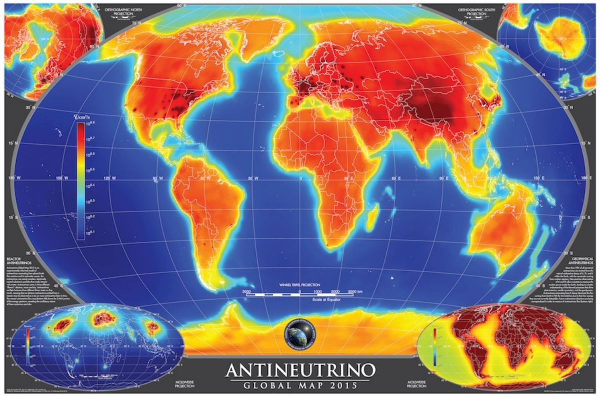
Neutron Dance:
Advanced Antineutrino Detectors for Science & Security

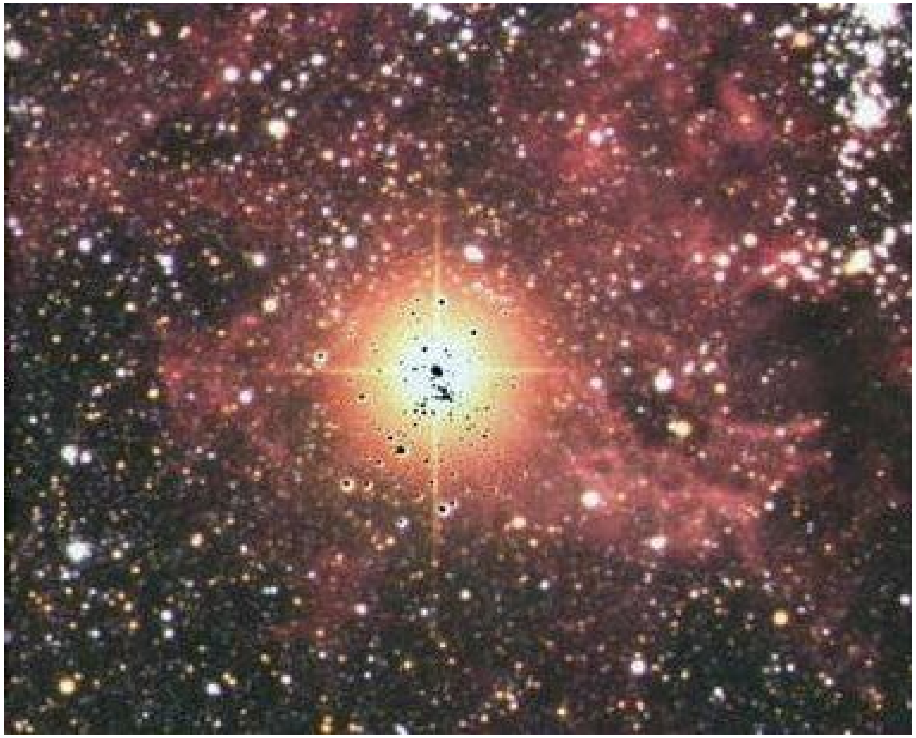


Matthew Malek
The University of Sheffield

NSCR Demokritos – Particle Physics Seminar
22 March 2022

In the Beginning…

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

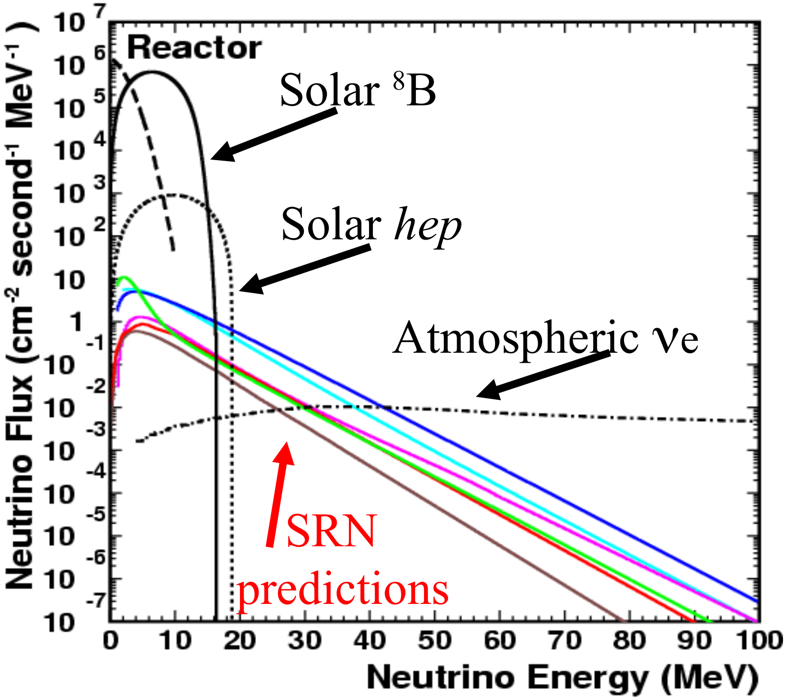


Core-collapse supernova emits ~10^{46} J energy

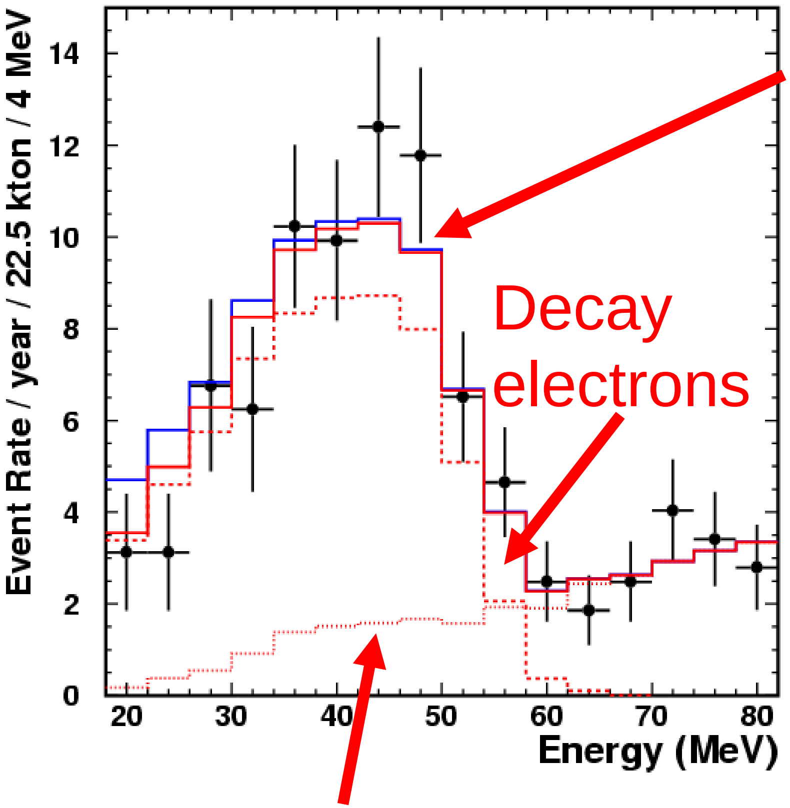
99% is released as neutrinos (all 6 types); mainly from neutrino cooling (also νe from neutronisation burst).

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

Diffuse background of SNν expected from all core-collapse supernovae that have ever exploded



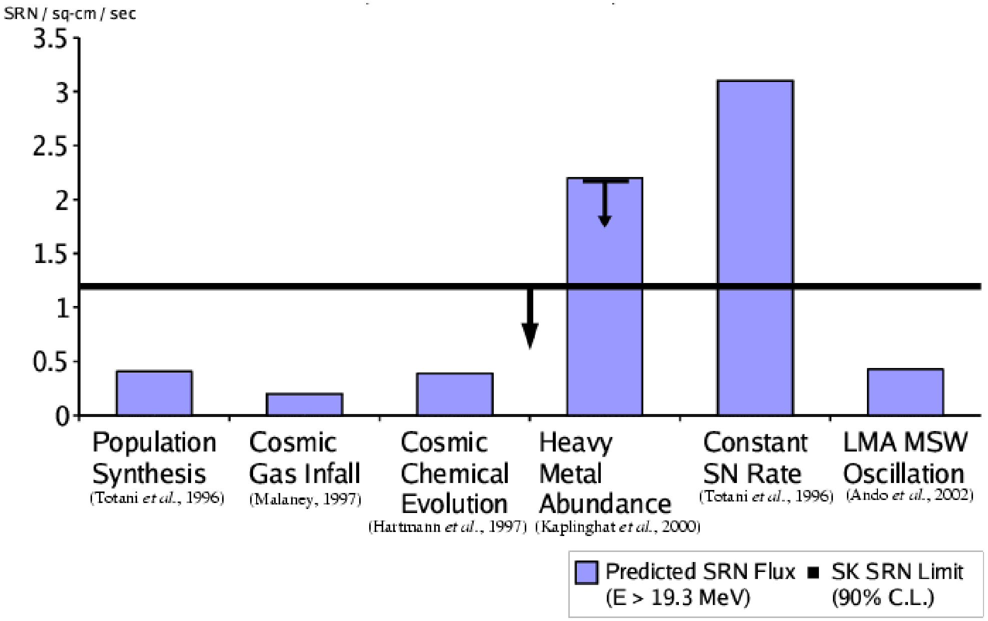
SRN Search Results



Total background (Atm. + decay e)

Decay electrons

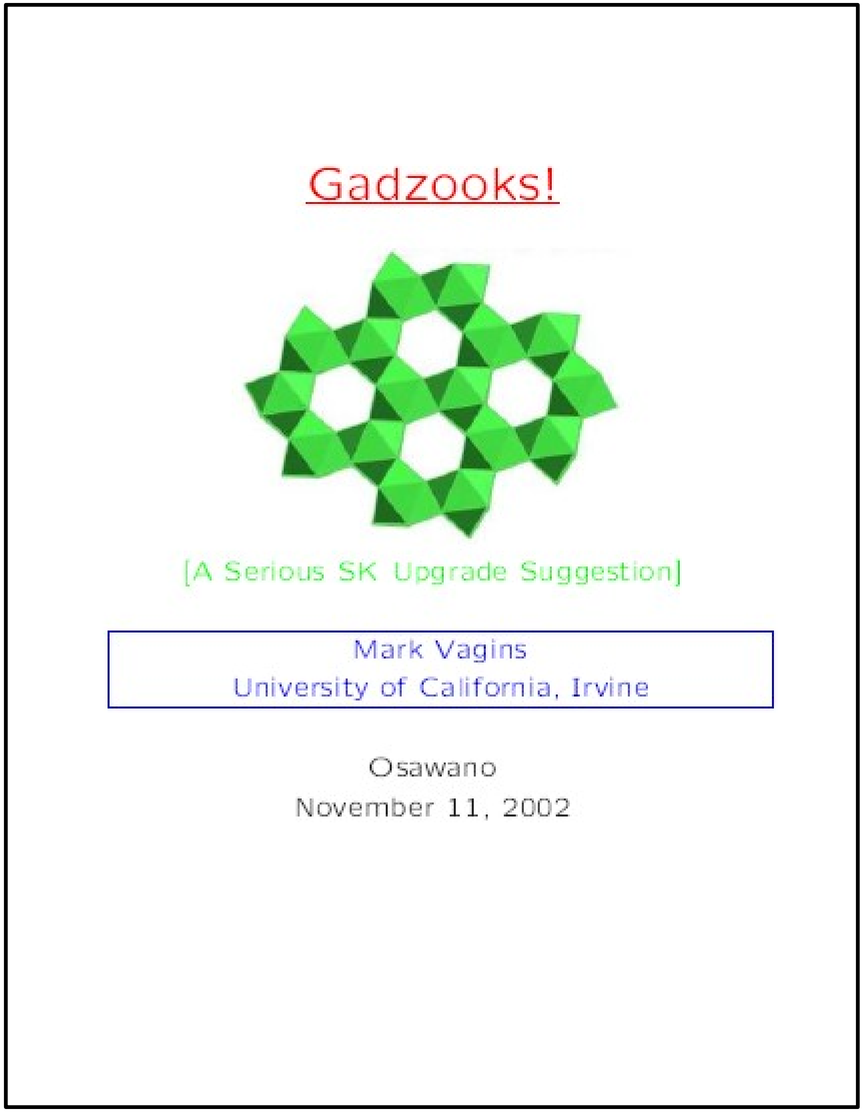
Atmospheric ν_e



- 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

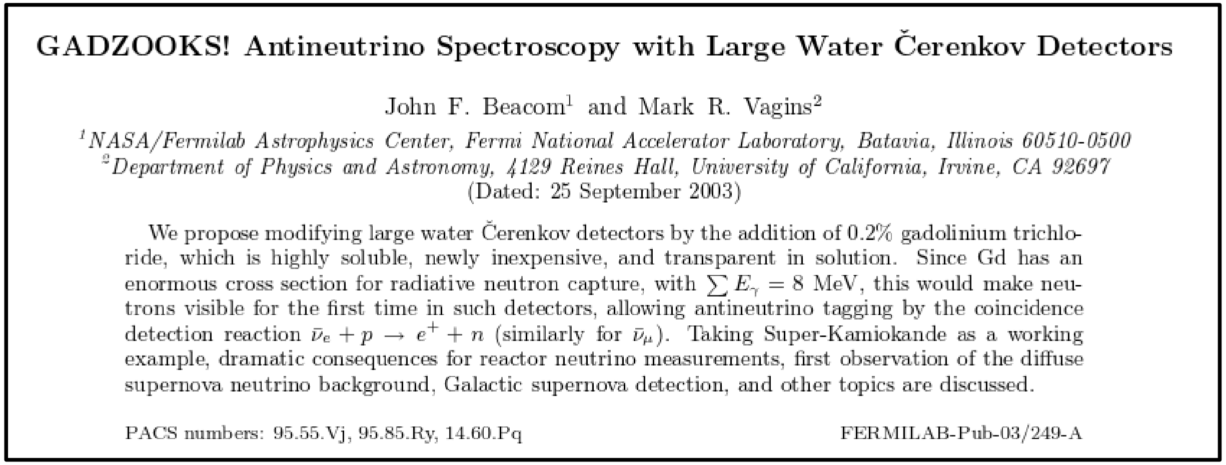


Gadzooks!

[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 $\bar{\nu}_e + p \to e^+ + n$ (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

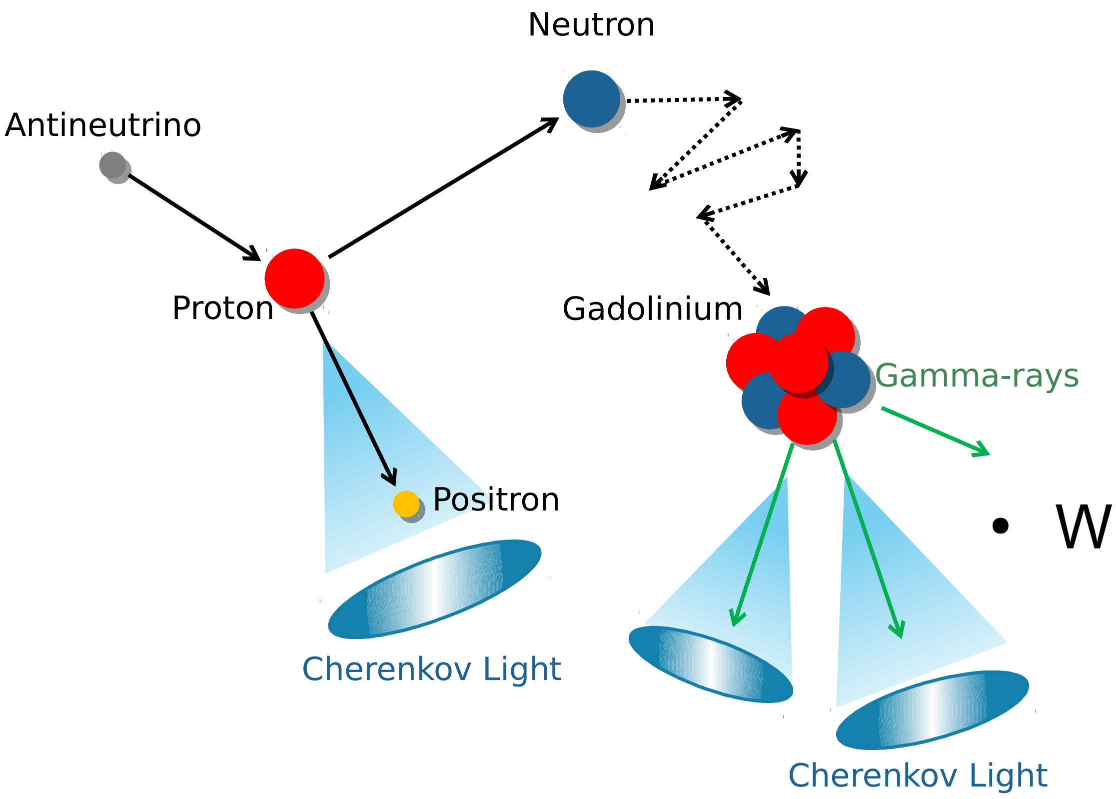
Beacom & Vagins, Phys.Rev.Lett. **93:171101** (2004)

