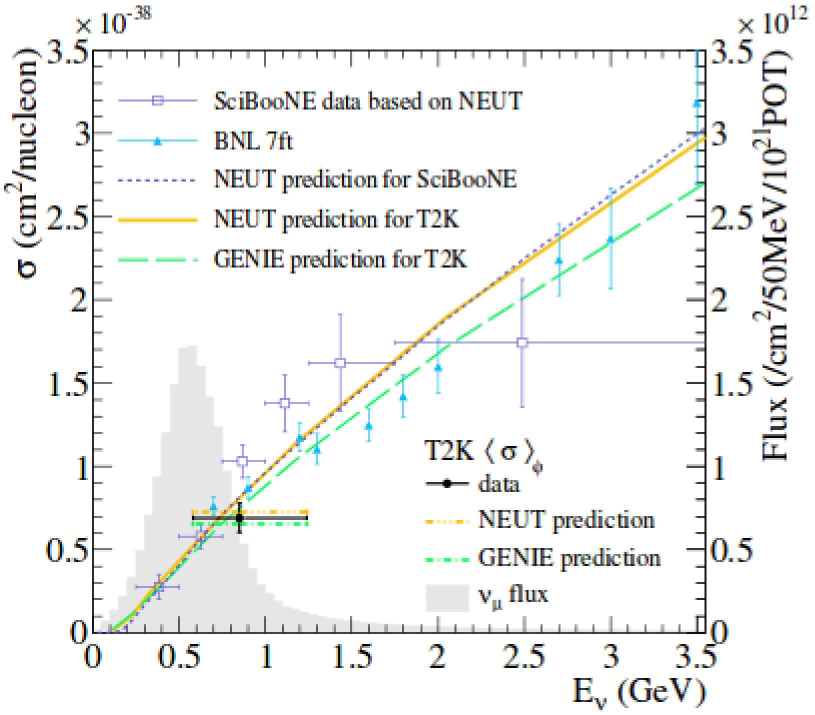
Primary physics objectives:

2) Neutrino cross-section measurements

νμ charged current inclusive cross sections on carbon:



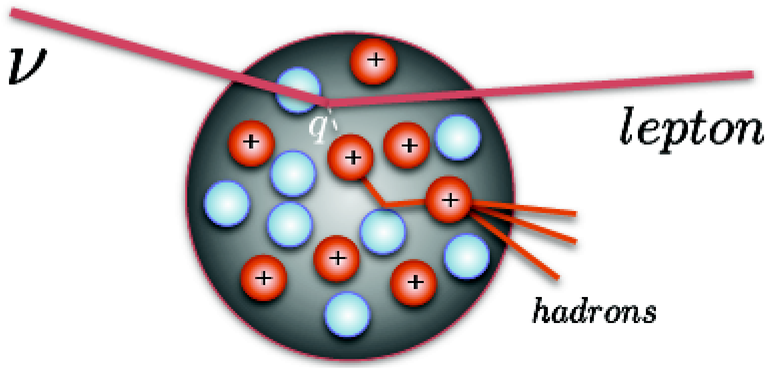
SciBooNE (arXiv: 1011.2131v3)



T2K ND (arXiv: 1302.4908v2)

No similar statistics sample exists on a water (oxygen) target...

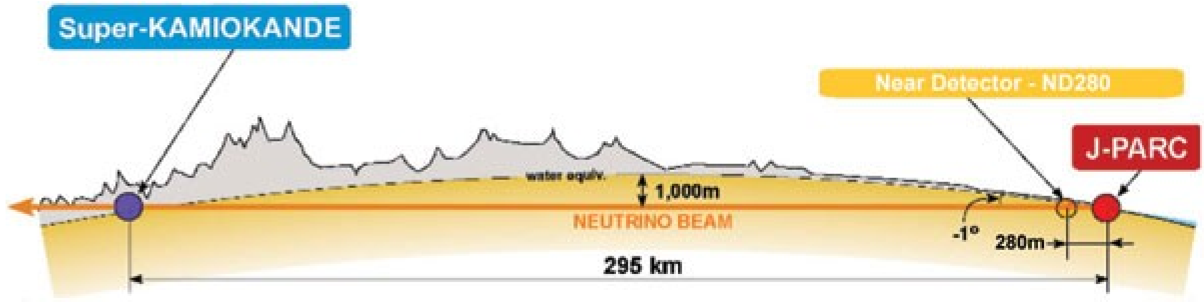
Neutrino Interactions



Studies of neutrino-nucleon interactions are also interesting in their own right! (see NuInt conference series)

ANNIE measurements can help constrain and distinguish between various interaction models.

Precision neutrino oscillation measurements:



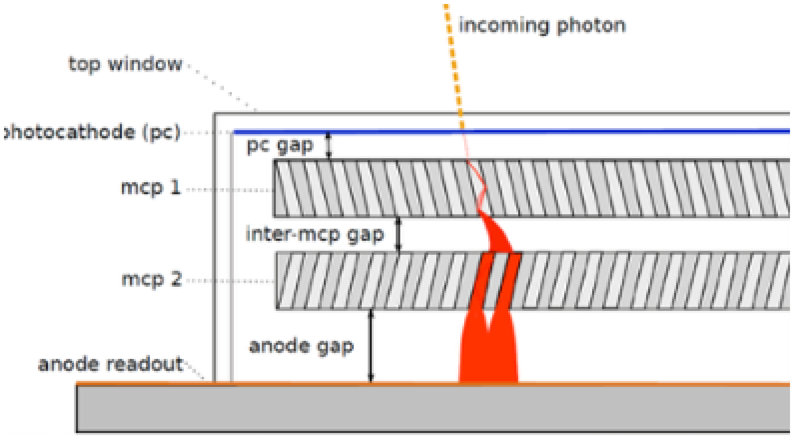
Neutrino cross-sections are a dominant systematic in long-baseline oscillation experiments, like T2K (or T2Hyper-K).

Reduction of this uncertainty will be necessary to conduct searches for δ_{CP}, resolve the mass hierarchy, octant degeneracy, etc.

Technical Goals

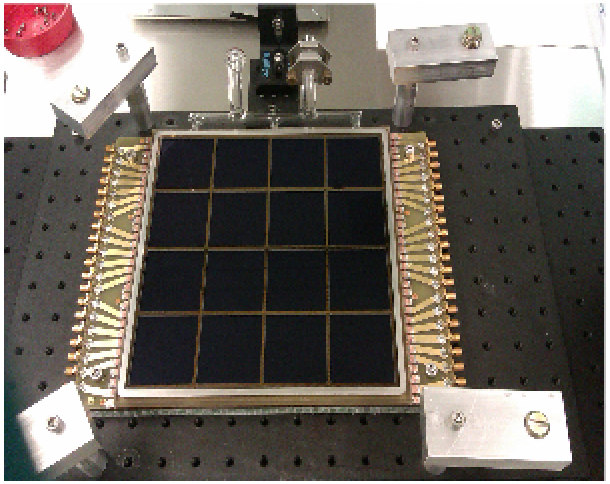
The University Of Sheffield.

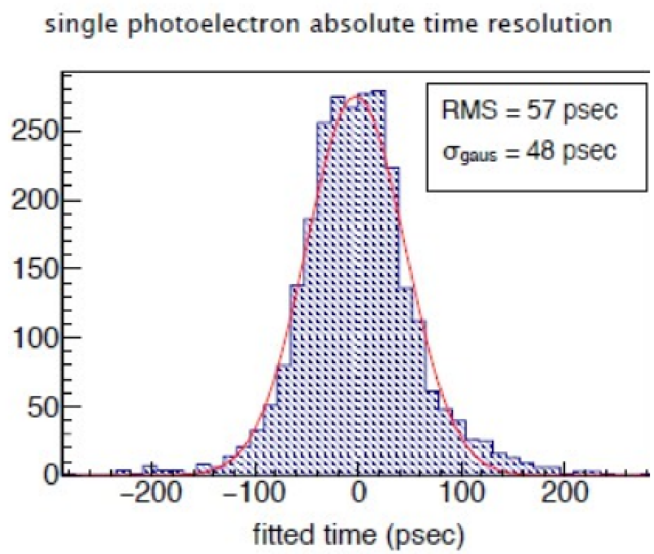
ANNIE is also a test for new technologies:

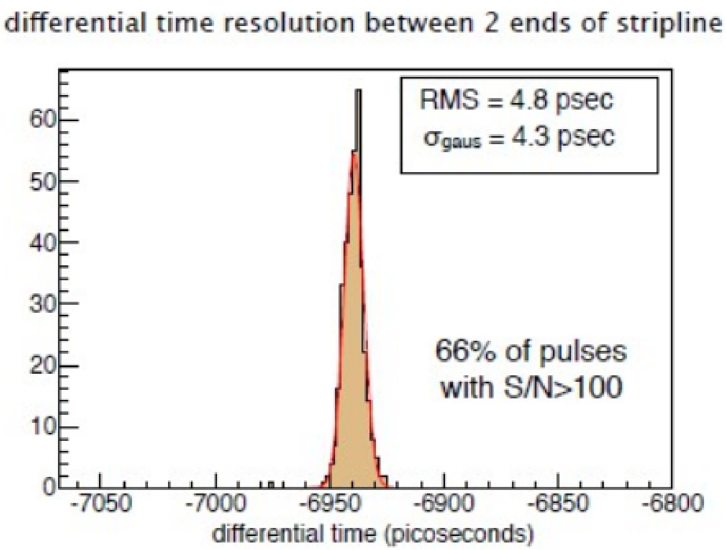


Large Area Picosecond Photo-Detectors (LAPPDs):

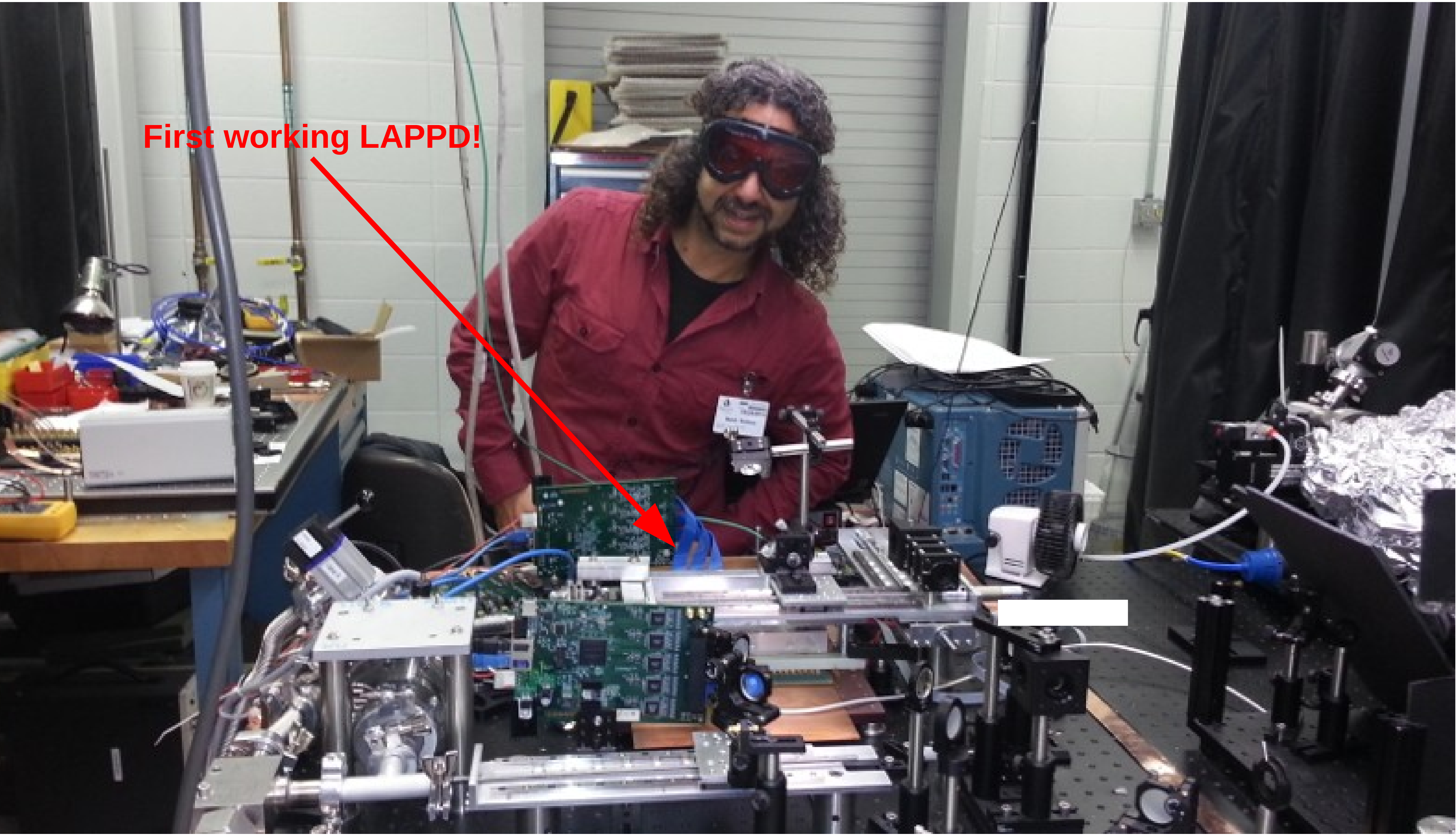
- Photocathode, microchannel plate (MCP), anode
- Fine spatial resolution (sub cm)
- ~50 psec timing resolution
- Gain of ~10^7





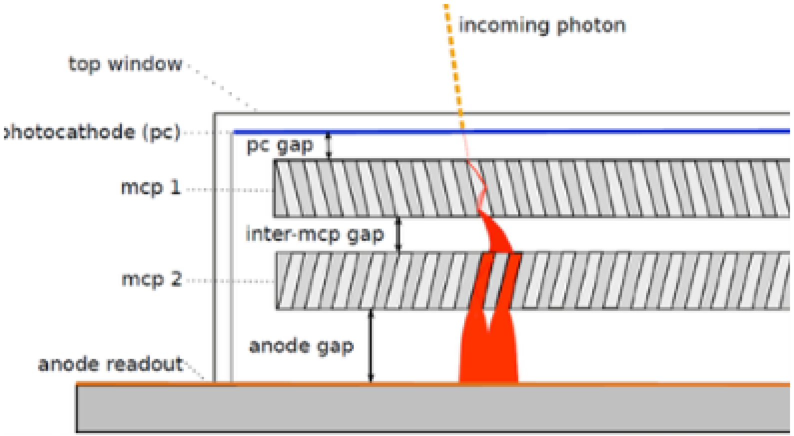


LAPPD Development

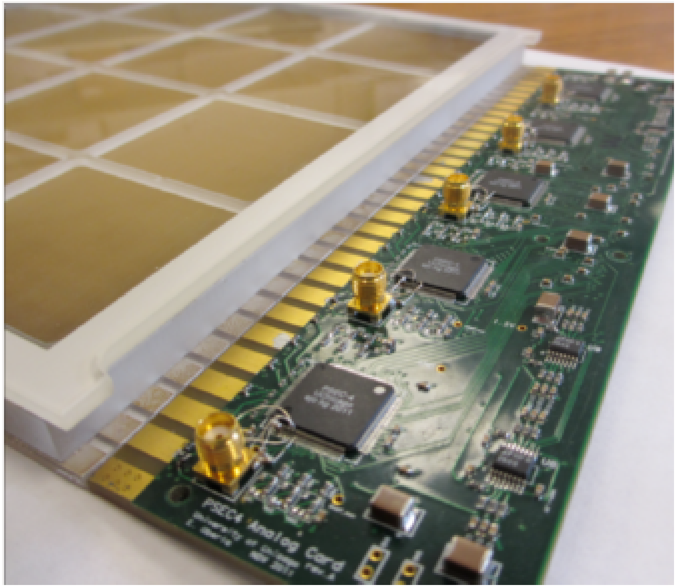


LAPPD Deployment

ANNIE is also a test for new technologies:



Large Area Picosecond Photo-Detectors (LAPPDs):
- Photocathode, microchannel plate (MCP), anode
- Fine spatial resolution (sub cm)
- ~50 psec timing resolution
- Gain of ~10^7



Starting in 2019, ANNIE will be the first particle physics experiment to use LAPPDs!

After years of development (2007 – 2015), the technology has been commercialised with Incom;
- First complete units produced last year,
- First LAPPDs sold this year,
- First LAPPD coming to UK next year!

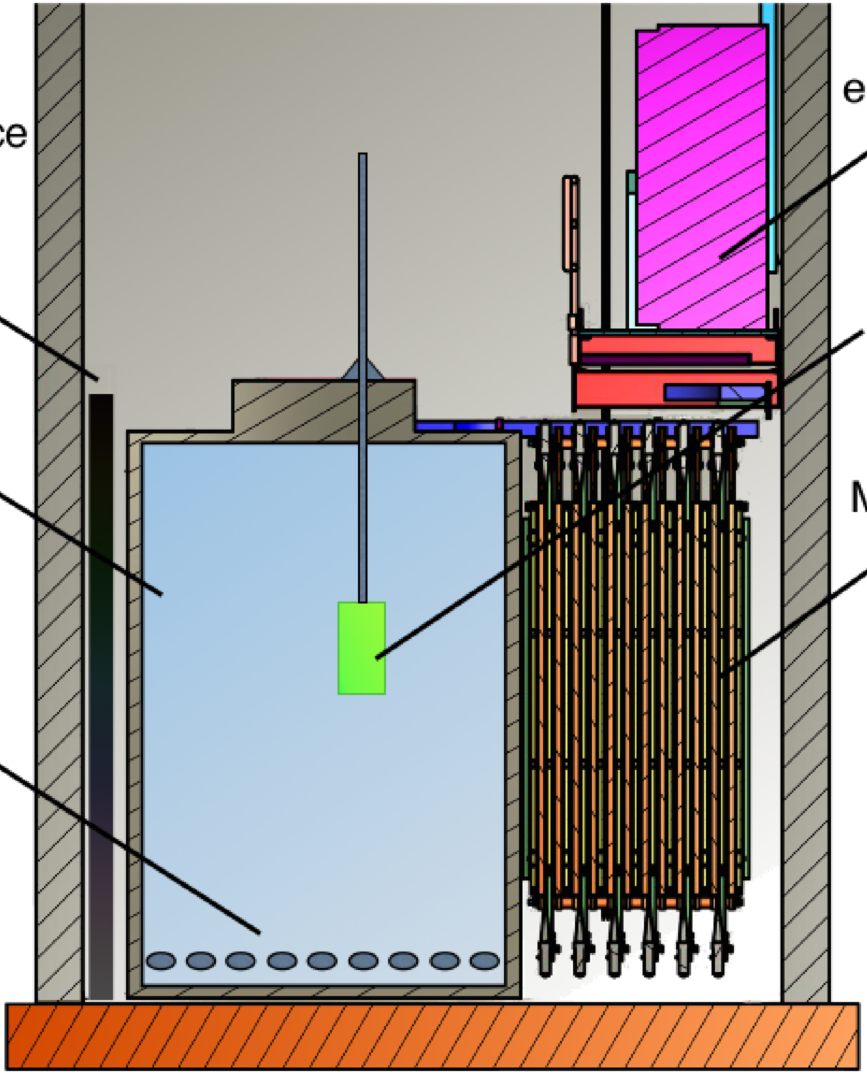
ANNIE Phase I

The University Of Sheffield.

