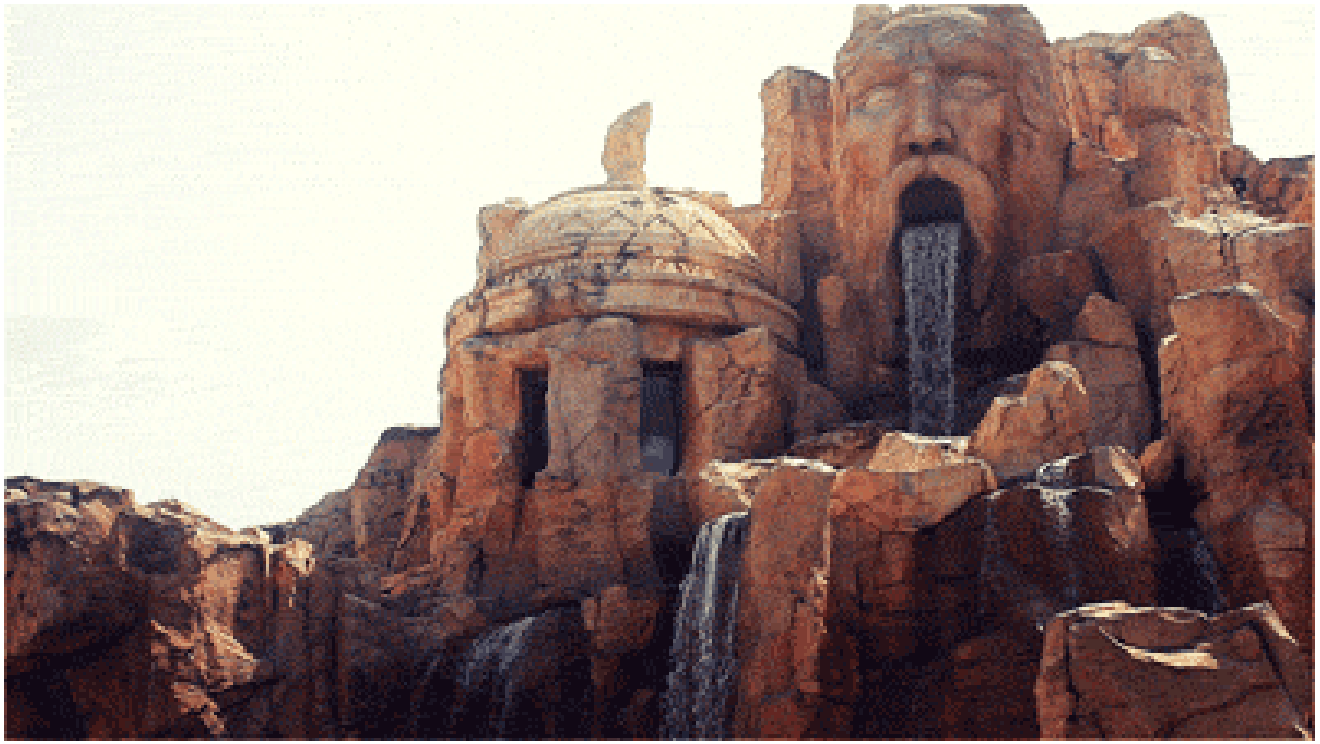
Status and Future of Gadolinium-loading in Water Cherenkov Detectors

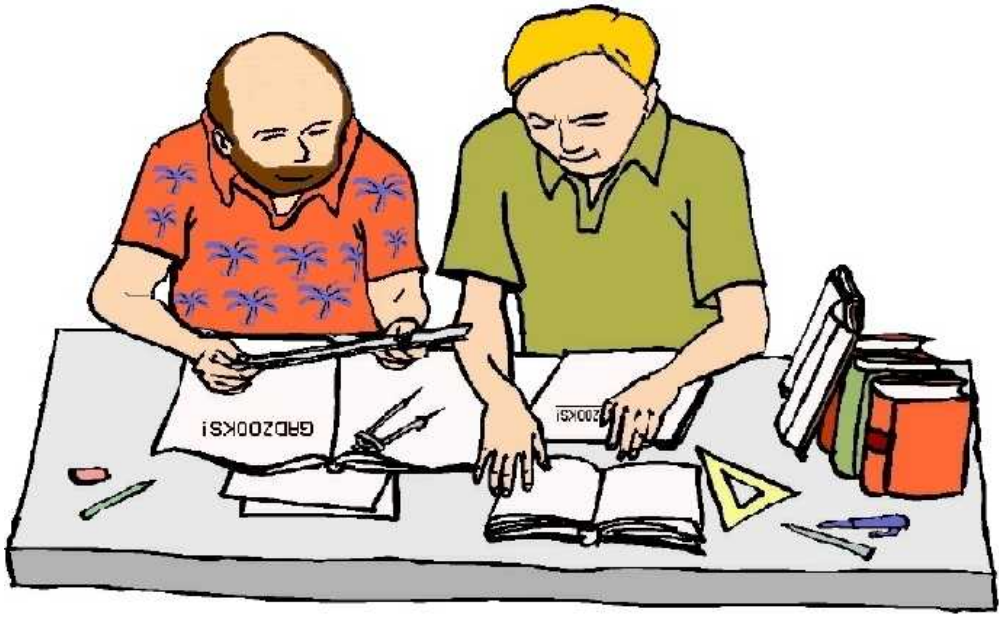


Mark Vagins

Kavli IPMU, UTokyo/UC Irvine

NNN15

Stony Brook, NY October 28, 2015



A decade ago theorist John Beacom and I wrote the original GADZOOKS!

(Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!) paper.

It proposed loading big WC detectors, specifically Super-K, with water soluble gadolinium, and evaluated the physics potential and backgrounds of a giant antineutrino detector.

[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

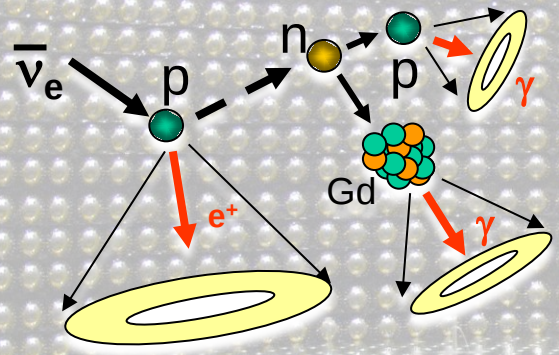
(237 citations → one every 17 days for eleven years)

As a result, when not busy scooping large quantities of gadolinium salts into big vats of water, I've been industriously traveling the globe spreading my message:

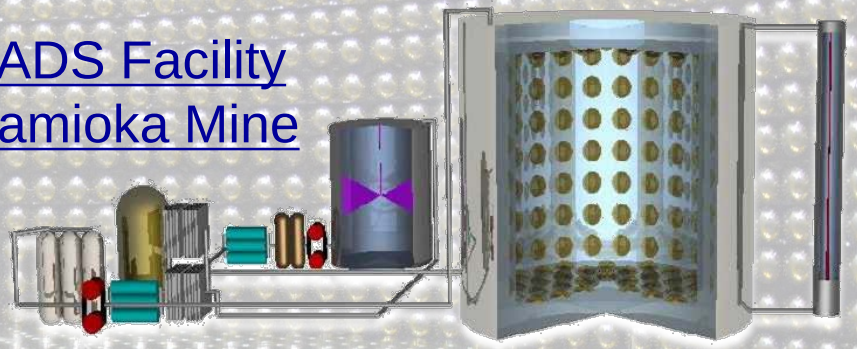
Super-Kamiokande
1KT @ KEK
LBNE WC
EGADS
WATCHMAN
Hyper-Kamiokande
ANNIE
nuPRISM
TITUS
IceCube (!)
.
.

EGADS/Super-K

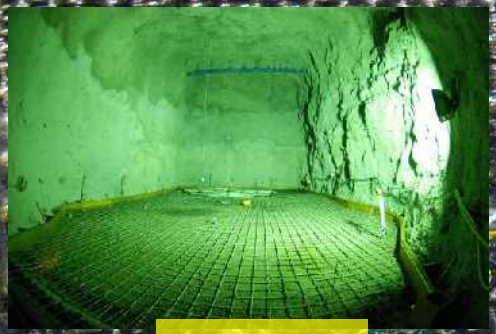
Adding **water soluble gadolinium** to **Super-K** will greatly enhance its ability to detect **supernova neutrinos** (and help with many other physics topics like **proton decay**). **EGADS** is a dedicated gadolinium demonstrator which includes a working 200 ton scale model of SK.



EGADS Facility
in Kamioka Mine



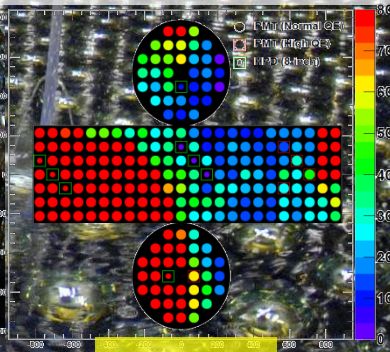
Beacom and Vagins, *Phys. Rev. Lett.*, 93:171101, 2004 [237 citations]



12/2009

11/2011

8/2013



6/2015

As of April 2015, the EGADS detector has been fully loaded (0.2%) with gadolinium sulfate, and functioning perfectly. The R&D phase of gadolinium loading is now coming to a close.

