Putting Gadolinium in Water Cherenkov Detectors



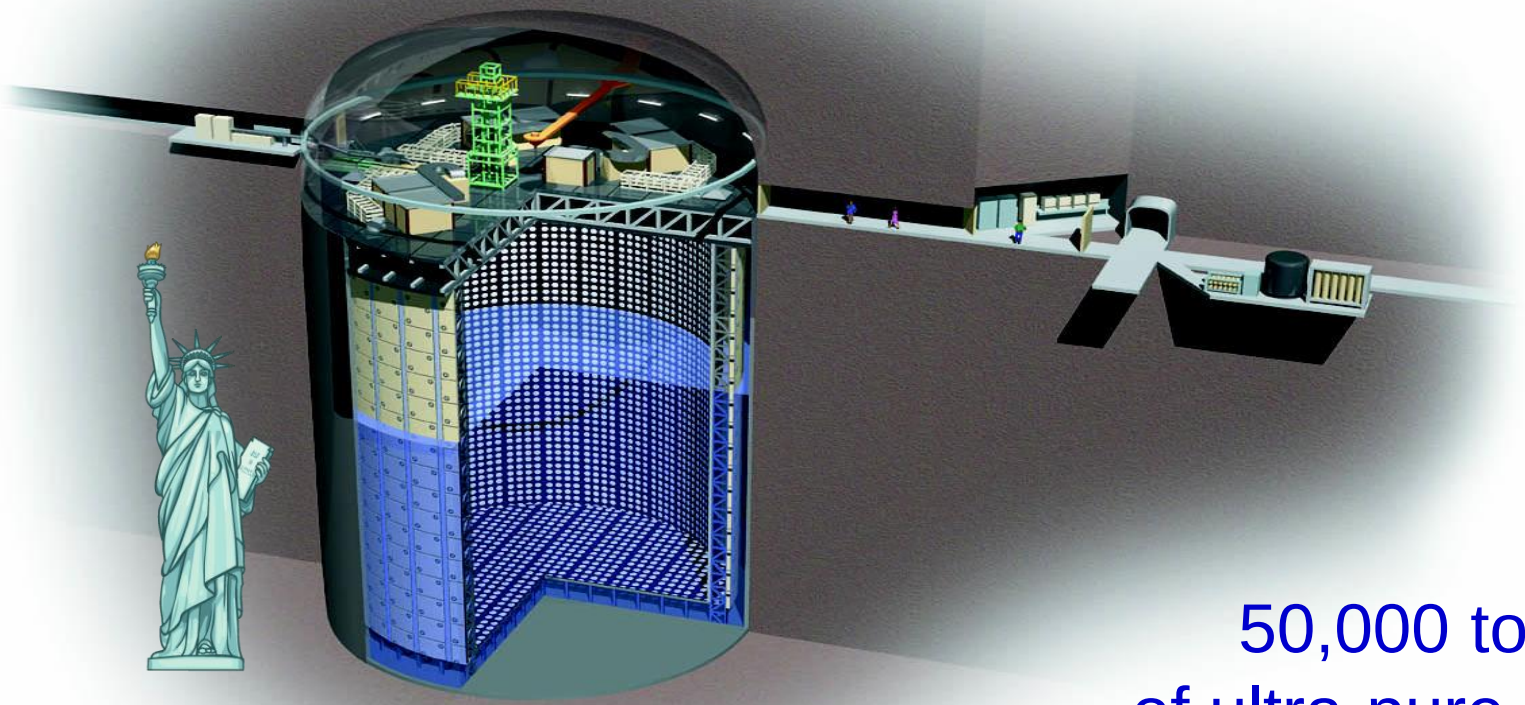
Mark Vagins

Kavli IPMU, UTokyo/UC Irvine

Coordinating Panel on Advanced Detectors (CPAD) 2026 Workshop

Seattle, Washington October 23, 2026

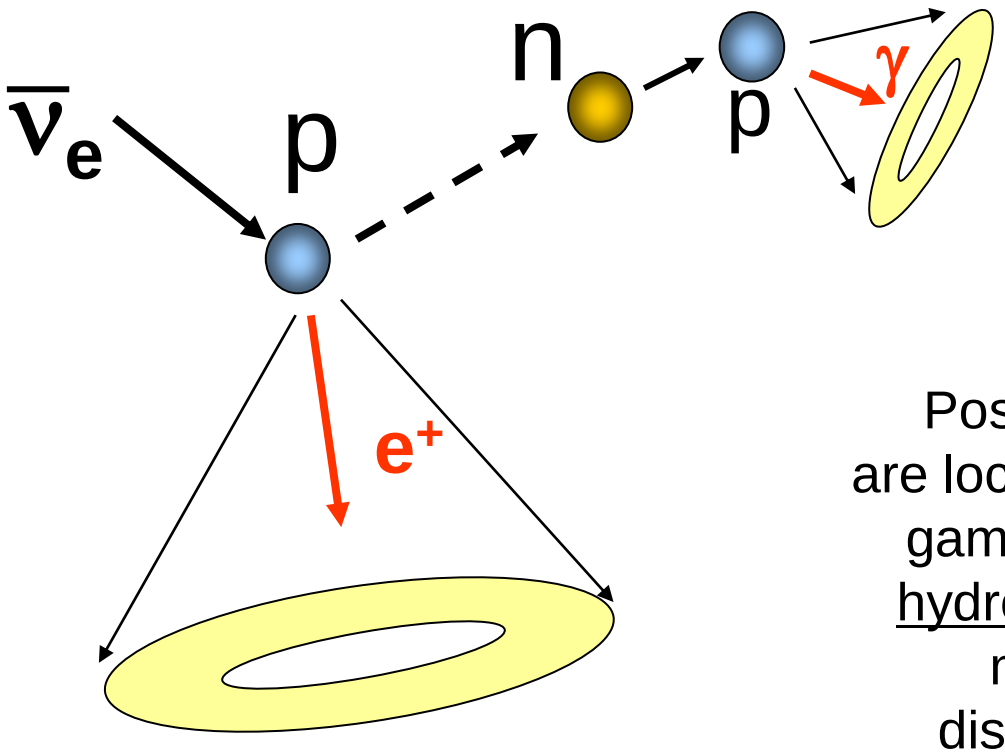
My beloved Super-Kamiokande (Super-K, SK)
– already the best supernova ν detector in the world –
has been taking data, with an occasional interruption, for over thirty years now… but no dramatic burst of SN neutrinos (like during SN1987A) has been seen so far.