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

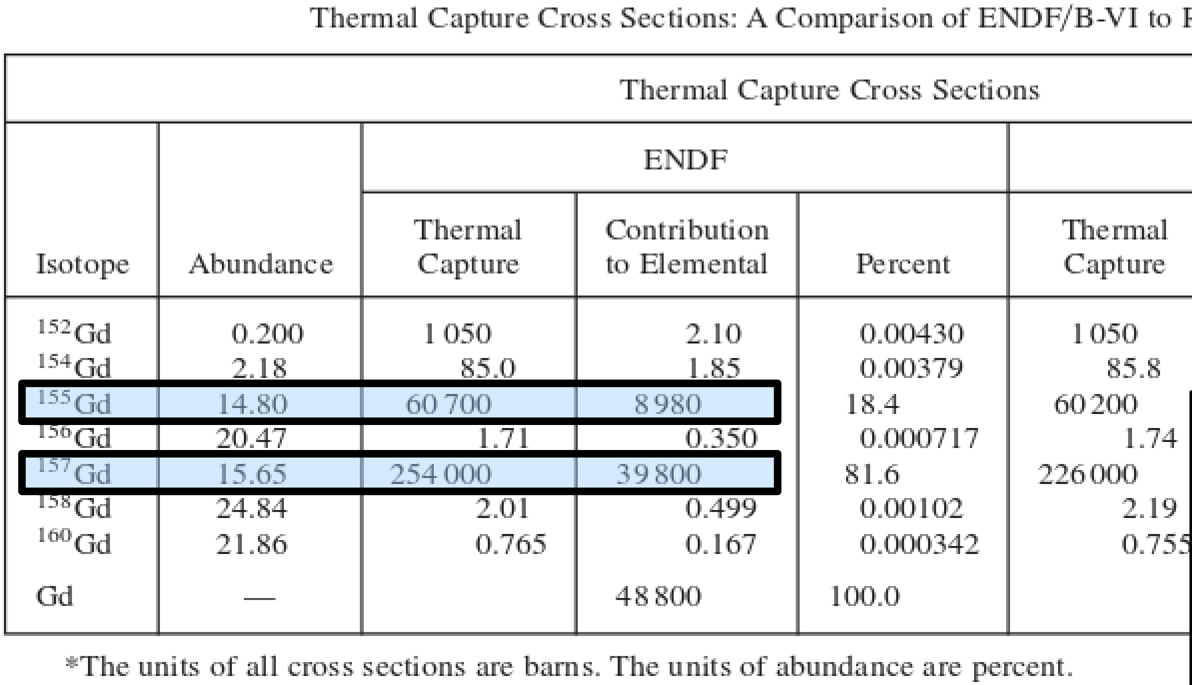
Tag antineutrinos via <u>coincidence</u> between positron and neutron from inverse beta decay:



- 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 ~30 μsec
  - ~8 MeV gamma cascade
  - 4 - 5 MeV visible energy
  - > 70% detection efficiency

Gd Capture X-Sections



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

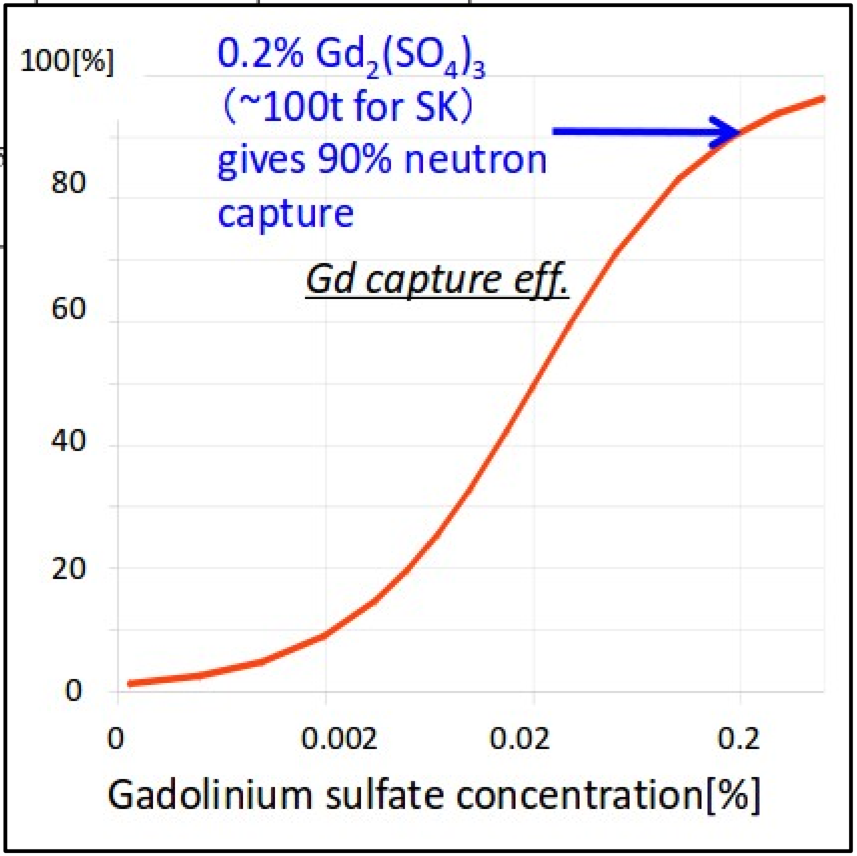
Thermal Capture Cross Sections							
		ENDF			RPI		
Isotope	Abundance	Thermal Capture	Contribution to Elemental	Percent	Thermal Capture	Contribution to Elemental	Percent
^{152}Gd	0.200	1 050	2.10	0.00430	1 050	2.10	0.00430
^{154}Gd	2.18	85.0	1.85	0.00379	85.8	1.87	0.00422
^{155}Gd	14.80	60 700	8 980	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



0.2% $Gd_2(SO_4)_3$
(~100t for SK)
gives 90% neutron capture

Gd capture eff.

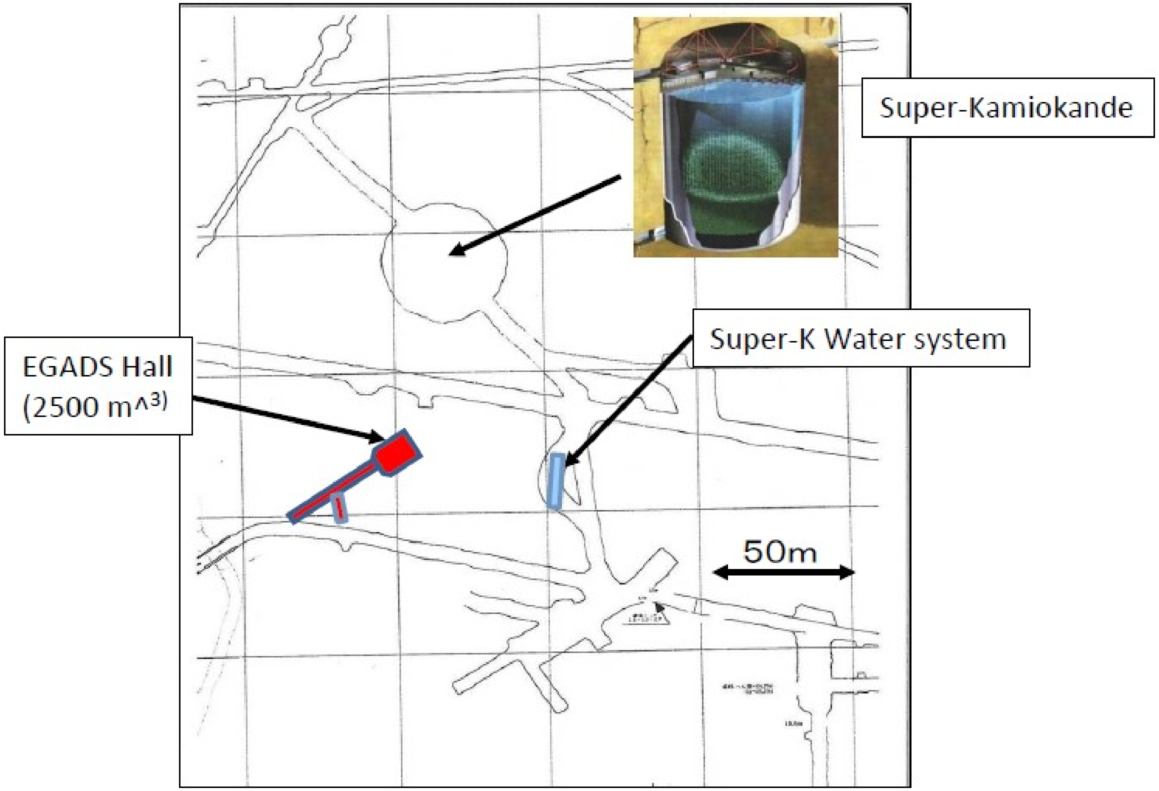
The EGADS Facility

EGADS = Evaluating Gadolinium's Action on Detector Systems

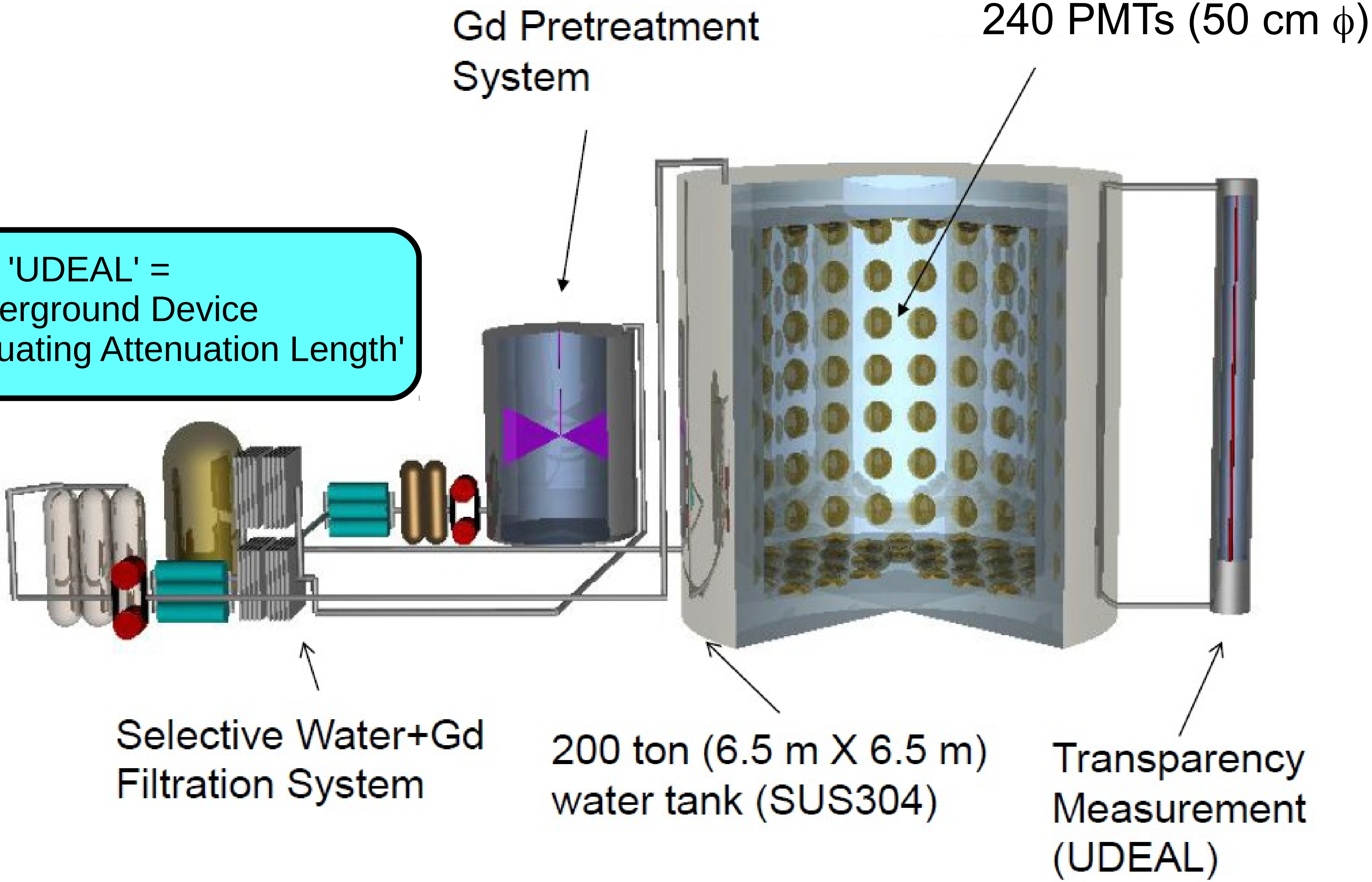
Dedicated test facility commissioned at Kamioka Observatory.

EGADS is a:

- 200 tonne R&D project, charged with establishing the technical viability of loading Gd into water Cherenkov detectors
- Uses $Gd_2[SO_4]_3$ (Gadolinium Sulphate) at 0.2% concentration
- Facility has its own water filtration system, 50 cm PMTs, DAQ, etc.

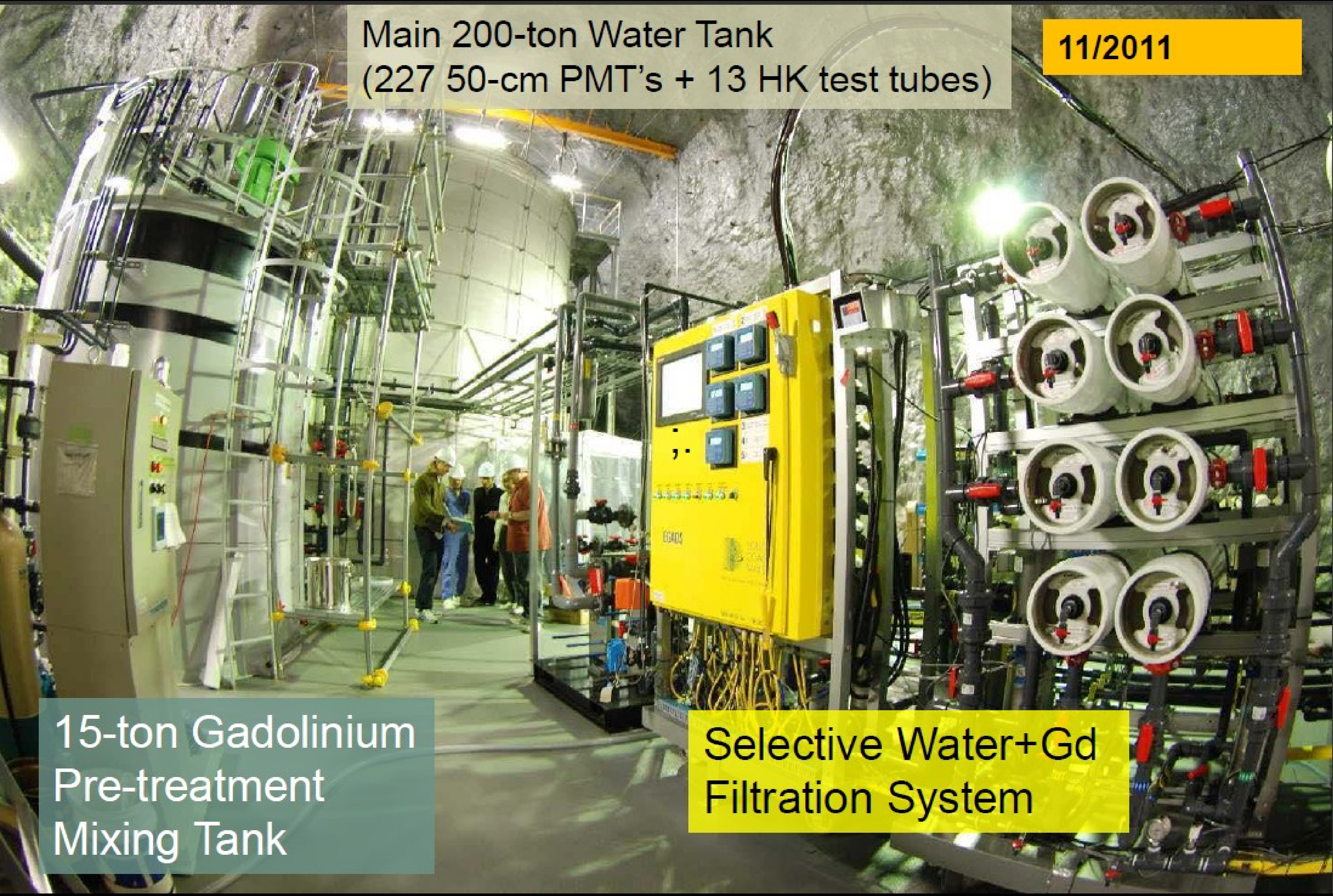


EGADS Facility



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

EGADS Facility



Main 200-ton Water Tank
(227 50-cm PMT's + 13 HK test tubes)