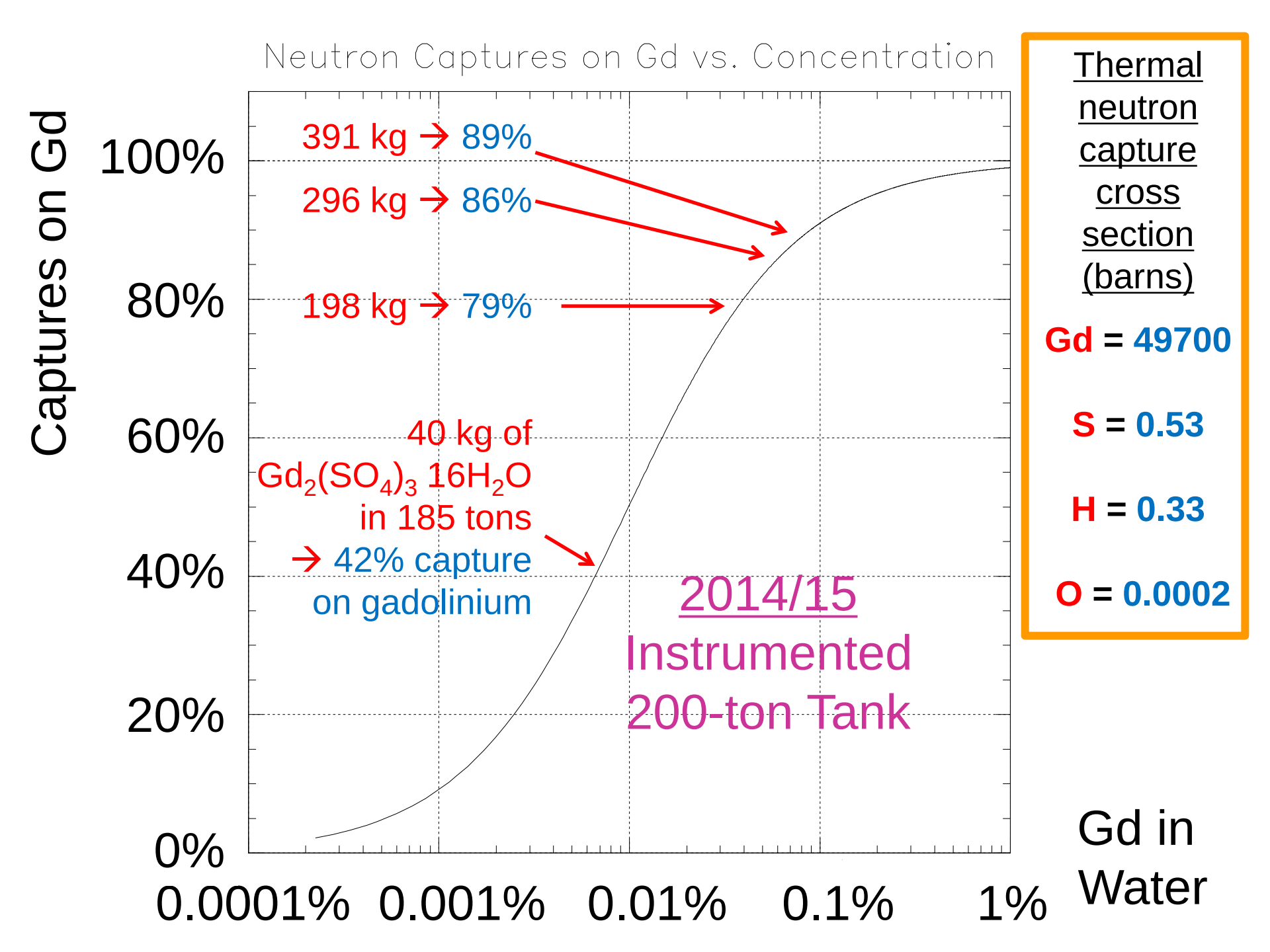
Gd loading the instrumented 200-ton EGADS tank (185 tons water volume)

Nov. 27th, 2014: Inject first 40 kg of $Gd_2(SO_4)_3*8H_2O$

Jan. 24th, 2015: Inject 158.4 kg more (198.4 kg total)

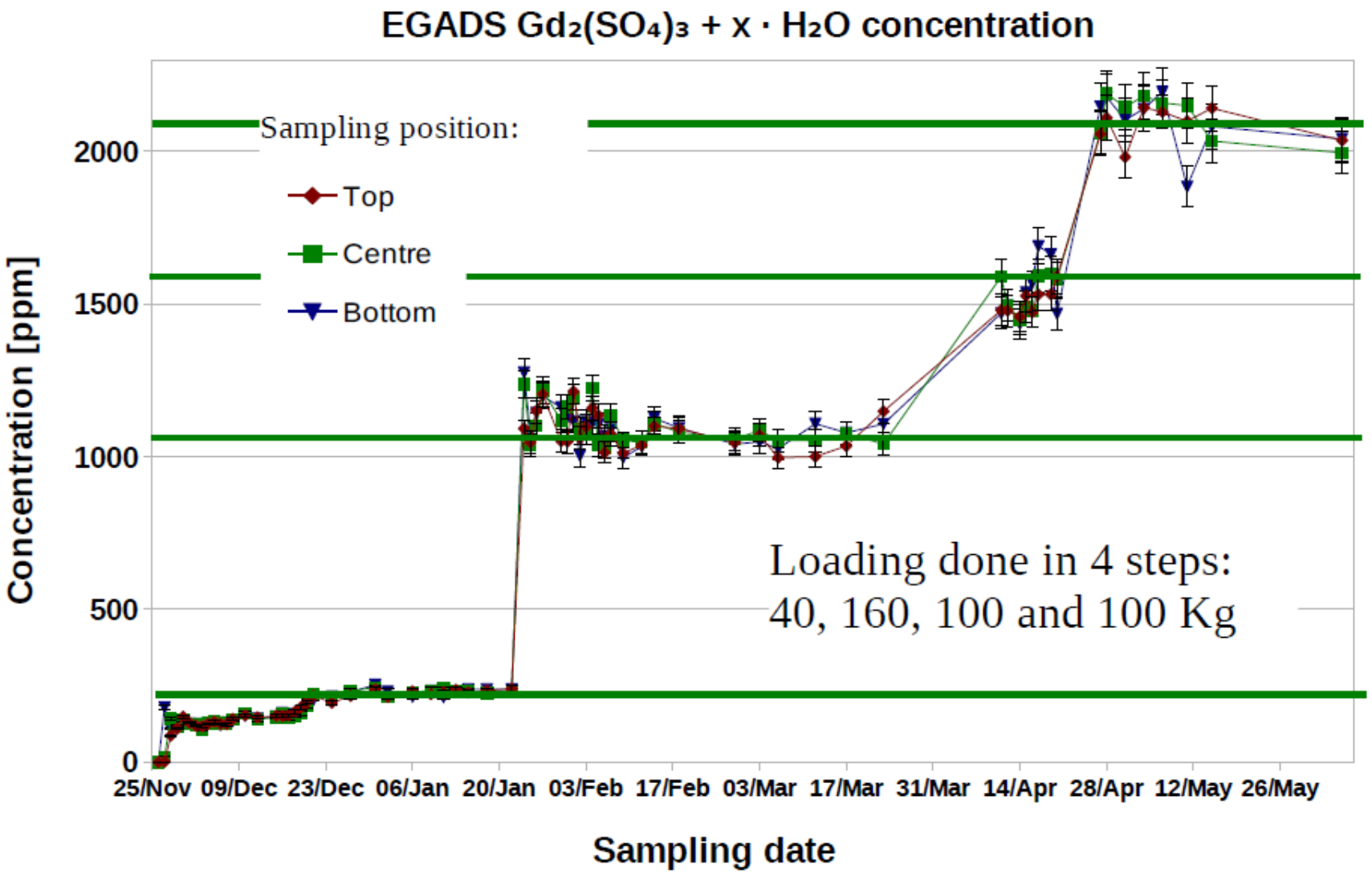
April 8th →10th : Inject 97.6 kg more (296 kg total)

April 21st →24th: Inject 94.6 kg more (390.6 kg total)

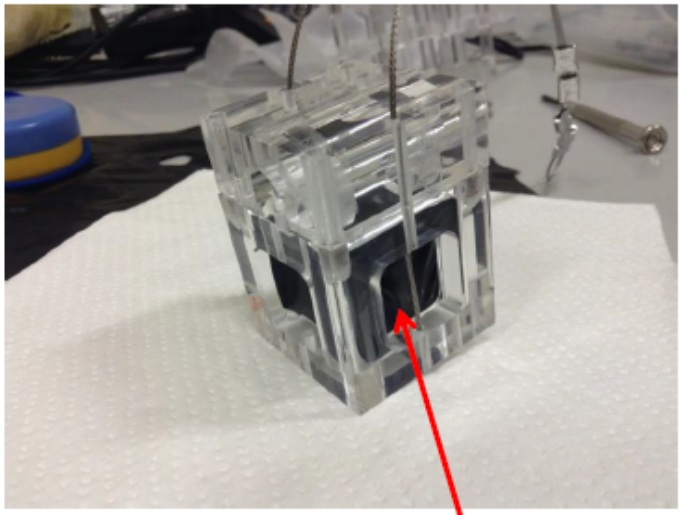

Neutron Captures on Gd vs. Concentration
Captures on Gd
100%
80%
60%
40%
20%
0%
0.0001%
0.001%
0.01%
0.1%
1%
Gd in Water
391 kg → 89%
296 kg → 86%
198 kg → 79%
40 kg of
Gd2(SO4)3 16H2O
in 185 tons
→ 42% capture
on gadolinium
2014/15
Instrumented
200-ton Tank
Thermal neutron capture cross section (barns)
Gd = 49700
S = 0.53
H = 0.33
O = 0.0002

