EGADS: Building the World's Most Advanced Supernova Neutrino Detector

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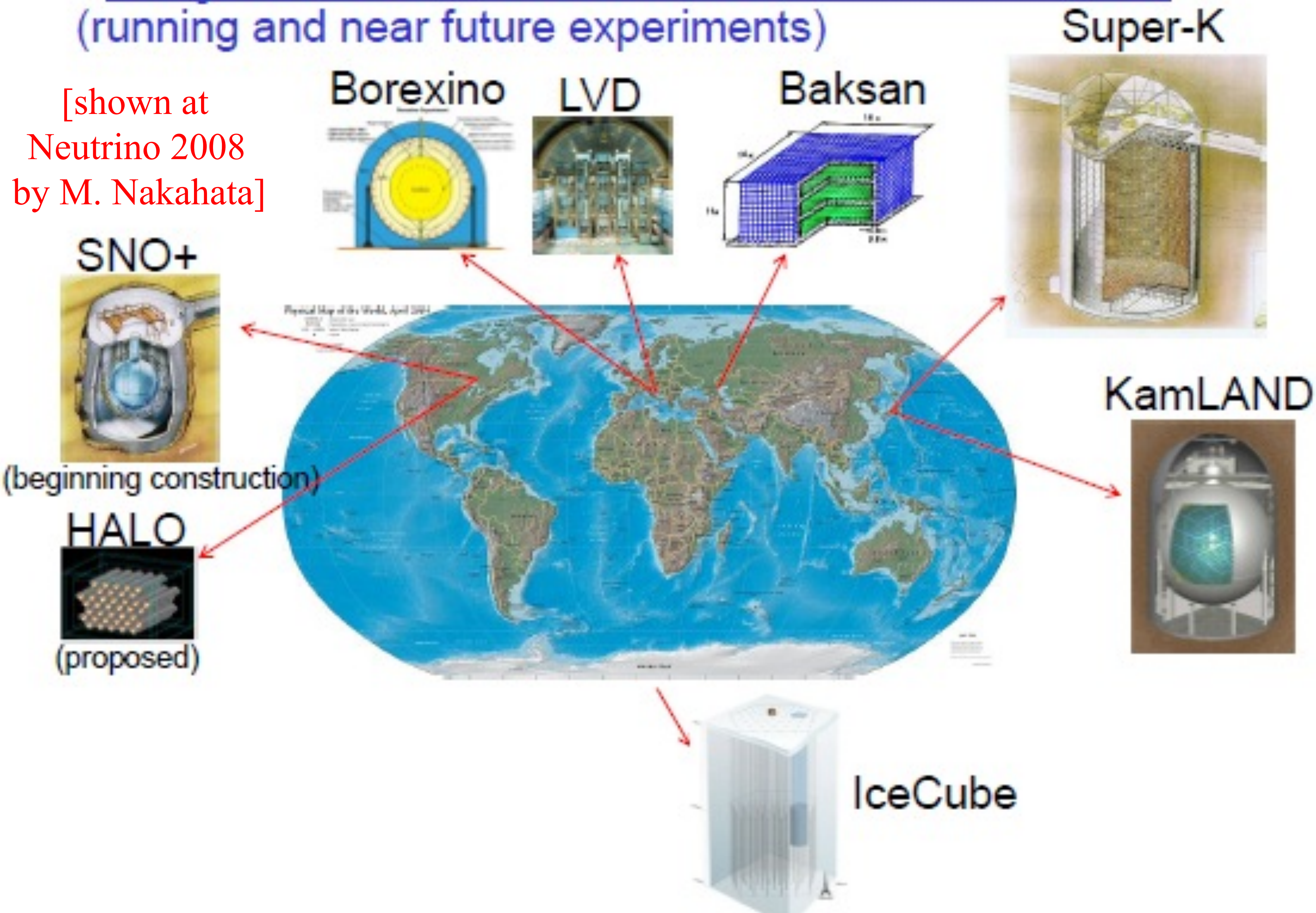
Supernova detectors in the world