50,000 tons
of ultra-pure water,
~13,000 PMT's

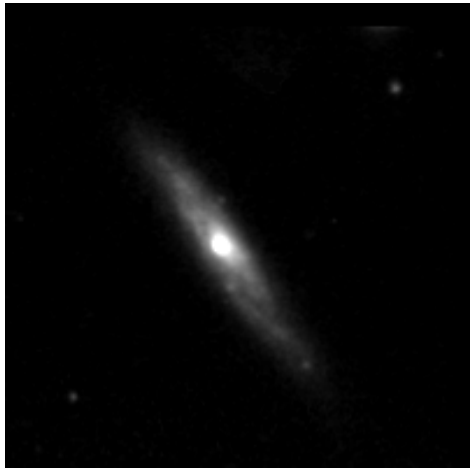
Inverse Beta Decay

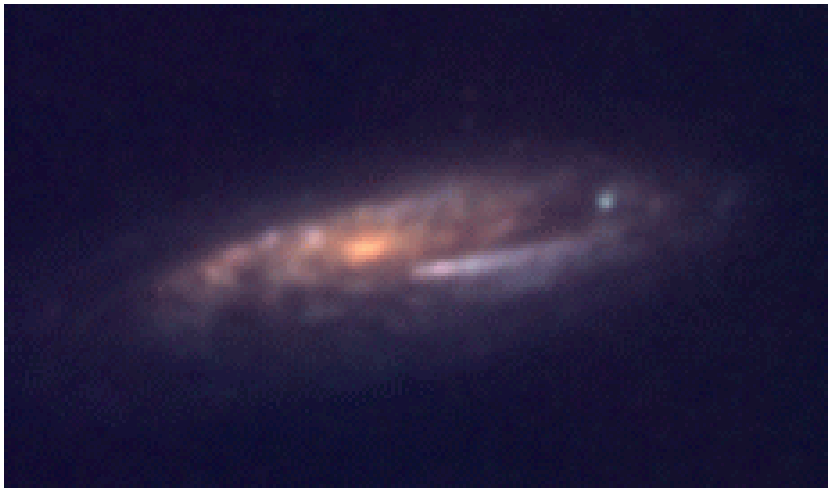
(primary supernova neutrino signal in WC detectors)



Positron and gamma ray vertices are located within ~50 cm, but 2.2 MeV gammas from neutron captures on hydrogen are difficult to detect and, more importantly, difficult to distinguish from backgrounds in water Cherenkov detectors.

This makes detection of neutrinos from distant SN explosions nearly impossible.







Here's how most supernovas look to us (video is looped).

There is about *one SN explosion per second* in the universe as a whole!





These produce the as-yet unobserved diffuse supernova neutrino background [DSNB], also known as the supernova relic neutrinos [SRN].



"Everyone complains about the (supernova neutrino) weather,
but no one *does* anything about it…"
So, after one of the sessions at Neutrino 2002 in Munich,
theorist John Beacom and I spent hours sitting in a subway
station, brainstorming ideas. But we did NOT start with gadolinium!



Date: Tue, 30 Jul 2002 03:45:09 -0700 (PDT)
From: Mark Vagins <vagins@danka.ps.uci.edu>
To: John Beacom <beacom@fnal.gov>
Subject: The briny, briny deep

Hey John,

I just spoke with Yoichiro Suzuki, who is also attending this meeting in Amsterdam. I brought up our scheme for making SK 1% salty.

He liked the idea a lot, and in fact said that salting SK was one of the future options he had been musing about. Naturally, he did say that we needed to carefully model a salty detector and get a feel for the true numbers.

He went on to say that the necessary water system modifications were possible, and that in the near future

"we must do something to get the new physics."

He also felt that 500 tons of salt was reasonable, saying to me,

"It's just 50 truckloads - you can shovel it yourself!"

This is a very positive thing indeed (other than the part about my shoveling half a kiloton of salt myself).

So, things sound pretty promising on this end. I wonder if it's worth putting out a phenomenological paper outlining how this will-salt-for-relics could work... it probably is, especially if there is a non-zero likelihood that SK will actually do something about it!

We must do something to get the new physics,
-Mark

As I didn't want to shovel 500 tons of NaCl into SK all by myself, we eventually turned to the best neutron capture nucleus known – gadolinium.



גדוליניום

"Gadol" = Great!

- $GdCl_3$ and $Gd_2(SO_4)_3$, unlike metallic Gd, are highly water soluble
- Neutron capture on Gd emits a 8.0 MeV γ cascade
- 100 tons of $GdCl_3$ or $Gd_2(SO_4)_3$ in SK (0.2% by mass) would yield >90% neutron captures on Gd
- Plus, they are easy to handle and store.



Gadzooks!



[A Serious SK Upgrade Suggestion]

Mark Vagins
University of California, Irvine

Osawano
November 11, 2002

Here's the very first transparency (i.e., what we older folks used before PowerPoint but after glass slides) I ever showed on the topic… nearly twenty-four years ago.

This was at an SK Collaboration meeting in Japan.

Please note the subtitle:

"A Serious SK Upgrade Suggestion"

As many of you now know, we did indeed eventually put out that “phenomenological paper.”





arXiv > hep-ph > arXiv:hep-ph/0309300

Search... Help

High Energy Physics - Phenomenology

[Submitted on 26 Sep 2003]