Gd Loading in EGADS from Atomic Absorption Spectrometer

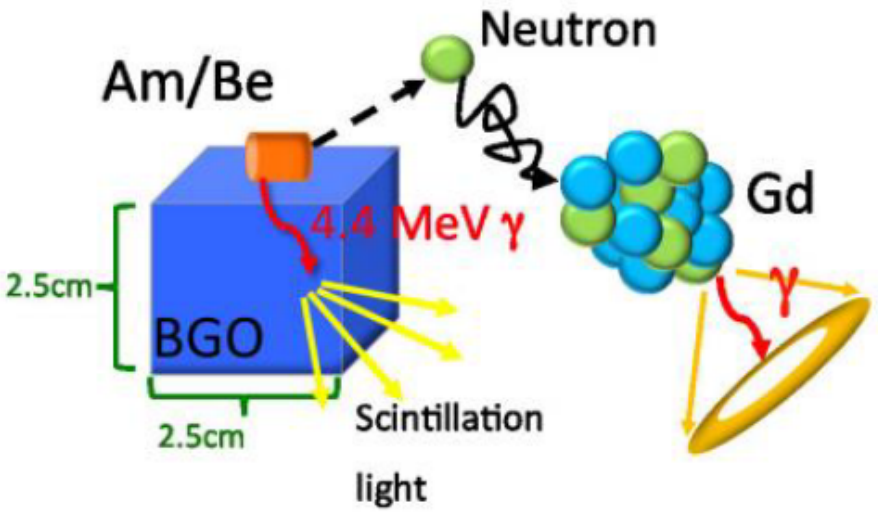
Loading history



How to estimate neutron capture



BGO is covered by black sheet, in order to prevent scintillation light to be too bright



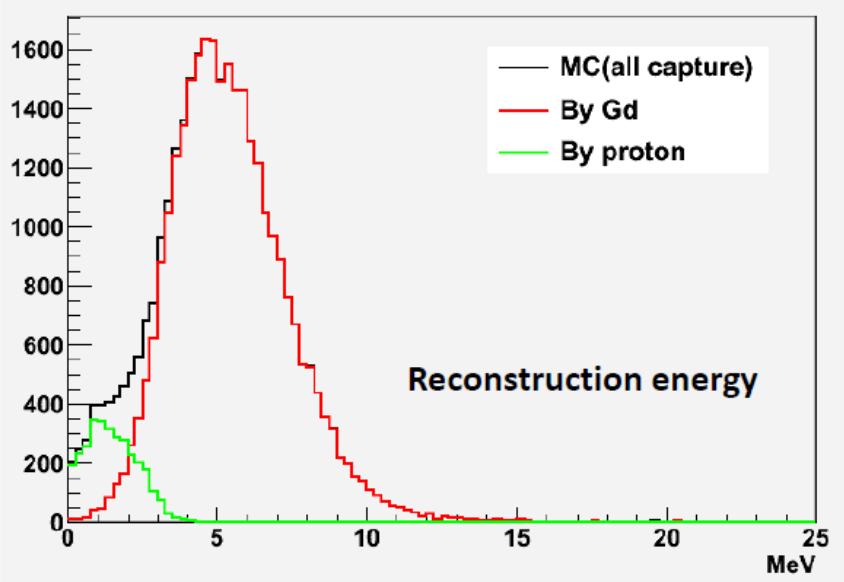
Use Am/Be as a neutron source :

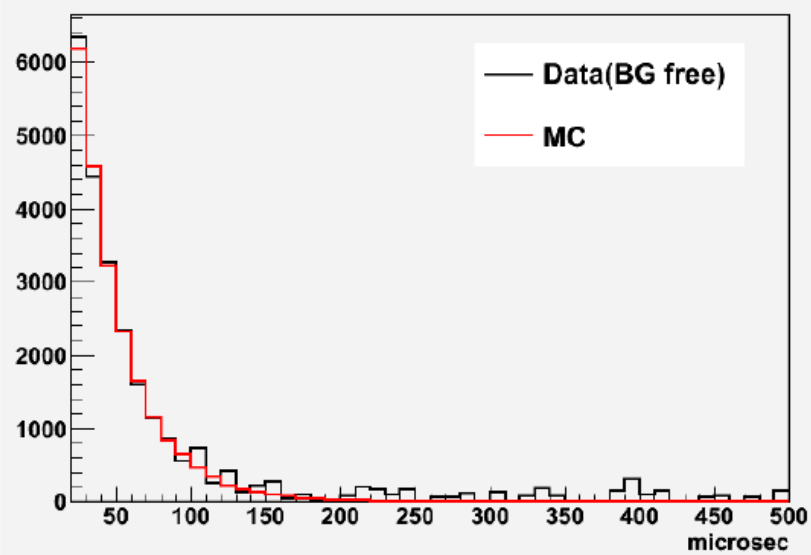
$$^{241}Am \rightarrow {}^{237}Np + \alpha$$
$$^{9}Be + \alpha \rightarrow {}^{12}C + n + \gamma(\sim 4.4MeV)$$

Neutron capture lifetime in EGADS with Am/Be source

Neutron Capture Efficiency
(2178ppm MC)

By Gd : 89.4%
By proton : 10.5%
By Ge : 0.04% (in BGO)
By Fe : 0.04% (in wire)
By O : 0.02%





Fitting by exponential function:

$$y = p_0 \times e^{\frac{-x}{p_1}} + p_2$$

MC (EGSIM) Setup
(GEANT4 + GLG4Sim)

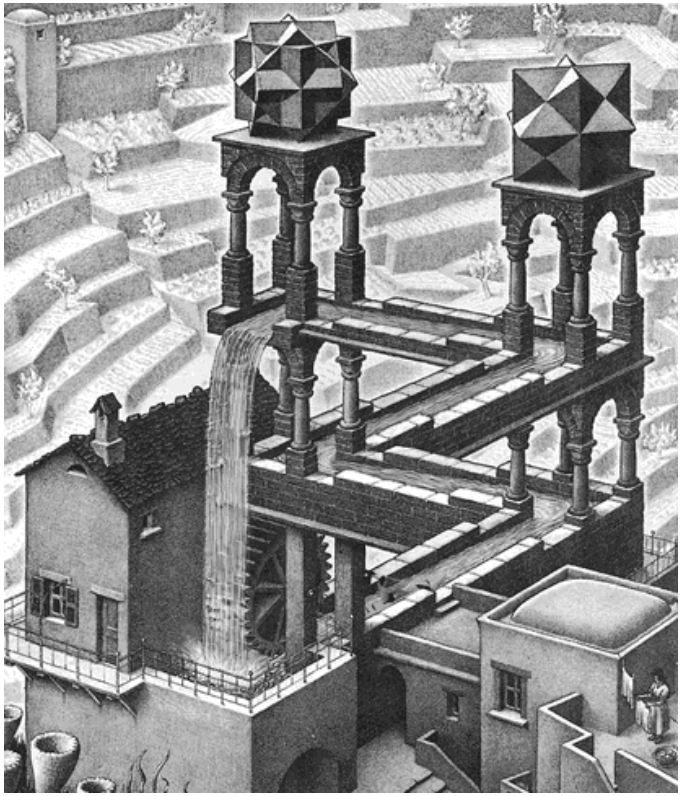
p_1 : average capture time of neutron (μsec)

	2178±76ppm	1055±37ppm	225±8ppm
Data	29.89 ± 0.33	51.48 ± 0.52	130.1 ± 1.7
MC	30.05 ± 1.14	53.47 ± 1.77	126.2 ± 2.8

The Essential Magic Trick

→ We must keep the water in any big Gd-loaded detector perfectly clean… *without removing the dissolved Gd.*

→ I've developed a new technology:
"Molecular Band-Pass Filtration"
Staged nanofiltration selectively retains Gd while removing impurities.



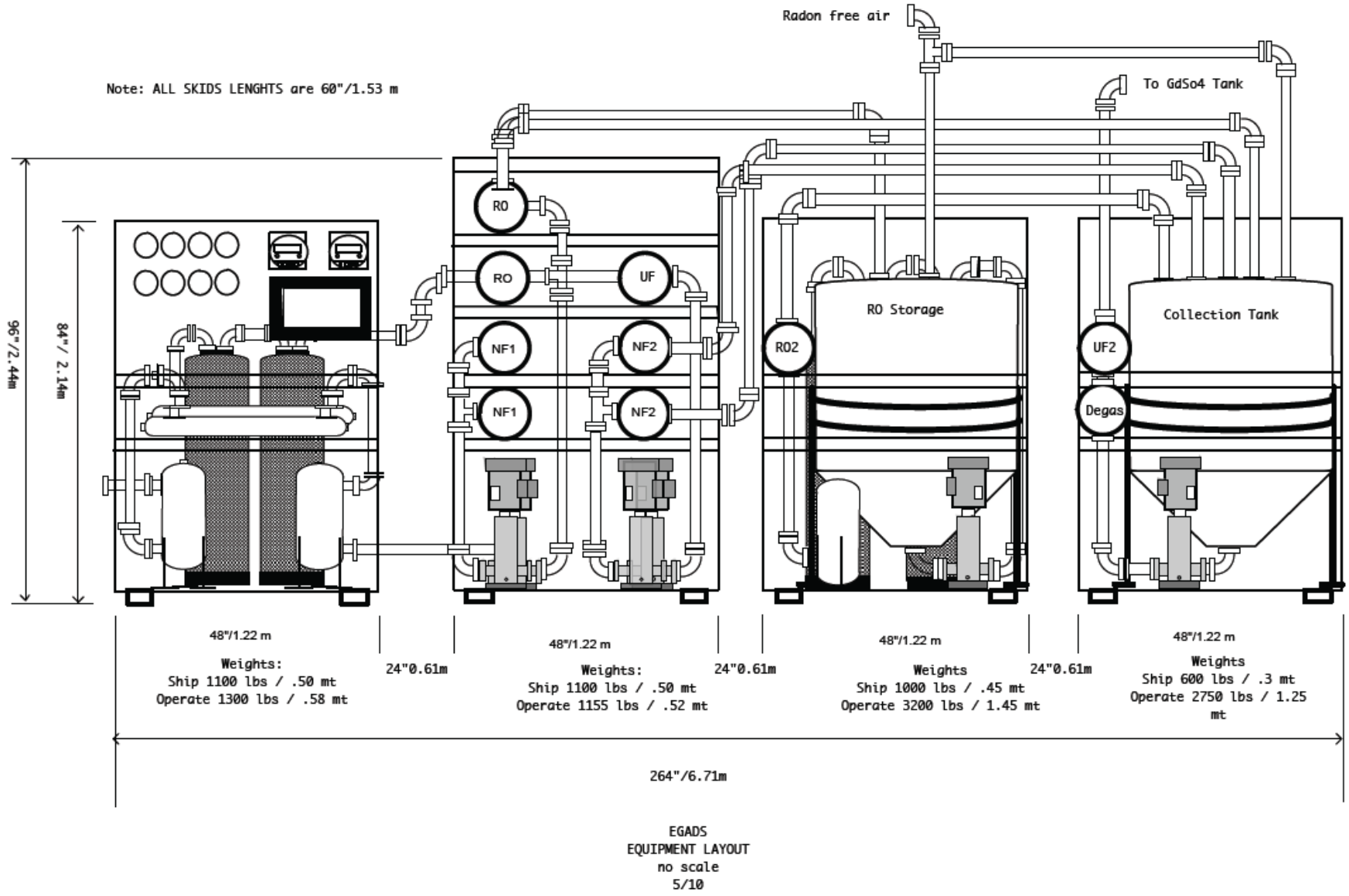
Amazingly, the darn thing works!