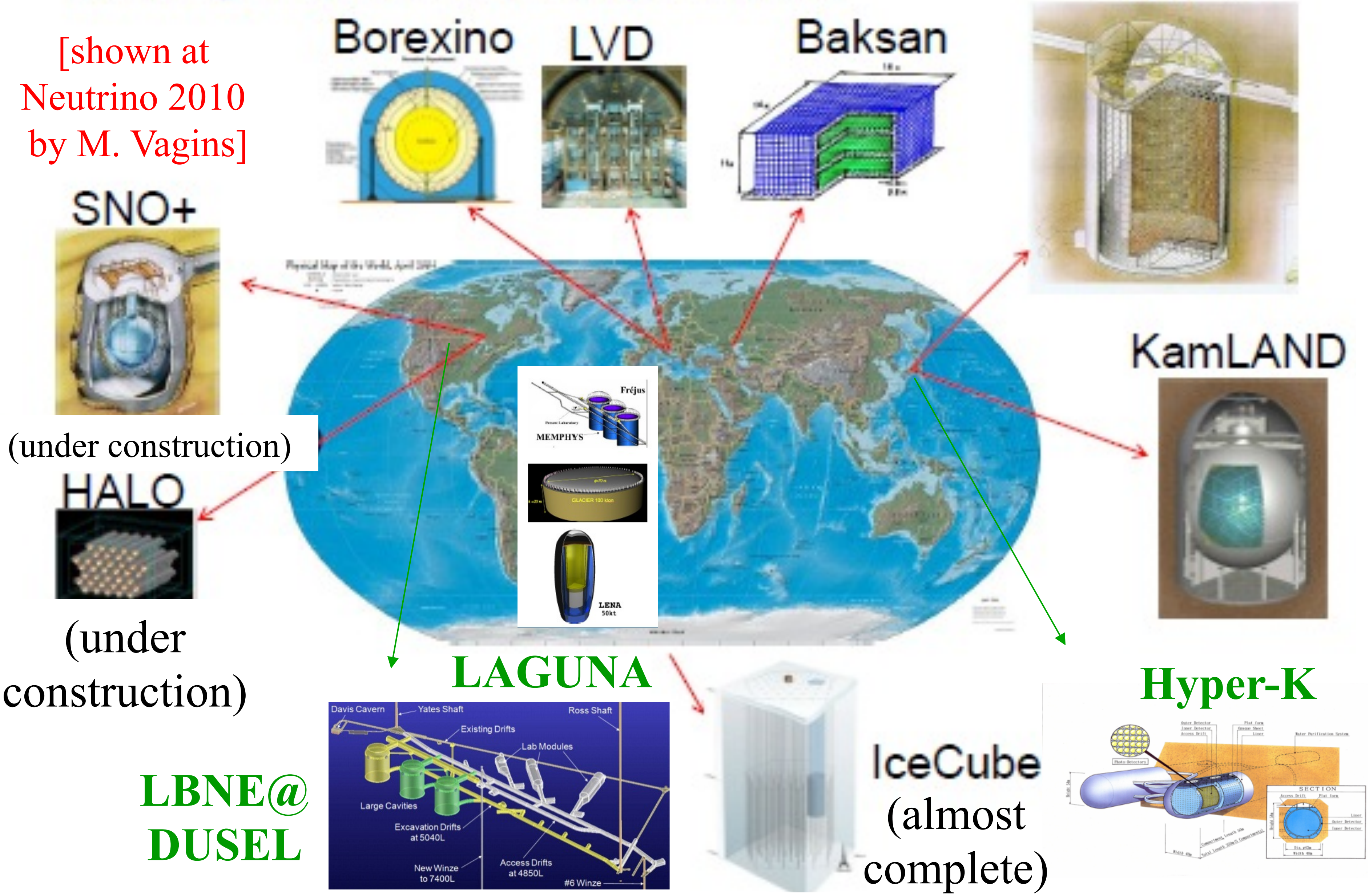
(running and near future experiments)

[shown at Neutrino 2008 by M. Nakahata]