11/2011

15-ton Gadolinium
Pre-treatment
Mixing Tank

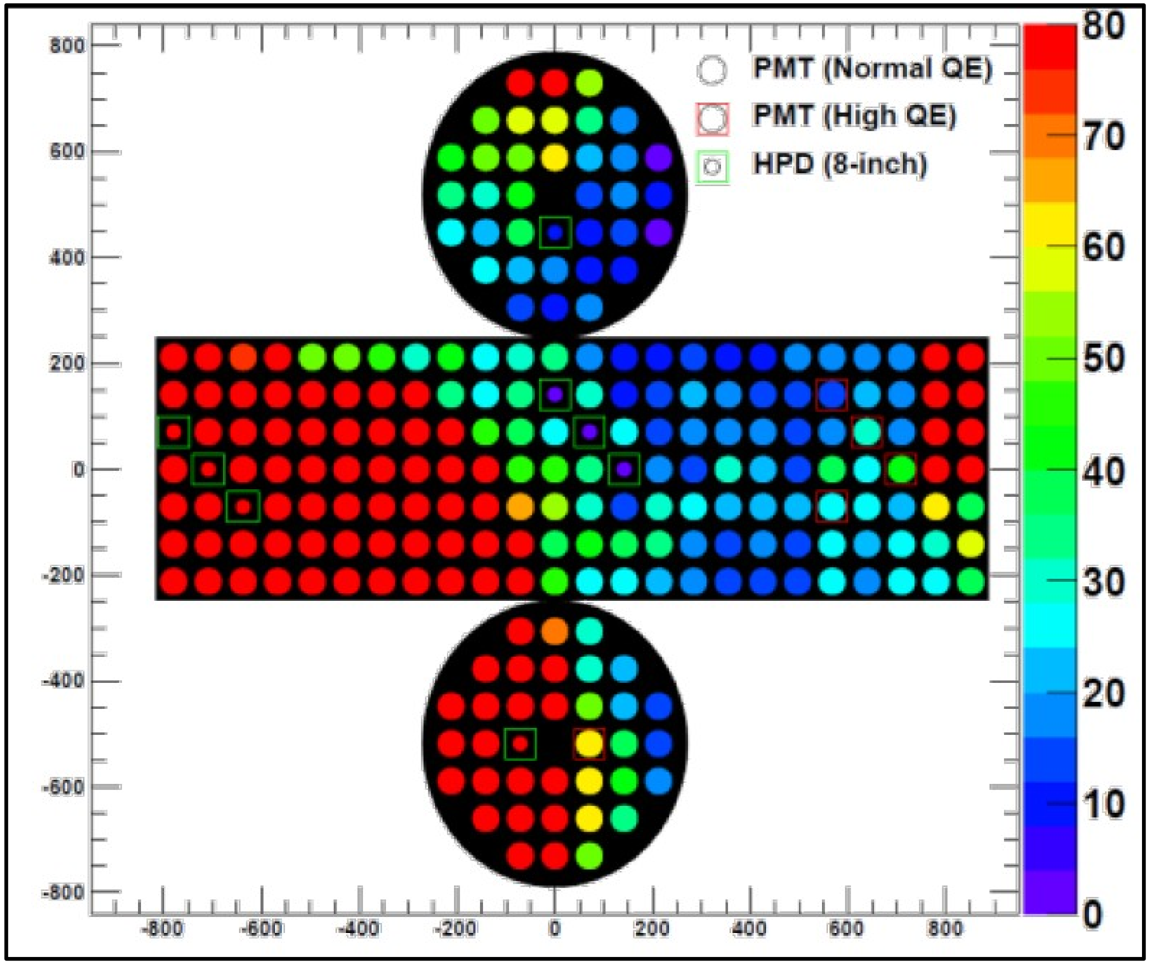
Selective Water+Gd
Filtration System

EGADS Facility

Ready for filling:
8th August 2013

EGADS Data Taking

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)

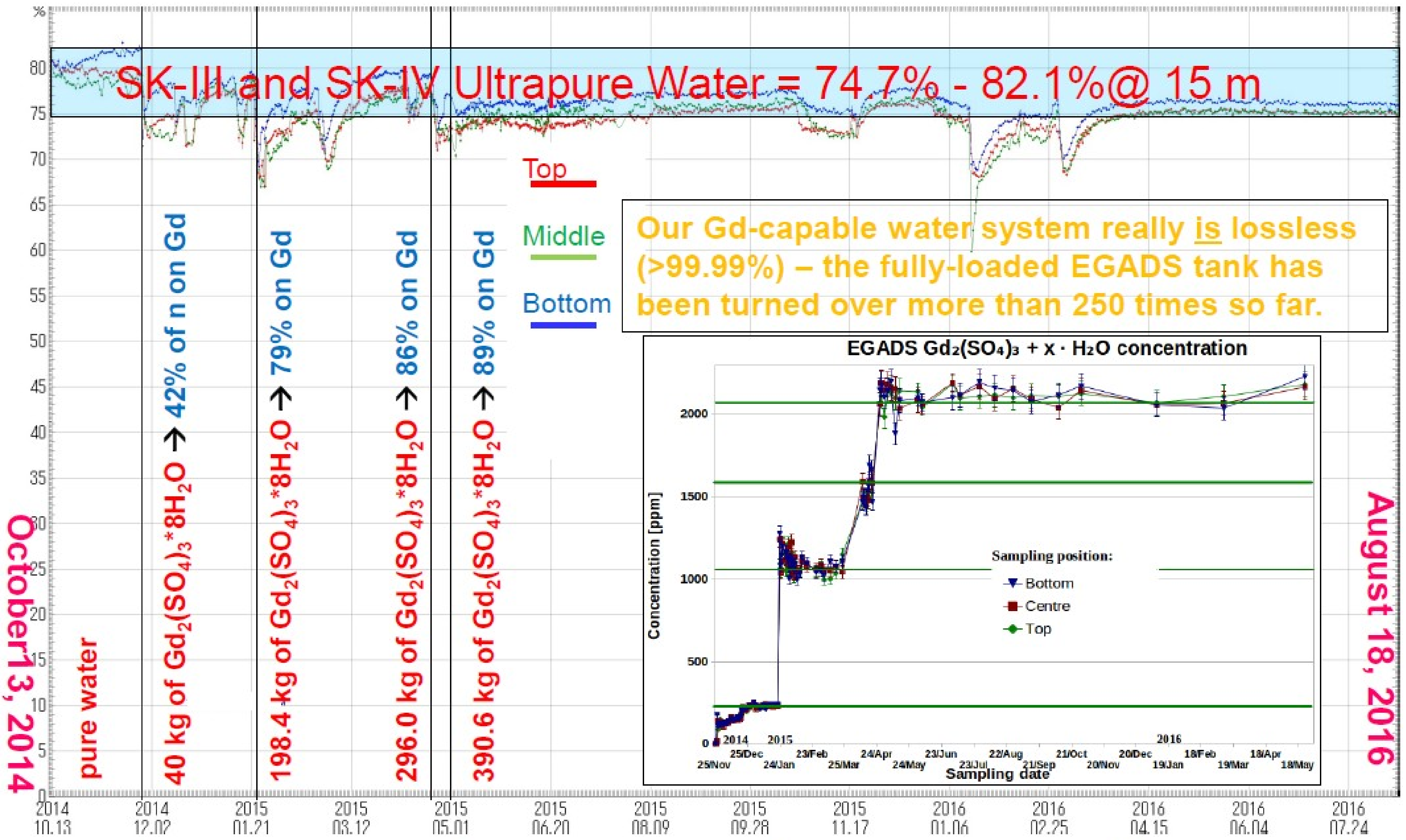
No problems encountered in this time period

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



SK-III and SK-IV Ultrapure Water = 74.7% - 82.1%@ 15 m

Our Gd-capable water system really <u>is</u> lossless (>99.99%) – the fully-loaded EGADS tank has been turned over more than 250 times so far.

October 13, 2014

pure water

40 kg of $Gd_2(SO_4)_3{*}8H_2O$ → 42% of n on Gd

198.4 kg of $Gd_2(SO_4)_3{*}8H_2O$ → 79% on Gd

296.0 kg of $Gd_2(SO_4)_3{*}8H_2O$ → 86% on Gd

390.6 kg of $Gd_2(SO_4)_3{*}8H_2O$ → 89% on Gd

August 18, 2016

EGADS $Gd_2(SO_4)_3 + x \cdot H_2O$ concentration

Gadolinium Loading → Steady-state Operations → Water System Tuning Studies → Steady-state Operations

What's Past is Prologue[*]

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.

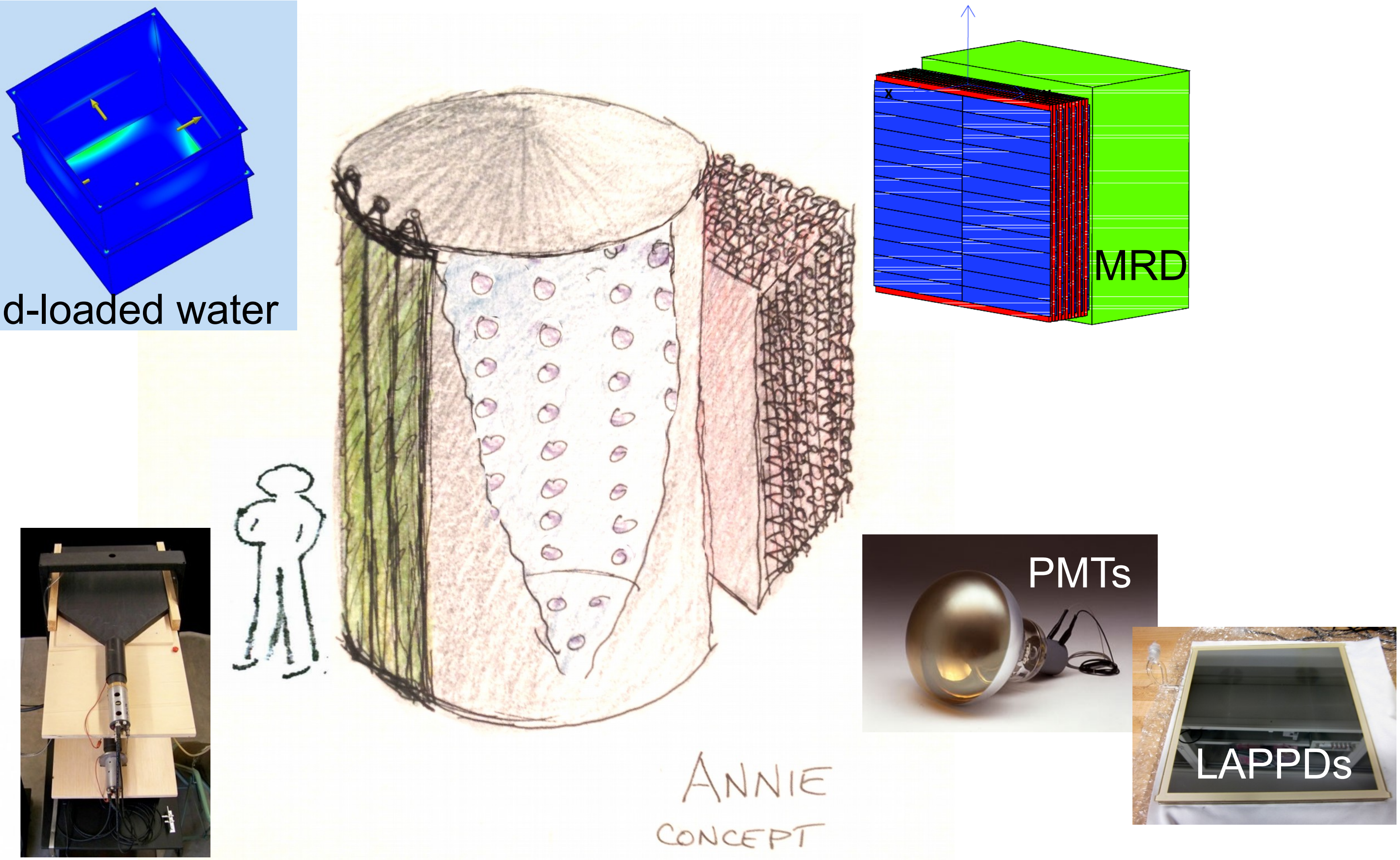
These include.....

[*] “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

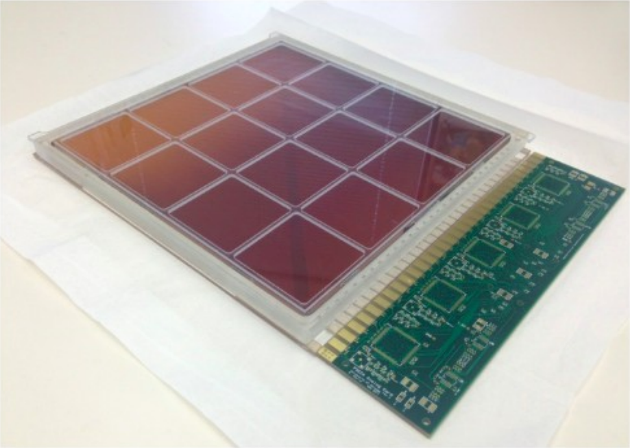


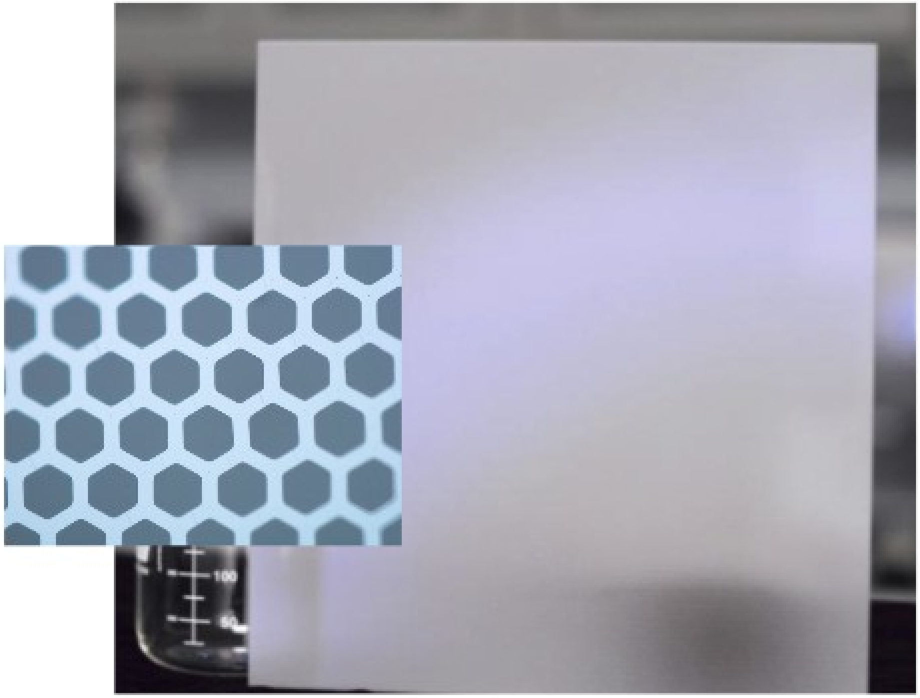
LAPPD Overview

- Overview of **L**arge **A**rea **P**icosecond **P**hoto-**D**etectors:

LAPPDs are:

- 400 cm^2 sensors (20cm x 20 cm)
- Based on microchannel plate technology (MCPs) [see next slide]
- Excellent resolutions:
    - Spatial: < 1 cm
    - Timing: < 100 ps (TTS)
- Capable of imaging single photons

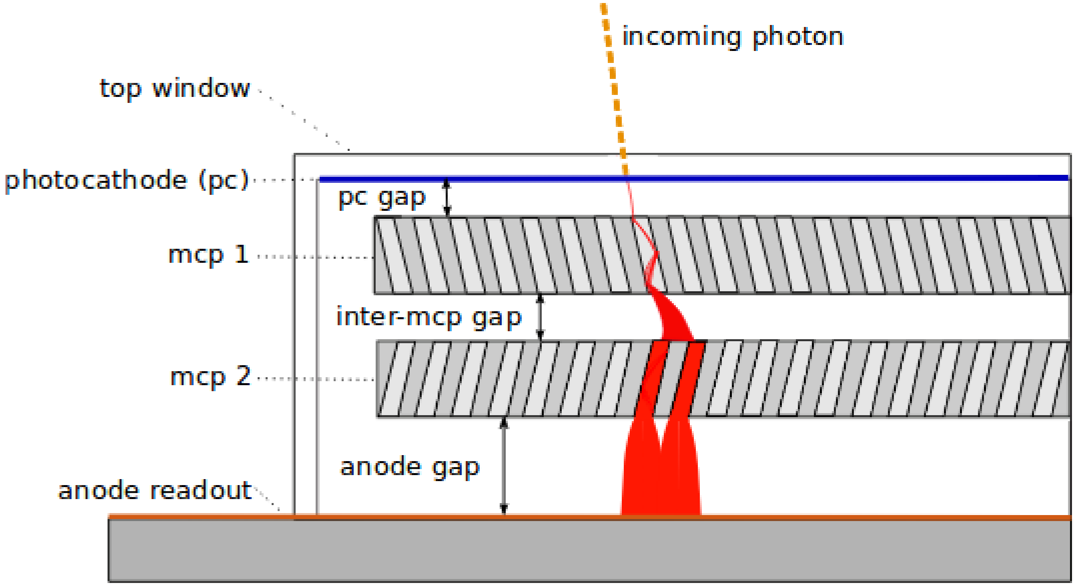




Microchannel Plate PMTs

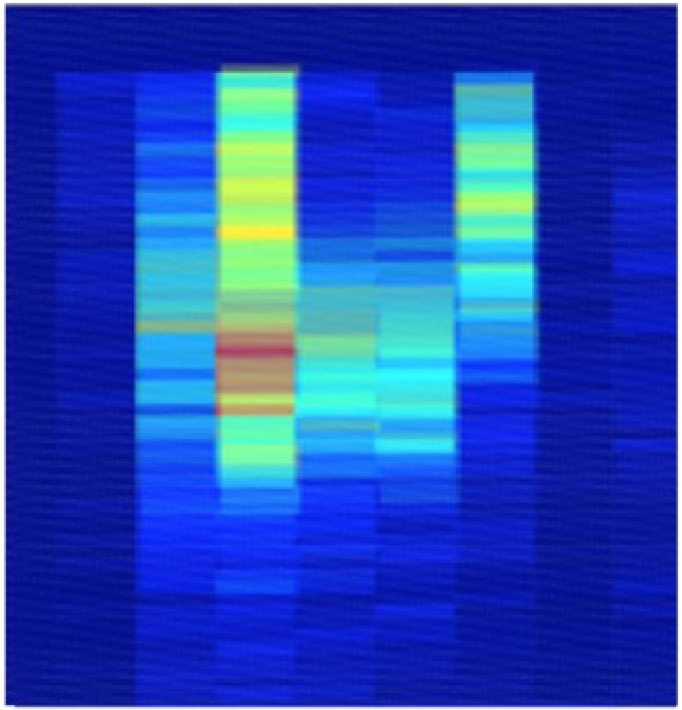
Microchannel plates themselves are not new technology
- Example: Used in night vision goggles since 1970s

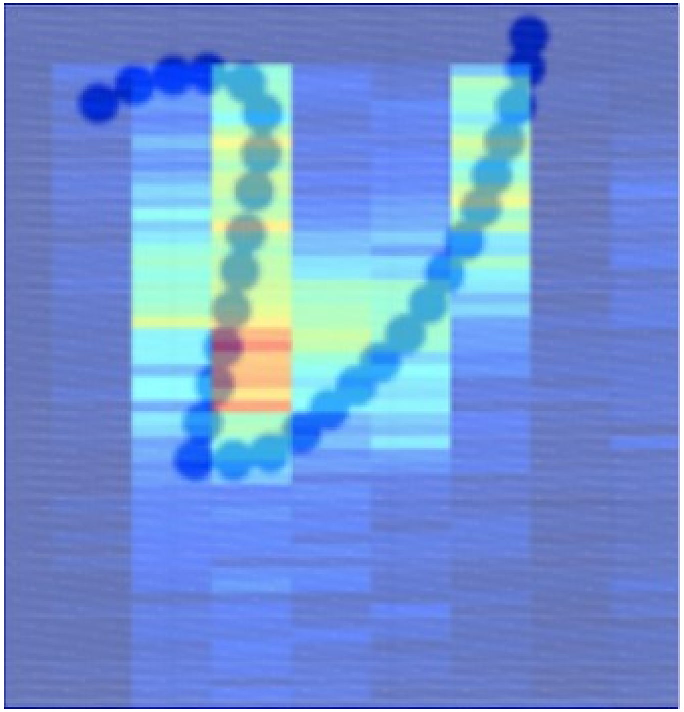
MCP PMTs are also not new
- Photonis Planacon has been in production for many years
- Limitations:
  - Small (~5cm x 5cm)
  - Expensive (~$10k)



The LAPPD project was formed in 2009 to make this technology practical for particle physics experiments!