This technology will support a variety of applications, such as:

→ Supernova neutrino and proton decay searches

→ Remote detection of clandestine fissile material production

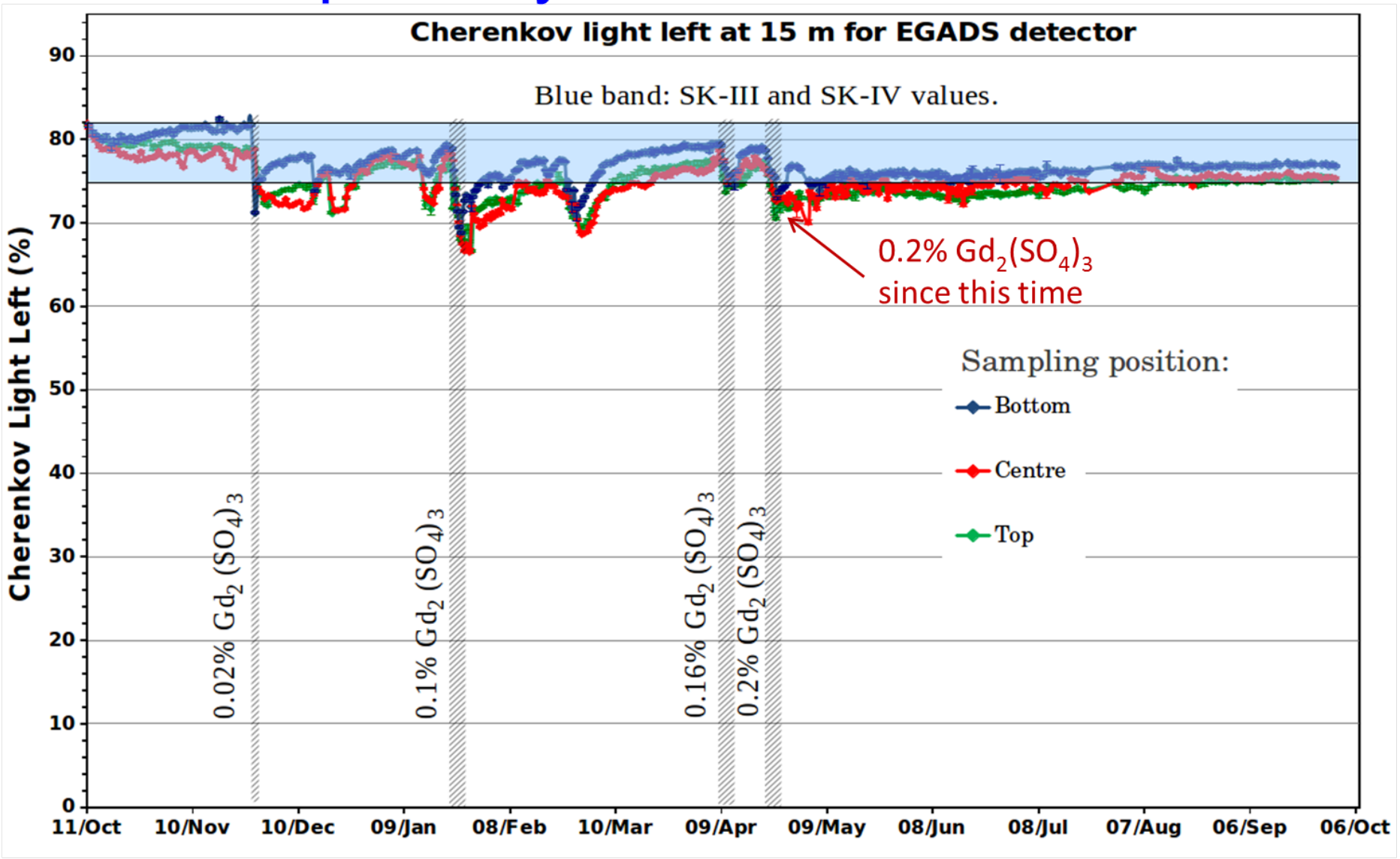
→ Efficient generation of clean drinking water without electricity



Modular design of EGADS main water system


Main 200-ton Water Tank with
227 50-cm PMT's + 13 HK tubes
(PMT's installed in summer of 2013)
15-ton Gadolinium
Pre-treatment
Mixing Tank
Selective Water+Gd
Filtration System
11/2011

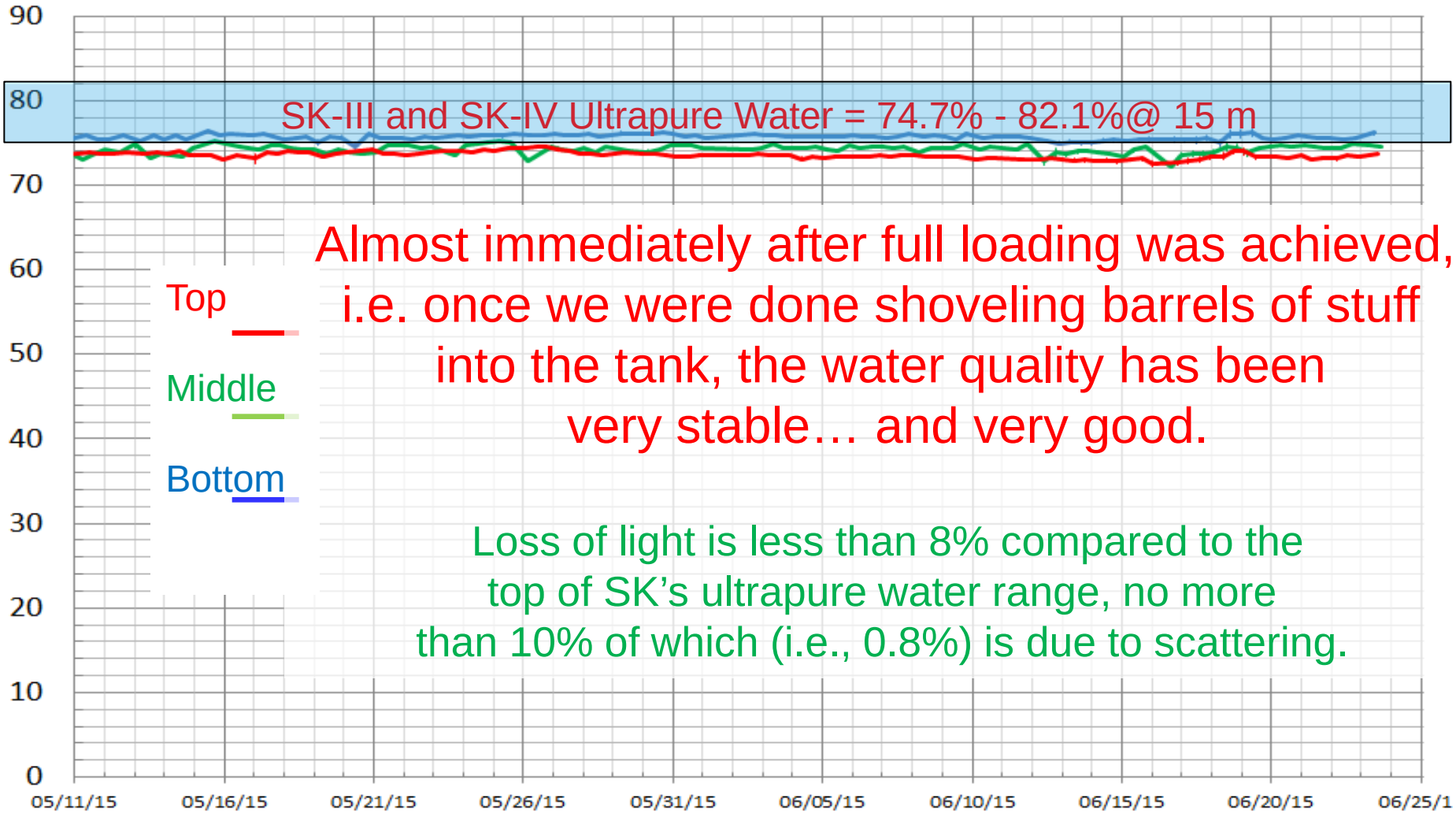
Transparency of Gd-loaded water



Oct 2014

Oct 2015

Light @ 15 meters in the 200-ton tank (Gd water, PMT's)



Almost immediately after full loading was achieved, i.e. once we were done shoveling barrels of stuff into the tank, the water quality has been very stable… and very good.