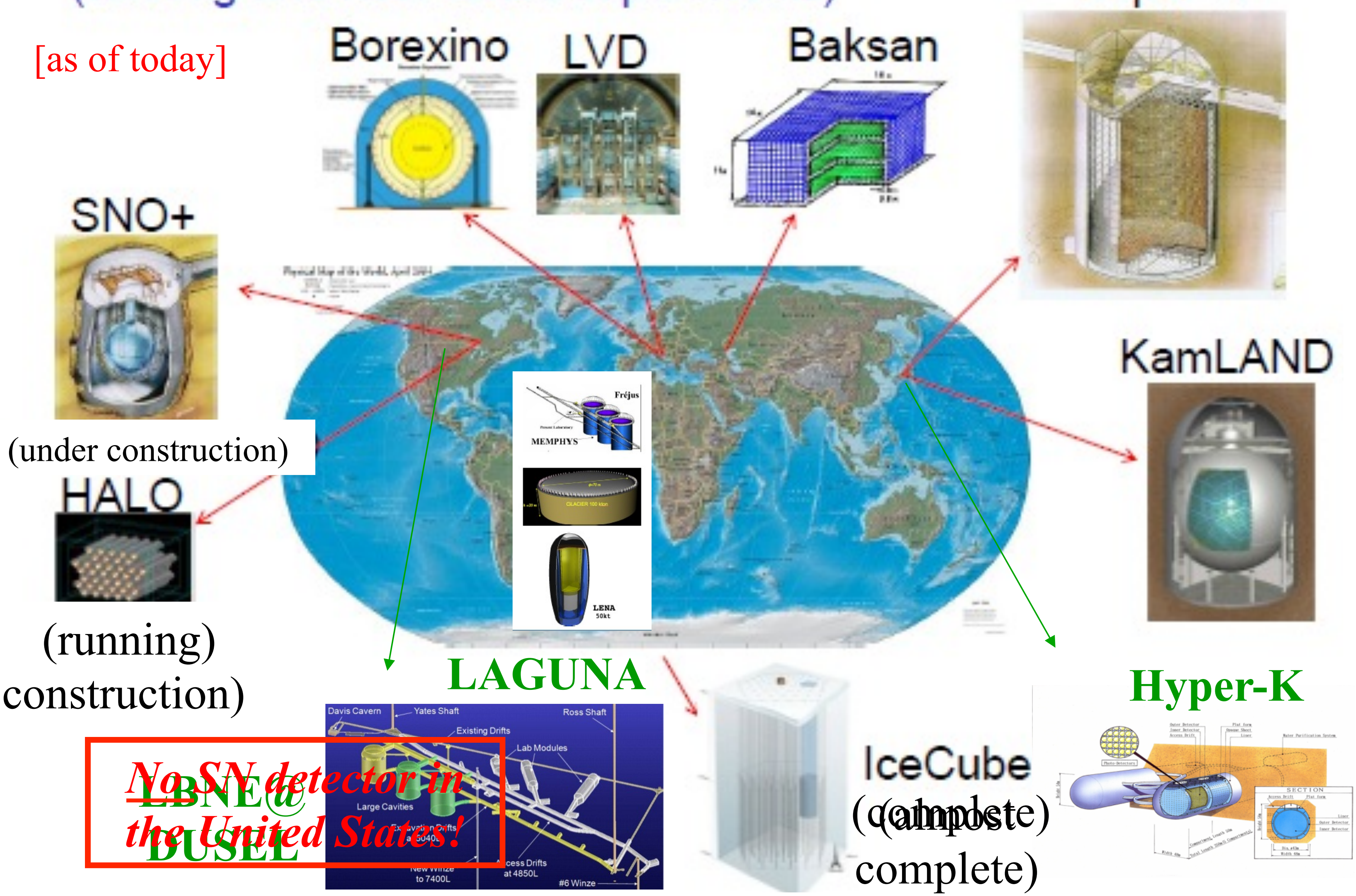
Supernova detectors in the world