Successful run in Fermilab's SciBooNE Hall: Apr '16 – Jul '17

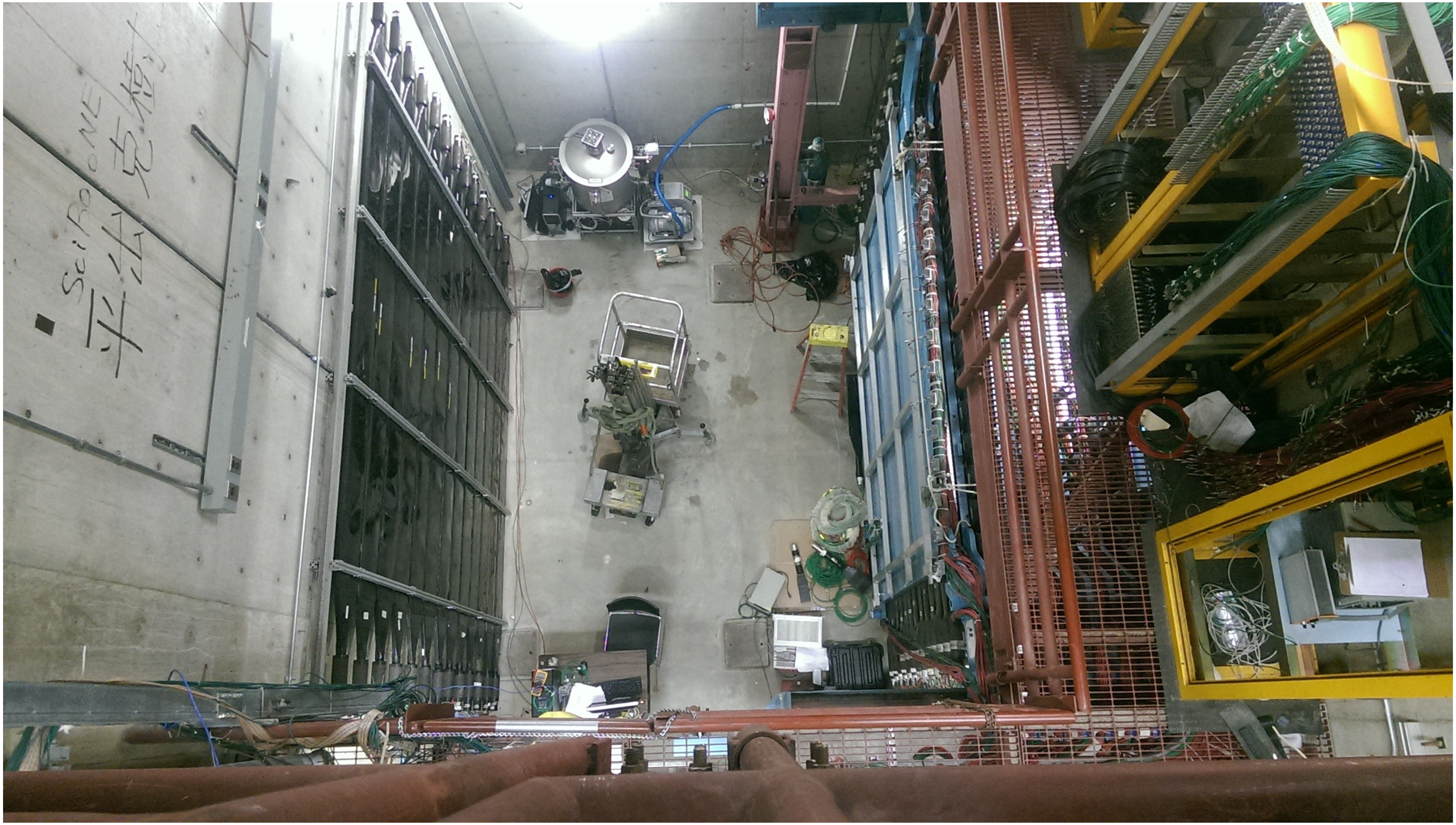
First phase has:
- 26 tonnes of pure water
- 60 PMTs
- Upsteam muon veto
- Two layers of MRD
- Neutron capture volume (Gd-loaded scintillator)

It did **not** have:
- Gd-loaded water
- LAPPDs
- Full (11 layer) MRD



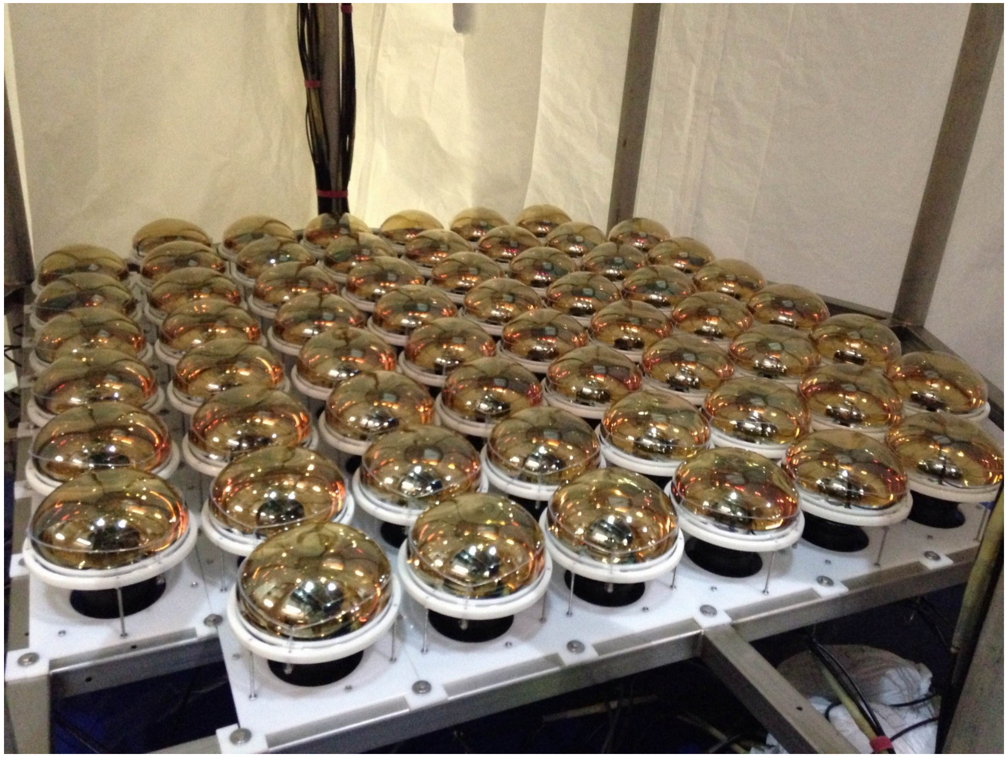
Phase I Installation (1)

The University Of Sheffield.



Phase I Installation (2)

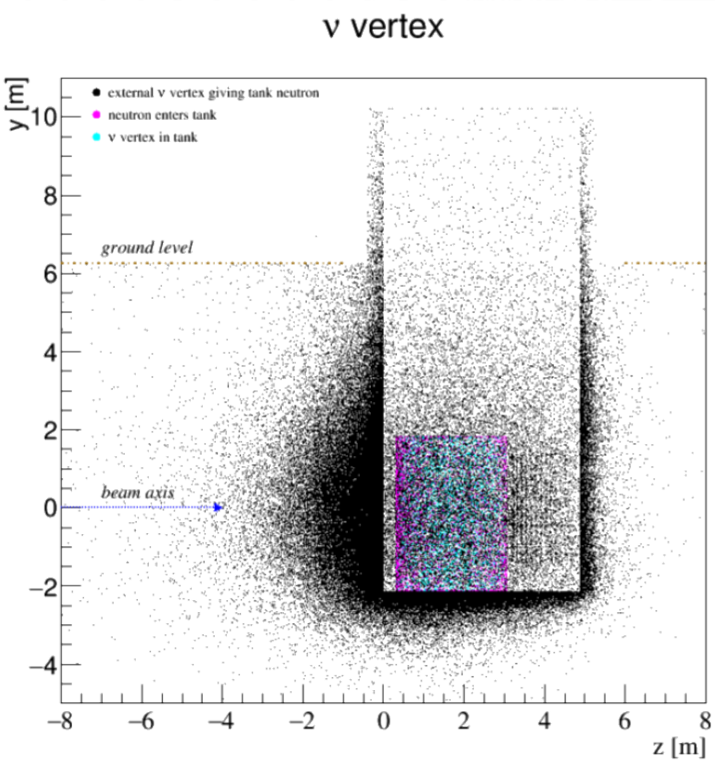
The University Of Sheffield.

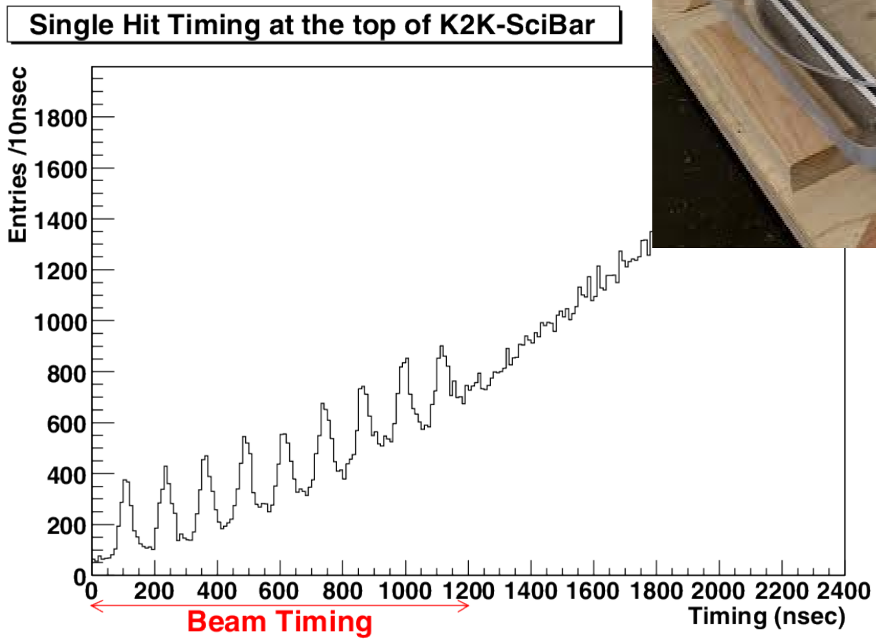


Phase I Goals

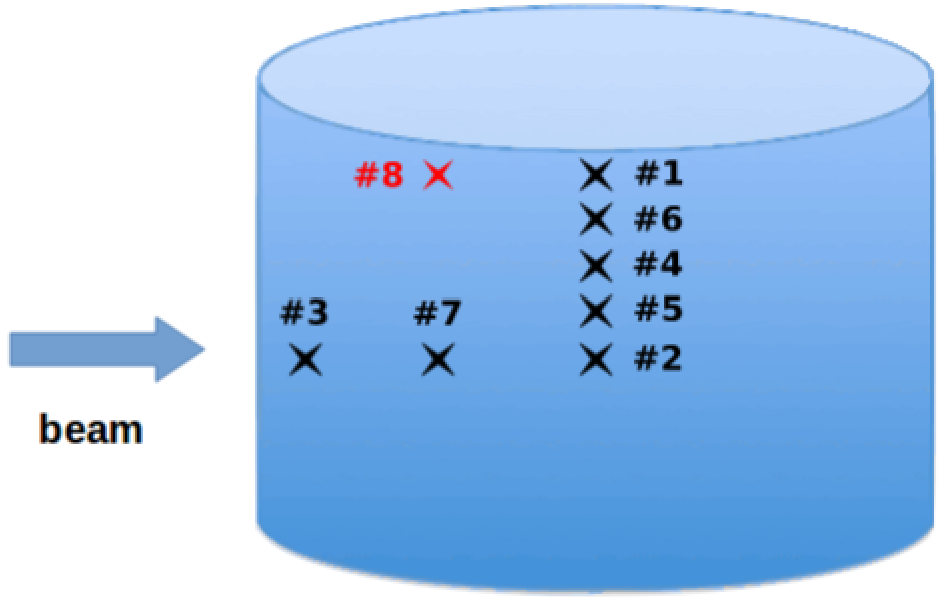
Mobile neutron capture volume (NCV) filled with 0.25% Gd-loaded scintillator.

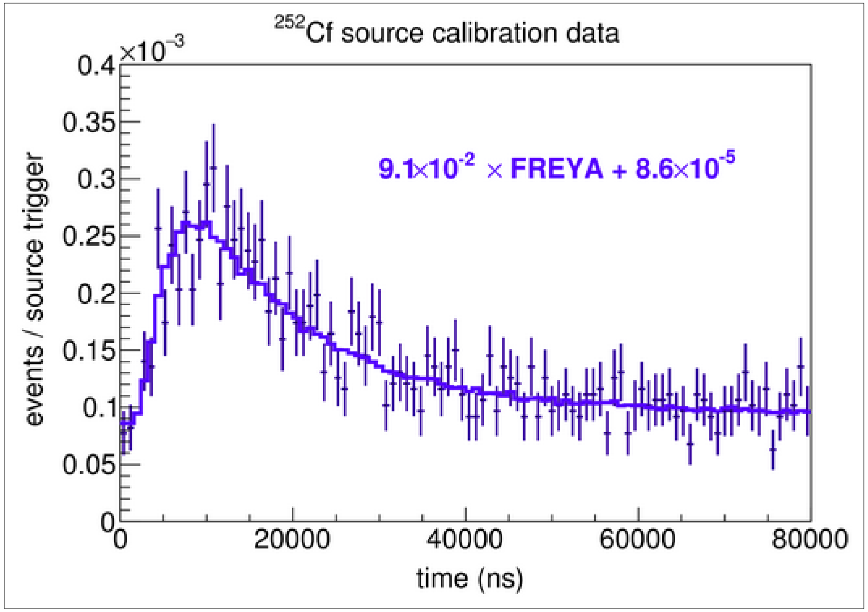
- Goal is to measure neutron BG in SciBooNE Hall from rock, skyshine, etc.
- Measure rate, positional, timing distrib.