GADZOOKS! Antineutrino Spectroscopy with Large Water Cerenkov Detectors

John F. Beacom, Mark R. Vagins

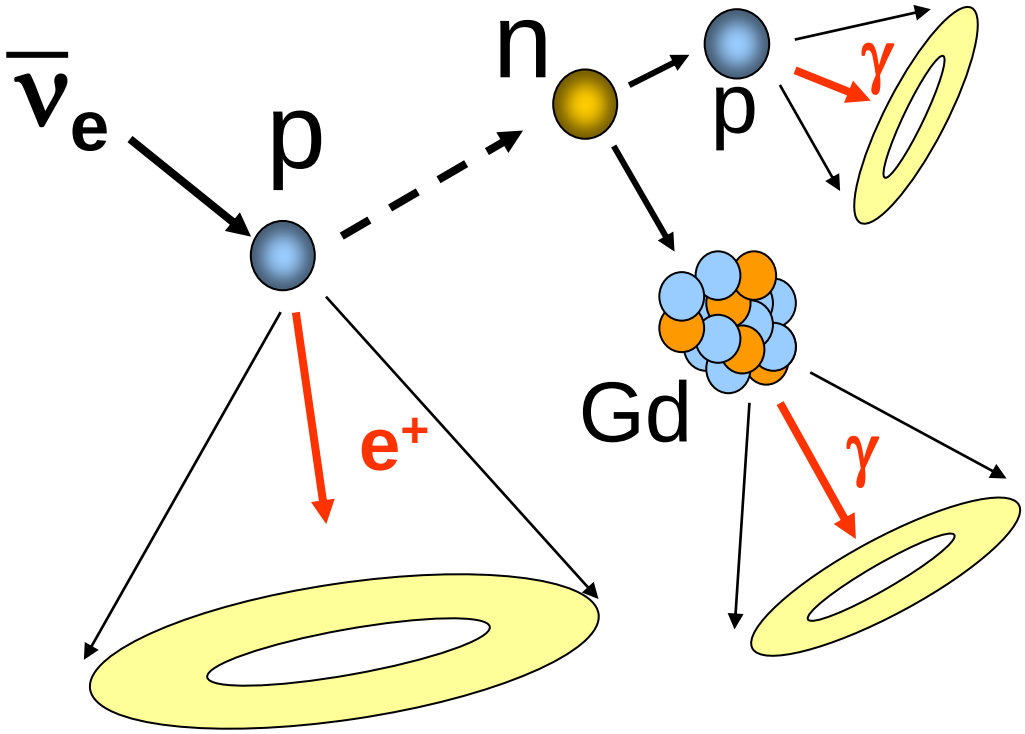
We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible 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.

Comments: 4 pages, 1 figure, submitted to Phys. Rev Lett. Correspondence to beacom@fnal.gov, mvagins@uci.edu
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Astrophysics (astro-ph); High Energy Physics - Experiment (hep-ex); Nuclear Experiment (nucl-ex); Nuclear Theory (nucl-th)
Report number: FERMILAB-Pub-03/249-A
Cite as: arXiv:hep-ph/0309300
(or arXiv:hep-ph/0309300v1 for this version)
https://doi.org/10.48550/arXiv.hep-ph/0309300
Journal reference: Phys.Rev.Lett. 93 (2004) 171101
Related DOI: https://doi.org/10.1103/PhysRevLett.93.171101

[*Phys. Rev. Lett.* 93 (2004) 171101 has exactly 641 citations!]

In addition to first introducing the term "DSNB", basically we said, "Let's add 0.1% gadolinium - using a water soluble gadolinium compound - to Super-Kamiokande!"





Positron and gamma ray vertices within ~50 cm.

Possibility 1: 10% or less

$n+p \rightarrow d + \gamma$

2.2 MeV γ-ray

Possibility 2: 90% or more

$n+Gd \rightarrow$ ~8 MeV γ

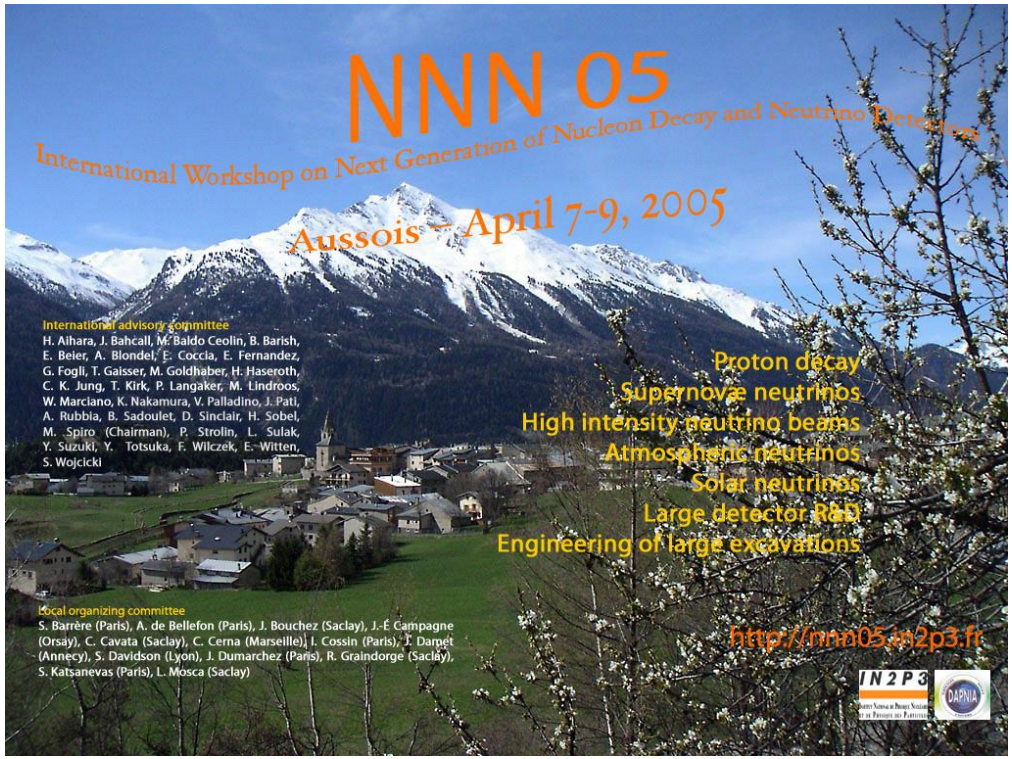
ΔT = ~30 μsec

$\bar{\nu}_e$ can be individually identified by delayed coincidence: "Gd heartbeat"

→ n-tags greatly reduce (10^{-4}) backgrounds to DSNB, etc

The GADZOOKS! proposal quickly starting getting a lot of attention, especially in the theory community:

At NNN05, before I had even given my talk, John Ellis suddenly stood up and demanded of the startled senior SK people in attendance:



Why haven't you guys put gadolinium in Super-K yet?



As I told him, studies are under way…

Now, John Beacom and I never wanted to merely propose a new WC technique – we wanted to make it work!



[Snowbird photo by A. Kusenko]

Suggesting a major modification of one of the world's leading neutrino detectors is indeed not the easiest route…

…so began many years of experimental and theoretical studies.