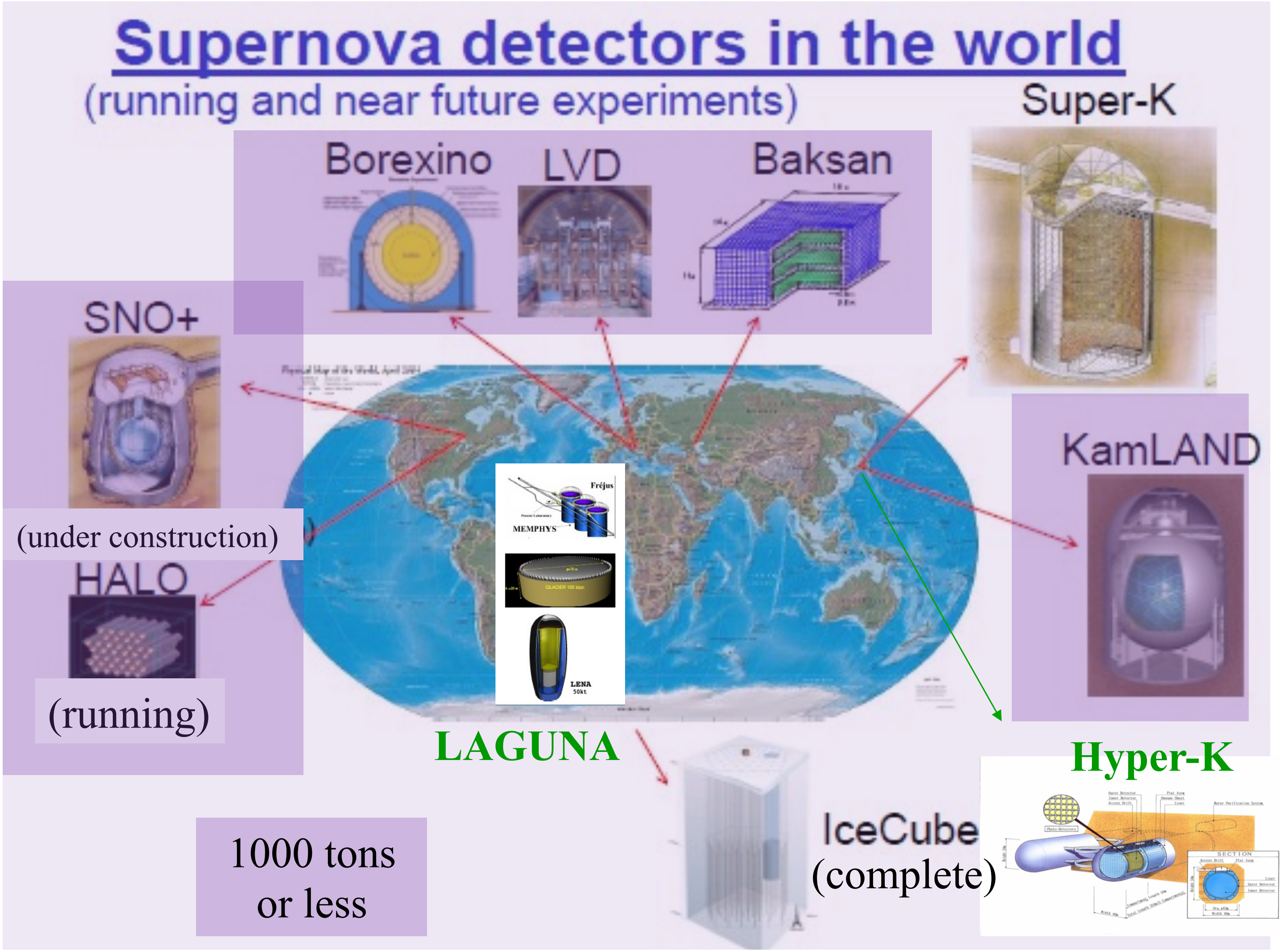
(running and near future experiments)