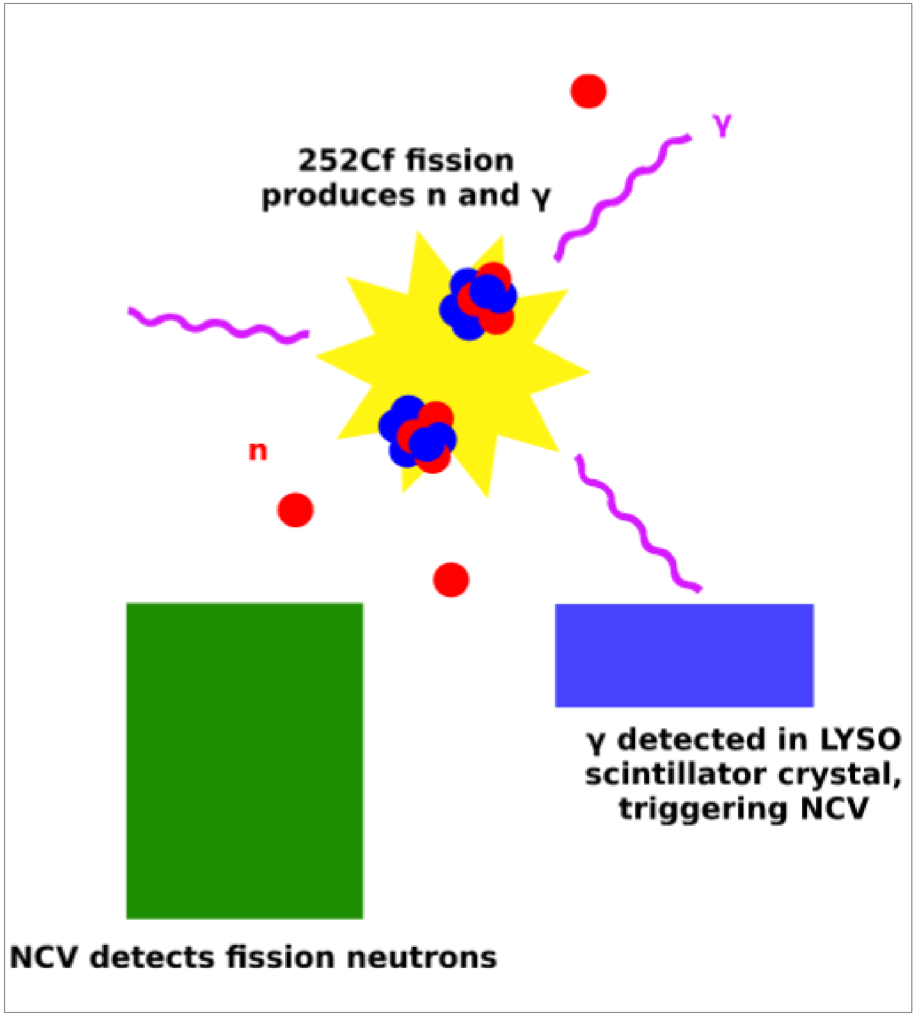




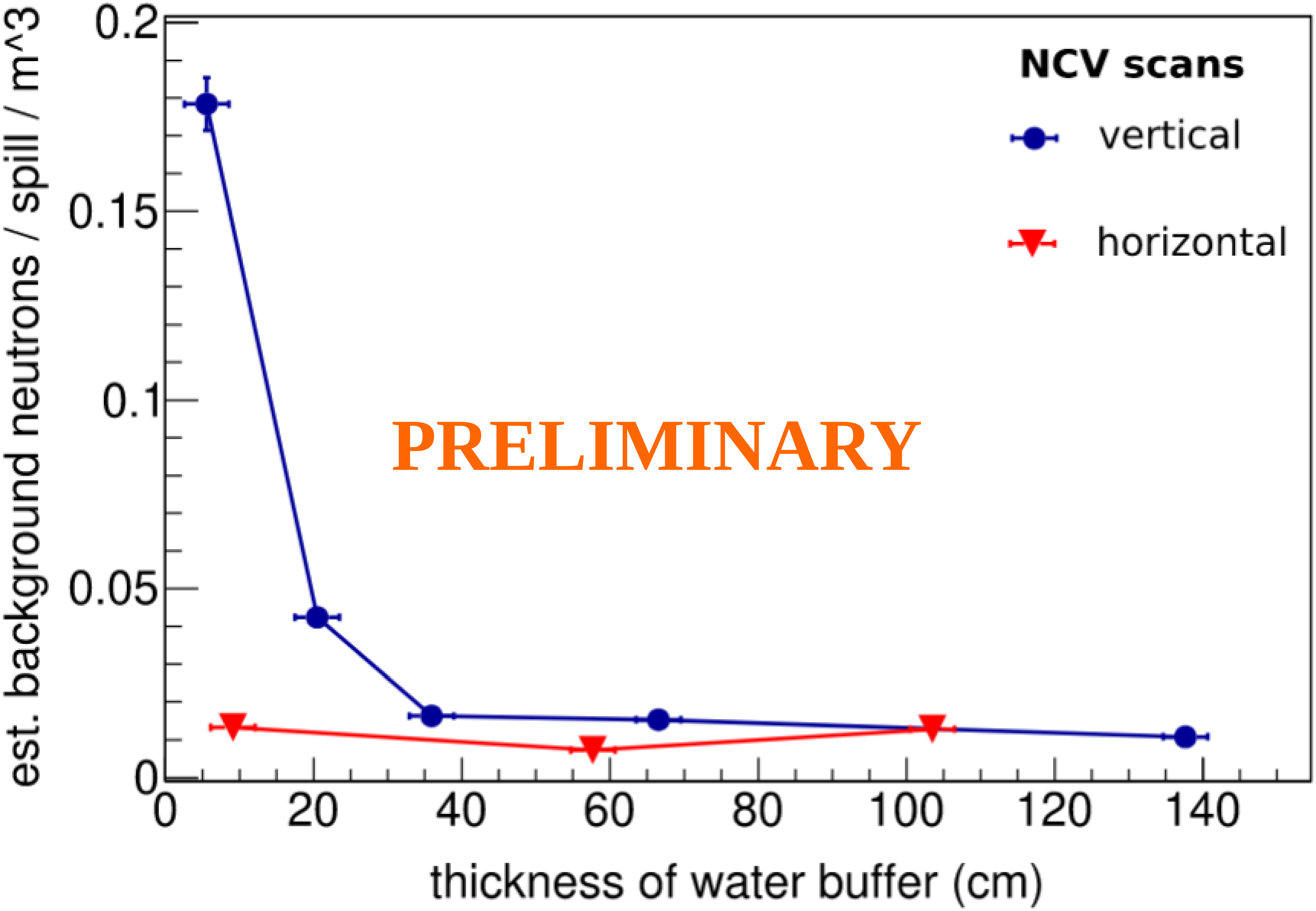
Phase I Data Taking







Phase I Results



ANNIE Phase II

Current status:
Under construction now!
(funded by US DOE)

MRD fully refurbished (all 11 layers)

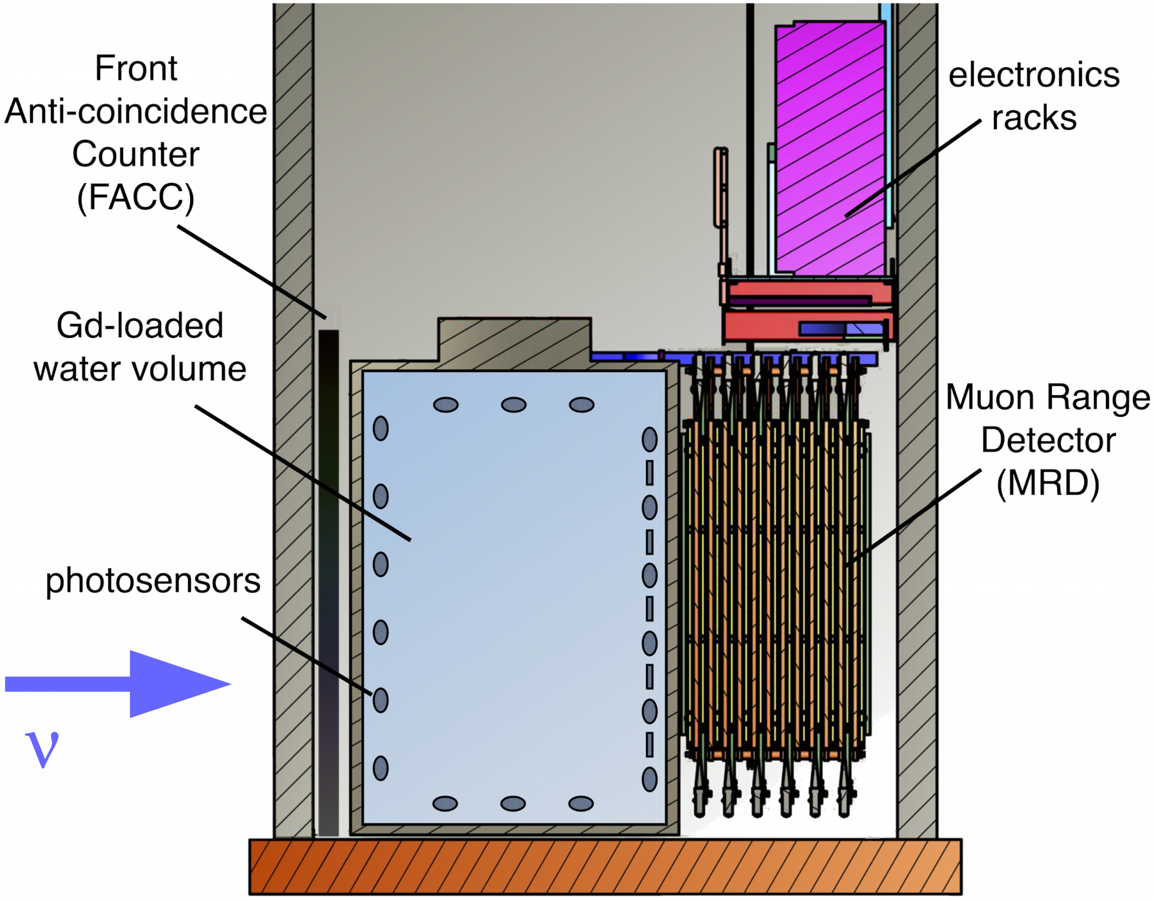
FACC working

40 new PMTs on order (130 total)

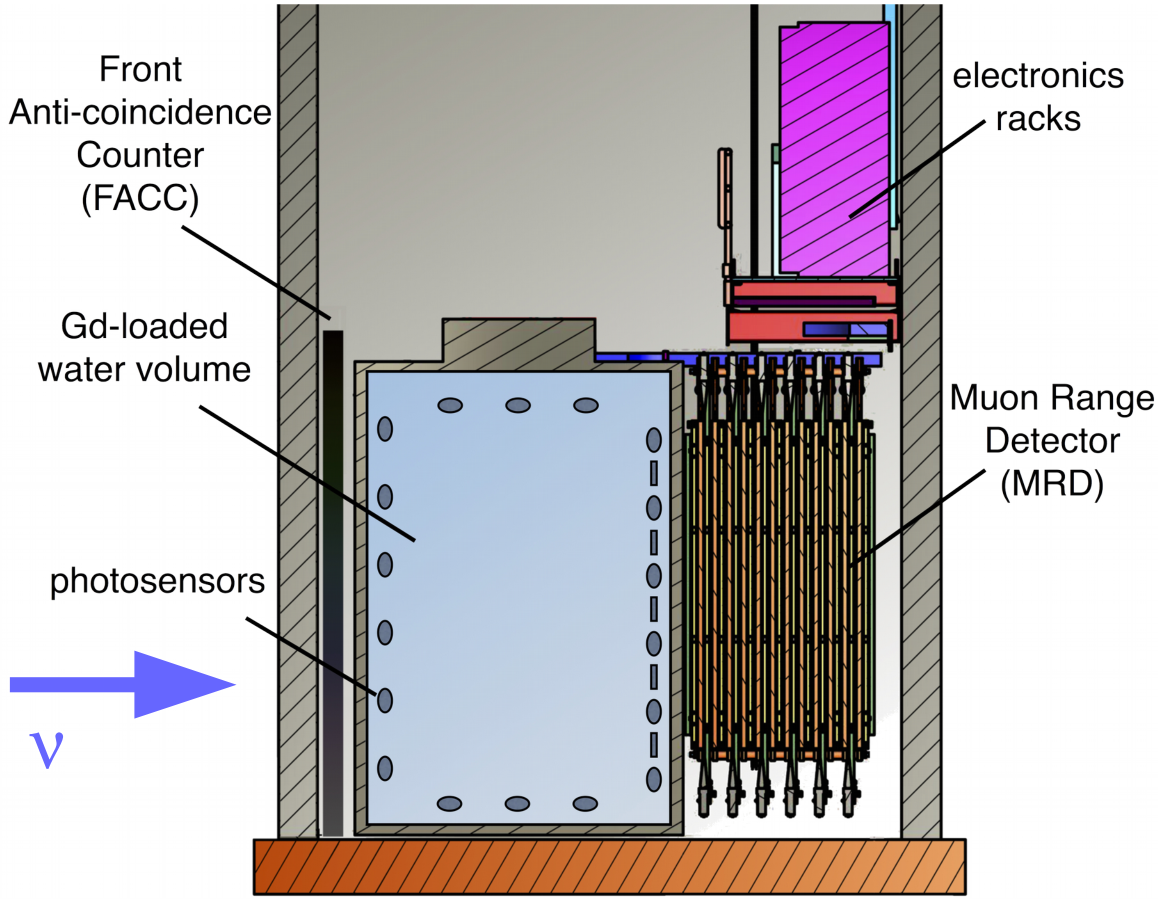
2 LAPPDs in-hand; three more in the pipeline

Reminder: Phase II (Physics run) will use Gd-loaded water

Scheduled to begin taking data in March 2019

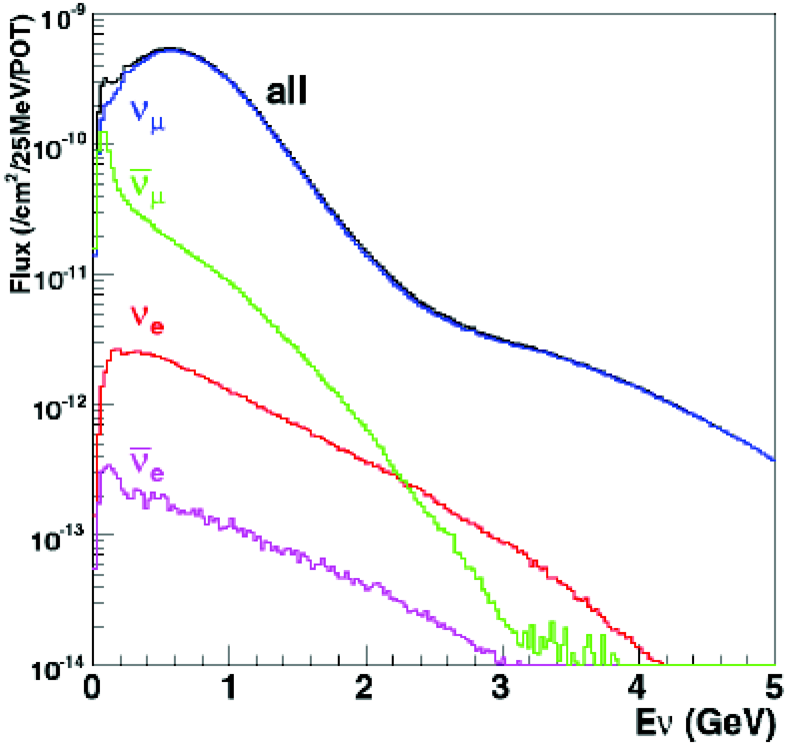


Neutrino Flux

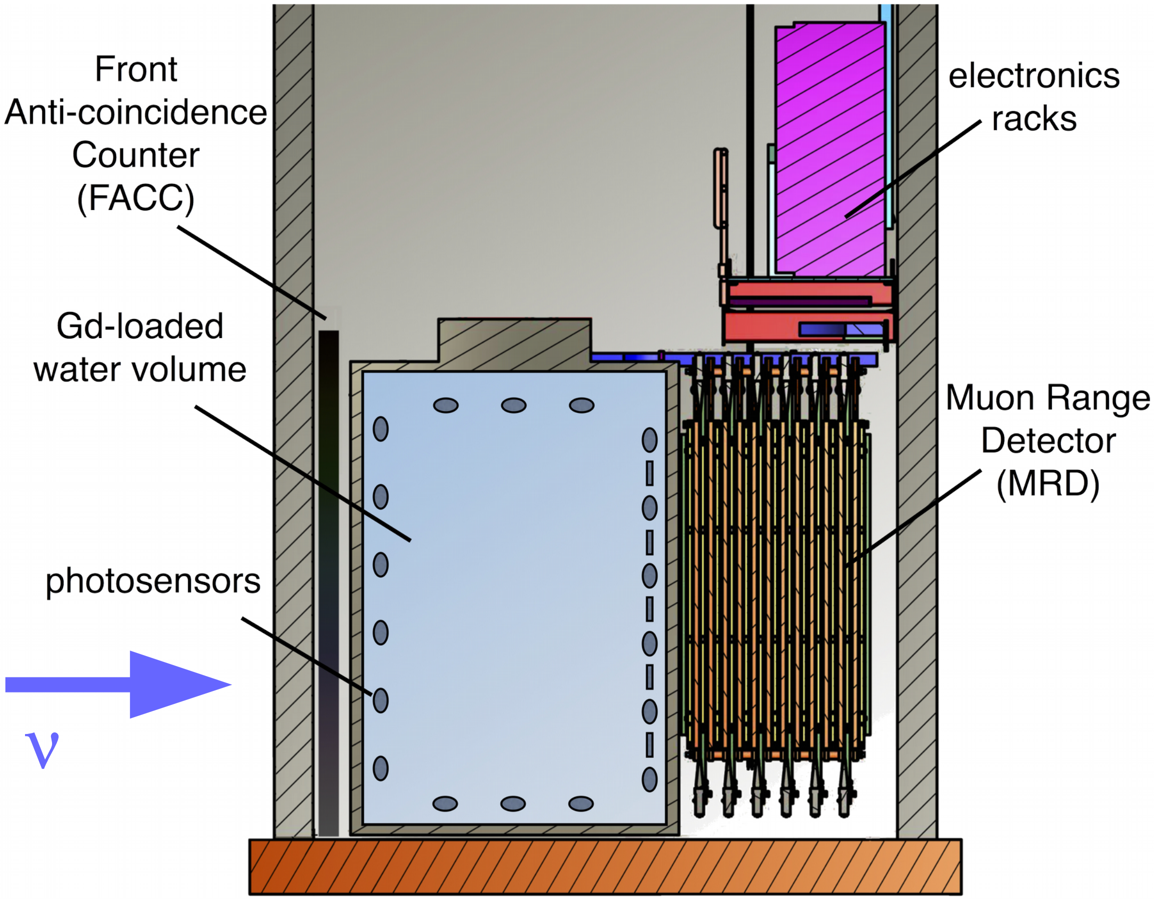


ANNIE runs commensalitically in the Booster Neutrino Beam (BNB).

Fluxes at this site:



Neutrino Event Rates



ANNIE runs commensalitically in the Booster Neutrino Beam (BNB).

Relevant BNB statistics at this site:

- On-axis neutrino beam
- 100 meters from target
- 4 x 10^{12} P.O.T. per pulse
- ~700 MeV peak energy
- 93% pure ν_μ (in neutrino mode)

ν-type	Total Int.	CC	NC
ν_μ	9892	6991	2900
ν_μ	130	83	47
ν_e	71	51	20
$\bar{\nu}_e$	3.0	2.0	1.0

Event rate is ~10,000 ν_μ interactions (7000 charged current) per tonne per year.
[Total volume is ~30 tonnes; fiducial mass still to be determined.]

What's Past is Prologue[*]

The University Of Sheffield.