Loss of light is less than 8% compared to the top of SK's ultrapure water range, no more than 10% of which (i.e., 0.8%) is due to scattering.

May 11, 2015

June 2, 2015

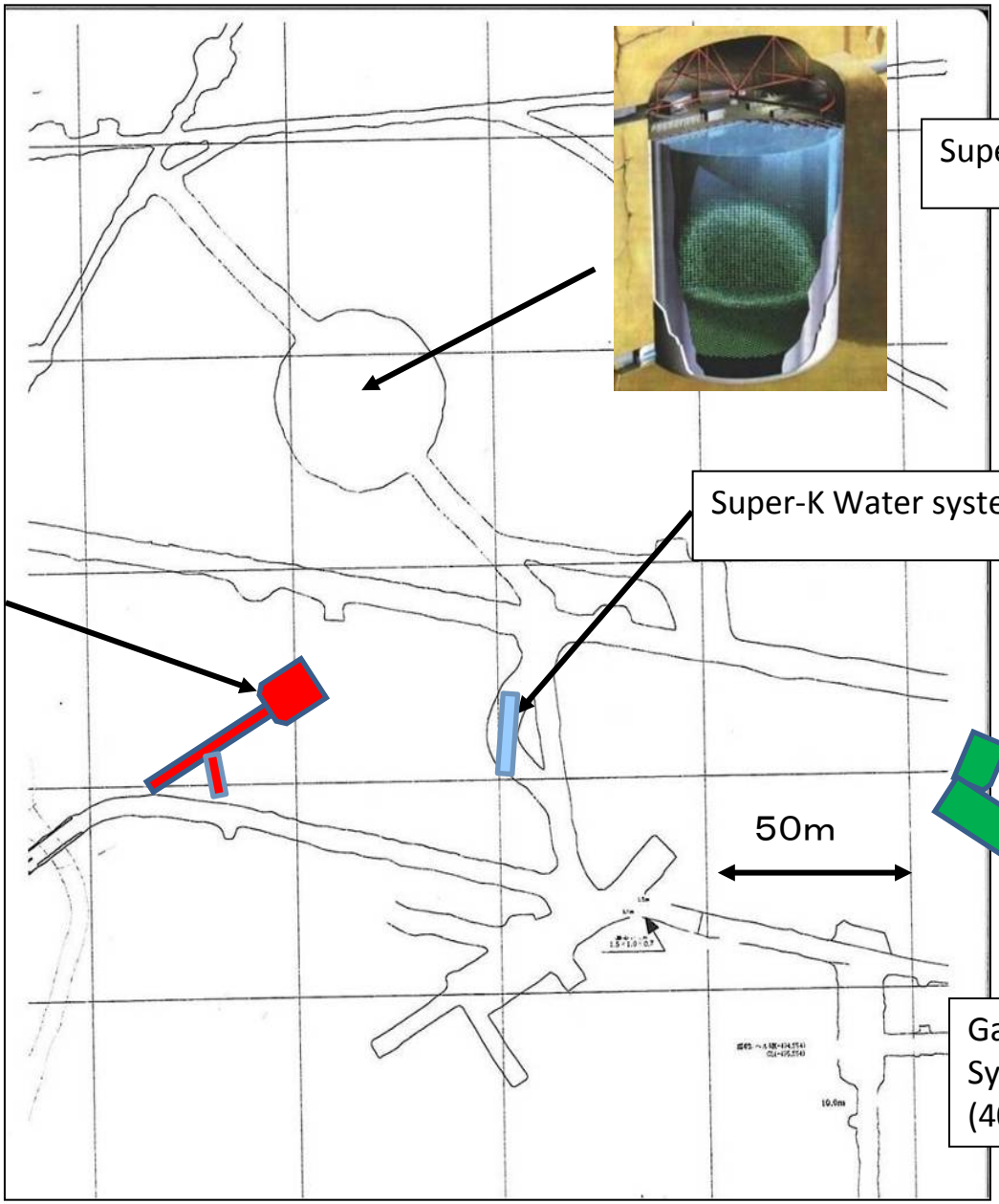
June 25, 2015

As was discussed in the original GADZOOKS! paper, as well as in the 237 papers to date which have cited it, the physics benefits provided to water Cherenkov detectors by dissolved gadolinium are numerous and compelling.

After years of testing and study
– culminating in these powerful EGADS results –
no technical showstoppers have been encountered. Therefore:

On June 27, 2015, the Super-Kamiokande collaboration approved the SuperK-Gd project which will enhance anti-neutrino detectability by dissolving gadolinium to the Super-K water.

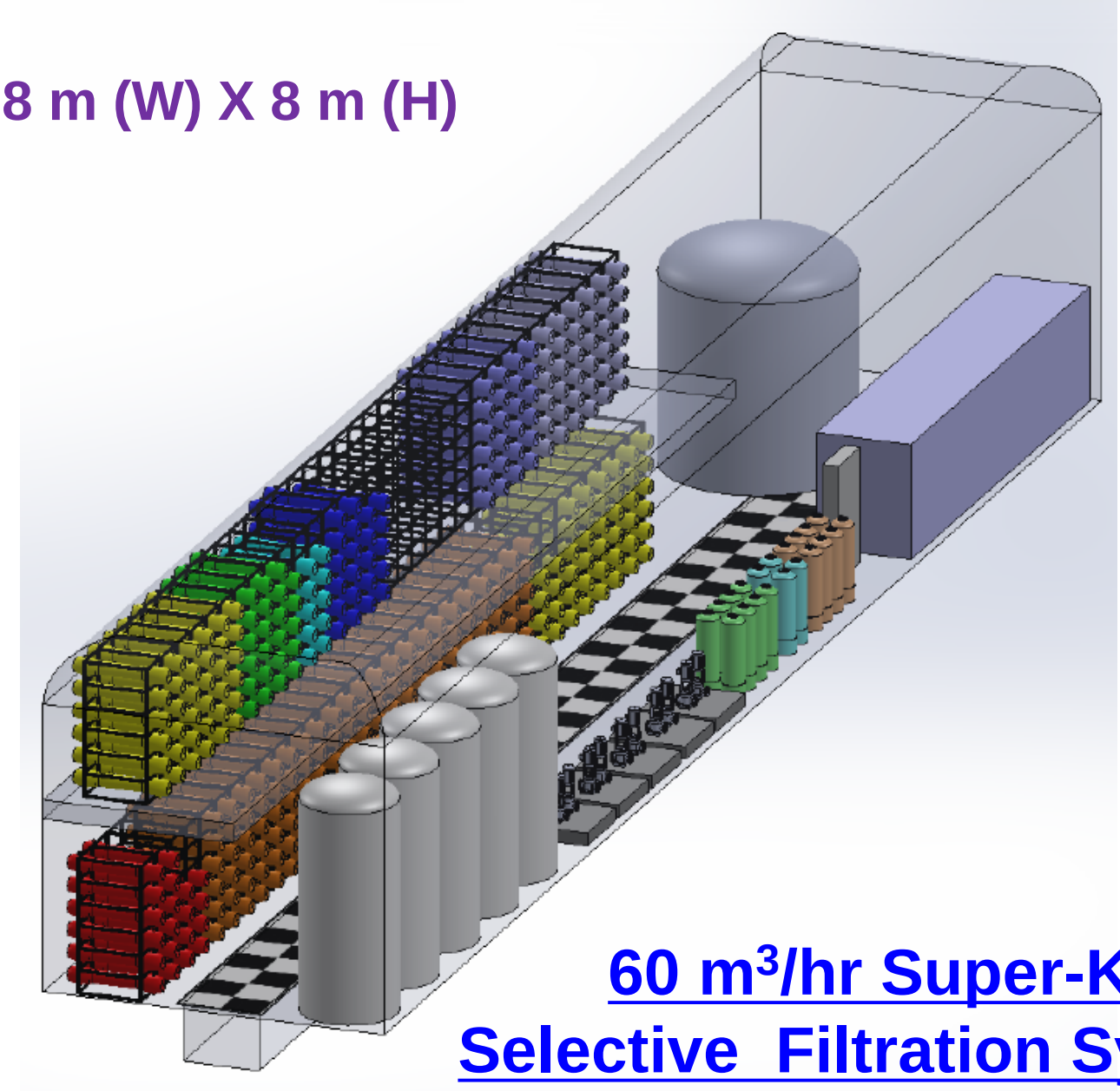
The actual schedule of the project including refurbishment of the tank and Gd-loading time will be determined soon taking into account the T2K schedule.