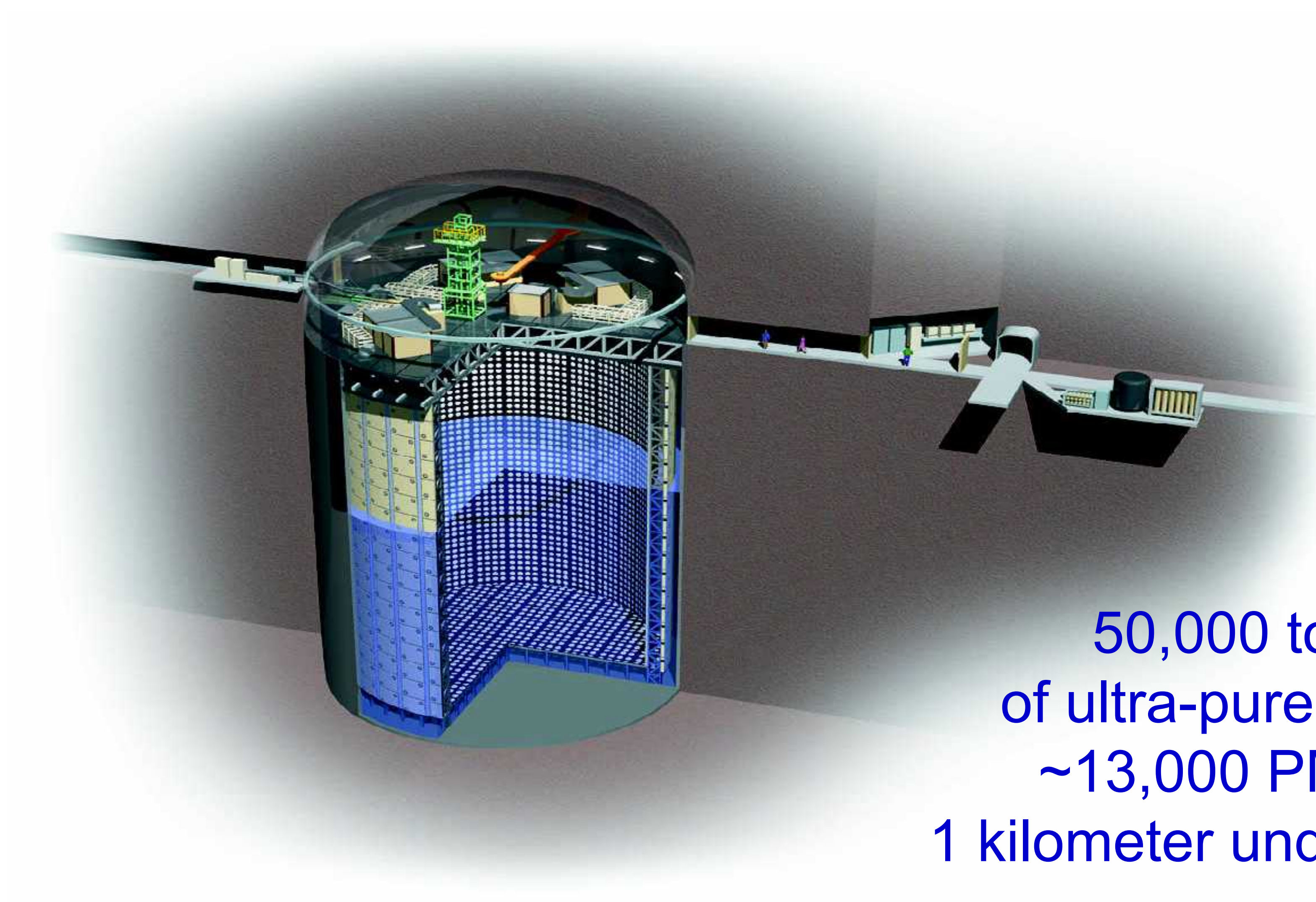
Supernova detectors in the world

(running and near future experiments)




Supernova detectors in the world
(running and near future experiments)
Super-K
Borexino
LVD
Baksan
SNO+
(under construction)
HALO
(running)
KamLAND
Fréjus
MEMPHYS
GLACIER 100 kton
LENA
50kt
LAGUNA
Hyper-K
IceCube
(complete)
1000 tons
or less

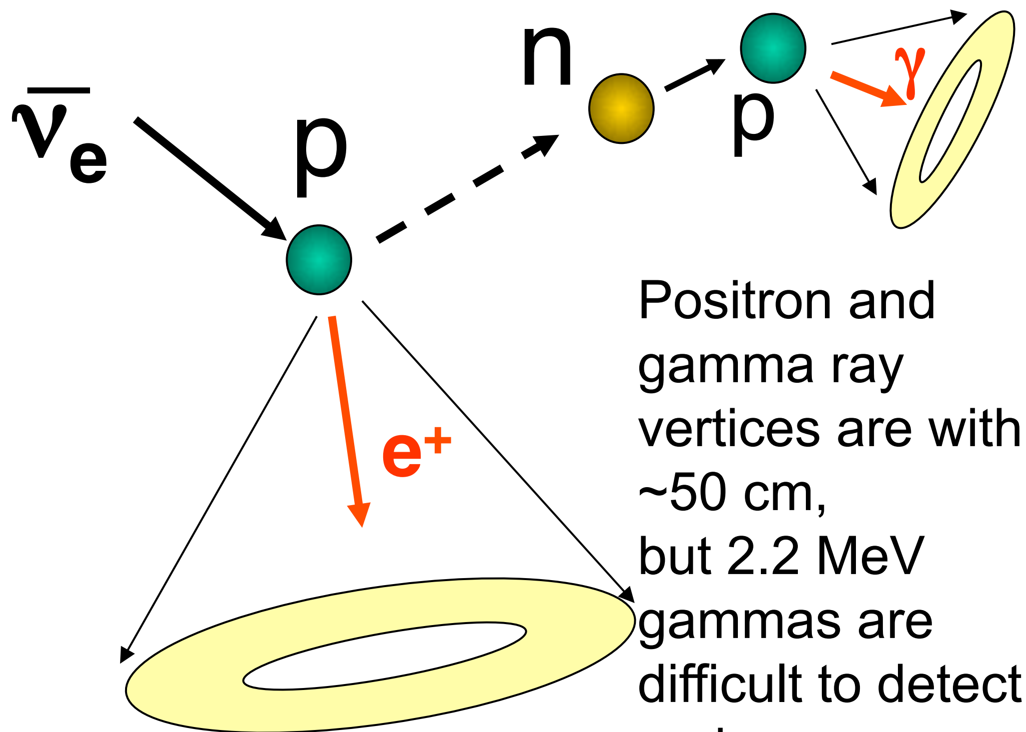
My beloved Super-Kamiokande – one of the best and most successful neutrino and proton decay detectors in the world – is nevertheless based on 30-year-old water Cherenkov technology.