Upcoming Experiments:

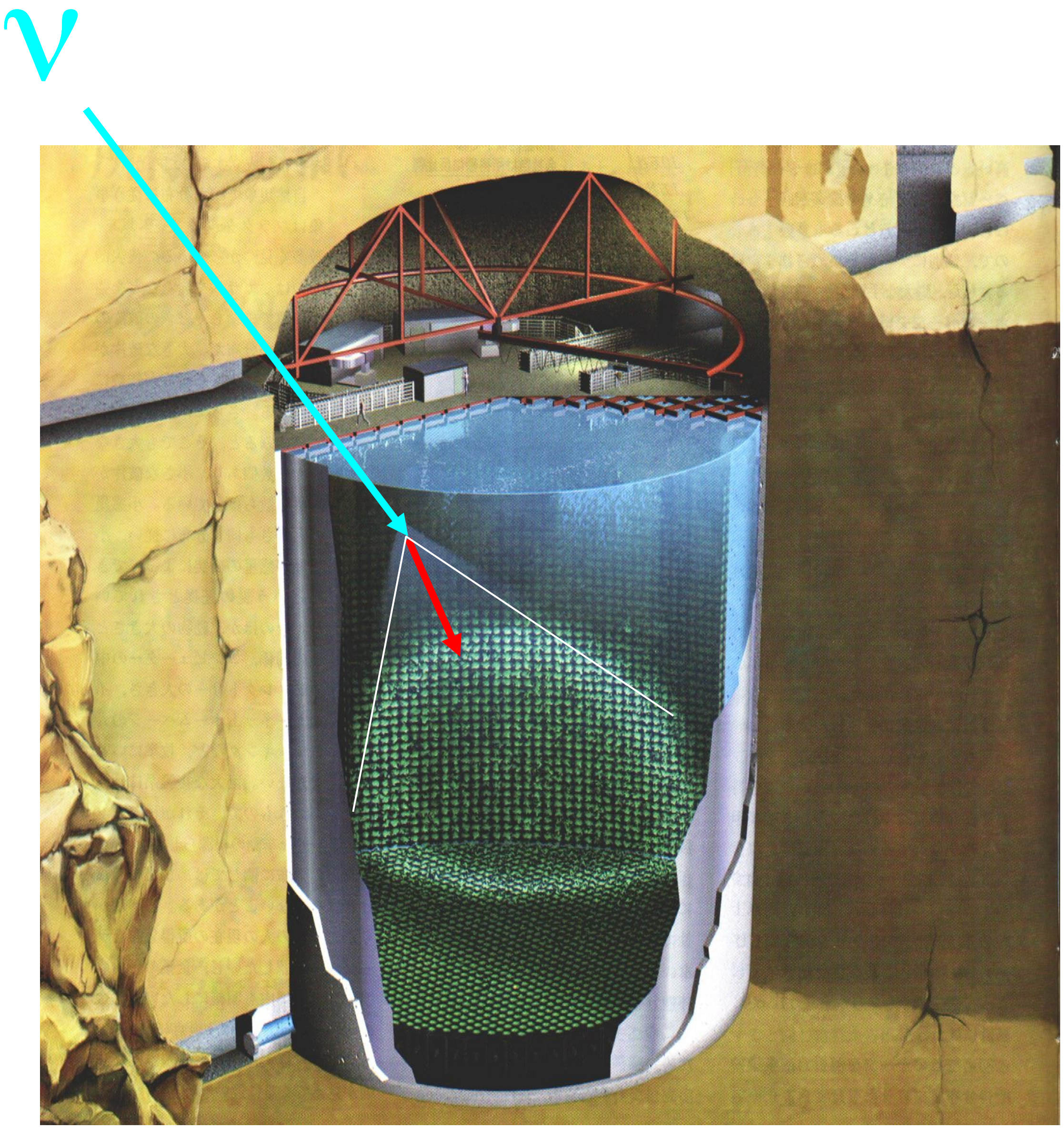
Now that the **concept** of Gd-loaded water Cherenkov experiments has been demonstrated and shown to be technically feasible, there are a host of upcoming experiments that plan to exploit it.

These include..… annie ...and also…..

[*] “The Tempest”, by William Shakespeare (Act II, Scene 1)

SK-Gd

The University Of Sheffield.



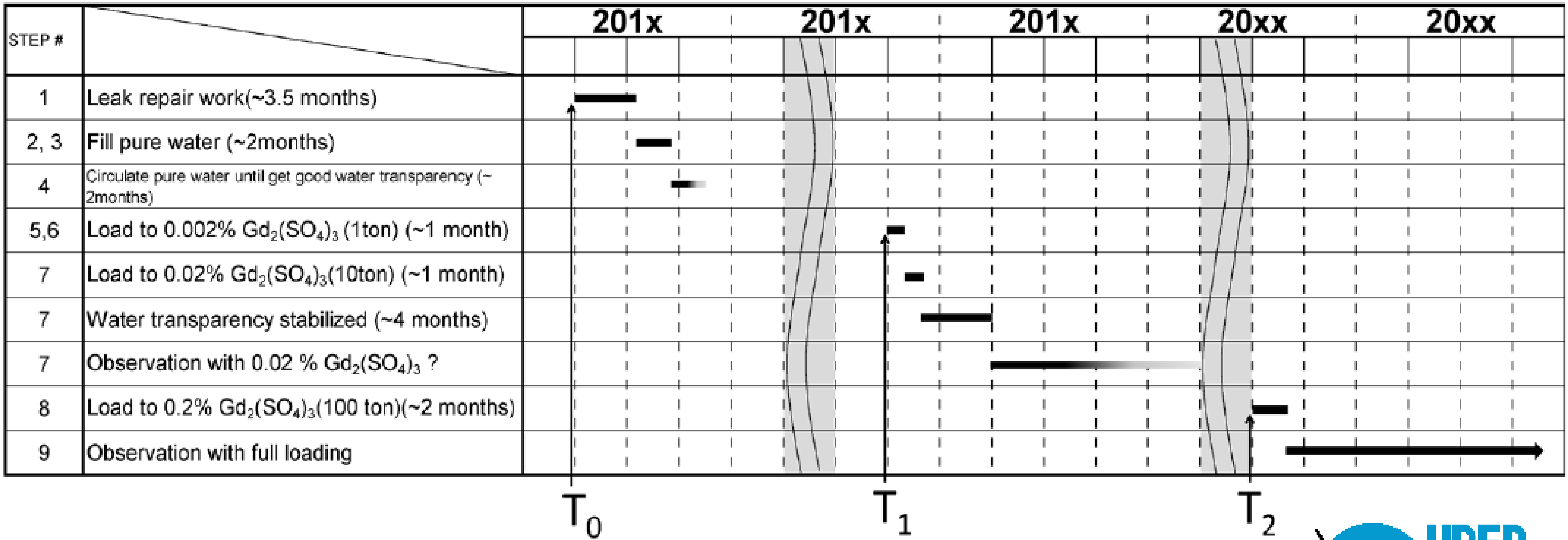
In June 2015, the Super-Kamiokande collaboration voted to add $Gd_2[SO_4]_3$ to the detector, opening up a new area of physics potential.

Possibilities include:

- Supernova relic neutrinos
- Identification of modes in a galactic supernova neutrino burst
- ν / $\bar{\nu}$ discrimination for atmospheric and accelerator neutrinos
- Reduced atmospheric background for proton decay searches

The next phase of T2K running (T2K-II) will use SK-Gd as the far detector.

SK-Gd Timeline



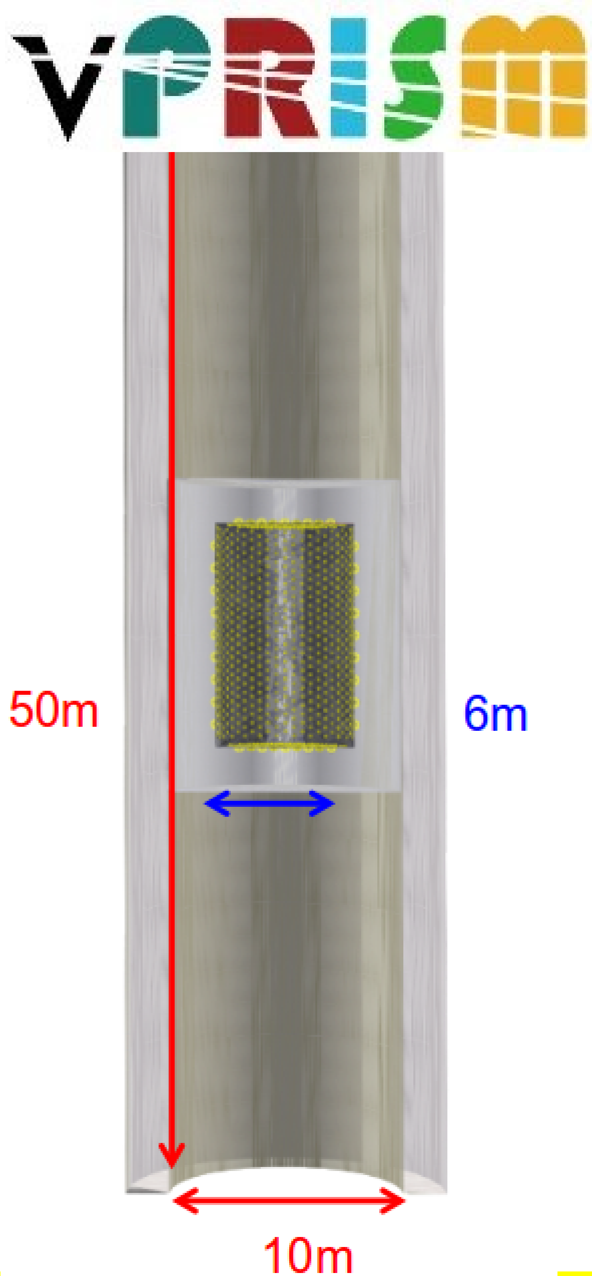
T_0 = Start refurbishment of SK detector

T_1 = Add first gadolinium sulfate (0.000% -> 0.002% → 0.020%)

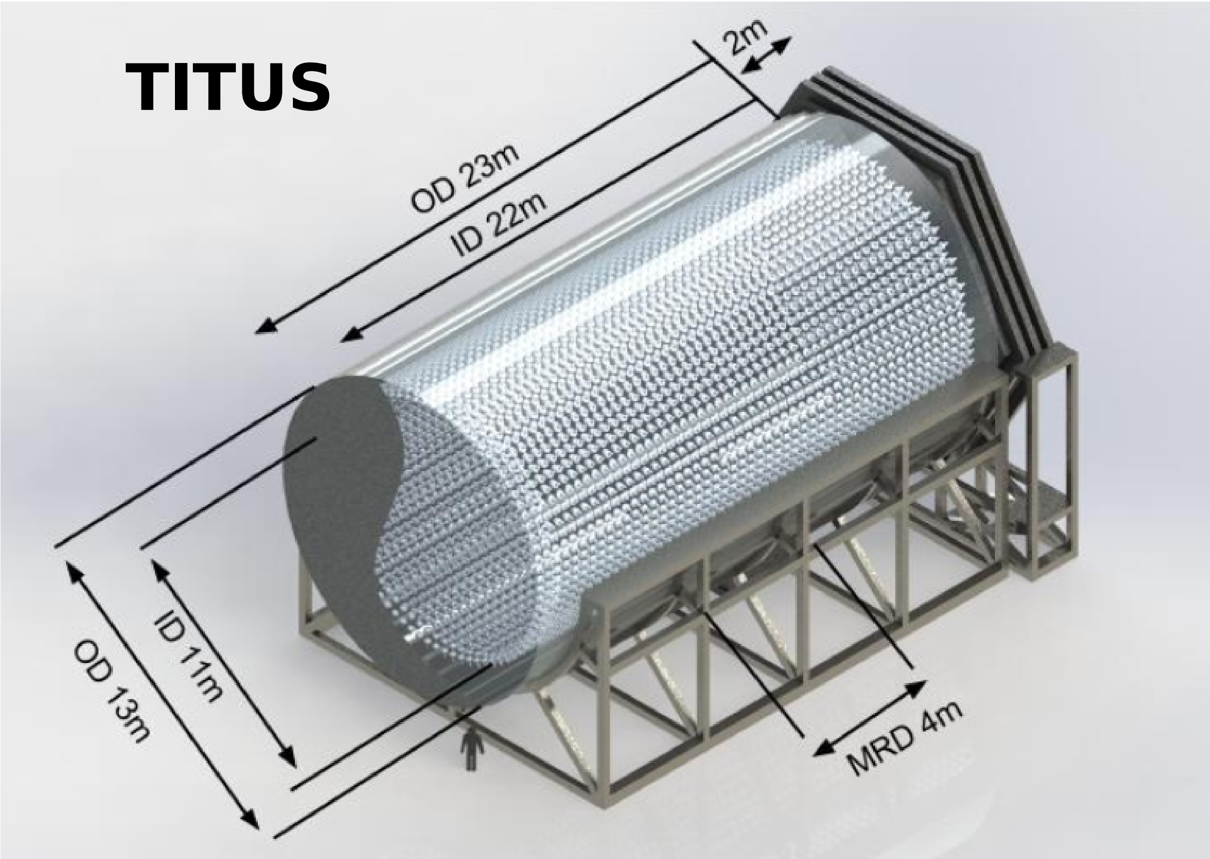
T_2 = Full loading of gadolinium sulfate (0.20%)

NuPRISM & TITUS

The University Of Sheffield.

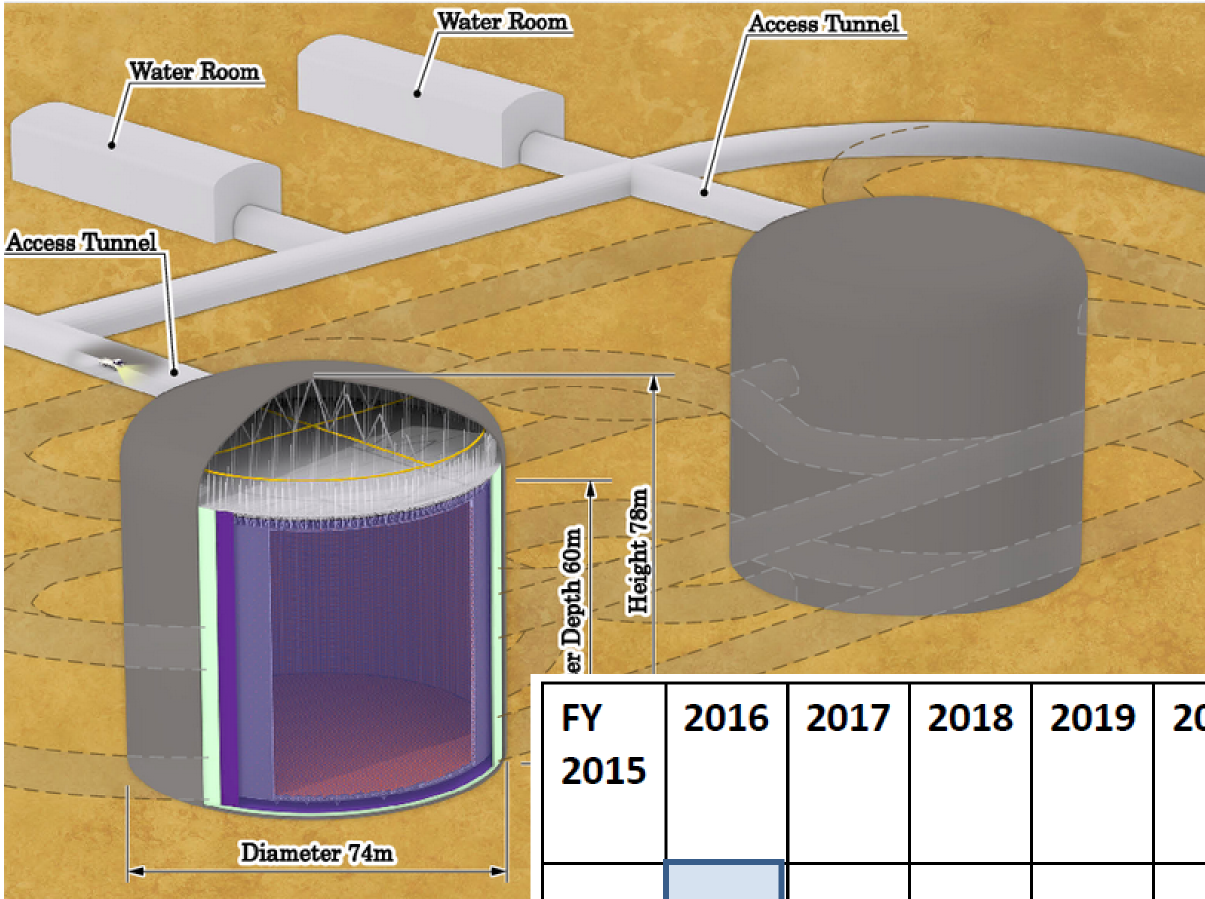


- Two new 'intermediate' distance WC detectors (~1 km) have been proposed for **T2K-II** and **Hyper-Kamiokande**.
- Both incorporate the Gd-loading technique in their designs.
- Have been merged into 'E61' → final design still pending



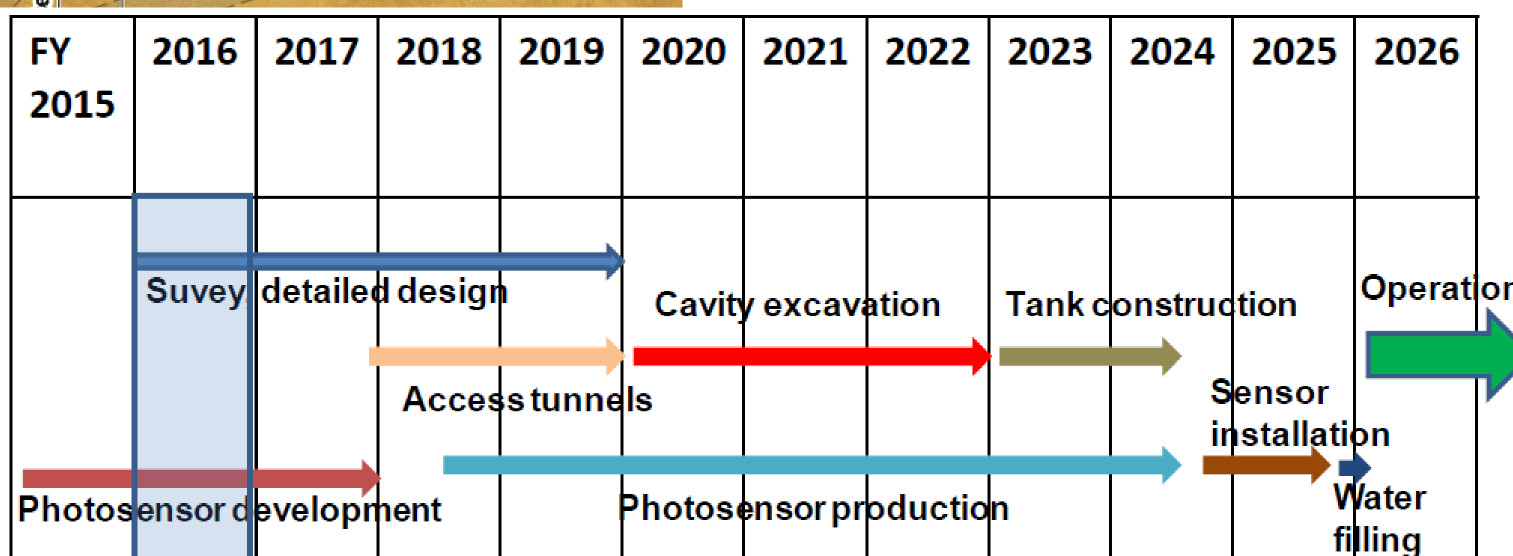
Hyper-Kamiokande

The University Of Sheffield.