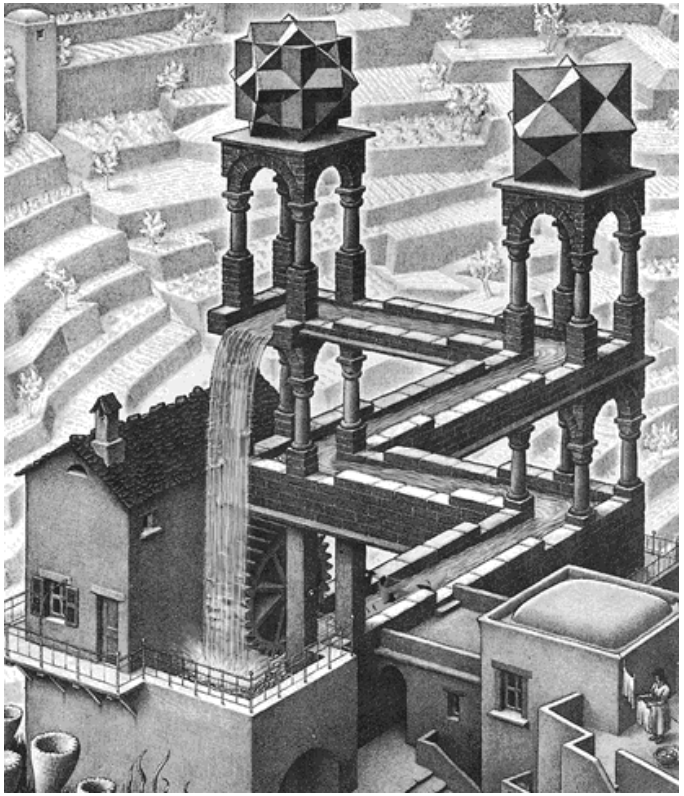
As a matter of fact, I very rapidly made two discoveries regarding $GdCl_3$ while carrying a sample from Los Angeles to Tokyo:



1) $GdCl_3$ is quite opaque to X-rays
2) Airport personnel get very upset when they find a kilogram of white powder in your luggage

The Essential Magic Trick

→ We must keep the water in any 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!

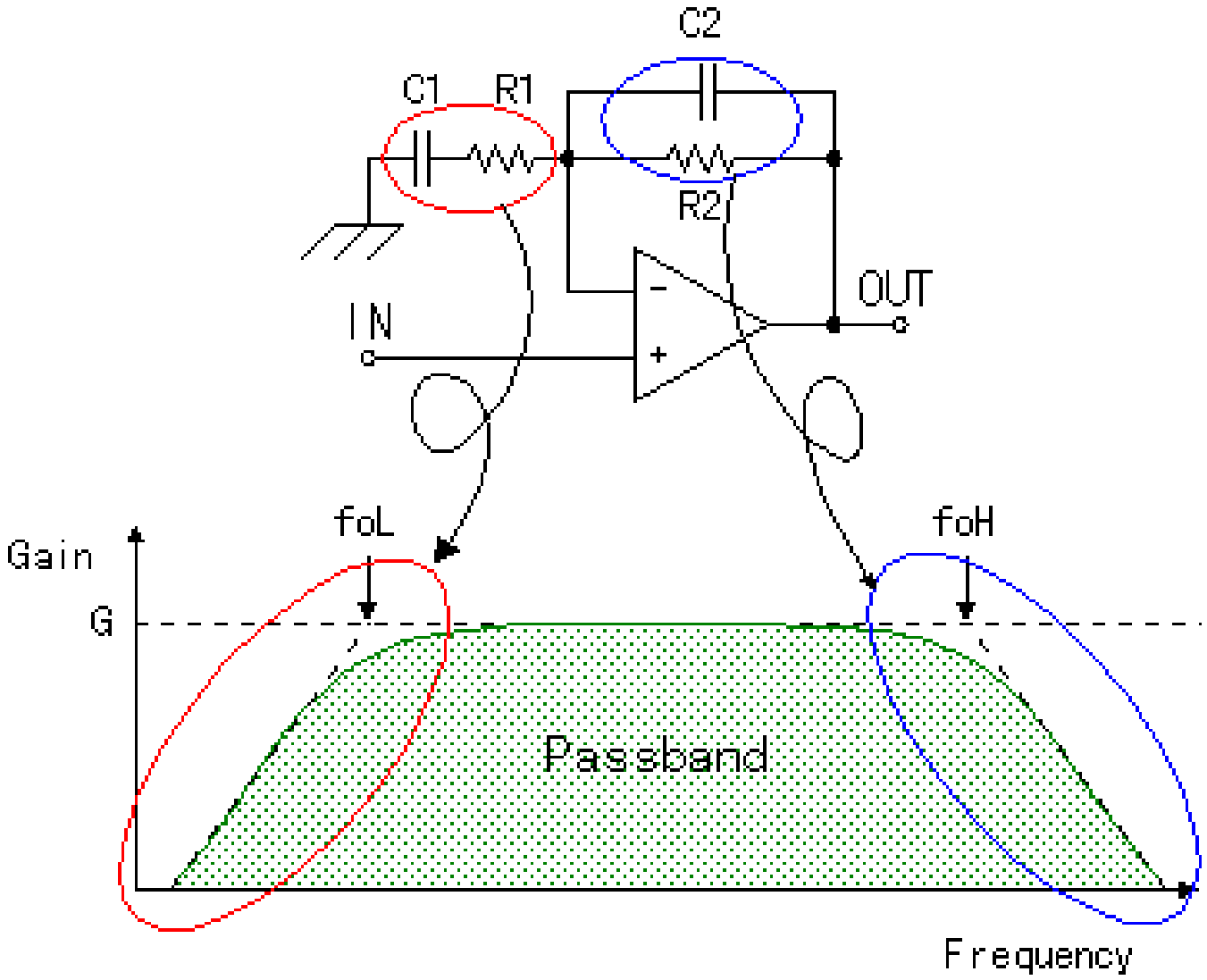
This technology can support a variety of applications, such as:

→ Supernova neutrino, dark matter, and proton decay searches

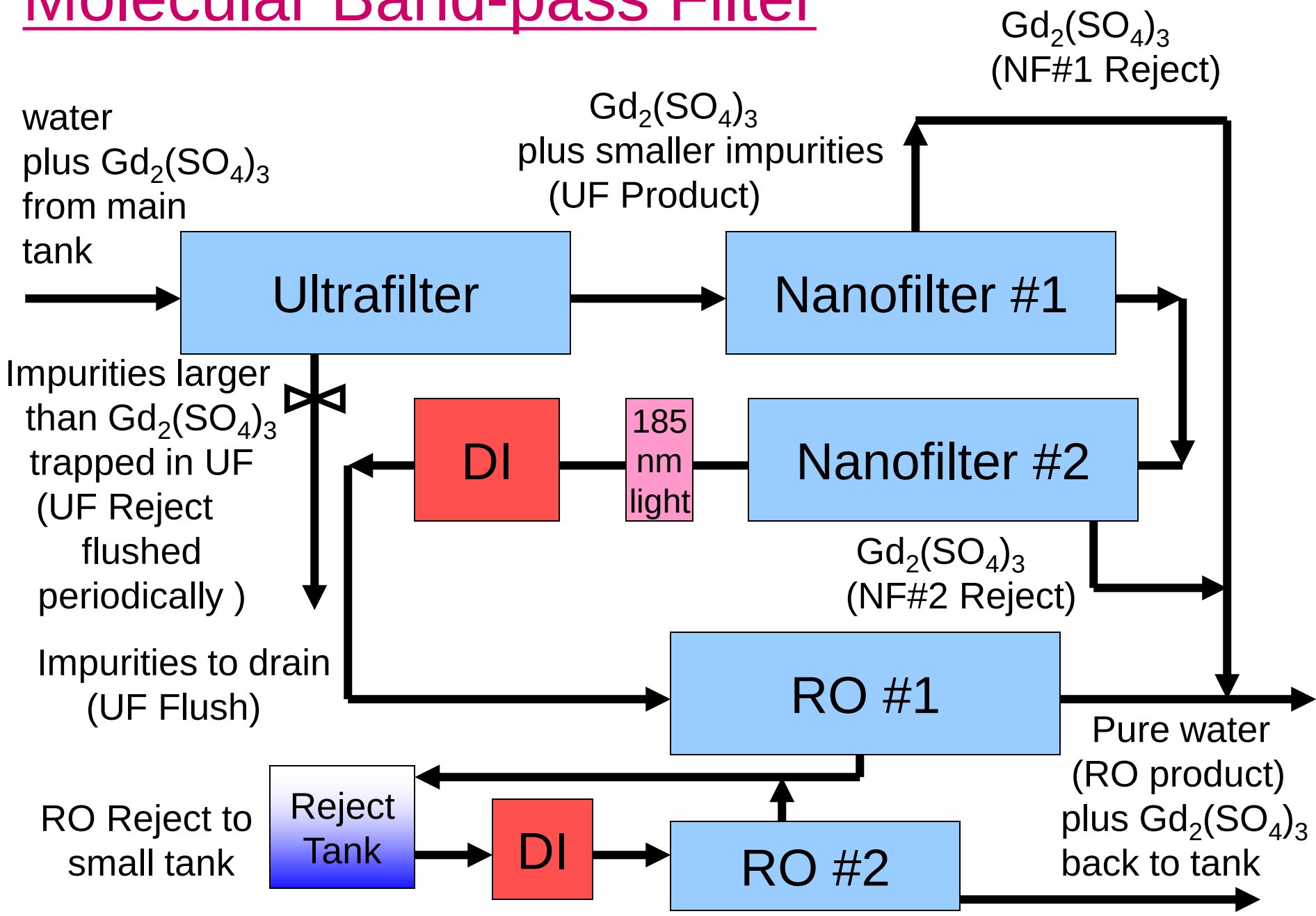
→ Remote detection of clandestine fissile material production