Super-Kamiokande
Super-K Water system
EGADS Hall
(2500 m3)
50m
Gadolinium Water
System Hall
(4000 m3)

New gadolinium water system hall; October 21st, 2015

New Super-K gadolinium water system

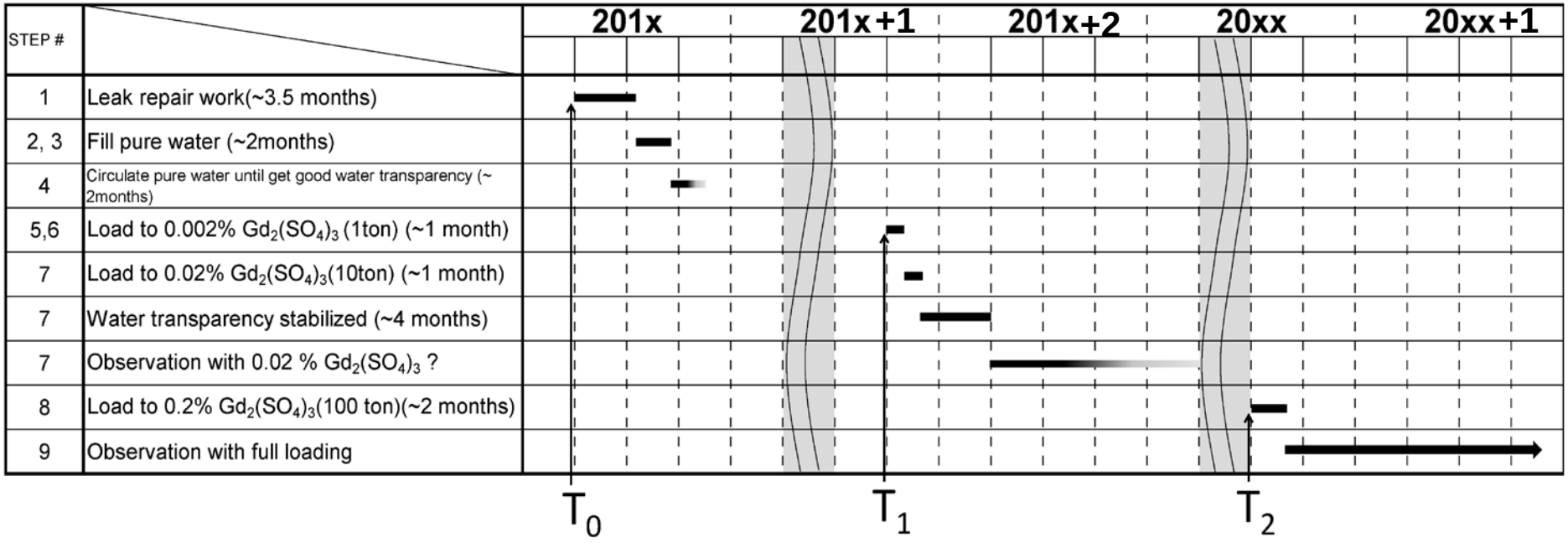
30 m (L) X 8 m (W) X 8 m (H)



60 m^3/hr Super-K Selective Filtration System

Timeline

Preliminary



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%)

[Please also see Ikeda-san's plenary Super-K talk]

Gadolinium loading is part of the executive summary!

In 2011, the official Hyper-Kamiokande Letter of Intent appeared on the arXiv:1109.3262

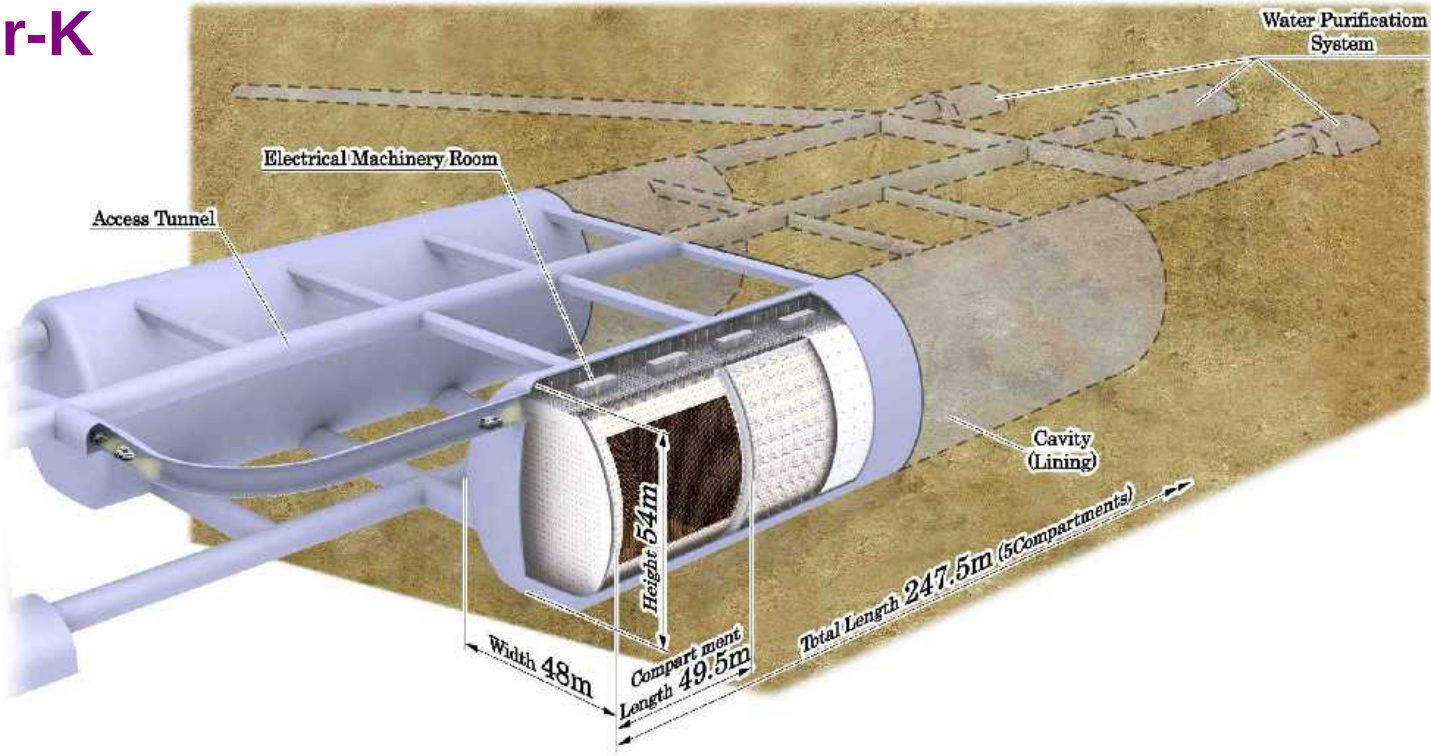
1.0 Mton total water volume

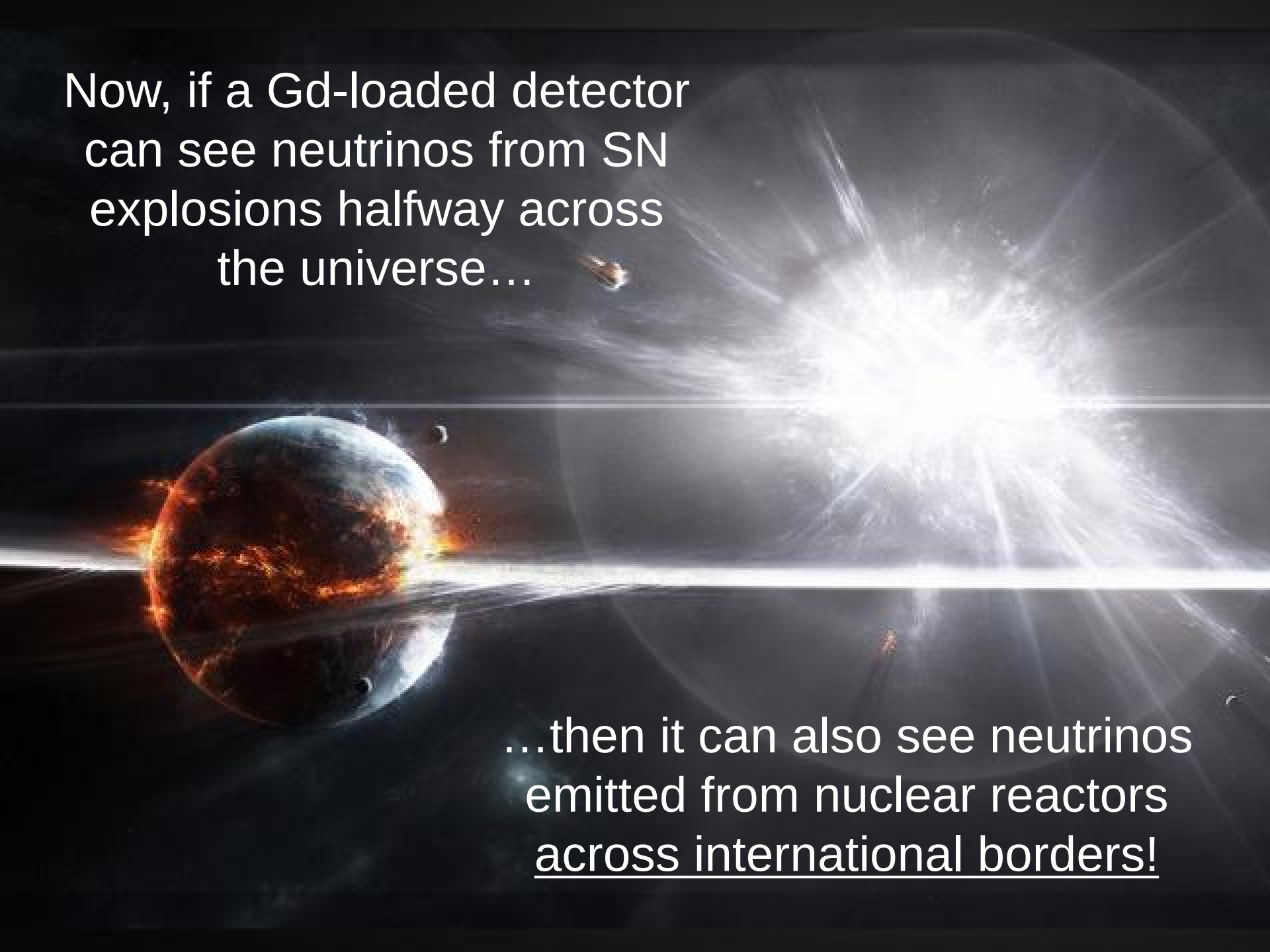
0.56 Mton fiducial volume

(25 X Super-K)

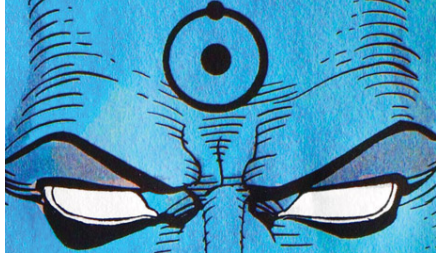
With Gd, Hyper-K should collect SN1987A-like numbers of supernova neutrinos...

every month!