MCP-PMT Imaging





For more information, please see:

A Brief Technical History of the Large-Area Picosecond Photodetector Collaboration (Adams *et al*, 2016) – https://arxiv.org/abs/1603.01843

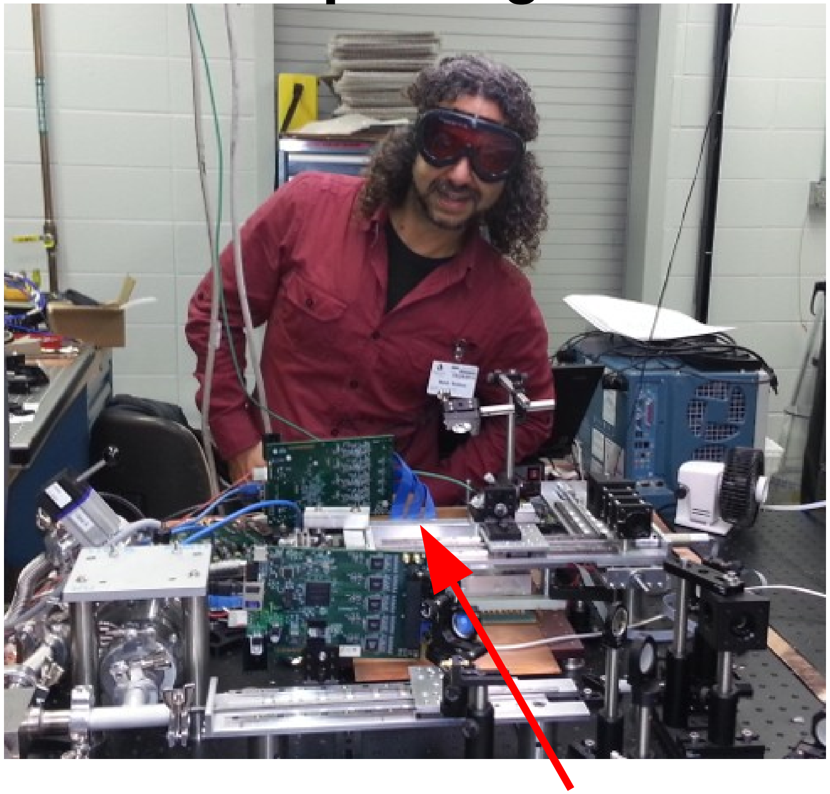
LAPPDs Milestones

Initial work focussed on advancing separate work packages

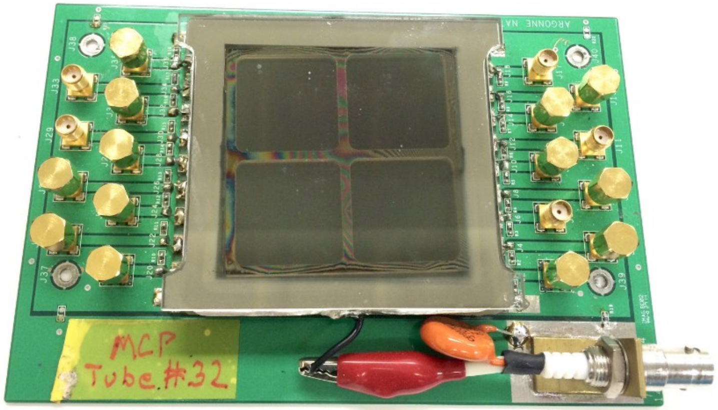
•

- Example: First “working” LAPPD had functional MCP… but needed to be continuously pumped <u>and</u> had a poor photocathode (aluminium)

- Small-scale (6cm x 6cm) prototype tiles were produced at Argonne National Lab to develop photocathode, electronics, etc.



First working LAPPD!
[not sealed; aluminium photocathode (QE = 10^{-7})]



For UK-based tests with the Argonne MCP-PMT, see:

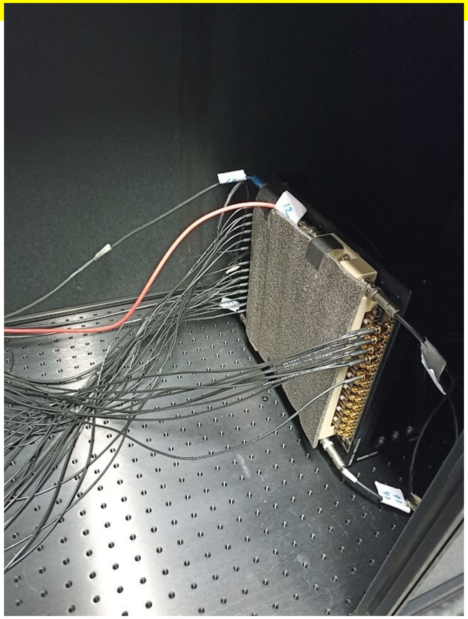
Characterisation and testing of a prototype 6 x 6 cm^2 Argonne MCP-PMT (G. A. Cowan *et al* 2016)
https://arxiv.org/pdf/1611.00185.pdf

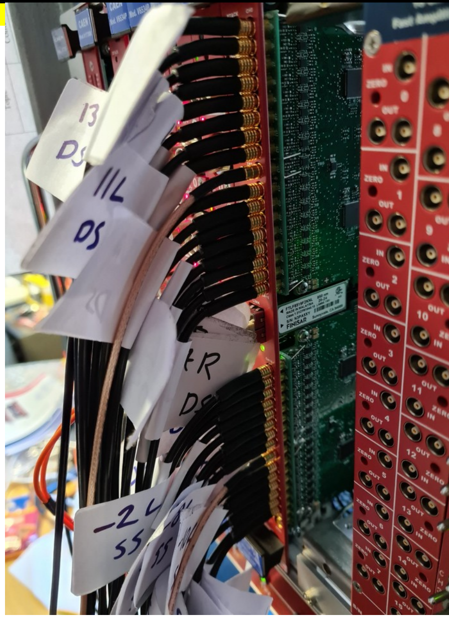
Initial Setup @ Sheffield

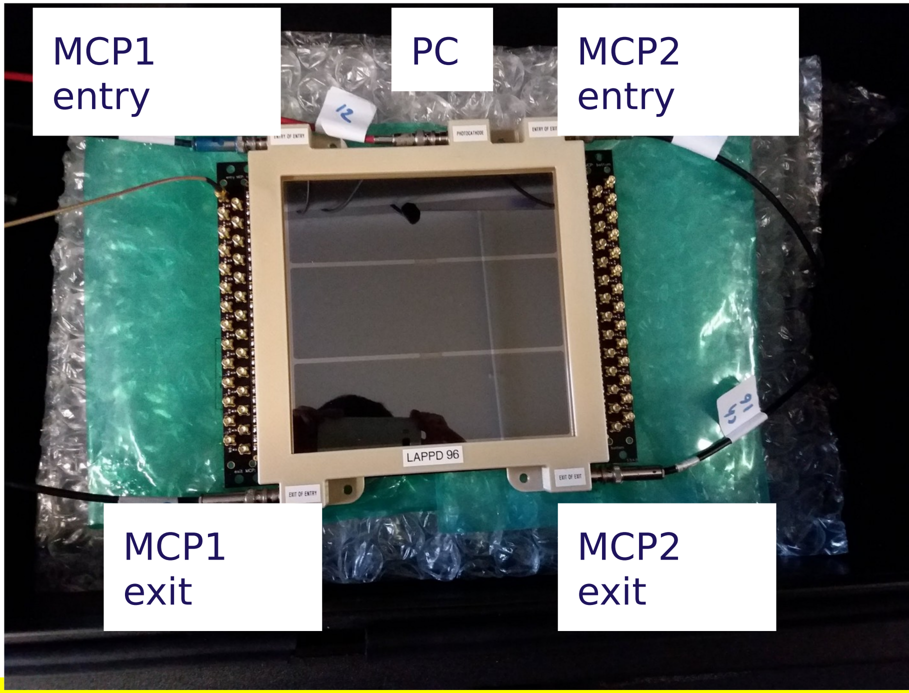
LAPPD 96 housed in custom dark box

- 5 HV connections used
  - Each MCP needs for entry + exit
  - Reminder: 2 MCPs per LAPPD
  - Also apply HV to photocathode
  - Resistor chain added (see next slide)

- Readout:
  - Initially used commercial scope (Tektronix 6)
  - Now using 32-channel VME digitiser (5 GS/s) from CAEN
  - Will transition later to PSEC
  - Signals via Incom SMA pickup

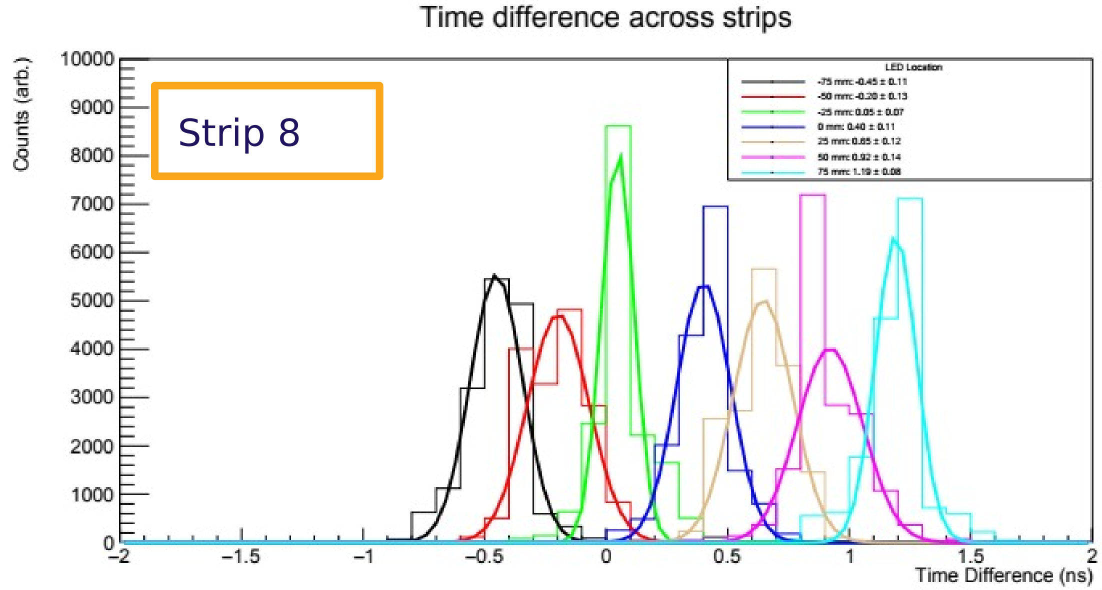


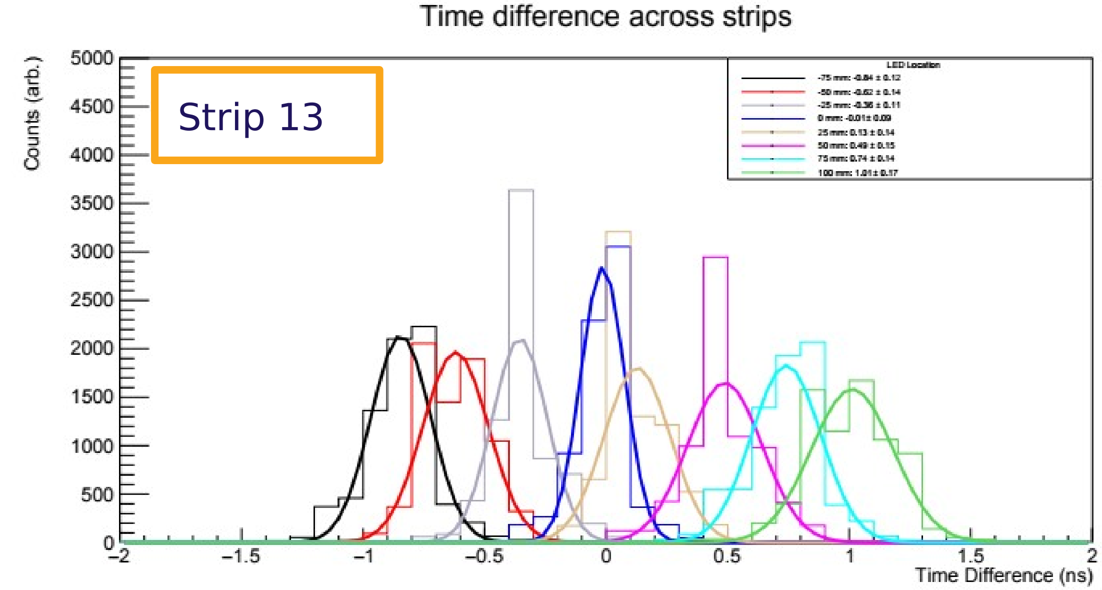




Initial Measurements

Timing & position





HOT OFF THE PRESS!

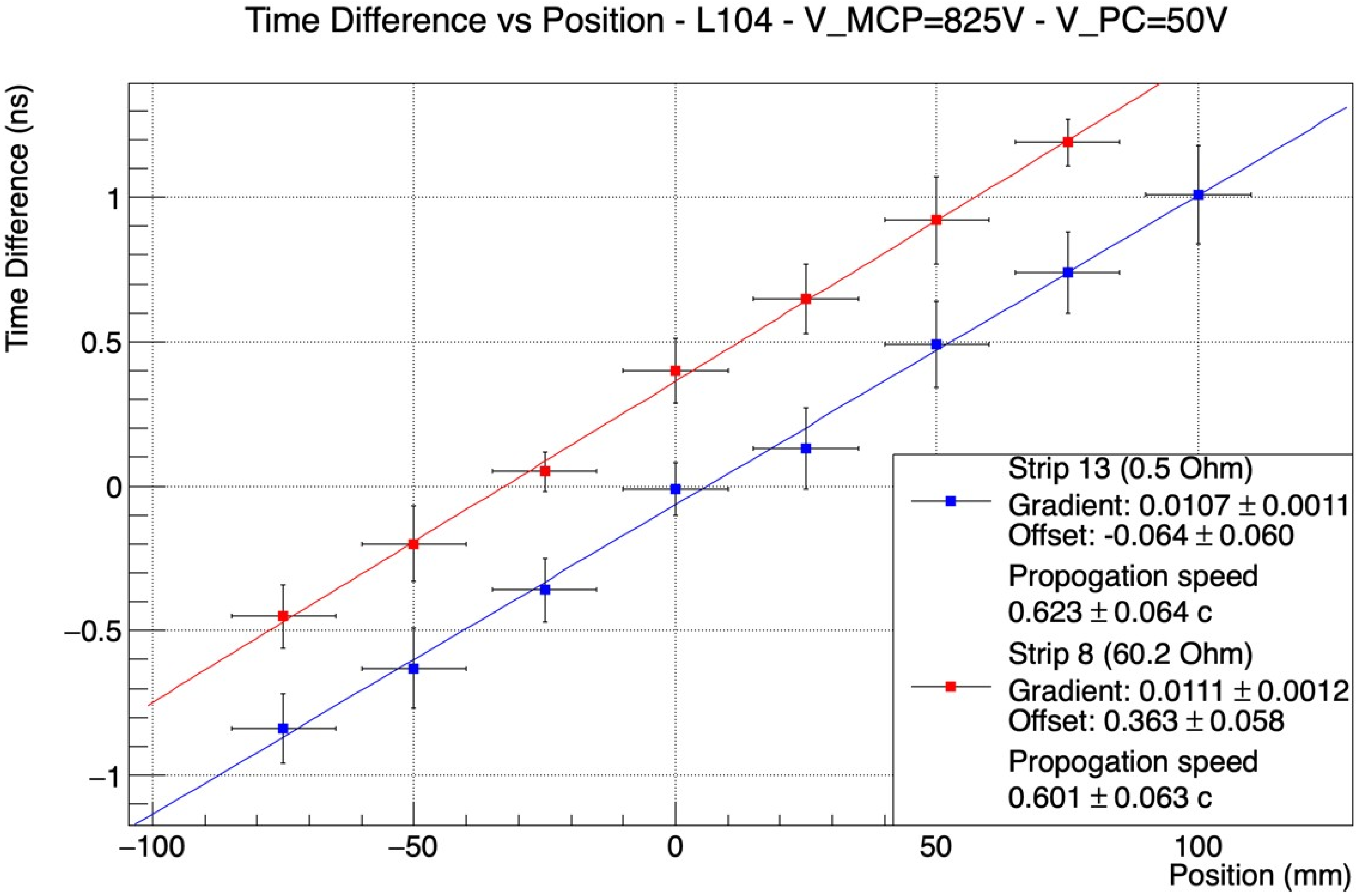
•(Last week!)