→ Efficient generation of clean drinking water without electricity

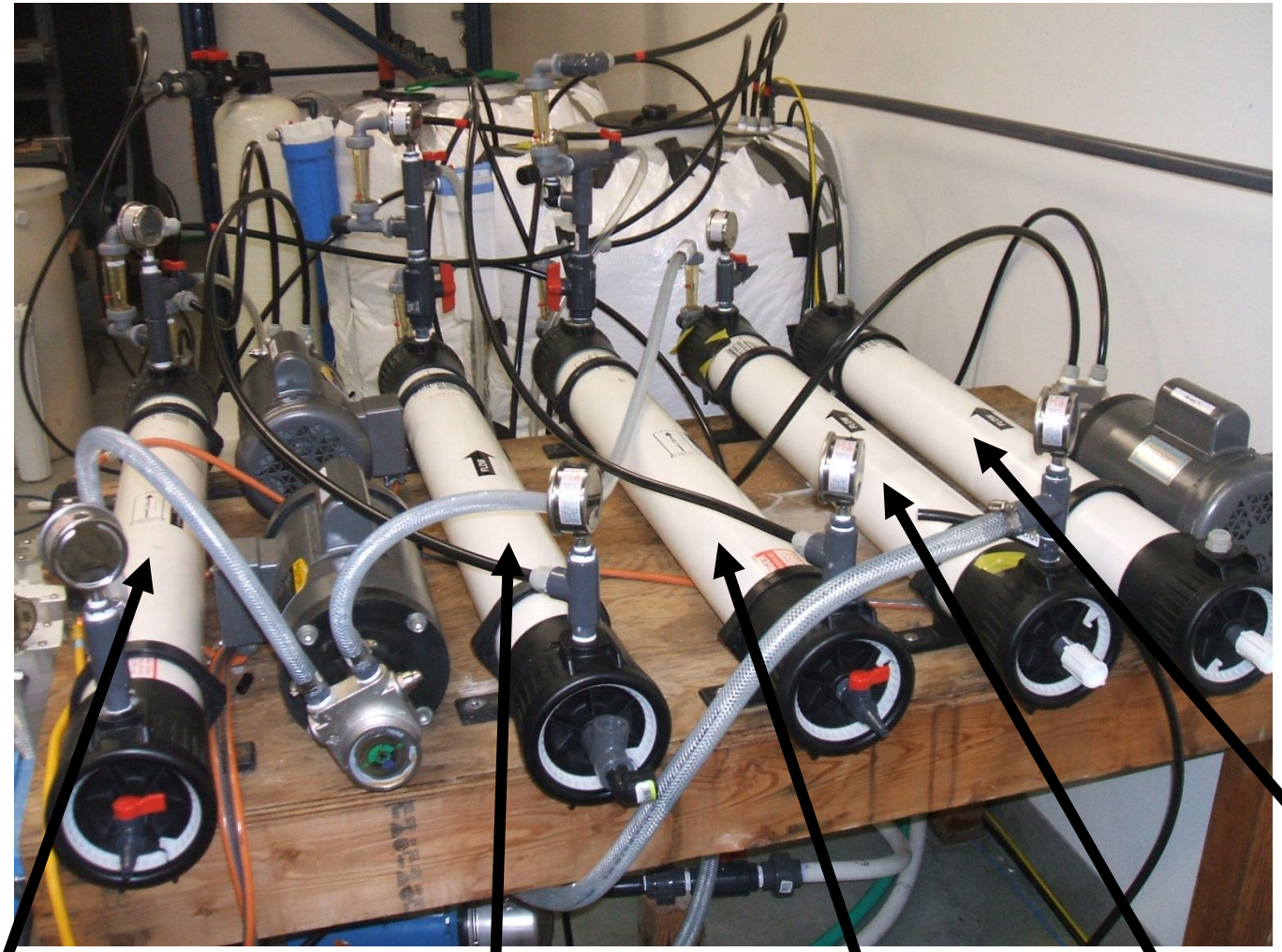
Electrical Band-Pass Filter



Molecular Band-pass Filter



My Prototype Selective Filtration Setup @ UCI in 2008



Nanofilter #1

Nanofilter #2

Reverse Osmosis

Ultrafilter

Membrane Pre-Flush

On March 15th, 2008, I received an official job offer from Hitoshi Murayama to join his newly-formed *Institute for the Physics and Mathematics of the Universe* at the University of Tokyo. It read, in part:

"In this position, you will be able to continue your research program in the Super-Kamiokande experiment and play a leadership role in its future program to dope it with a Gadolinium compound to enhance its neutron detection capability, which may well lead to the first detection of relic supernova neutrinos."

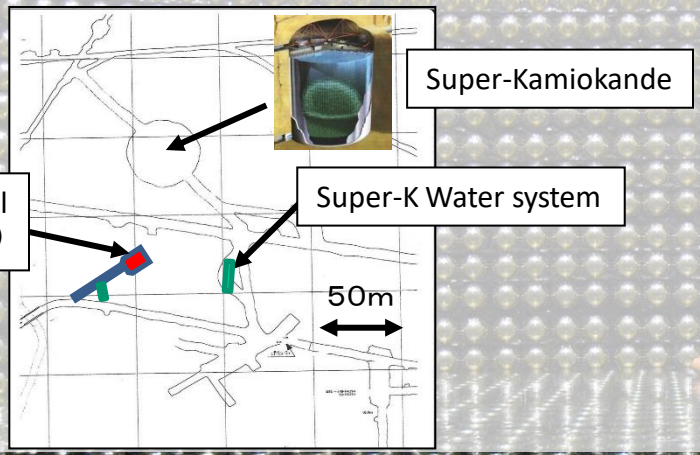
So I promptly joined IPMU - as its first full-time foreign professor - while retaining a without-salary position at UCI.



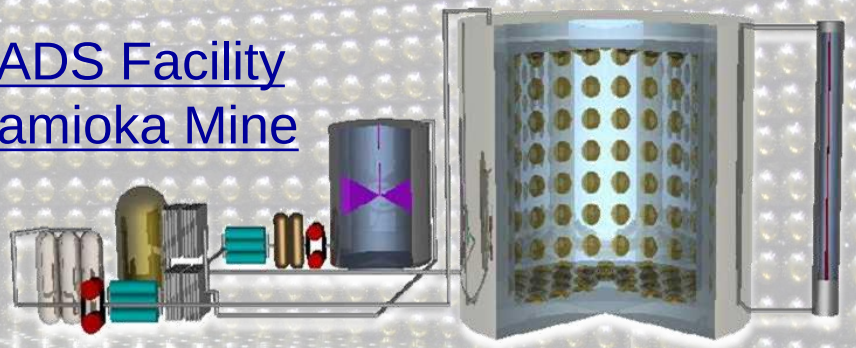
IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

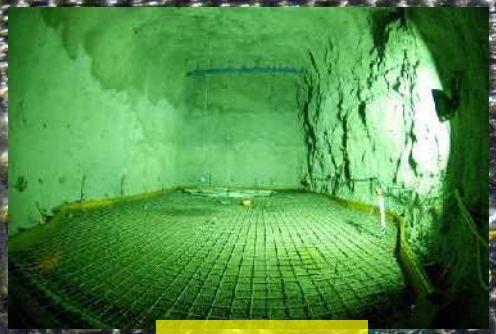
EGADS, the Gd-in-Water Pathfinder

IPMU/ICRR built **EGADS** (Evaluating Gadolinium's Action on Detector Systems), as a dedicated Gd testbed which includes a working 200-ton scale model of SK.