Now, if a Gd-loaded detector can see neutrinos from SN explosions halfway across the universe…
…then it can also see neutrinos emitted from nuclear reactors across international borders!

The WATCHMAN Collaboration



A. Bernstein, S. Dazeley

C. Mauger, G. Mills, K. Rielage, G. Sinnis

UC Berkeley: G. Orebi Gann, K. Van Bibber, B. Land, K. Vetter, C. Roecker, D. Hellfeld

M. Yeh

Iowa State: M. Wetstein

UC Davis: R. Svoboda, M. Askins, D. Danielson

U of Hawaii: J. Learned, J. Maricic, S. Dye, M. Duvall

UC Irvine: M. Vagins, M. Smy

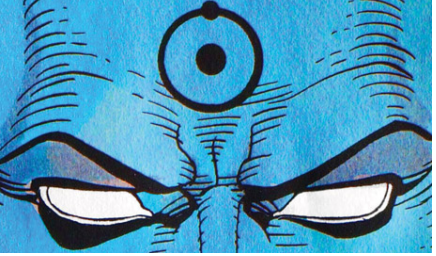
U. Michigan: I. Jovanovic, J. Nattress

Penn State: Doug Cowen

V. Tech: S.D. Rountree, B. Vogelaar, P. Jaffke

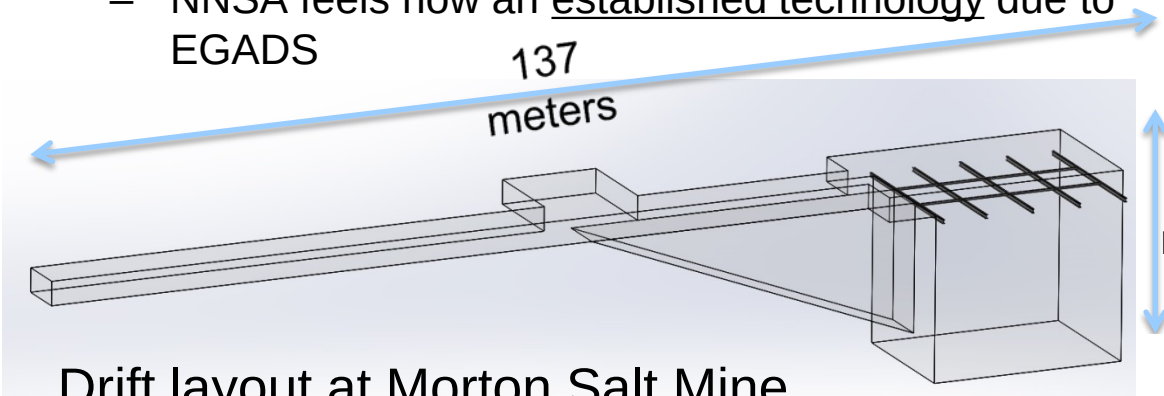
U. Tenn: Y. Kamyshkov, T. Handler, Z. Bingham, B. Chance, B. Rybolt

34 collaborators 3 National Laboratories, 9 Universities, 19 senior personnel, 1 post-doc, 8 Ph.D students, 2 Undergrads

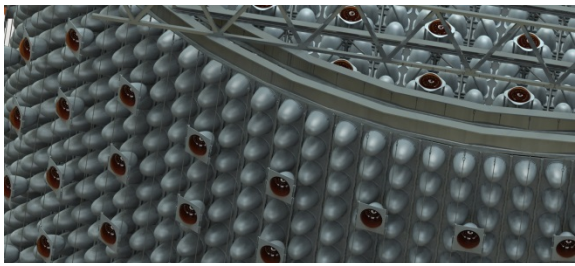


Baseline WATCHMAN Detector Design

- Stainless cylindrical tank, assembled in place in existing IMB cavern
- 3.5 kilotons total volume Gd-H_2O, 1 kton fiducial
- 4810 inner 12” PMTs, 40% + HQE → 50% more light collection than Super-K
  - Largest cost item, main schedule determinant
- Active outer veto
- Compatible with pure water, Gd+water, or WbLS
  - Pure LS fill would require inner vessel
- Gadolinium-doped water recirculation the key technical advance
  - NNSA feels now an established technology due to EGADS



Drift layout at Morton Salt Mine



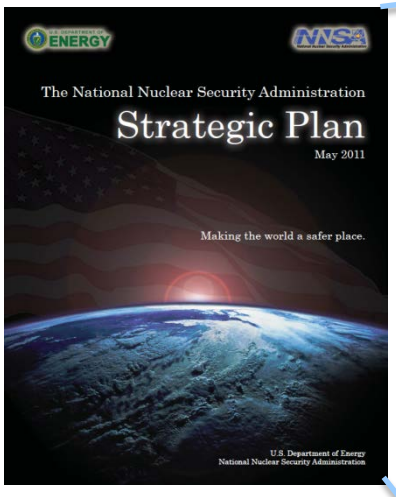
Close-up of Veto PMT Wall

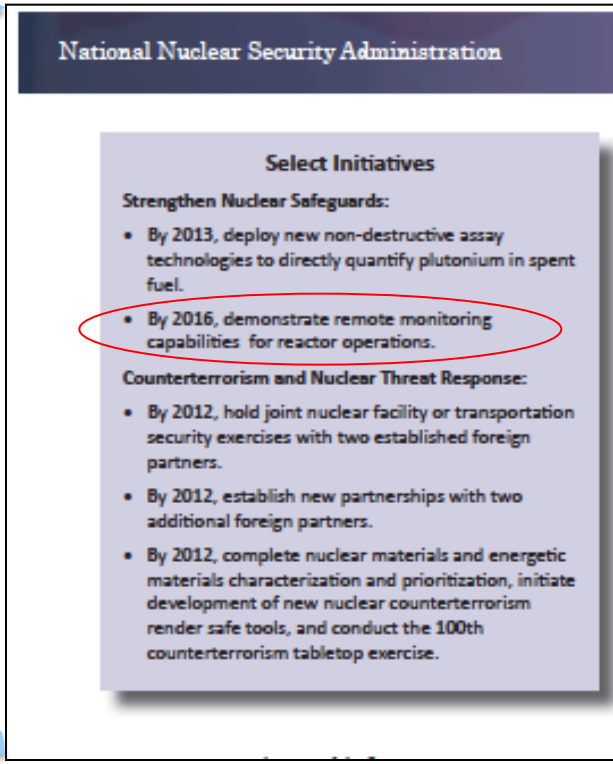
Remote Reactor Monitoring is still an NNSA Strategic Goal, but..

Office of Science did not accept proposed joint funding model

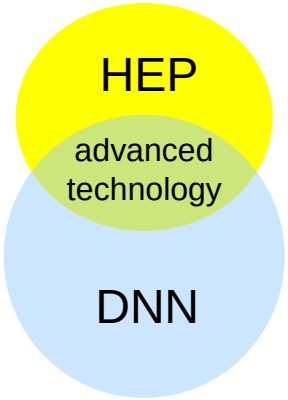
May 28 2015 - DOE-SC-HEP decision not to support WATCHMAN deployment

N.B: DNN is still supportive and claims ~$20M-$30M is set aside

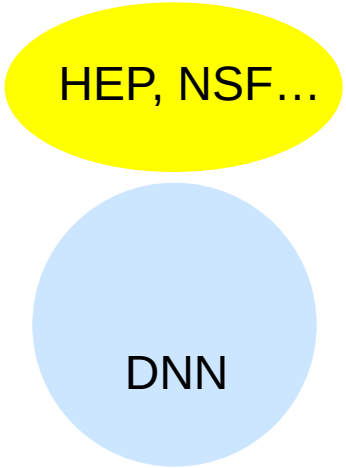




Original Model



New Model



We have fissioned into two distinct projects with separate missions:

NNSA-DNN – Defense Nuclear Nonproliferation
DOE-SC-HEP – High Energy Physics

[A. Bernstein]

Meanwhile, at Fermilab:

ANNIE approved by FNAL for Phase 1 run this year at FNAL BNB

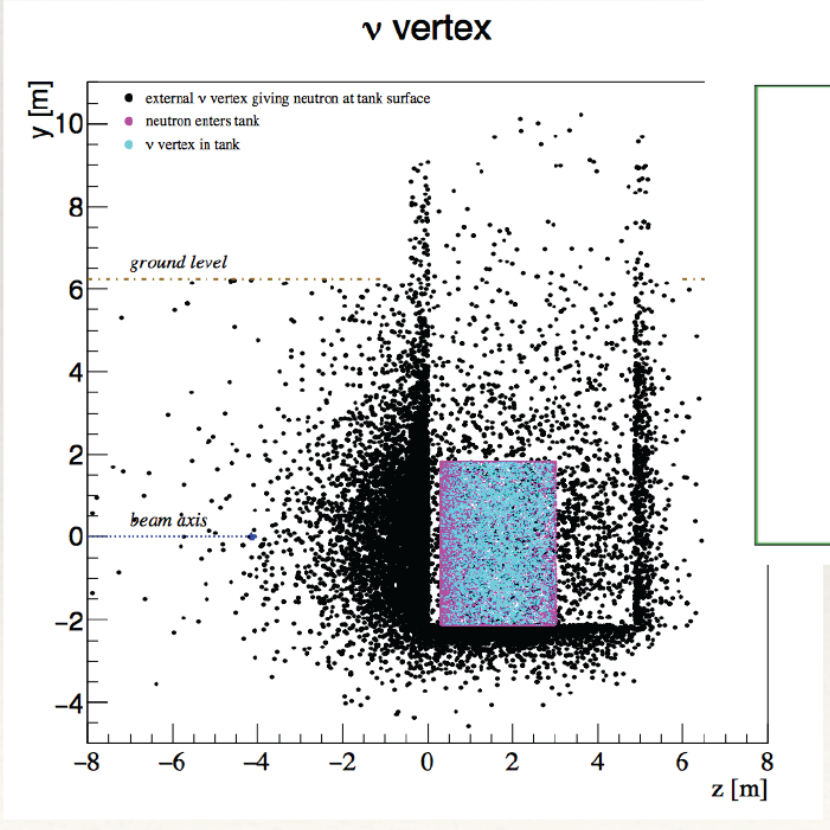
Phase 1 is a measurement of the neutron background during neutrino beam oeprations