Measurements made by stepping LED along the strip (parallel) in 25mm increments:

- -75 mm
- -50 mm
- -25 mm
- 0 mm
- +25 mm
- +50 mm
- +75 mm

Strong position tracking is clearly visible (see next slide)

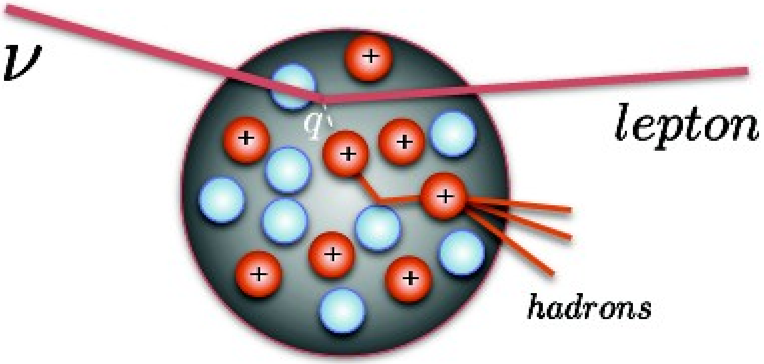
Initial Measurements

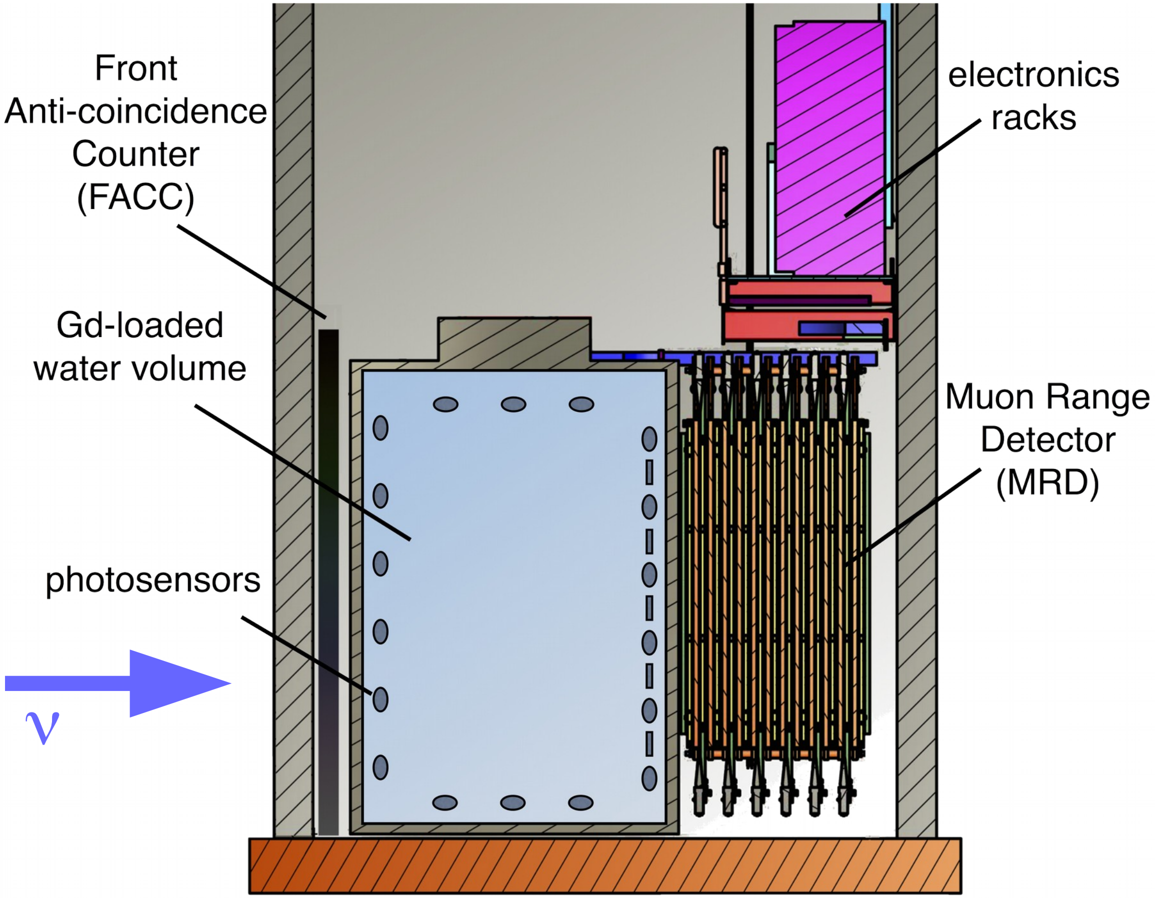


The ANNIE Experiment

Primary physics objective:

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





Current status:

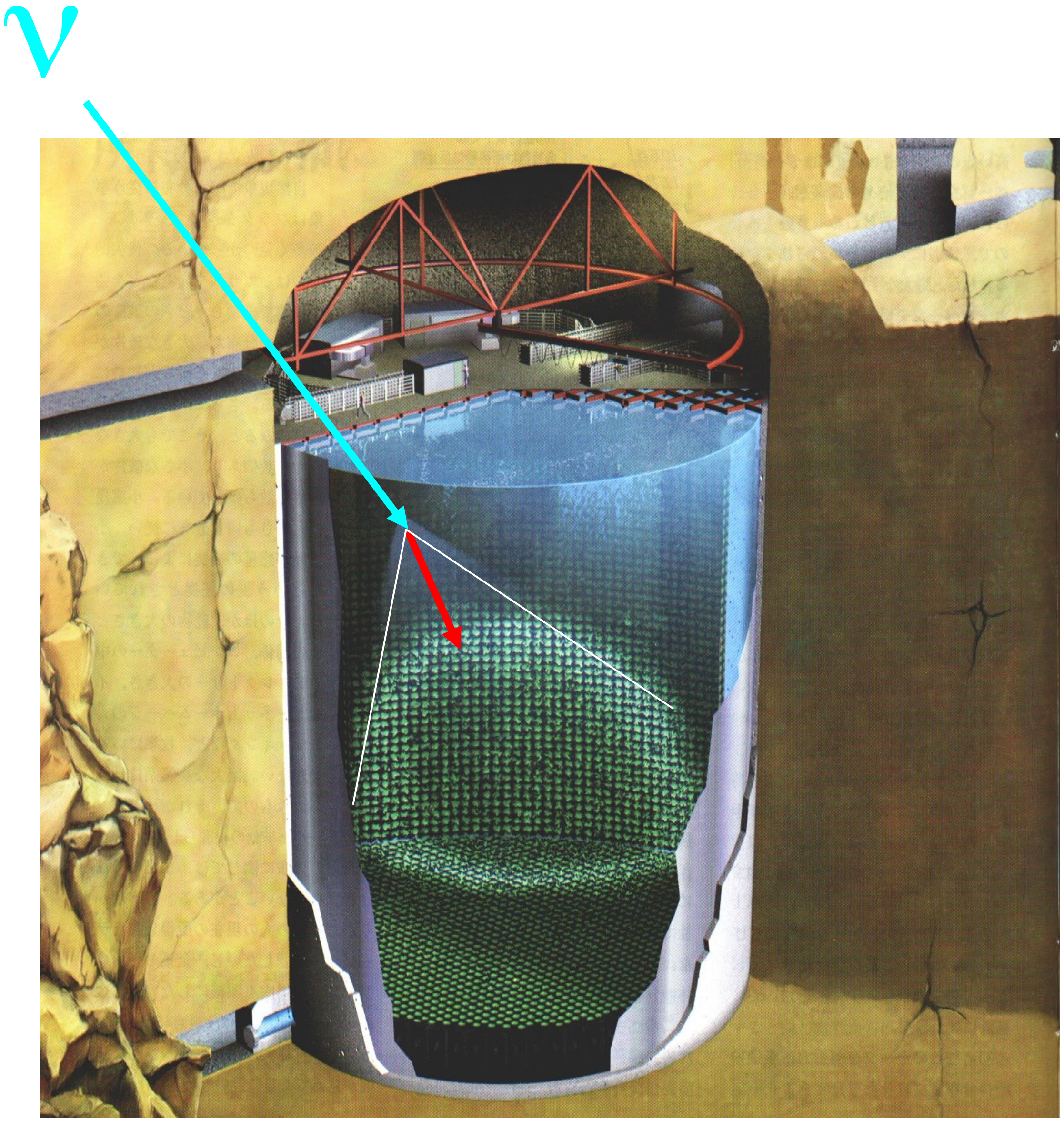
All PMTs installed

26 tonne water volume is fully loaded with Gadolinium

MRD completed
LAPPDs being prepared

Commissioning w/ beam data NOW

SK-Gd



In 2020, the Super-Kamiokande collaboration added 0.02% $Gd_2[SO_4]_3$ 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 uses SK-Gd as the far detector.

COMING SOON: In May 2022, the concentration will be tripled!

The Story So Far...

To recap:

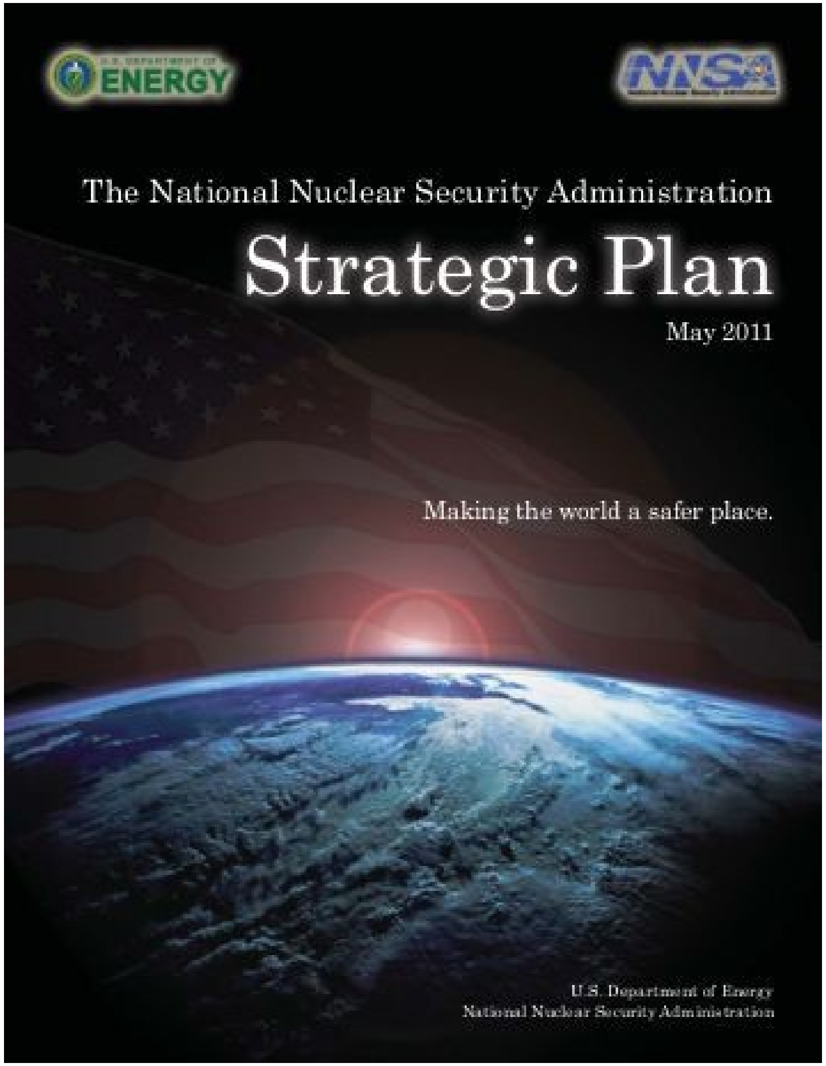
The motivation is clear; loading water Cherenkov neutrinos detectors with gadolinium brings new life to an old technology.

The **technical** capability has been demonstrated.

The **physics** benefit is well-established, with implementation at scales ranging from 26 tonnes (ANNIE) to 50,000 tonnes (Super-K), starting this year, and other experiments (*e.g.*, WCTE, IWCD) continuing to turn on over the next decade.

That's great... but what about security applications?

The WATCHMAN Charge



The National Nuclear Security Administration

Strategic Plan

May 2011

Making the world a safer place.

U.S. Department of Energy
National Nuclear Security Administration

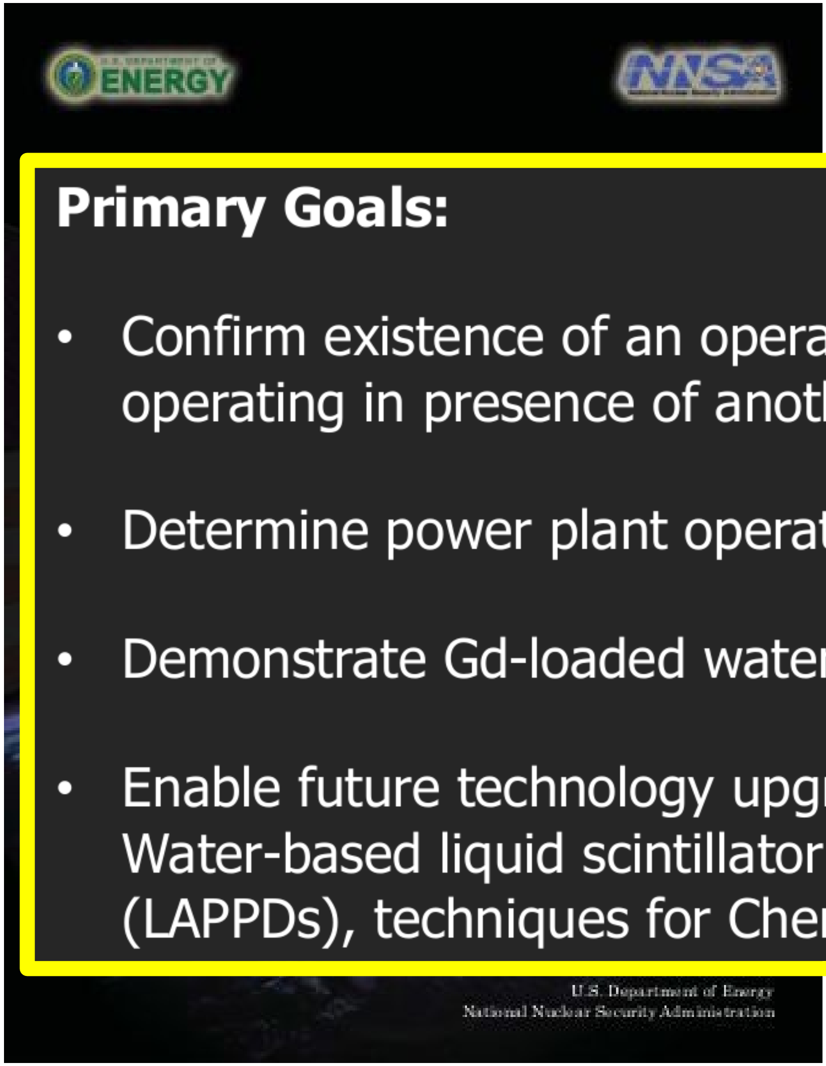
The goal of the WATCHMAN project is to harness the techniques described earlier for nuclear threat reduction.

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

UK involvement via **Ministry of Defence** (MoD) under 1958 US-UK Mutual Defence Agreement.

Main funding in UK from **Science & Technology Facility Council** (STFC) via an award from the **UKRI** Fund for International Collaboration.