EGADS Facility
in Kamioka Mine





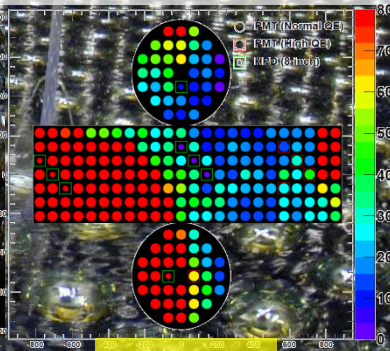
12/2009



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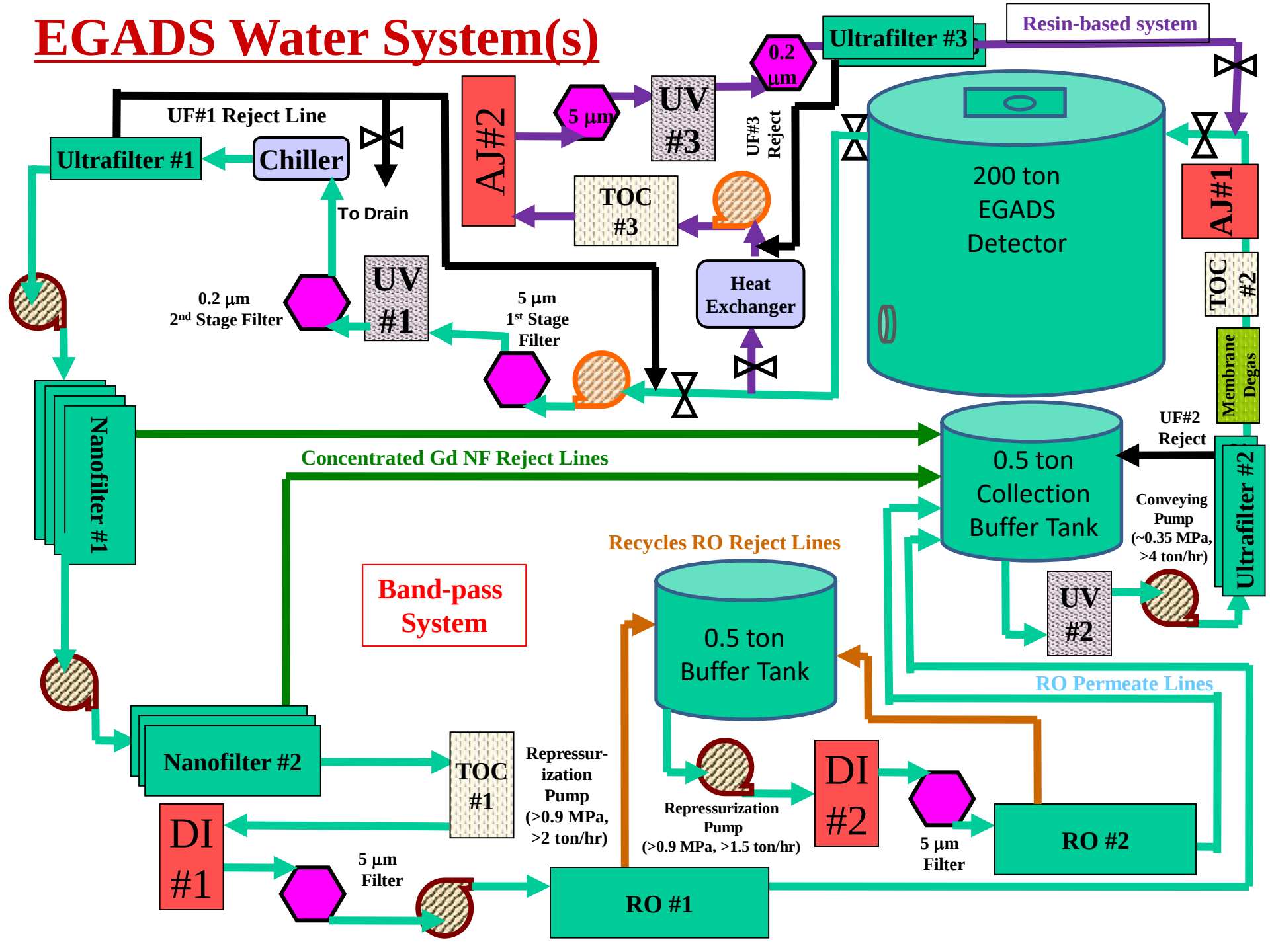
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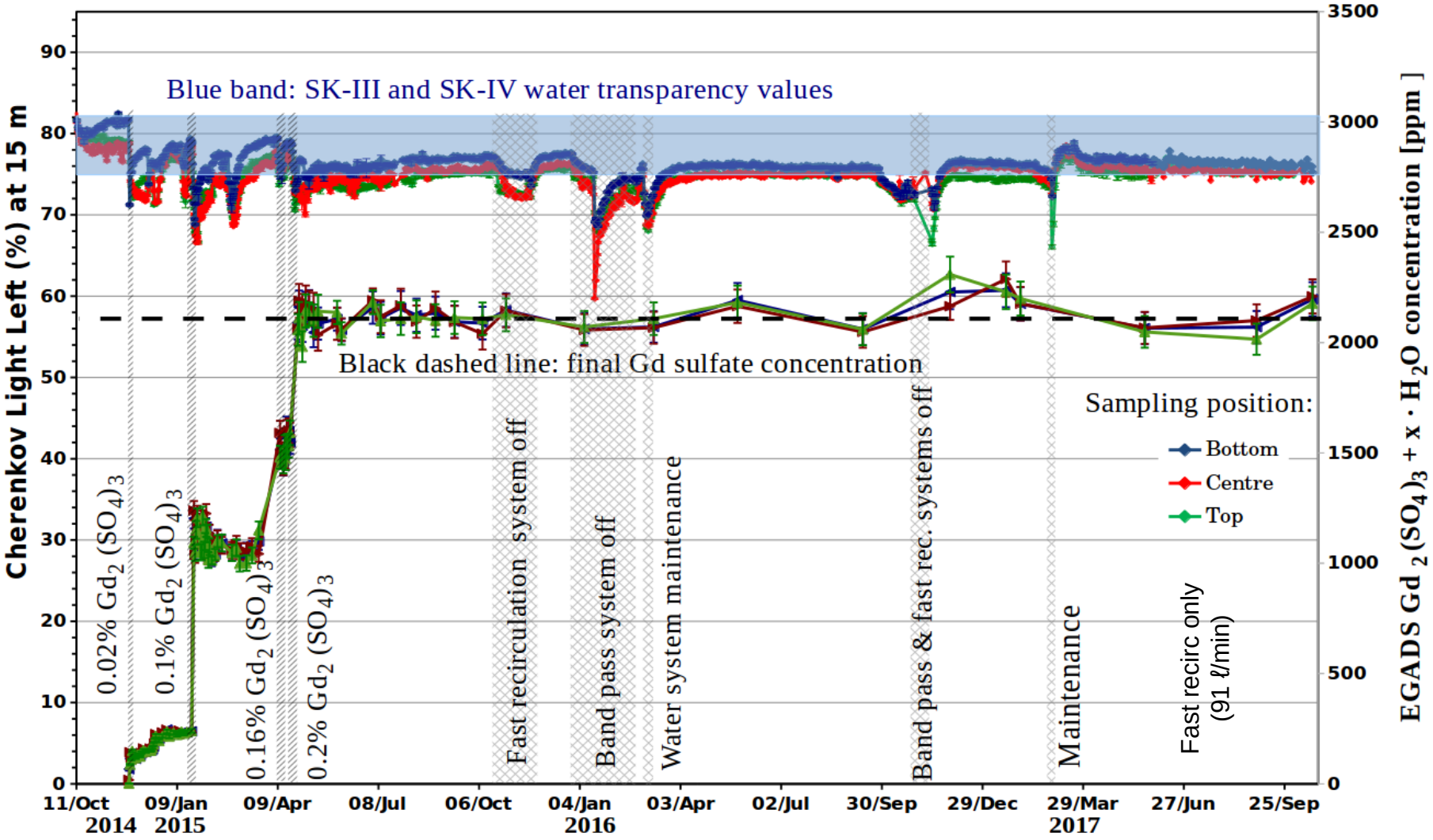
Well over $10,000,000 - not counting salaries - has been spent developing and proving the viability of the Gd-in-water concept.

["Evaluation of gadolinium's action on water Cherenkov detector systems with EGADS," Ll. Marti et al., *Nucl.Instrum.Meth.* **A959** 163549 (2020)]

EGADS Water System(s)



Light @ 15 meters and Gd conc. in the 200-ton EGADS tank



After two and a half years at full (0.2%) Gd loading, during stable operations EGADS water transparency remained within the SK ultrapure range.