Broad physics programme:

- Neutrino oscillation:
  - Atmospheric neutrinos
  - Solar neutrinos
  - Accelerator neutrinos
- Proton decay
- Neutrino astrophysics
  - Supernova burst
    - (~160,000 events @ 10 kpc)
  - Supernova relic neutrinos
- Indirect WIMP searches



The Story So Far...

To recap:

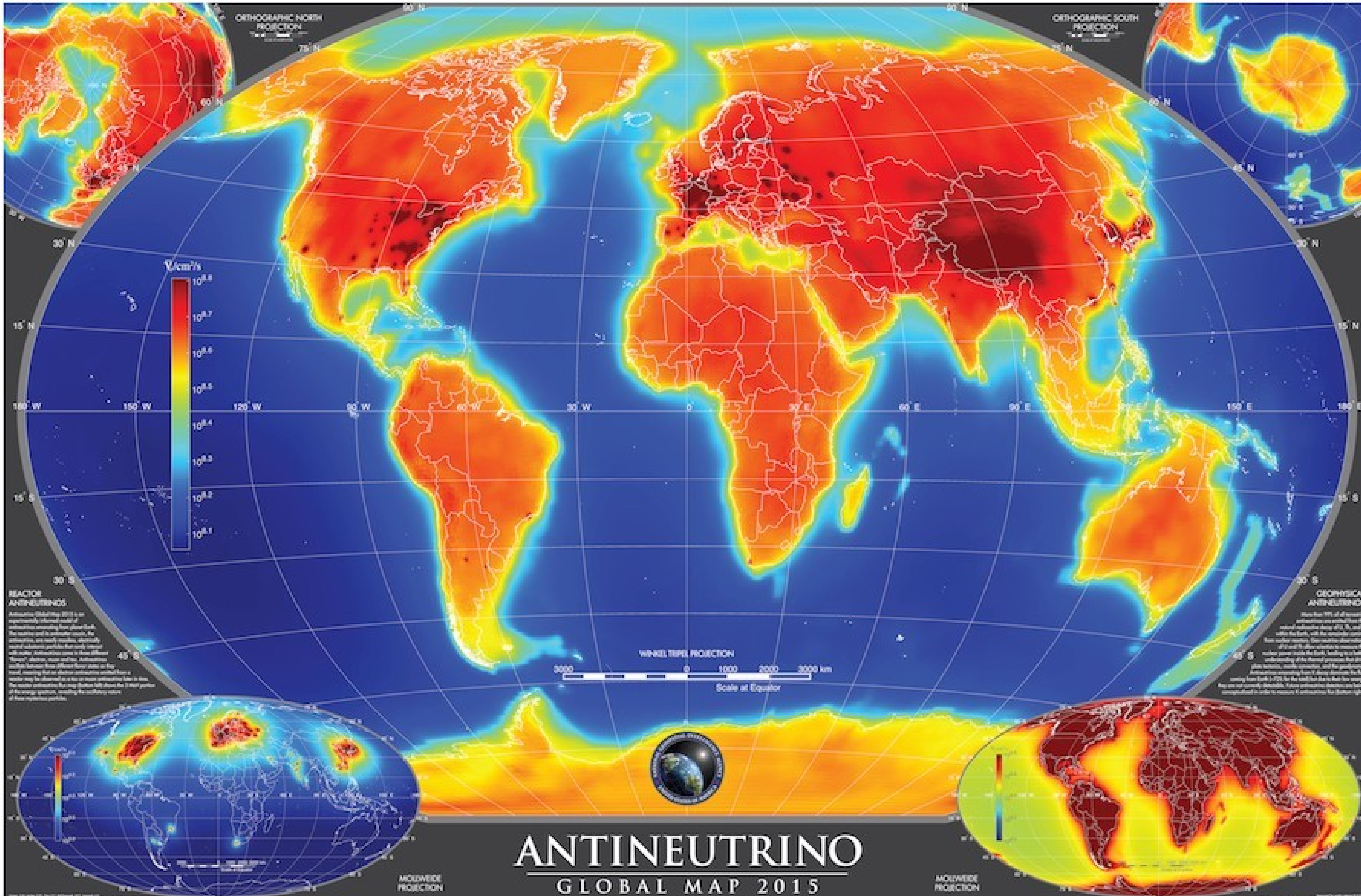
The motivation is clear; loading water Cherenkov neutrinos detectors with gadolinium brings new life to an old technology.

The **technical** capability has been demonstrated.

The **physics** benefit is well-established, with new experiments planned at scales ranging from 26 tonnes (ANNIE) to 520,000 tonnes (Hyper-K), starting from next year and continuing to turn on over the next decade.

That's great... but can we also use anti-neutrino detection for **impact**?

The WATCHMAN Project



WATCHMAN Overview

WATCHMAN = WATer CHerenkov Monitor for Anti-Neutrinos

Physics is fun, but the real world is a dangerous place... and getting more so all the time.

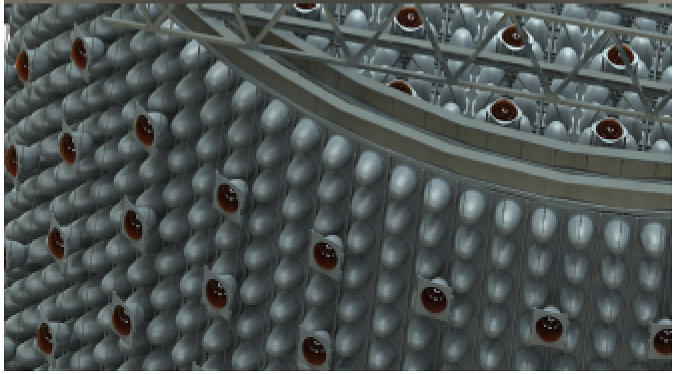
The goal of the WATCHMAN project is to harness the techniques described earlier for nuclear threat reduction.

Primary sponsor is the Office of Defense Nuclear Nonproliferation (DNN) at the National Nuclear Security Administration (NNSA) in the United States.

Secondary sponsors are UKRI/STFC and the Ministry of Defence (MOD) in the UK.

What is WATCHMAN?

The University Of Sheffield.



Objective:

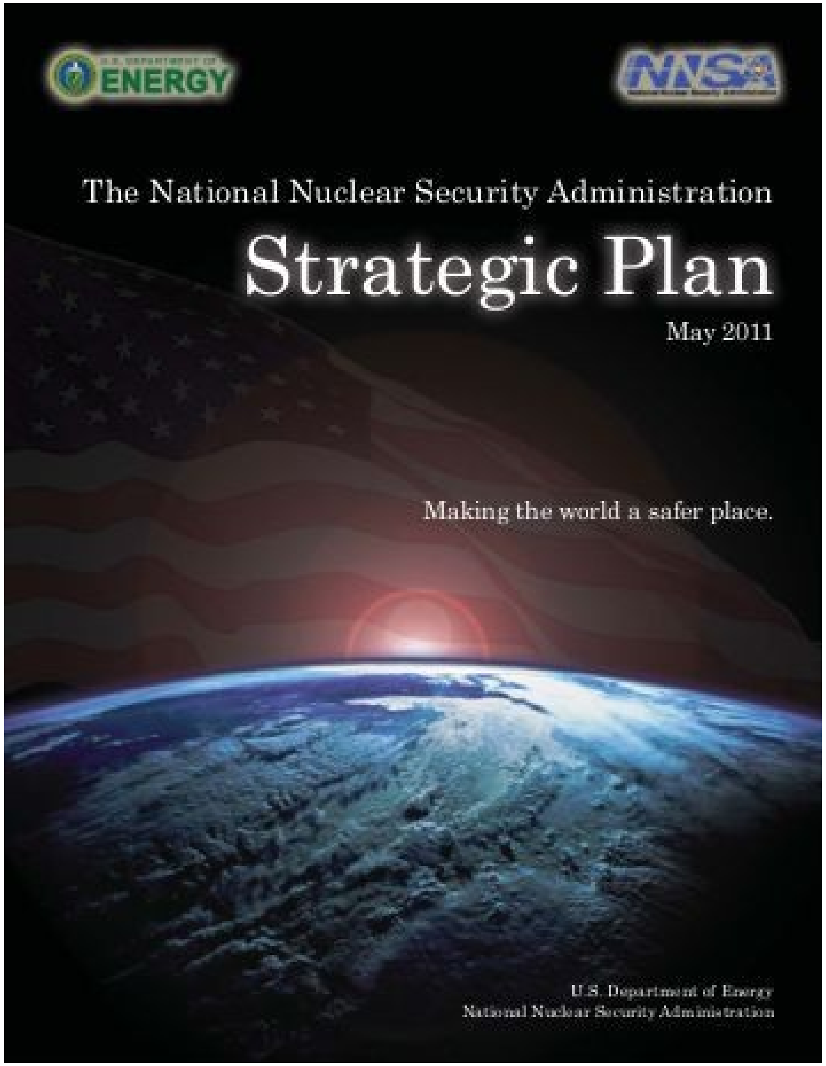
Remote monitoring of small fission reactors (~40 MWth) via detection of antineutrino emissions.

Initial project goal is to observe reactor on/off states at approximately 10 – 30 km distance from reactor.

Prototype Design Features:

- Medium scale (~1 ktonne fiducial mass) water-based gadolinium-loaded antineutrino detector
- Initial prototype to demonstrate monitoring of a single known reactor site
- Rationale is to develop a detector design that can be scaled to larger masses for smaller reactors and larger standoff distances

The WATCHMAN Charge



We have been charged by the sponsor with the following goal:

Verify, to 3σ confidence, the presence of a nuclear reactor (if one exists) within 30 days.

This requires reducing backgrounds to ~330 events per day.

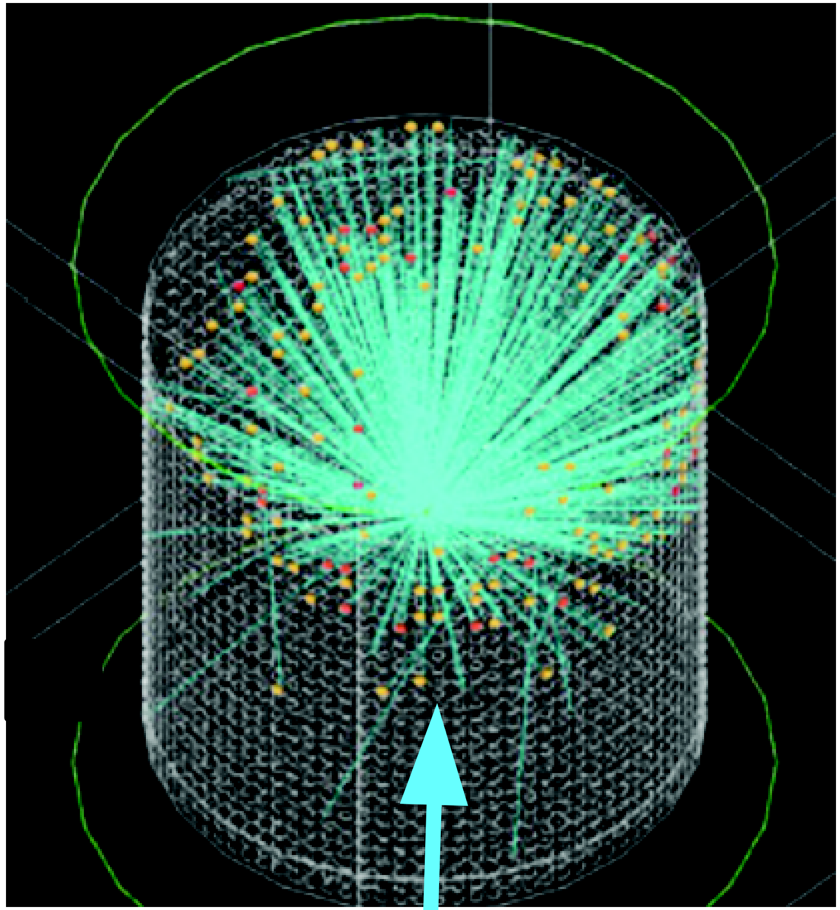
Additionally, the reactor signal is **limited** to *no more than* 10 events/day.
→ Very different way of thinking!

The WATCHMAN Design

The University Of Sheffield.

The baseline design includes:

- ~1 ktonne fiducial mass
- ~1.5 meter active veto region
- 0.1% Gd-loaded water
- 25% PMT coverage
  - 10” (or 12”) high QE PMTs
  - Low radioactivity PMTs
  - Mounted on high quality stainless steel frame (SS304)

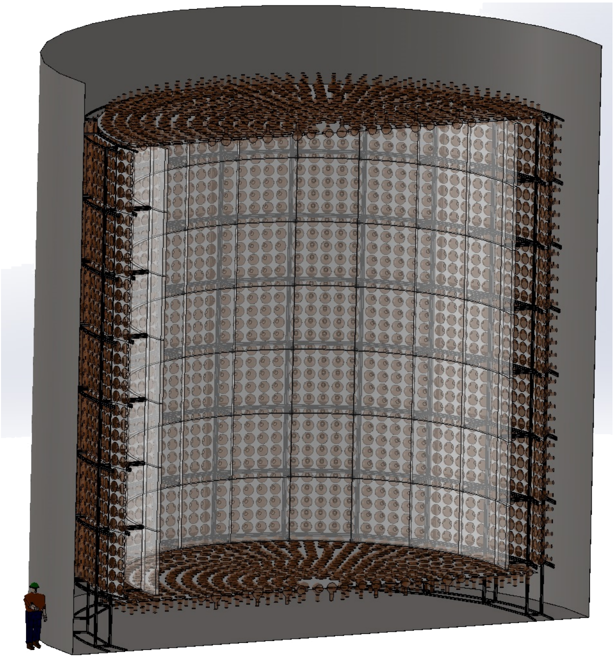


Visualisation of an elastic scattering event in the WATCHMAN detector

WATCHMAN Collaboration

WATCHMAN is a partnership of Universities and Defence / Defense Agencies across the USA & the UK:

- ~80 collaborators (including students)
- 21 institutions
- 2 countries



WATCHMAN Site

The University Of Sheffield.

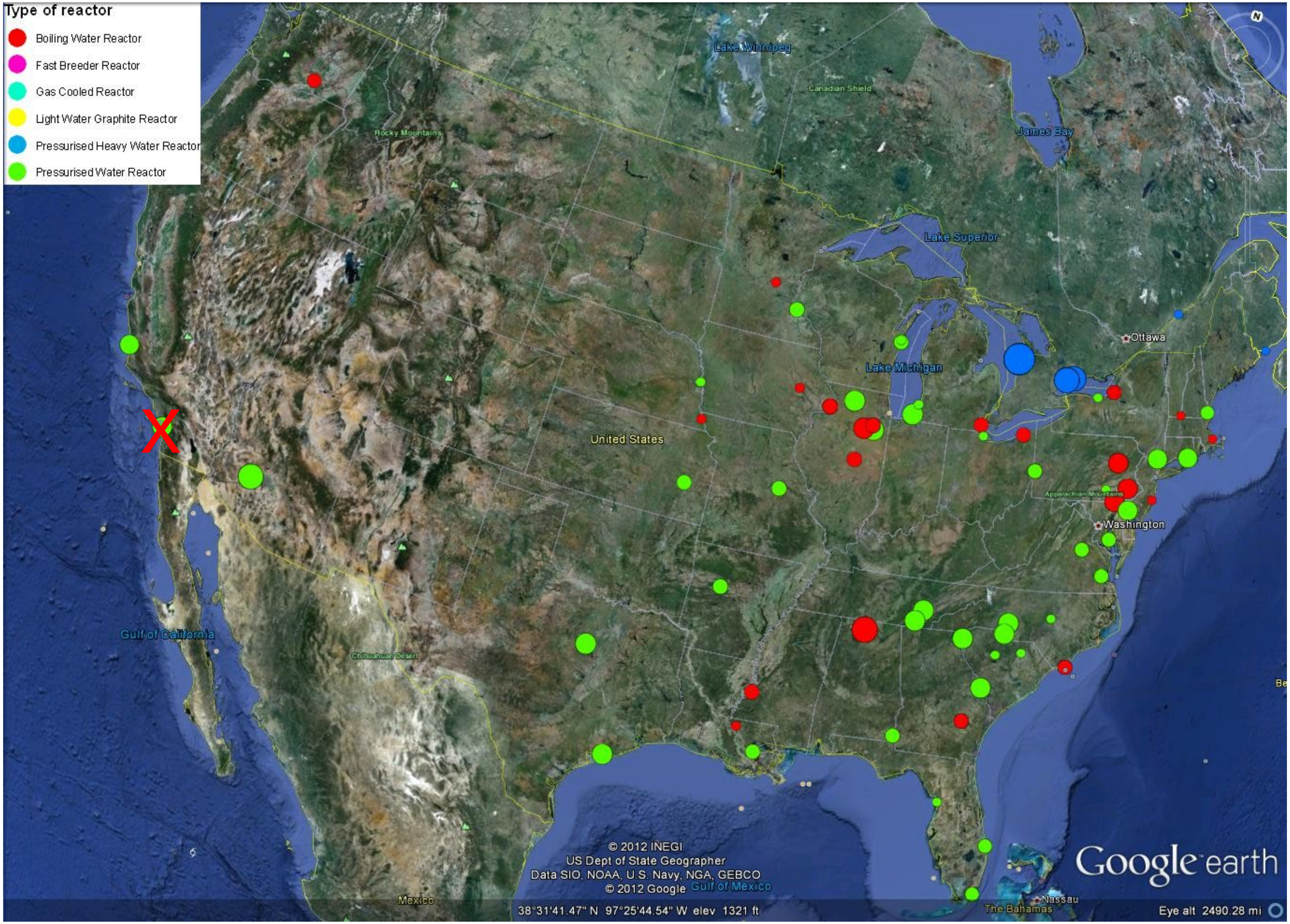
The WATCHMAN prototype site requires:

(a) an underground laboratory (or potential to build one) that is within ~30 km of

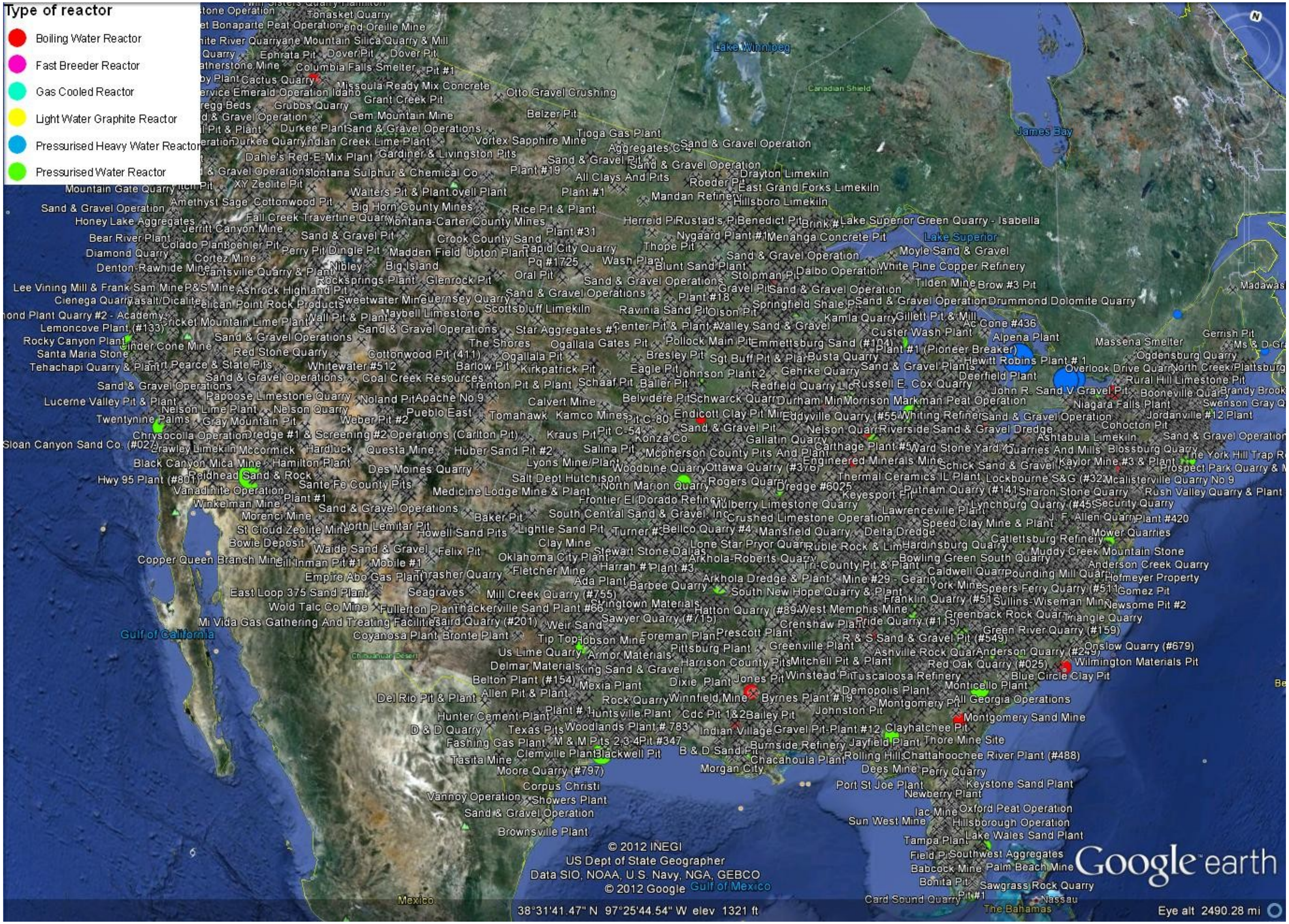
(b) a nuclear reactor

→ This places a significant constraint on the choice of site!

Map of US Reactors



Map of US Mines



Potential WATCHMAN Sites

The WATCHMAN prototype site requires:

(a) an underground laboratory (or potential to build one) that is within ~30 km of

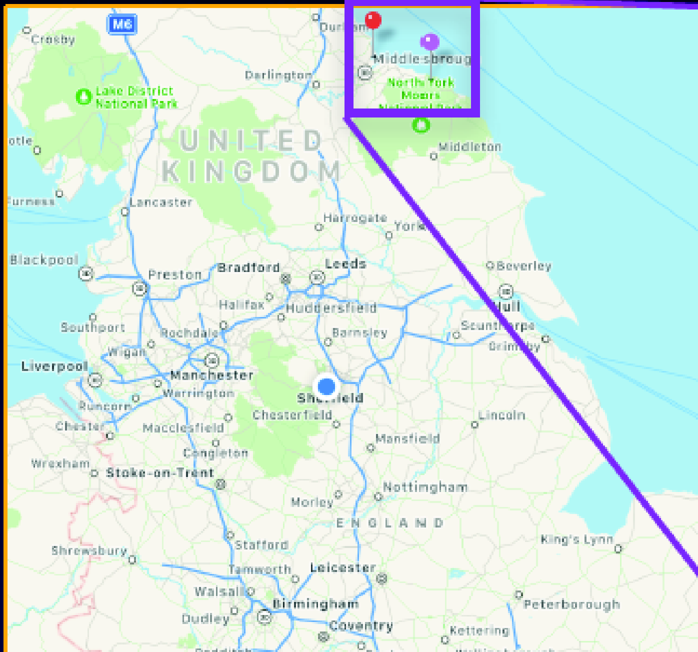
(b) a nuclear reactor

Search results:

– Only one site in the USA satisfies criteria

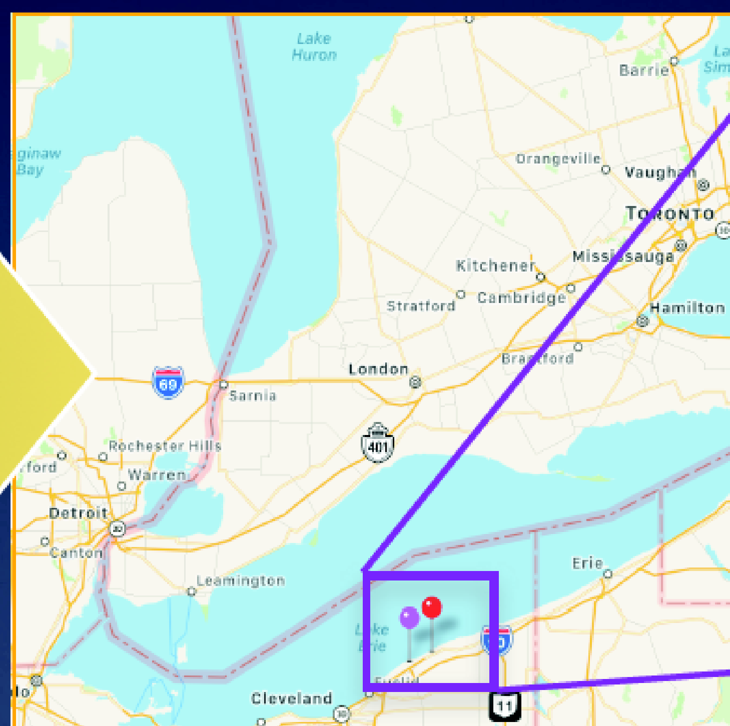
– Another candidate site in UK fits both criteria

Potential Sites



Boulby Mine:
2800 m.w.e.
Operating Potash/ Polyhalite mine
Existing science lab hosts DM expts, etc.
New cavern needed for WATCHMAN
Hartlepool reactor:
Twin AG reactors
Total output 2x1.58 GWth

Morton/Fairport Mine:
1300 m.w.e.
Operating Potash mine
Former IMB site
No excavation needed
Perry reactor:
Single BW reactor
Total output 3.7GWth

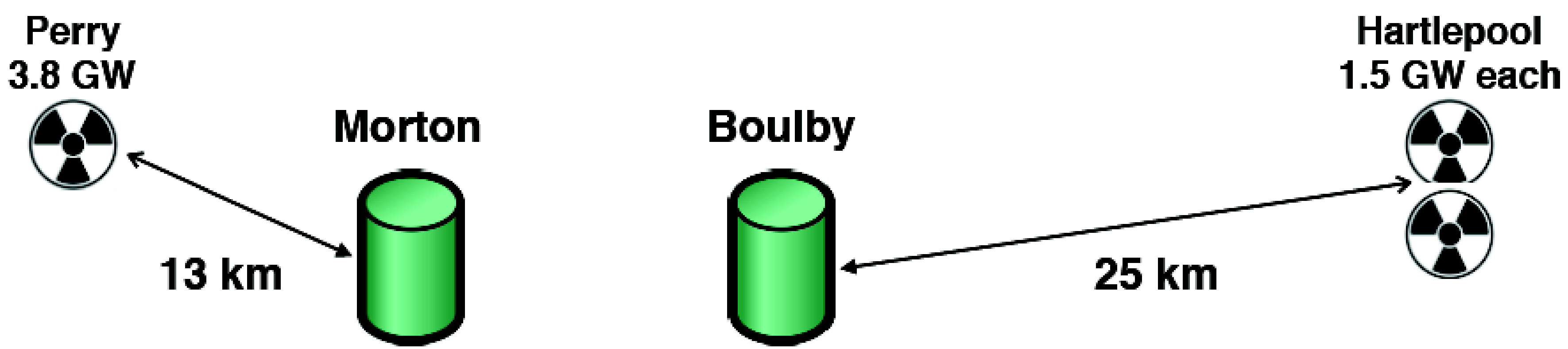


Reactor Neutrino Fluxes

The University Of Sheffield.

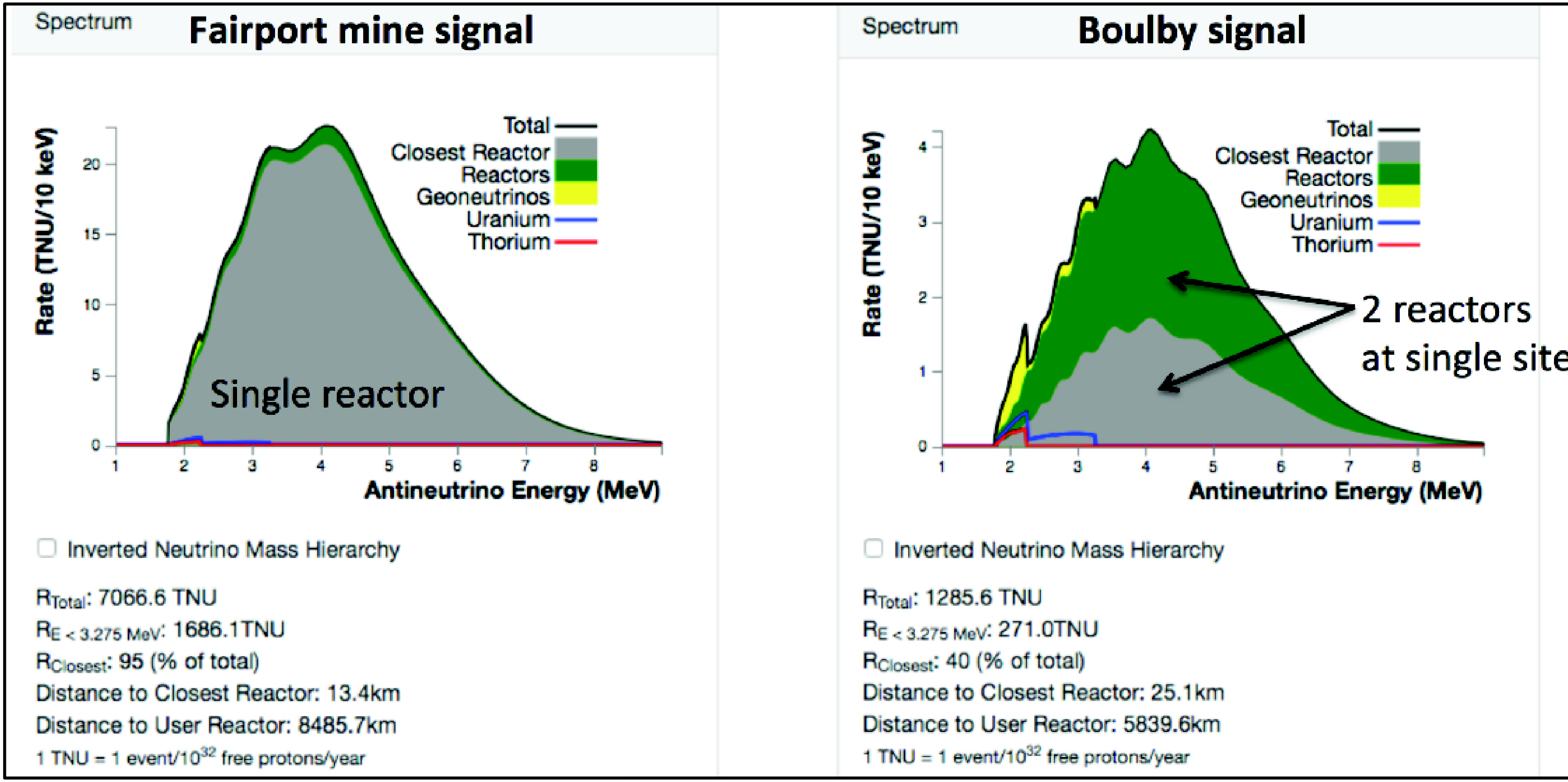
Calculation of fluxes at WATCHMAN sites involves:

(a) evaluation of total generated flux at reactors
(b) oscillations in transit
(c) antineutrino cross-sections (elastic and quasi-elastic)
(d) backgrounds from other reactors



	P_{th}(MW)	Type	Cores	L(m)	D(m.w.e.)
Perry-Morton	3758	BWR	1	13000	1560
Hartlepool-Boulby	3000	GCR	2	25000	2800

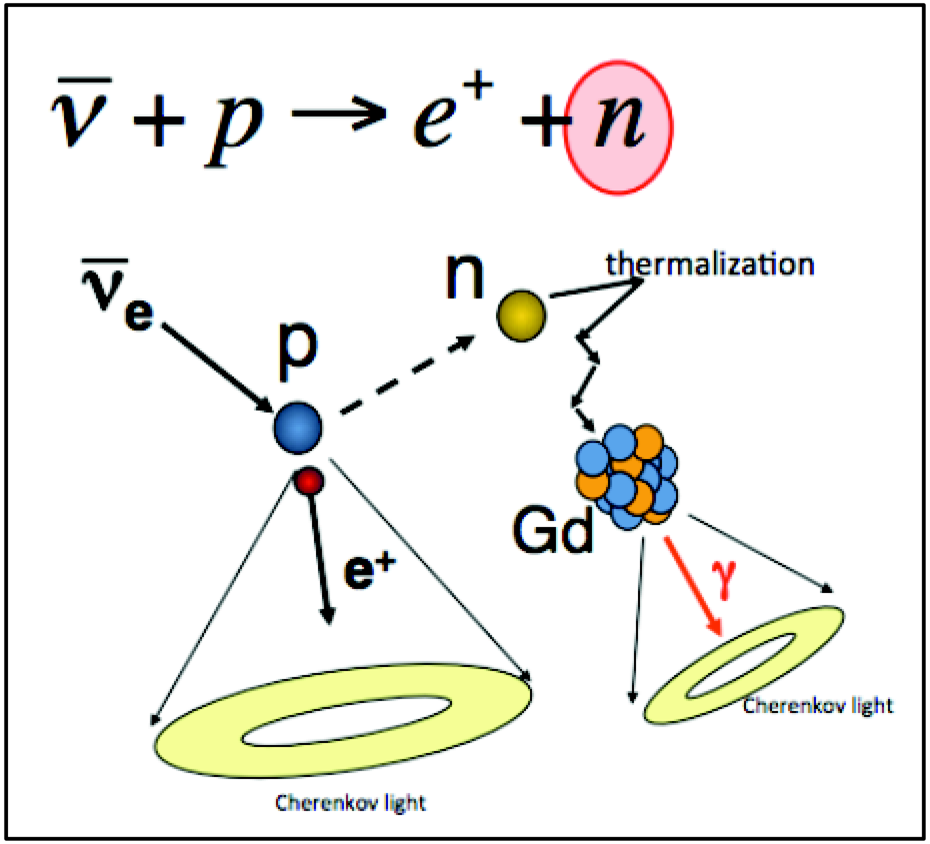
WATCHMAN site fluxes



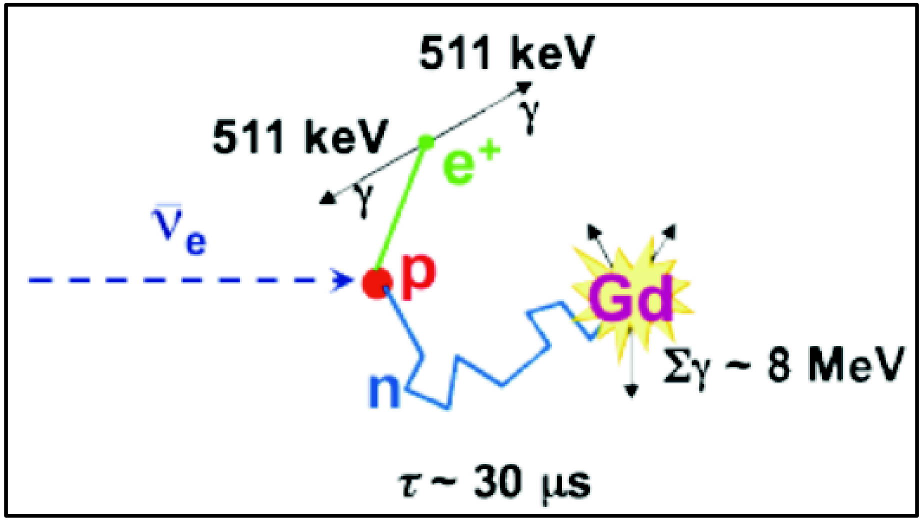
Thanks to Antineutrino Global Map project (see title slide), there is now an online tool to get such reactor fluxes (and natural backgrounds)!