The WATCHMAN Charge



The goal of the WATCHMAN project is to harness the techniques described earlier for

Primary Goals:

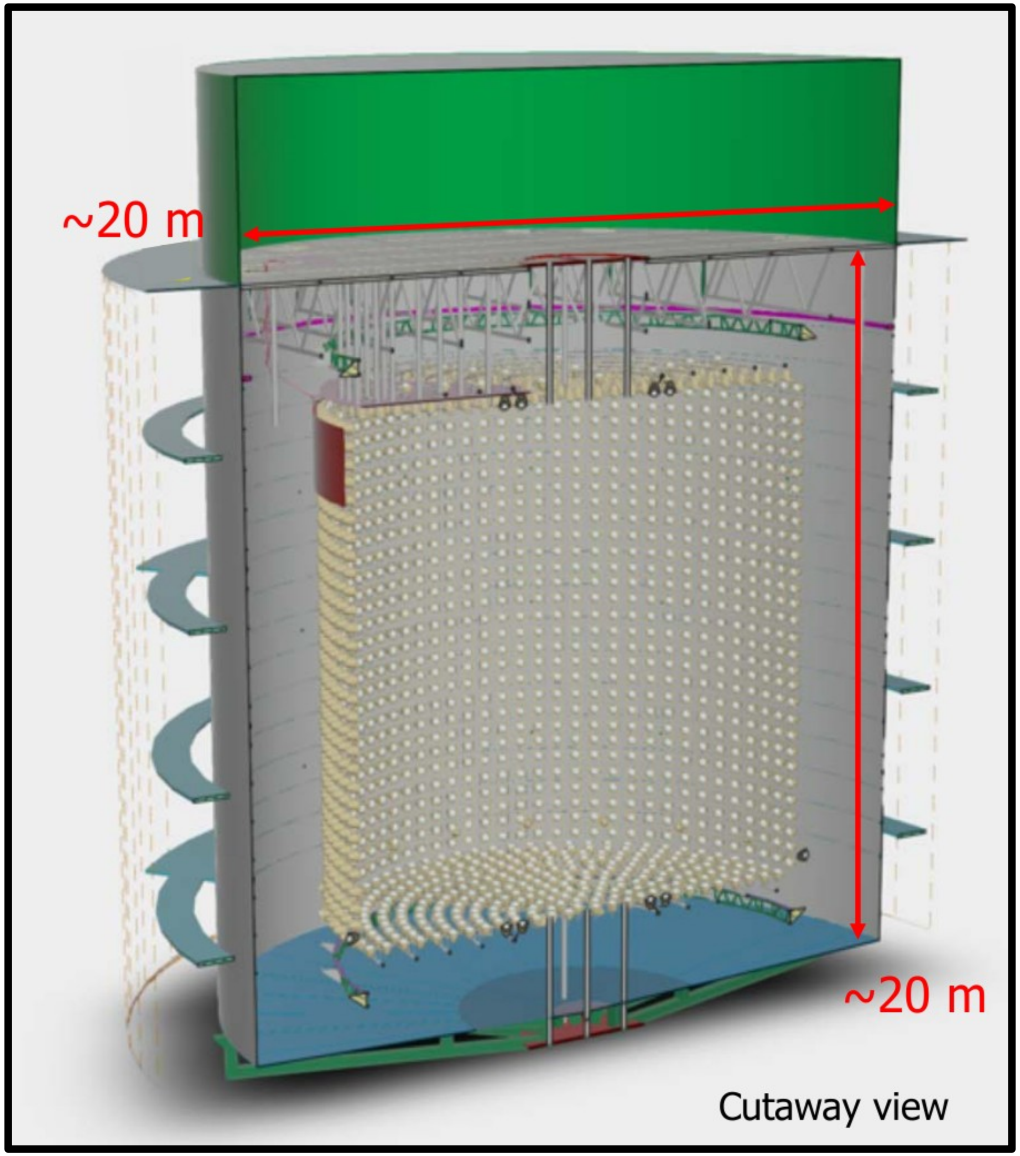
- Confirm existence of an operating reactor (ie. determine unknown reactor is operating in presence of another known reactor)
- Determine power plant operational status with and without prior knowledge
- Demonstrate Gd-loaded water as a scalable detector medium
- Enable future technology upgrades:
  Water-based liquid scintillator WbLS, Large-Area Picosecond Photodetectors (LAPPDs), techniques for Cherenkov and scintillation light separation, etc.

Collaboration.

The WATCHMAN Design

Baseline design includes:

- ~1 ktonne fiducial mass
- 0.1% Gd-loaded water
- ~3600 Hamamatsu 10” PMTs with:
  - High quantum efficiency (~30%)
  - Low radioactivity (esp. U and Th)
  - 20% photocathode coverage
- Active veto region (~1 metre)
- Multiple access points:
  - Calibration ports
  - Large central plug



Cutaway view

WATCHMAN Collaboration

The
WATCHMAN
Collaboration

By the numbers:
- 2 countries (US & UK)
- 21 universities
- 3 US laboratories
- 2 UK laboratories
- 125 total collaborators

UK participation:
- 5 universities (so far): Sheffield plus Glasgow, Edinburgh, Liverpool, Warwick
- STFC-Boulby Underground Lab
- Atomic Weapons Establishment
- ~50 total collaborators
- £9.7M funding from STFC (via UKRI Fund for International Collab.)
- £1M funding from Ministry of Defence

WATCHMAN Collaboration

WATCHMAN Site

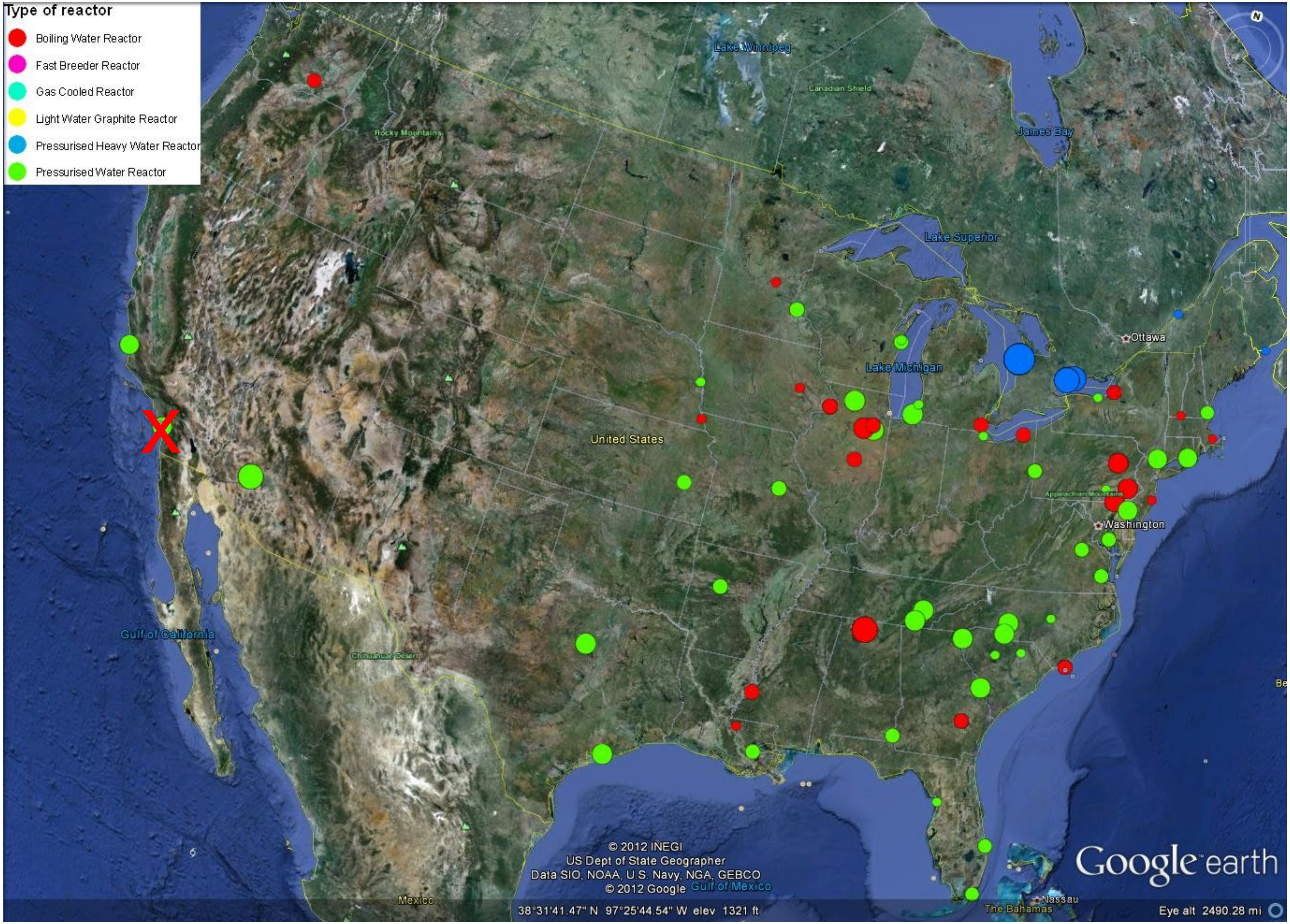
The ideal WATCHMAN prototype site requires:

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

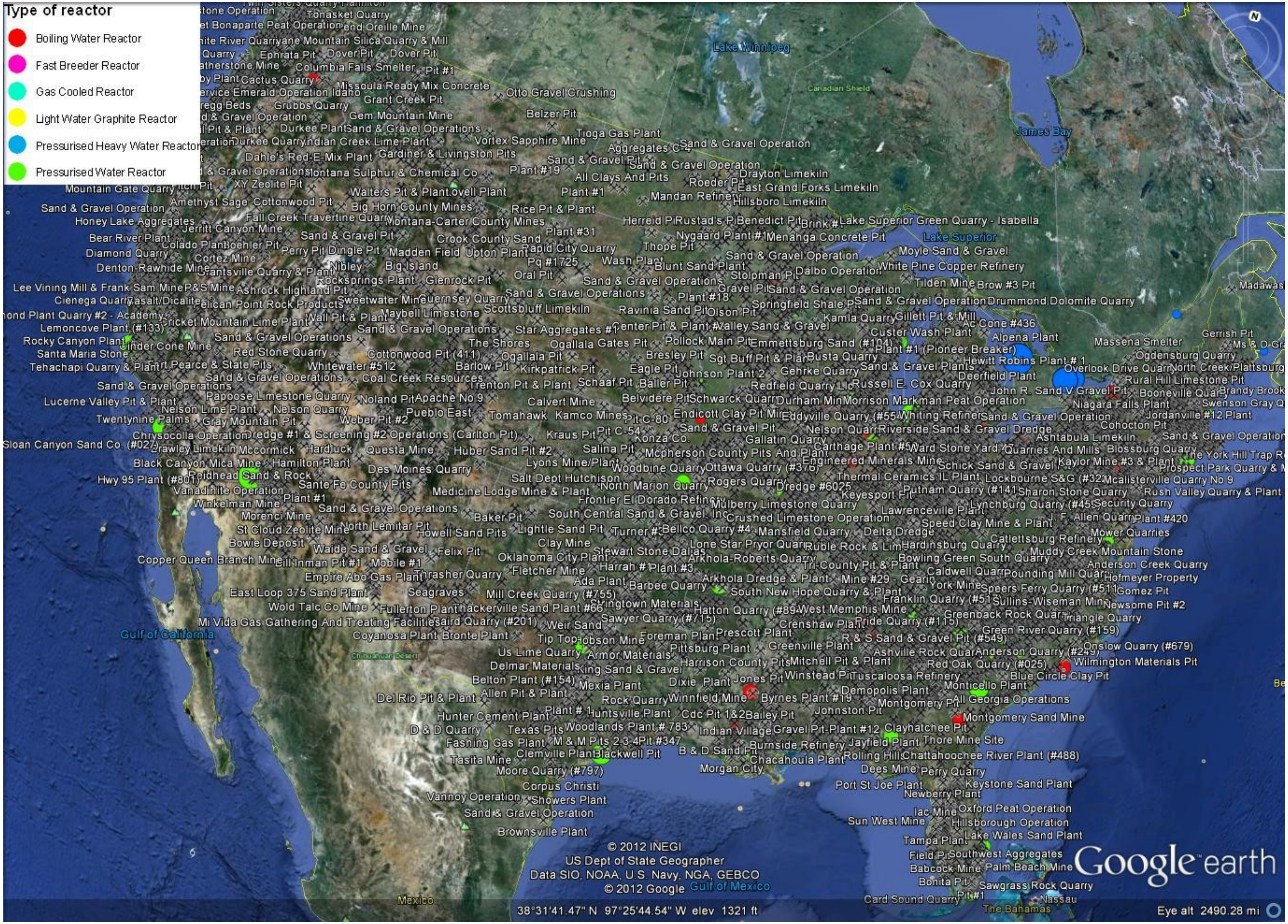
(b) a nuclear reactor

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

Map of US Power Reactors



Map of US Active 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

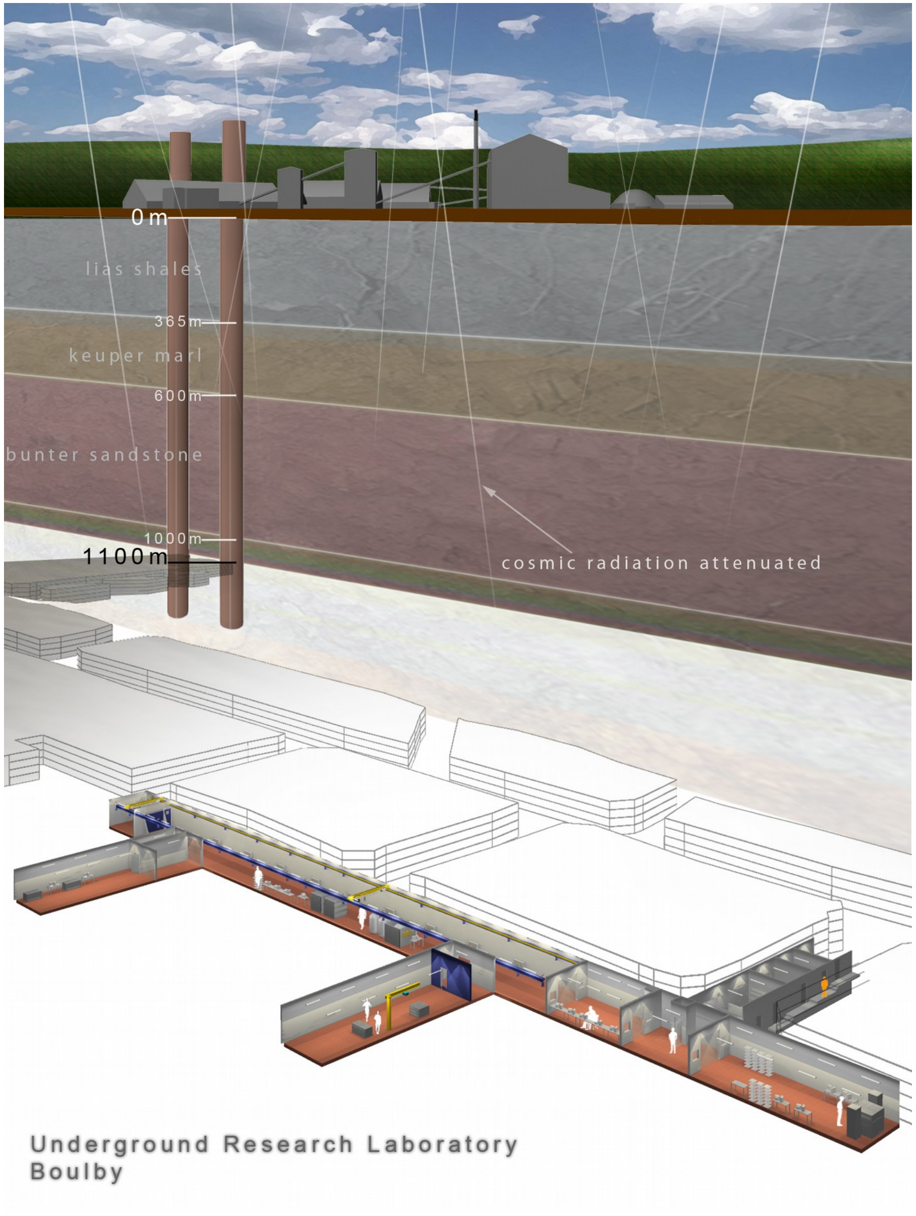
Search results:

– Only <u>one</u> site in the USA satisfies criteria

– Can go to four if allow underwater deployment, or permit shallow sites with greater backgrounds

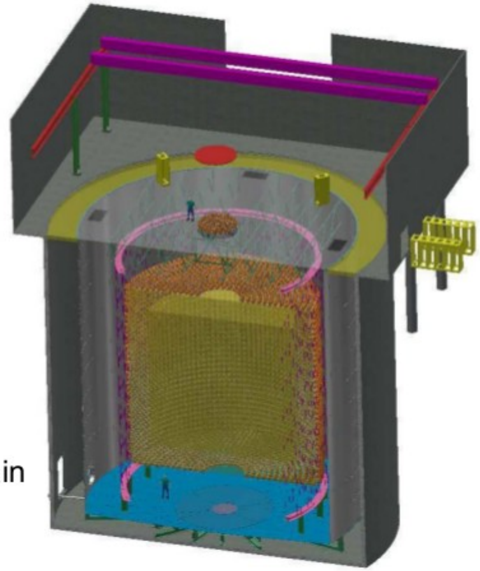
– Additionally, another candidate site in UK fits all criteria

STFC / Boulby Underground Lab



Depth:
1100 metres underground
2800 metres water equivalent
10^{-6} cosmic ray muon attenuation