→ No detectable loss of Gd after more than 650 complete turnovers. ←

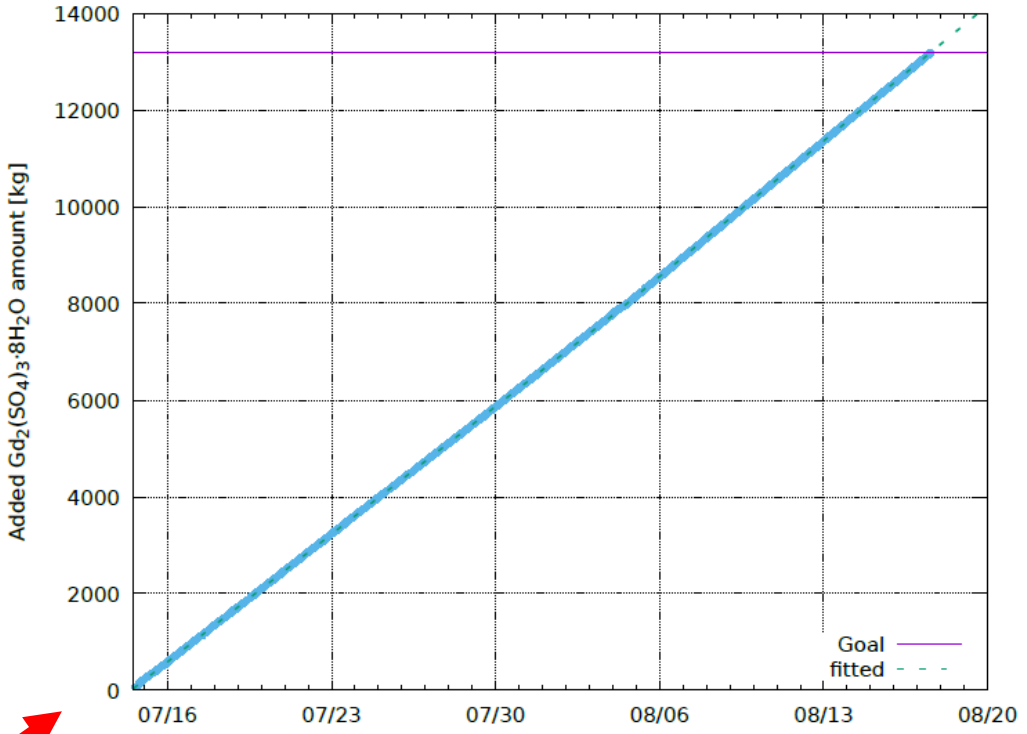
Loading Super-Kamiokande with Gadolinium (First Step)

After nearly 20 years of R&D, planning, and preparation, culminating with a major detector refurbishment in 2018/9, Super-K was finally loaded with 0.01% gadolinium (meaning 13.2 tons of $Gd_2(SO_4)_3*8H_2O$) in July/August 2020 → SK-VI





Gd Loading Super-Kamiokande in 2020



"First Gadolinium Loading to Super-Kamiokande", Super-K Collaboration, *Nuclear Inst. And Methods in Physics Research*, **A 1027** (2022) 166248

Loading Super-Kamiokande with Gadolinium (Next Step)

To bring the loading up to 0.03% Gd, in the summer of 2022 we added another 26 tons of $Gd_2(SO_4)_3*8H_2O$ to Super-K → SK-VII



These two lots of gadolinium sulfate for SK, at 13 and 26 tons, are by far the largest orders of gadolinium in human history… and ultra-pure, too!

About 75% of the neutrons in SK are now being (visibly) captured on Gd.

"Second Gadolinium Loading to Super-Kamiokande", Super-K Collaboration, *Nuclear Inst. And Methods in Physics Research*, **A 1065** (2024) 169480

Getting Gd into SK required studies of:

- Selective Filtration (IPMU/UCI/ICRR)
- Material Compatibility (Okayama/LSU/Mitsui)
- Water Transparency (UCI/Okayama/LLNL)
- Gd Solubility (UCI/ICRR)
- Gd Removal (UCI/IPMU)
- Radioactive Backgrounds (ICRR/UCI/Madrid)
- Neutron Tagging (ICRR/Okayama/UCI)
- Detector Simulation (ICRR/IPMU/Okayama/UCI)
- DAQ (Okayama/ICRR)
- Phenomenology (Fermilab/OSU/UCI/IPMU)

This has taken a tremendous amount of effort by many people… on this occasion I want to give a big *"thank you"* to all of them!

Gd-H_2O: Everybody's Doing It, Man…







Name	Location	Main Goal	Water Volume	$Gd_2(SO_4)_3$ Loaded
EGADS	Kamioka	Gd R&D, SN Watch	200 tons	Since 2013
ANNIE	Fermilab	High-E Neutron Multiplicity	26 tons	Since 2019
Super-K-VI/VII	Kamioka	DSNB, SN Burst, PDK, ATM/Sol/LB ν	50 ktons	Since 2020/2
XENONnT Water Shield	Gran Sasso	Dark Matter Detection	700 tons	Since 2023
WCTE	CERN	IWCD/mPMT Demonstrator	50 tons	May 2025 (completed)
30-ton Test Tank	BNL	Nuclear Non-Proliferation Demonstrator	30 tons	early 2027 (expected)
BUTTON	Boulby	Underground Demonstrator	30 tons	mid-2027(?) (op funds?)
Hyper-K-II(?)	Kamioka	DSNB, SN Burst, PDK, ATM/Sol/LB ν	258 ktons	203X(?)



The view from the top of the barrel…
HK will begin taking data in 2028
with eight times SK's fiducial volume!

June 28th, 2025

As announced at Neutrino 2026, Super-Kamiokande now has a 2.6-sigma (and steadily growing) indication of the DSNB flux thanks to Gd loading!
So, will Hyper-Kamiokande also be loaded with gadolinium?

Certainly not on Day 1, but samples of all wetted materials are being tested for compatibility with both pure water and Gd-loaded water.
Catchment for any possible leaks is also carefully designed.

→ Gd is being actively preserved as a future HK upgrade option! ←

I currently control more gadolinium than any other private citizen in the world, and I readily share it and my Gd-enabling filtration technology with all who ask.



So, now you know how I become the Gdfather.