For more detail, see S.Dye's recent preprint at **nucl-ex:1611.01575**

WATCHMAN Signal



Signal is positron annihilation, followed by ~8 MeV γ cascade from Gd de-excitation ~30 μs after.



Experimental signature:

(a) exactly two Cherenkov flashes
(b) occurring within a ~100 μs window
(c) and also within a 1m^3 voxel

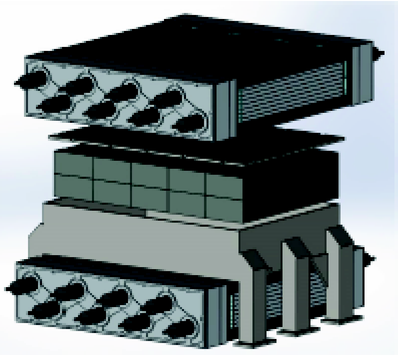
A Brief History

2012 – 2015:
Background measurements include:

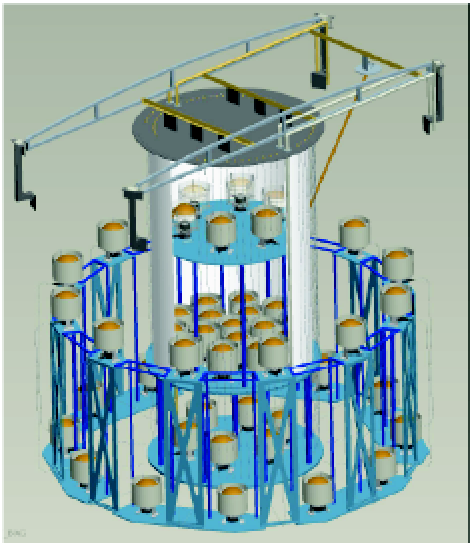
• Muon And Recoil Spectrometer (MARS), measured muogenic fast neutrons at Kimballton Underground Research Facility (KURF),

• Long-lived radio nuclides (such as ^{9}Li) measured with WATCHBOY using gadolinium trichloride (not sulfate!)

In parallel, technology for large Gd-loaded water cherenkov detectors established at EGADS (in Japan)



MARS



WATCHBOY

A Brief History

2015:

• DOE-HEP pulls out of WATCHMAN. Rumours of project demise.

2016:

• WATCHMAN invites UK groups to join collaboration (AWE, Boulby, Sheffield).

• Boulby reconsidered as site

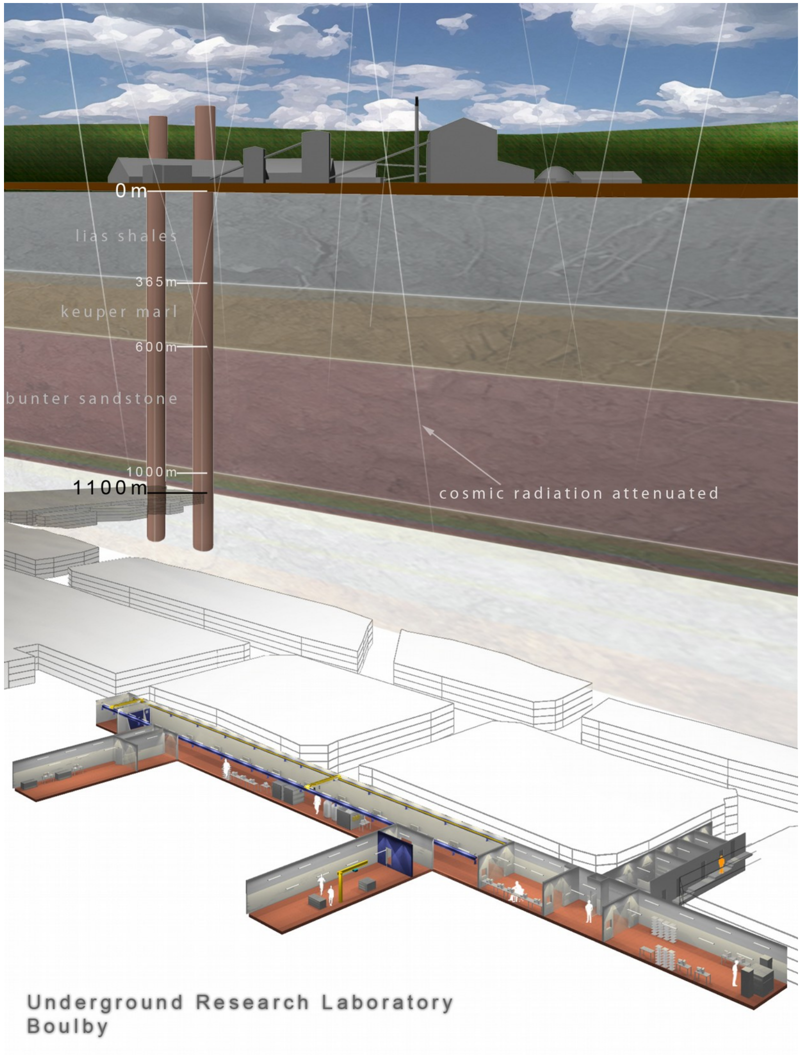
Mar 2017:

• Proposal submitted to NNSA

Apr 2017:

• NNSA visit to Boulby and proposal review

A Brief History



Oct 2017:

- Funding approved by NNSA!
- $33M for construction of detector
- Boulby selected as preferred site
- Project expanded into AIT (Advaned Instrumentation Testbed)

Jan 2018:

- Project kickoff meeting at Sheffield

May 2018:

- New UK groups admitted to collaboration (Edinburgh, Liverpool)

Jun 2018:

- STFC applies to UK RI for WATCHMAN funding (support for Boulby & academics)

UK Involvement

Original:

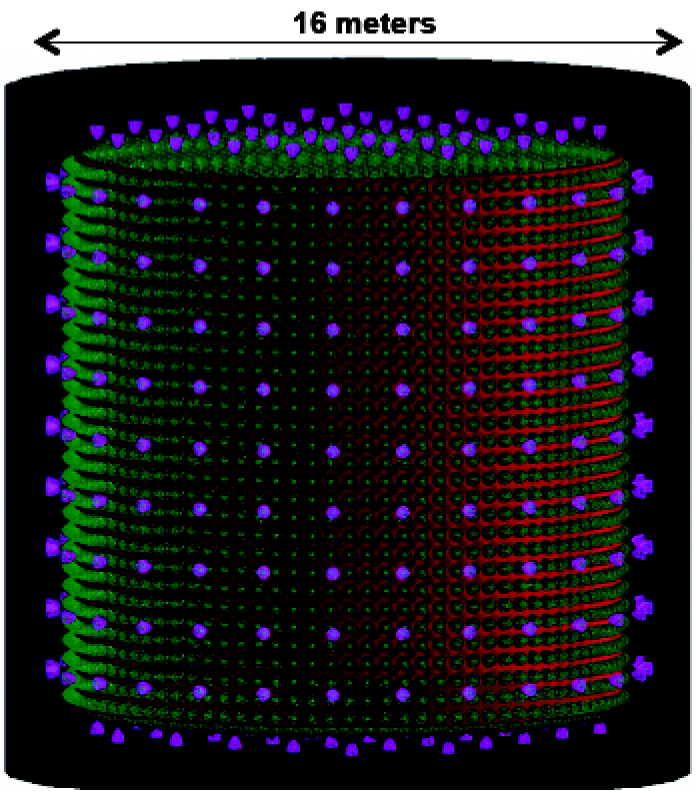
- **Site:** Jon Burns & Sean Paling (conveners)
- **Tank:** Neil Spooner (convener)
- Water
- **PMTs** [AWE, Edinburgh, Sheffield]
- **DAQ:** Lee Thompson (co-convener)
- **Calibration** [Liverpool, Sheffileld]
- **Cleanliness** [EVERYBODY!]
- **Simulations** [AWE, Sheffield]

Later:

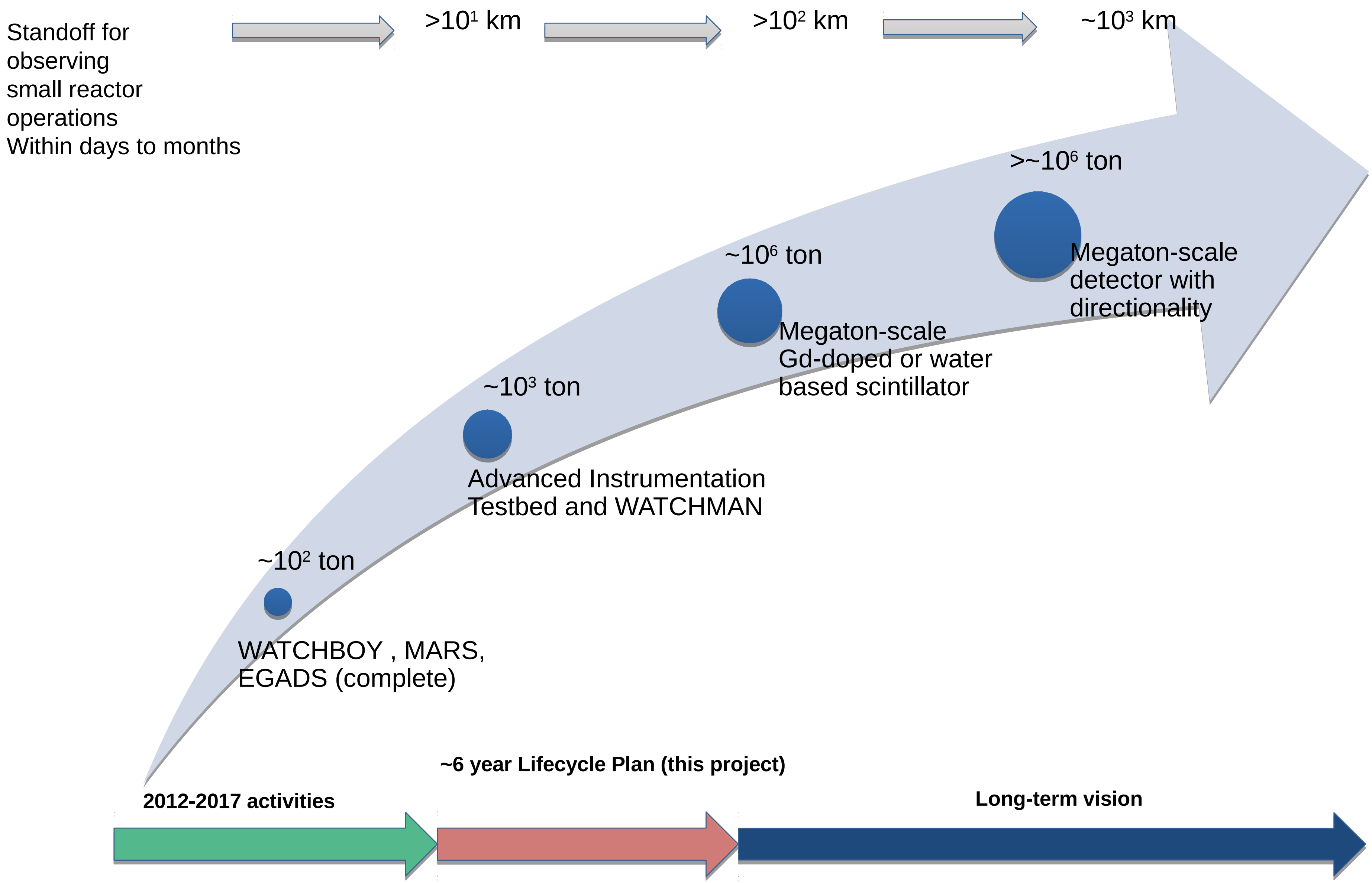
- **Governance** [Jon B., Sean P., Matthew M.]

Most recently:

- **HV** [Sheffield]
- **DAQ software** [Ben Richards, QMUL?]
- **Future R&D:** Matthew Malek (co-convener)
- **Near-field monitoring:** Jonathan Coleman (convener)



Long Term Plan

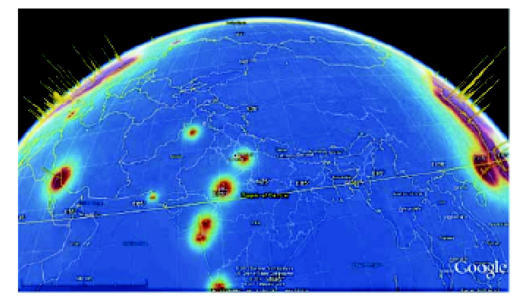


WATCHMAN Summary

- **Despite rumour of WATCHMAN's demise (2015), we are alive & well!**
  - US HEP funding is not happening, but DNN is eager to continue
  - Expect decision this Summer (~August 2017) and, hopefully, start soon after
- **WATCHMAN is getting attention in both the popular press, the general physics landscape, and specialised conferences:**

Neutrinos and National Security

By Michael Lucibella



Global map of reactor neutrino emission.
Photo courtesy of Glenn Jocher and John Learned, University of Hawaii

APS March Meeting, Denver — The Department of Energy (DOE) is funding the WATer CHerenkov Monitor of AntiNeutrinos (WATCHMAN), a prototype neutrino detector that can monitor whether a nuclear reactor 400 kilometers away is enriching the raw material for nuclear weapons. If successful, the WATCHMAN Collaboration's research could make it nearly impossible for countries to hide their illicit nuclear enrichment. It also r the start of the neutrino's transformation into a practical tool for uses outside of basic research.

Applied Antineutrino Physics 2016

1st - 2nd December

UNIVERSITY OF LIVERPOOL

Conclusions

- **After ~15 years of extensive R&D, gadolinium loaded water is ready!**
- **Many experiments ready to adopt to enhance physics reach:**
  - ANNIE, SK-Gd, T2K-II, Hyper-Kamiokande

- **ANNIE will be the first to use Gd-loading for physics measurements**
  - ANNIE Phase I making BG measurements since April 2016; will end in July 2017
  - ANNIE Phase II will start in October 2018
    - Phase II will make use of Gd-loading for neutron yield and neutrino cross-sections measurements
    - Phase II will also test use of LAPPDs in water Cherenkov detectors

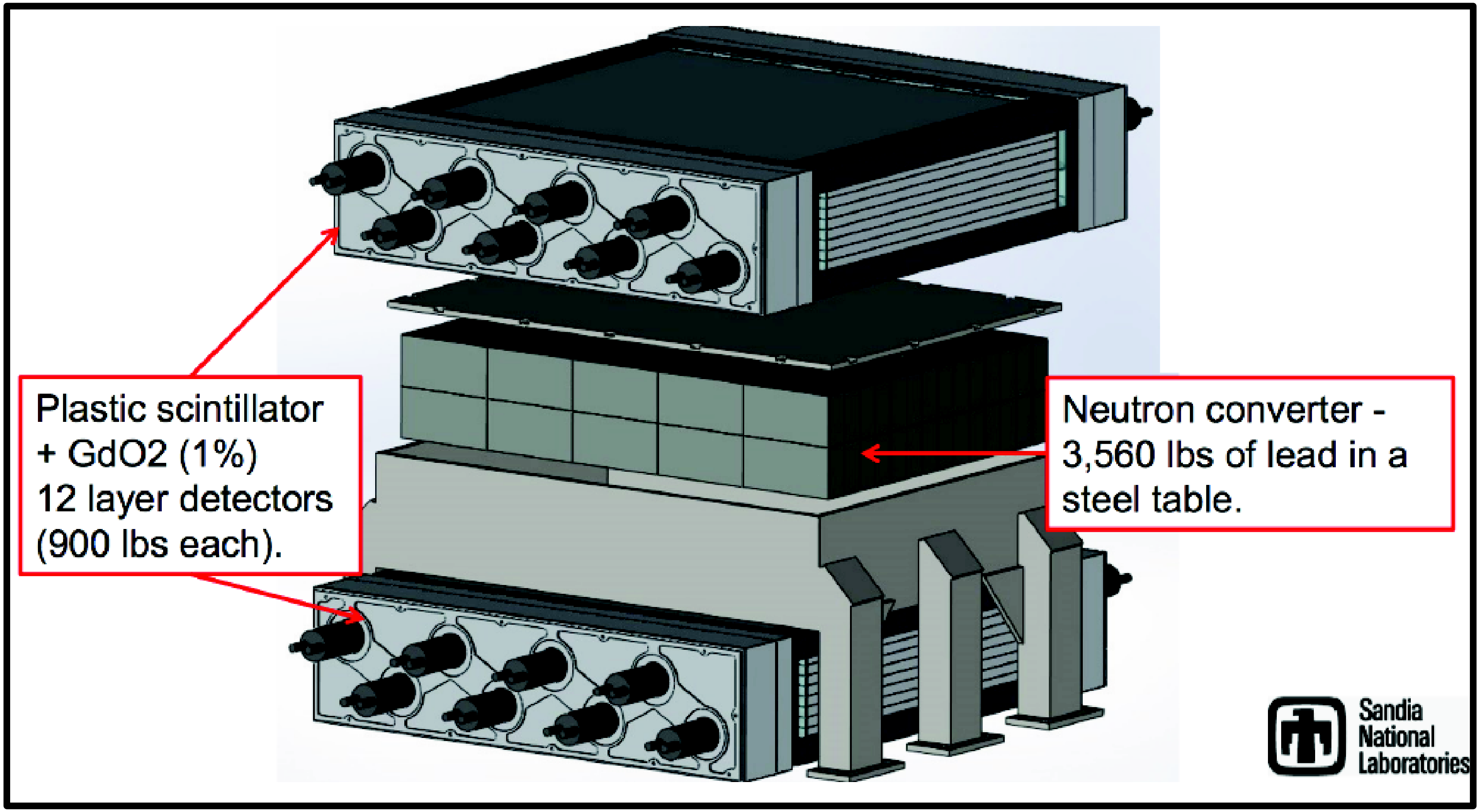
- **WATCHMAN prototype construction started**
  - Hope to minimize a source of global catastrophic risk
  - Defenc/se agencies are very interested; collaborations with Universities fruitful
  - If protoype successful, deployment overseas not long afterwards

- **Significant physics potential for WATCHMAN also**
  - Following successful initial run, WATCHMAN can be used for reactor neutrino physics, supernova neutrino detection, sterile neutrino searches
  - Also possibility to use as testbed for future technologies, esp. water-based liquid scintillator (WbLS) in preparation for proposed experiments like THEIA

Thank you for listening!