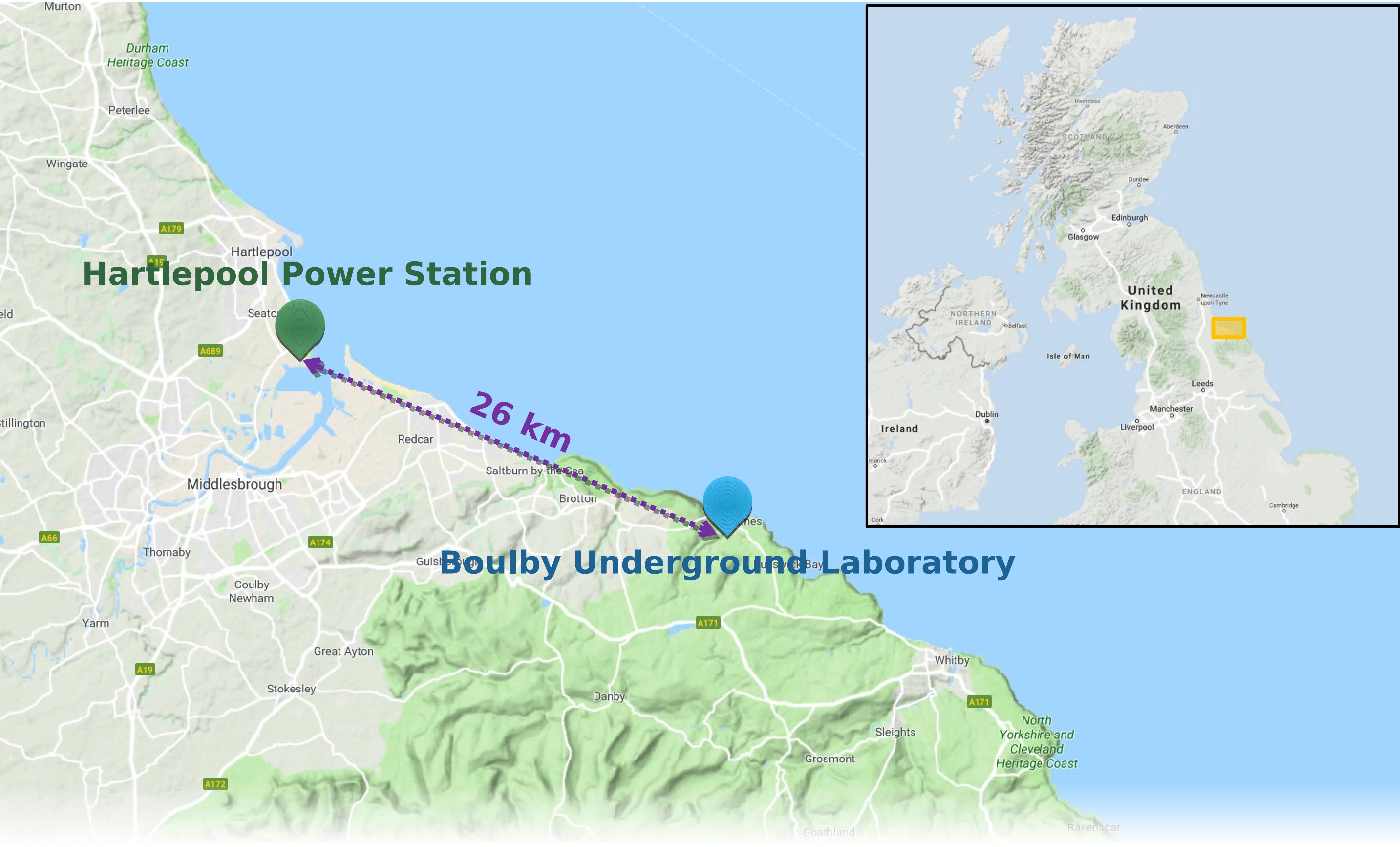
Operating lab for > 20 years
Current lab from 2017



JG Boissevain Design

New cavern needed to accommodate WATCHMAN (~25m ϕ x ~25m h)

Proximity to Reactor(s)

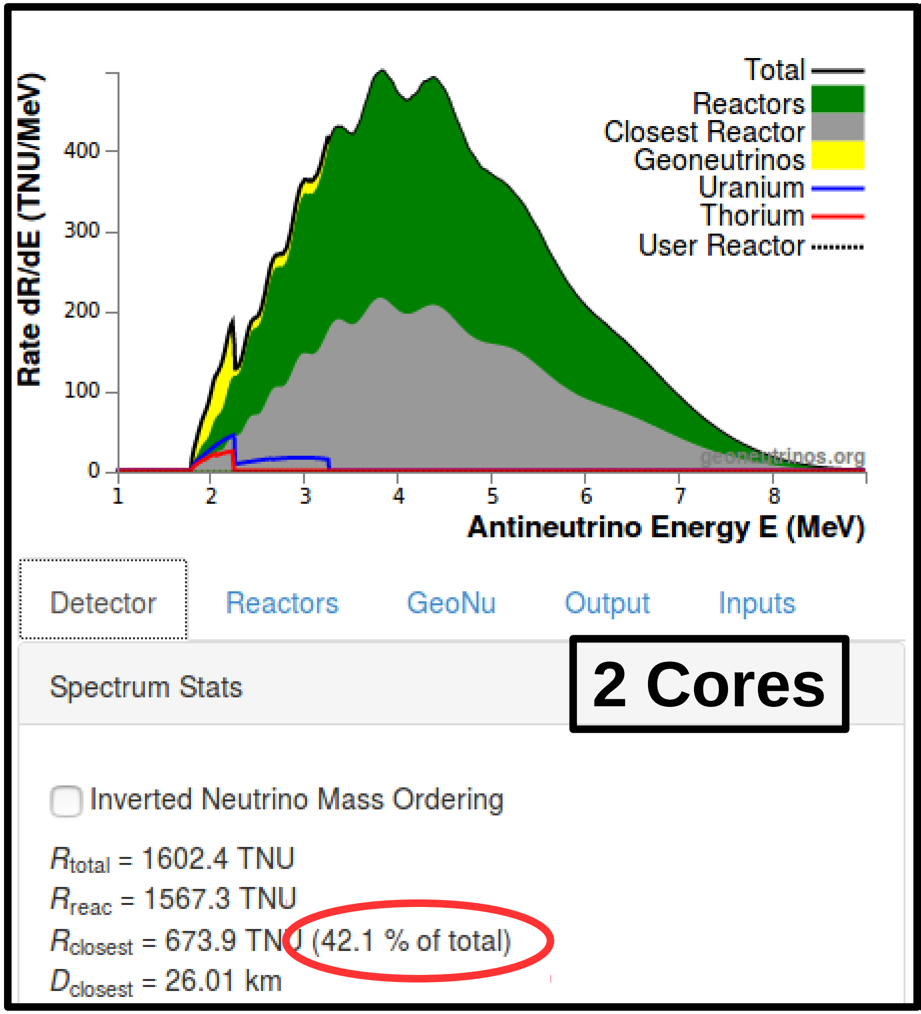


EDF Hartlepool Nuclear Plant

Dual-core reactor complex
Advanced gas-cooled reactors (AGR)
1550 MW_{th} per reactor core
~26 km standoff from Boulby Lab

Can look for flux difference between 1-core & 2-core operation
Potential for future complementary work with near-field detection

Hartlepool Signal @ Boulby

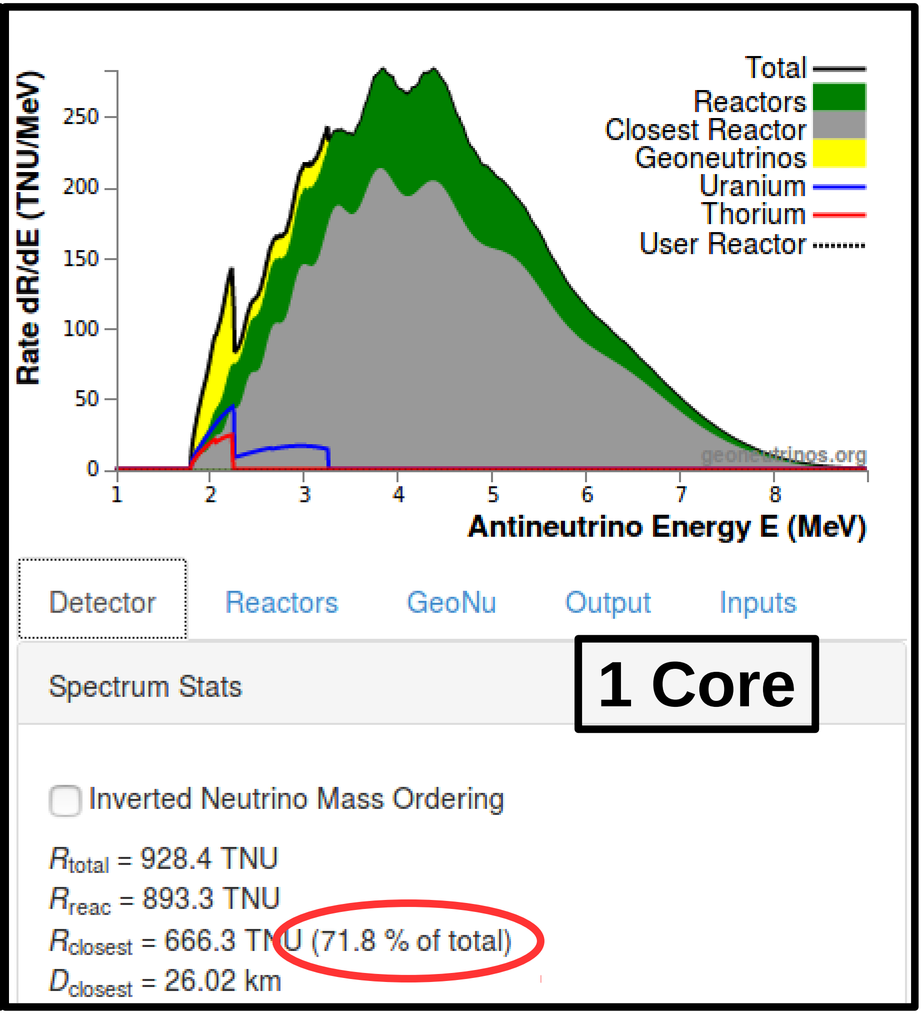


Spectrum Stats

2 Cores

☐ Inverted Neutrino Mass Ordering

R_{total} = 1602.4 TNU
R_{reac} = 1567.3 TNU
$R_{closest}$ = 673.9 TNU (42.1 % of total)
$D_{closest}$ = 26.01 km



Spectrum Stats

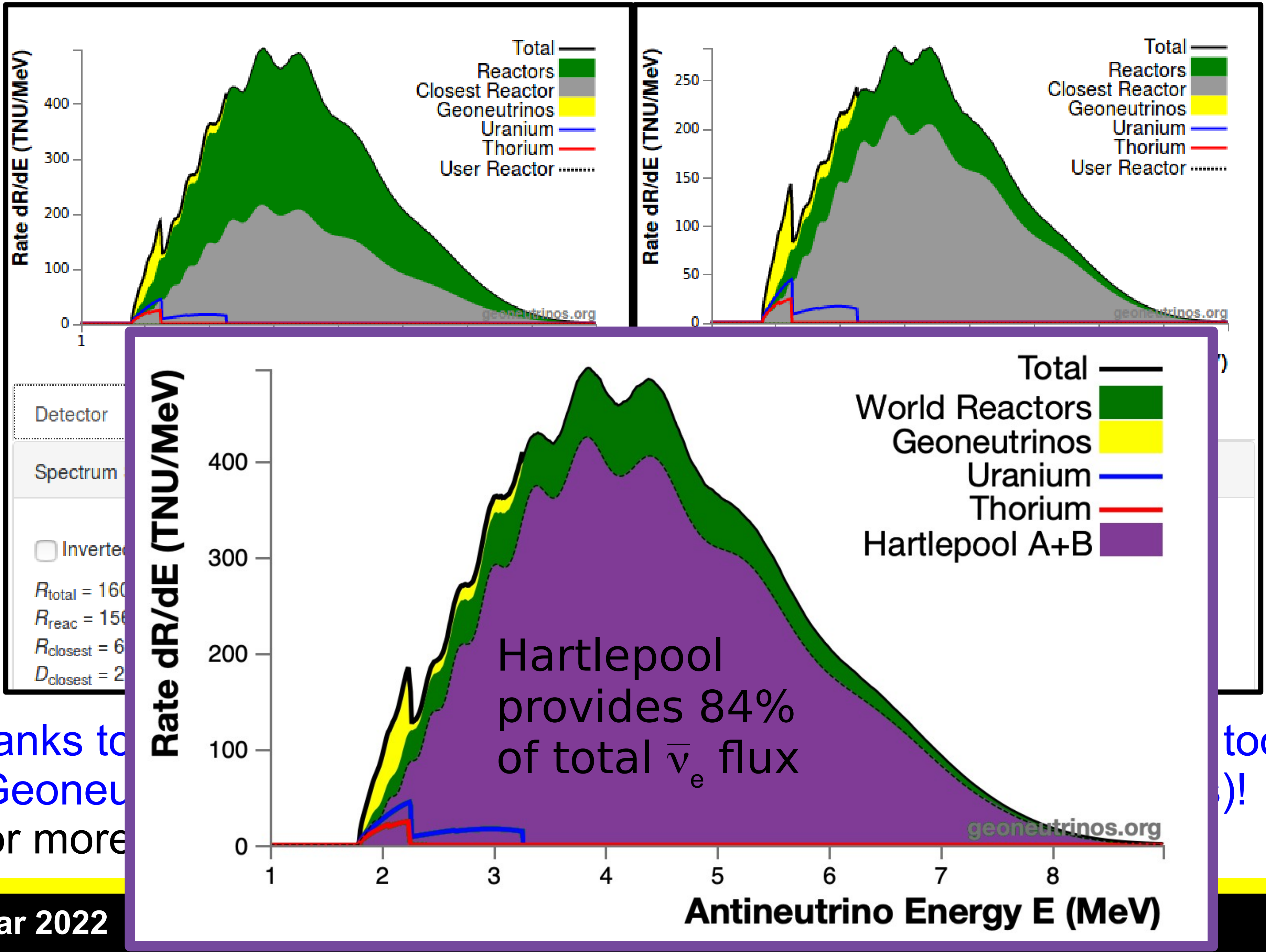
1 Core

☐ Inverted Neutrino Mass Ordering

R_{total} = 928.4 TNU
R_{reac} = 893.3 TNU
$R_{closest}$ = 666.3 TNU (71.8 % of total)
$D_{closest}$ = 26.02 km

Thanks to Antineutrino Global Map project, there is now an online tool – Geoneutrinos.org – to get such reactor fluxes (and backgrounds)!
(For more detail, see S.Dye's preprint at nucl-ex:1611.01575)