FNAL is putting resources into ANNIE construction

The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

J. F. Beacom[8], F. Di Lodovico[16], H. Frisch[14], R. Hill[14], T. Katori[16], F. Krennrich[5], M. Malek[10], G. Orebi-Gann[7], M.C. Sanchez *[5], M. Smy[12], R. Svoboda[11], M. Vagins[12], R. Wagner[1], A. Weinstein[5], and M. Wetstein[5]

[1] *Argonne National Laboratory; Lemont,*
[3] *Fermi National Accelerator Laboratory; Bata*
[5] *Iowa State University; Ames, IA 5*
[7] *University of California at Berkeley; Berkel*
[8] *Ohio State University; Columbus, OH*
[10] *University of Sheffield; Sheffield S1*
[11] *University of California at Davis; Davis,*
[12] *University of California at Irvine; Irvine*
[14] *University of Chicago, Enrico Fermi Institute;*
[16] *Queen Mary University of London; Lon*



Fermilab

Directorate

TECHNICAL SCOPE OF WORK

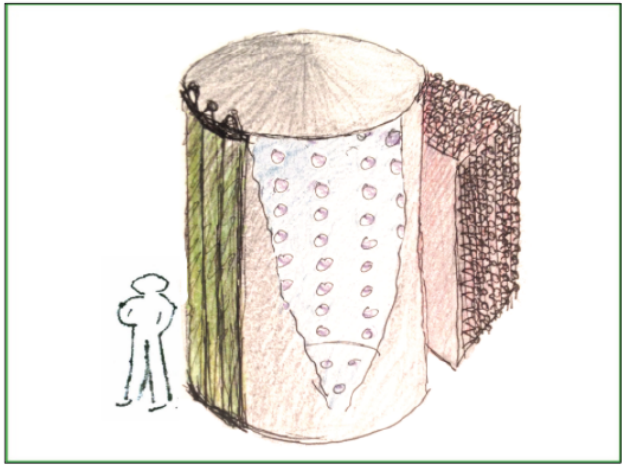
FOR THE 2015 FERMILAB SCIBOONE HALL PROGRAM

T-1063

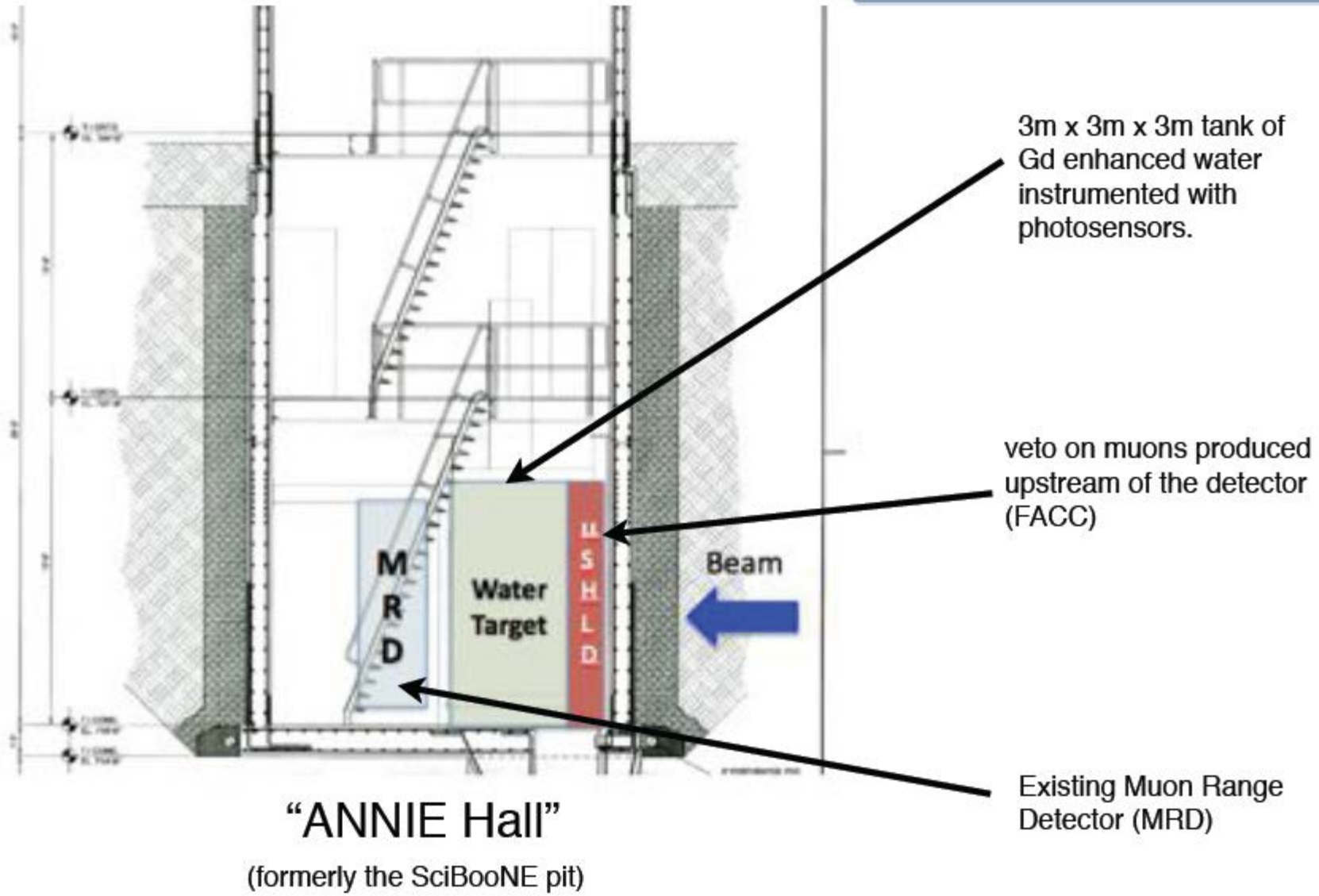
ANNIE:

Accelerator Neutrino Neutron Interaction Experiment

August 31, 2015



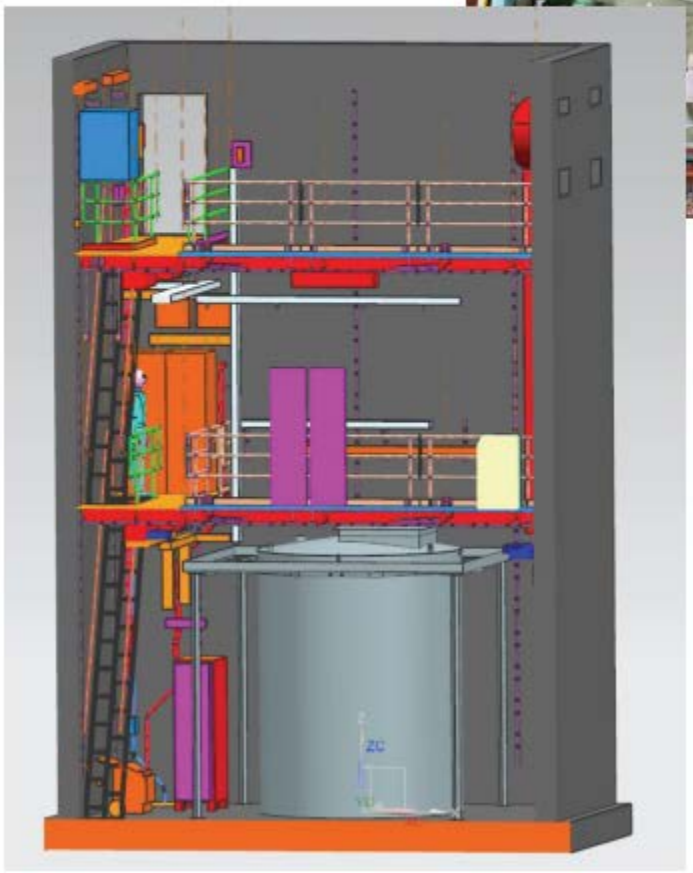
[B. Svoboda]


3m x 3m x 3m tank of Gd enhanced water instrumented with photosensors.
veto on muons produced upstream of the detector (FACC)
Existing Muon Range Detector (MRD)
M R D
Water Target
U S H L D
Beam
"ANNIE Hall"
(formerly the SciBooNE pit)

[M. Wetstein]

FNAL Engineering drawings for ANNIE

Construction of ANNIE FACC



ANNIE tank in Dzero Hall

[B. Svoboda]

It’s been a long journey to Gd-loaded WC detectors, both in the US and Japan, but the idea has clearly taken hold. After well over a decade of innovation, study, and lots of scooping…