BG Study: MARS

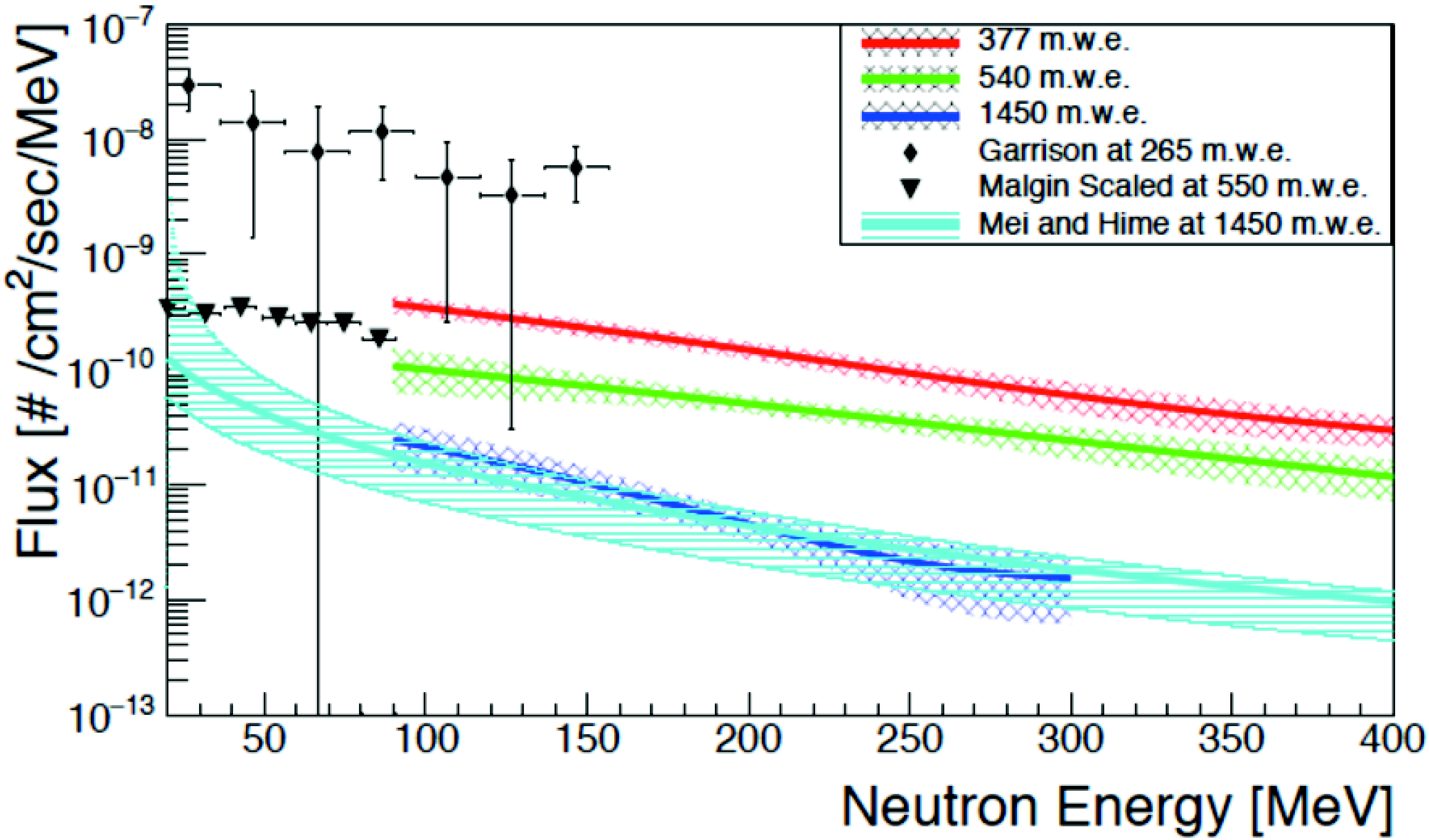
MARS = Multiplicity And Recoil Spectrometer



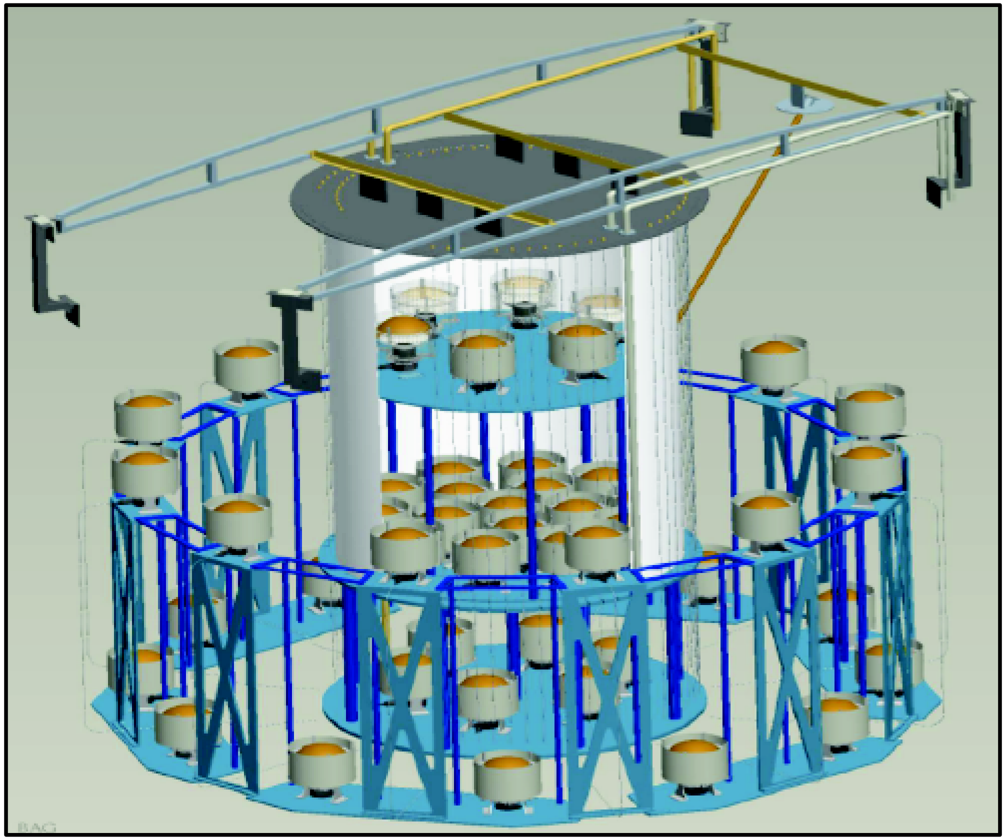
- A single fast neutron can produce a multiplicity of particles that can mimic an antineutrino signal in water
- Muon veto rejects muon-induced neutron production within detector

Preliminary MARS Results

Data taken from 2013 – 2015 at KURF (Kimballton, Virginia)



BG Study: WATCHBOY



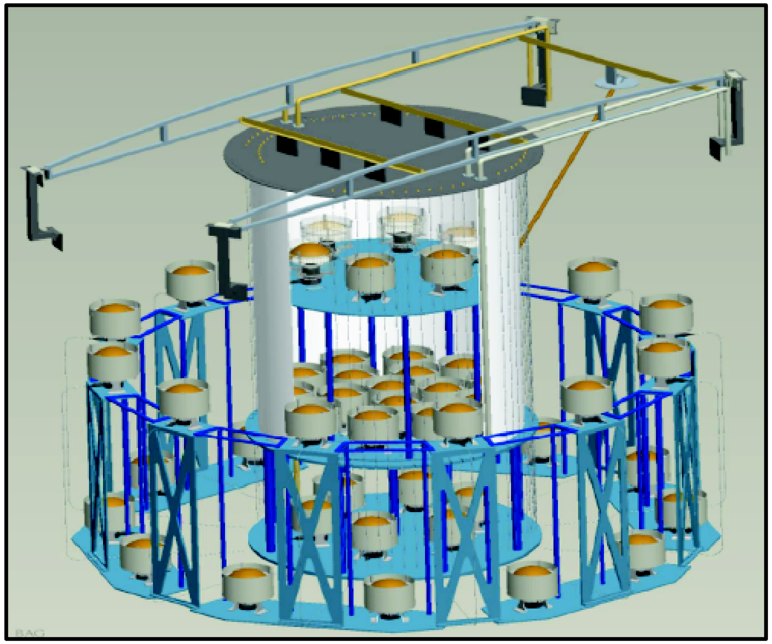
WATCHBOY is a 'mini-WATCHMAN' ('WATCHMANino'?) with:

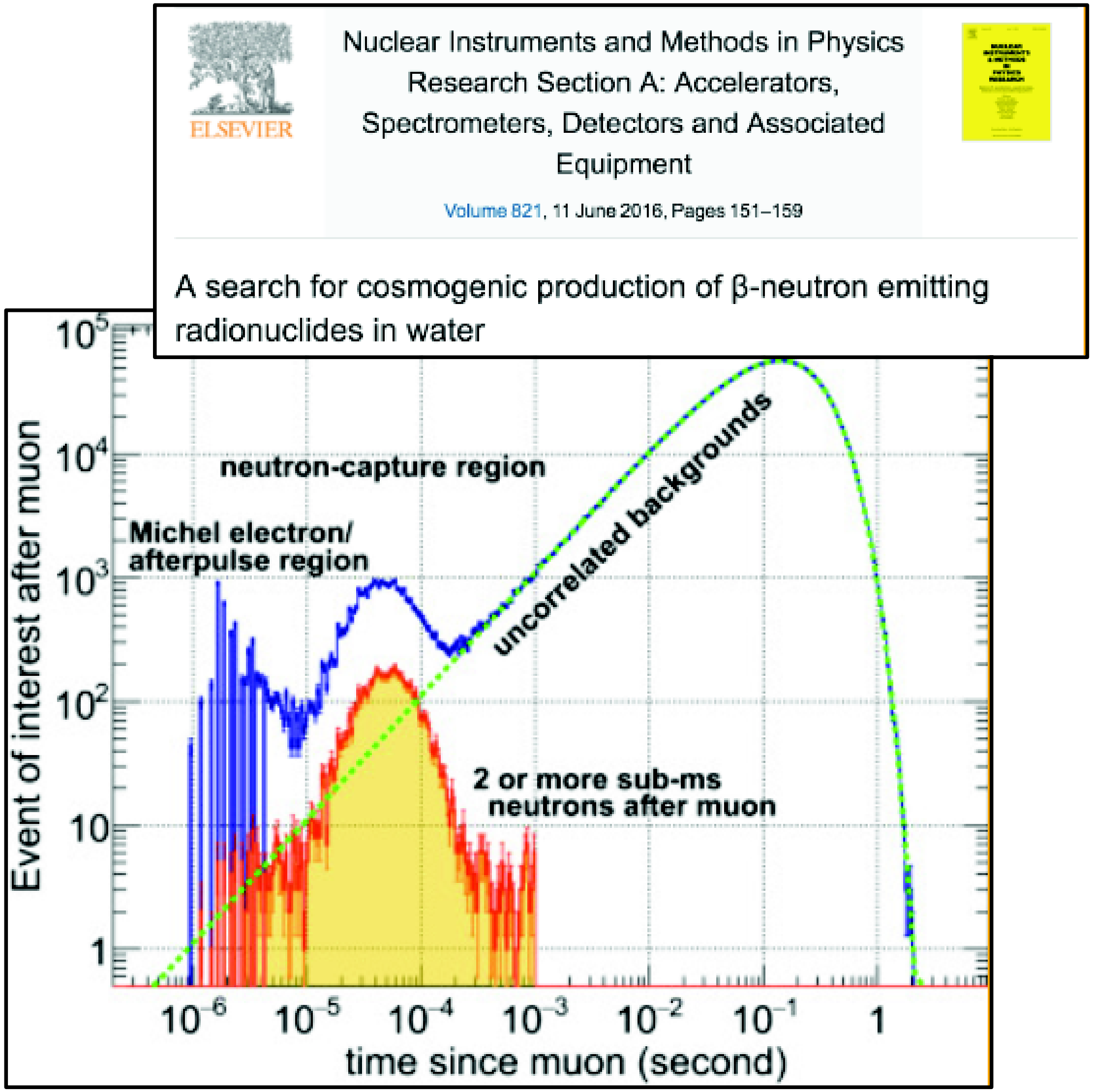
- 2 tonne target (water + Gd_2Cl_3)
- 10 tonne veto (pure water)

Built to measure long-lived radionuclides (*e.g.*, ^{9}Li, ^{8}He)

Event is tagged with preceeding muon; allows removal of nearly all backgrounds due to pile-up from other muons.

WATCHBOY Results

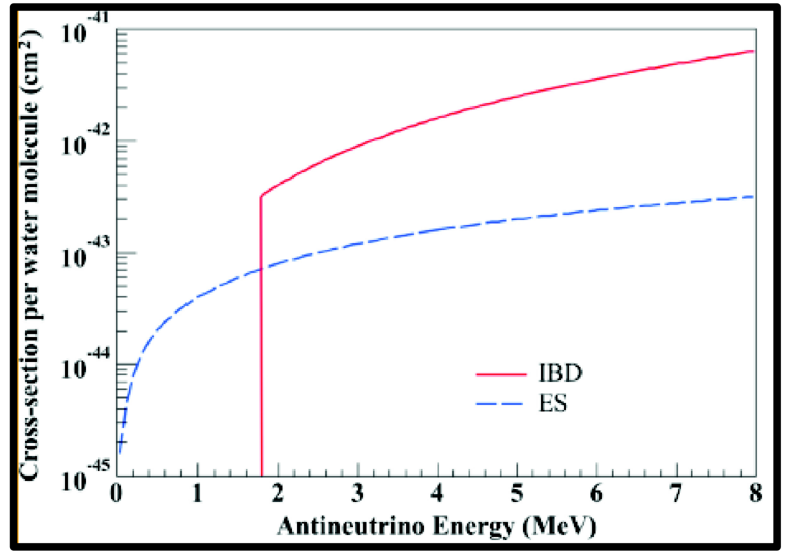




The uncorrelated events are fit between 1 ms and 2 s.

Good agreement between data and expectation!

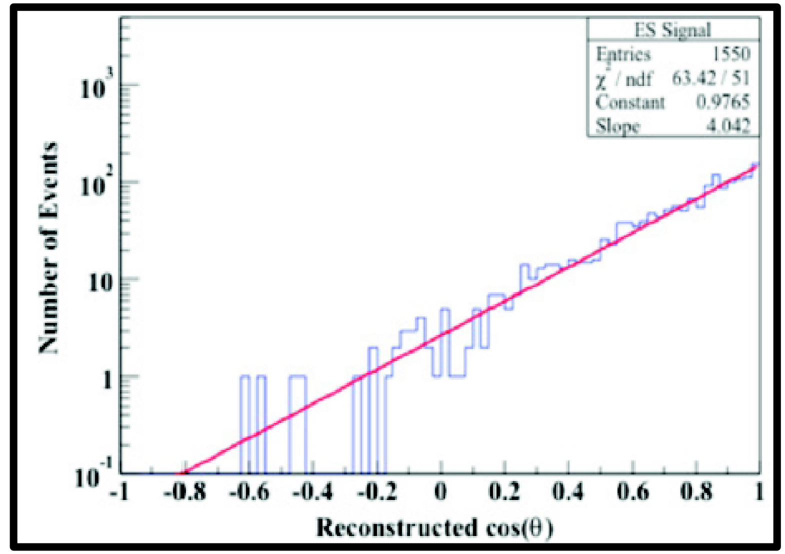
Other possibilities exist for expanding on the WATCHMAN concept, like using the elastic scattering events for directionality.

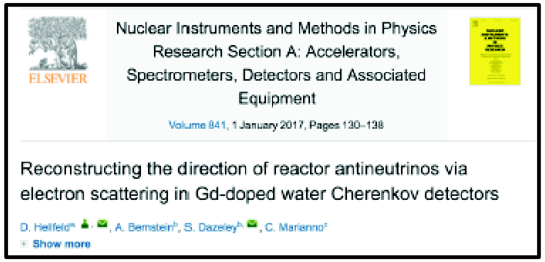


Benefits:

– Ability to distinguish sources when multiple reactors are present
– Ability to locate a clandestine reactor that has been found

Directionality enhances the potential of WATCHMAN, but is not necessary for the original charge.





ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 841, 1 January 2017, Pages 130–138

Reconstructing the direction of reactor antineutrinos via electron scattering in Gd-doped water Cherenkov detectors

D. Hellfeld, A. Bernstein, S. Dazeley, C. Marianno

Show more