Hartlepool Signal @ Boulby



Detector

Spectrum

☐ Inverte

R_{total} = 160

R_{reac} = 156

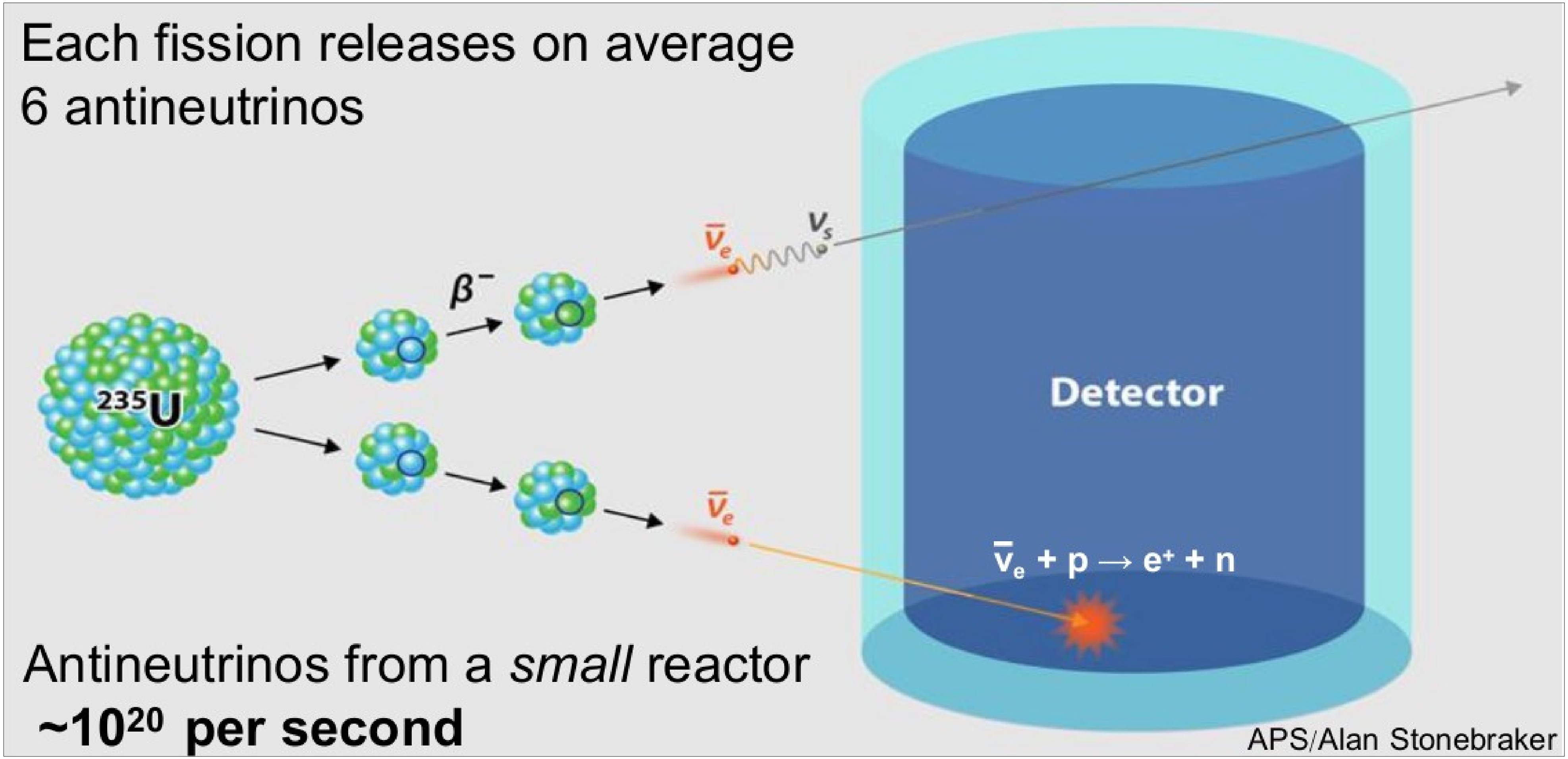
$R_{closest}$ = 6

$D_{closest}$ = 2

Hartlepool provides 84% of total $\bar{\nu}_e$ flux

Thanks to tool
– Geoneu)!
(For more

WATCHMAN Concept


Each fission releases on average 6 antineutrinos

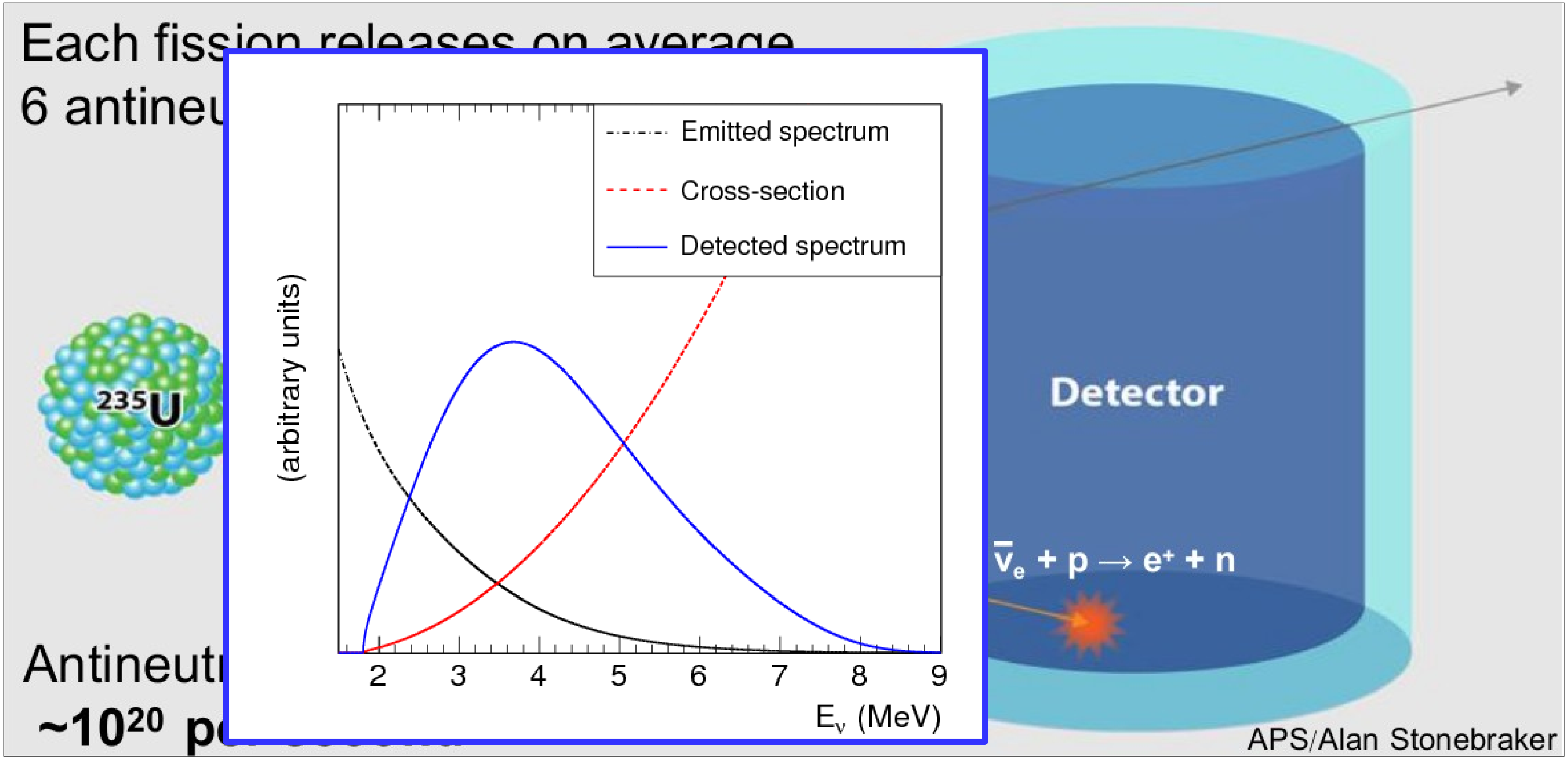
Antineutrinos from a *small* reactor

~10^{20} per second

APS/Alan Stonebraker

For a 3 GWth reactor complex (*e.g.*, Hartlepool), O(10^{21}) fissions per second, resulting in O(10^{22}) $\bar{\nu}_e$ emitted *isotropically* per second.

WATCHMAN Concept

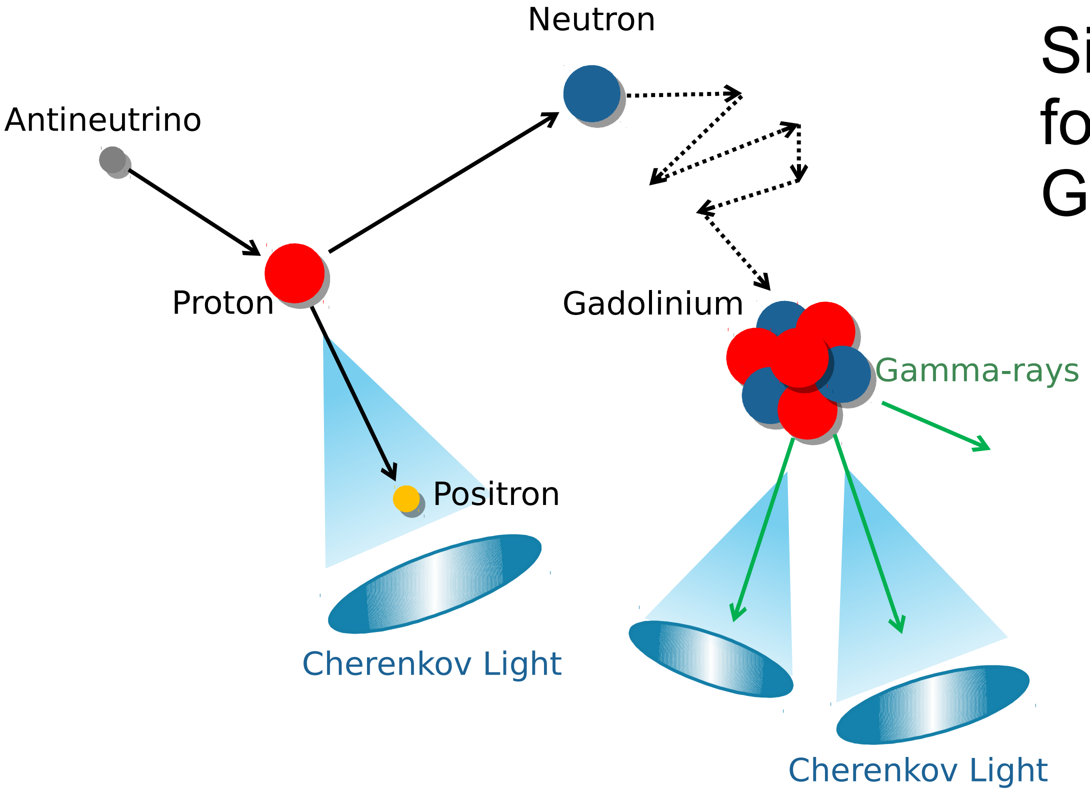


APS/Alan Stonebraker

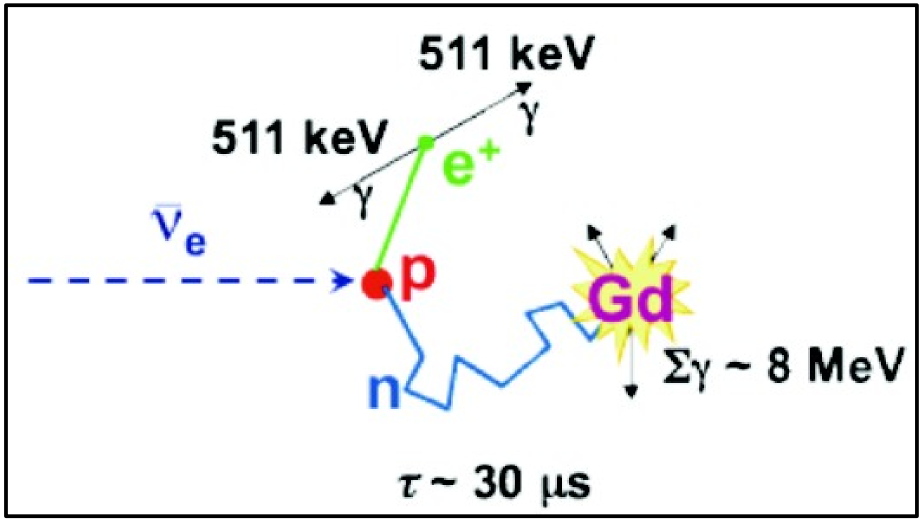
For a 3 GWth reactor complex (*e.g.*, Hartlepool), $O(10^{21})$ fissions per second, resulting in $O(10^{22})$ $\overline{\nu}_e$ emitted *isotropically* per second.

→ For 26 km standoff, expect "several" events per day per kilotonne

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

Non-Proliferation Scenarios

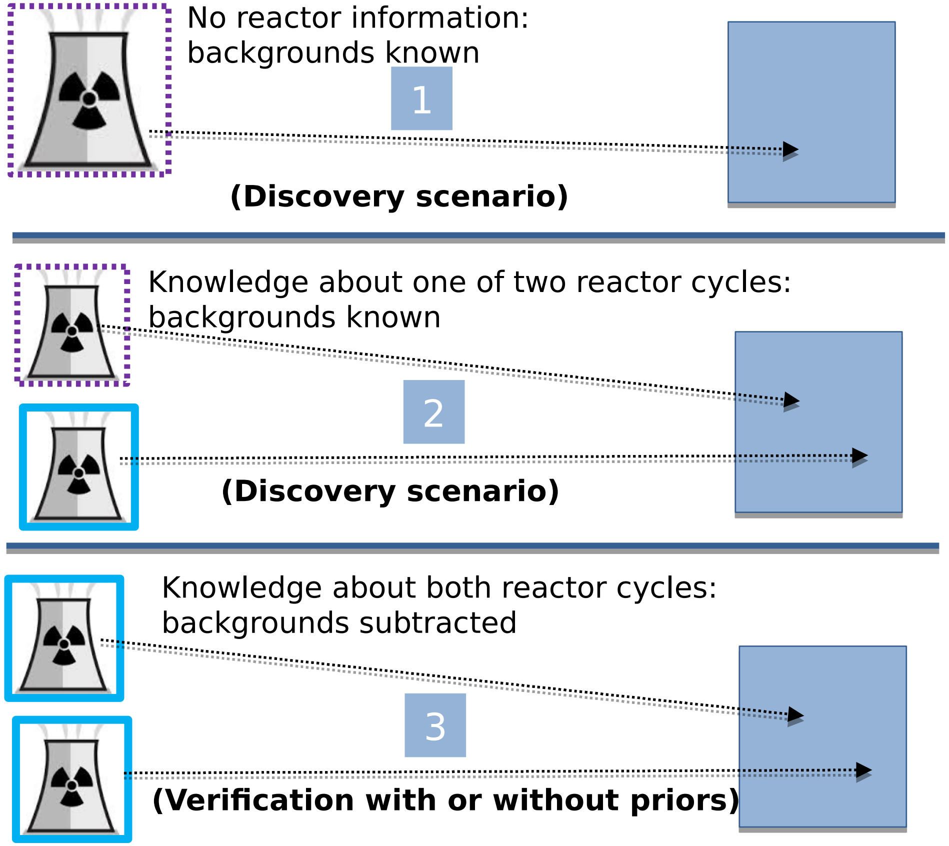
Discovery Scenarios (Project Goal 1):

- **Case 1:** Determine whether any reactor is present.

- **Case 2:** Knowing that one reactor is operating, determine that a second reactor has turned on.

Verification Scenario: (Project Goal 2)

- **Case 3:** Confirm operational status with or without prior knowledge of both reactor cycles.



No reactor information:
backgrounds known

1

(Discovery scenario)

Knowledge about one of two reactor cycles:
backgrounds known

2

(Discovery scenario)

Knowledge about both reactor cycles:
backgrounds subtracted

3

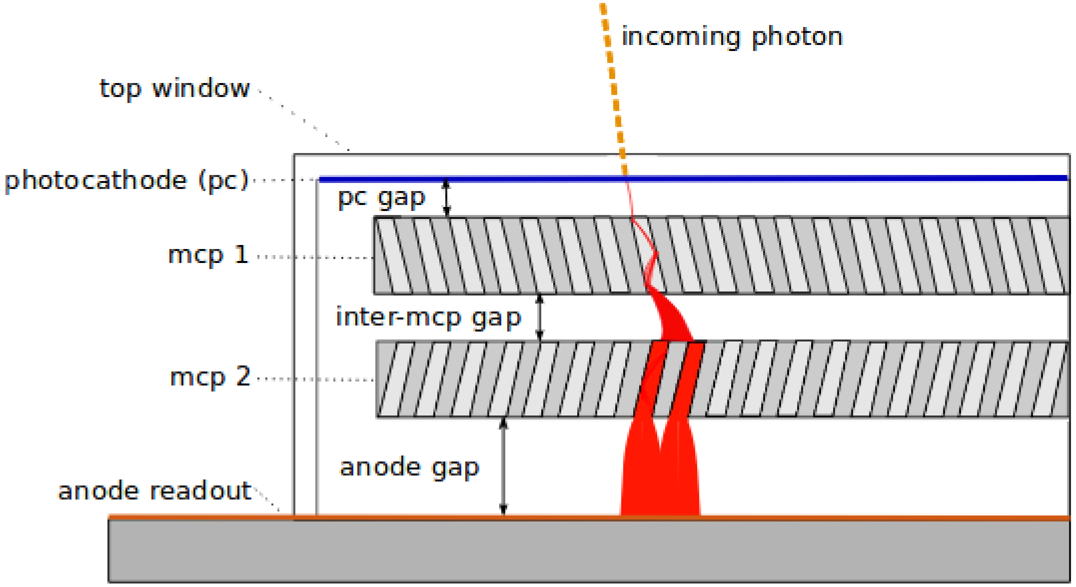
(Verification with or without priors)

Non-proliferation use cases are in development within the collaboration. These will be further developed in consultation with sponsors and also with the non-proliferation community.

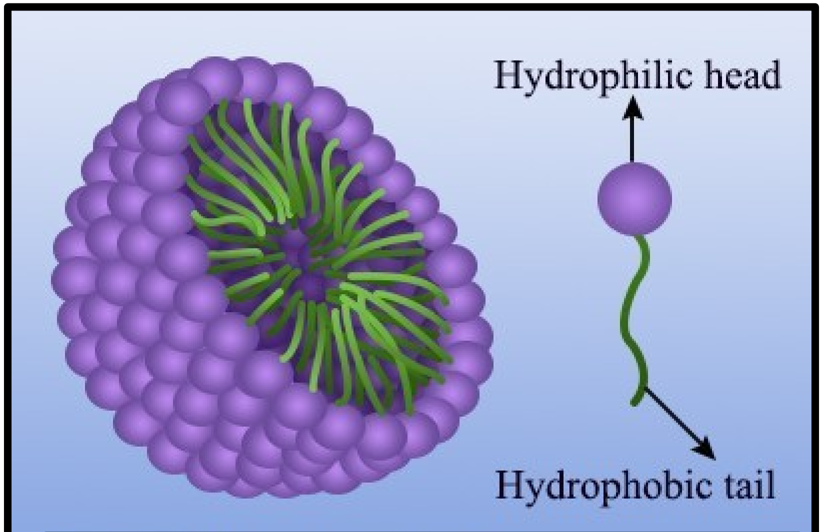
Future Options

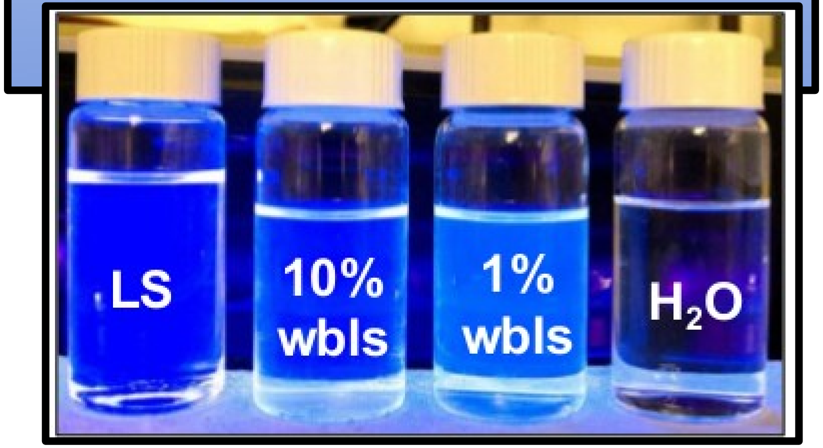
We are exploring other options for enhanced detection technologies:

Large Area Picosecond Photo-Detectors (LAPPDs):



Water-based Liquid Scintillator (WbLS):





Future goals include enhancing capacity for **non-proliferation** as well as science goals like: **geoneutrinos**, **CNO solar ν**, **neutrinoless double-beta decay ($0\nu\beta\beta$)**, and **direct detection of dark matter**.

Summary

- **After ~20 years of extensive R&D, gadolinium loaded water is in use!**
- **Many experiments about to adopt to enhance physics reach:**
  - ANNIE, SK-Gd

- **Application of Antineutrino Physics also relevant for security**
  - Hope to minimize a source of global catastrophic risk
  - Defens/ce agencies are very interested, in strong collaboration with universities

- **Advanced Instrumentation Testbed is proceeding at Boulby Underground Lab**
- **Main goal for WATCHMAN is nuclear non-proliferation**
  - Variants include enclosing photosensors in optical modules, alternative photosensors (*e.g.*, SiPMs), techniques to increase light collections (*e.g.*, wavelength shifting plates, retro reflectors, Winston cones)
  - Options also being explored for alternative target material (*e.g.*, liquid scintillator, WbLS, 4-MU)

- **Significant <u>physics</u> potential for WATCHMAN as well:**
  - Excellent supernova neutrino detector; UK group is currently designing supernova trigger
  - With suitable upgrades, WATCHMAN can be used for reactor neutrino physics, CNO-cycle solar neutrinos, neutrinoless double beta decay, geoneutrinos… and possibly even direct detection of dark matter!

Thank you for listening!