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

Inverse Beta Decay

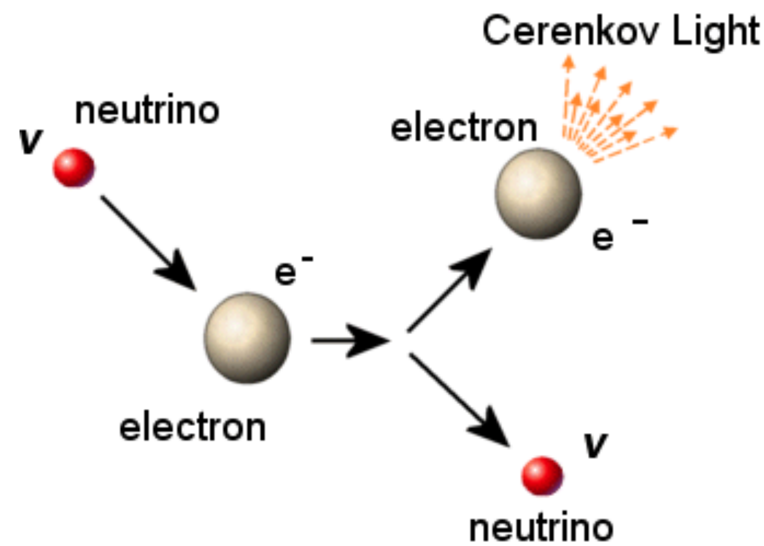
(~80% of events →dominant)



Positron and gamma ray vertices are within ~50 cm, but 2.2 MeV gammas are difficult to detect and, more importantly, difficult to distinguish from backgrounds.

Elastic Scattering

(~3% → directional)



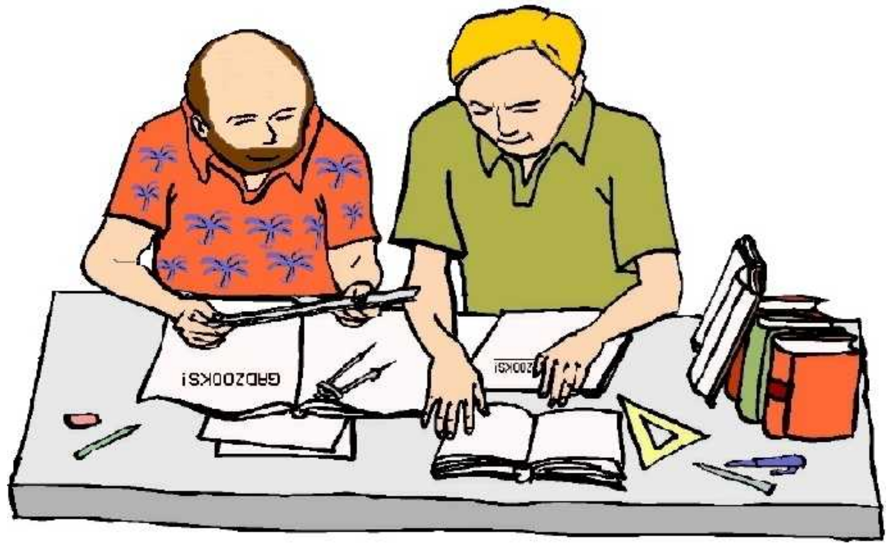
Super-Kamiokande has now been taking data, with an occasional gap, for over sixteen years now. But what does the future hold?

On July 30th, 2002, at ICHEP2002 in Amsterdam, Yoichiro Suzuki, then the newly appointed head of SK, said to me,

"We must find a way to get the new physics."

גדוליניום

“Gadol” = Great!



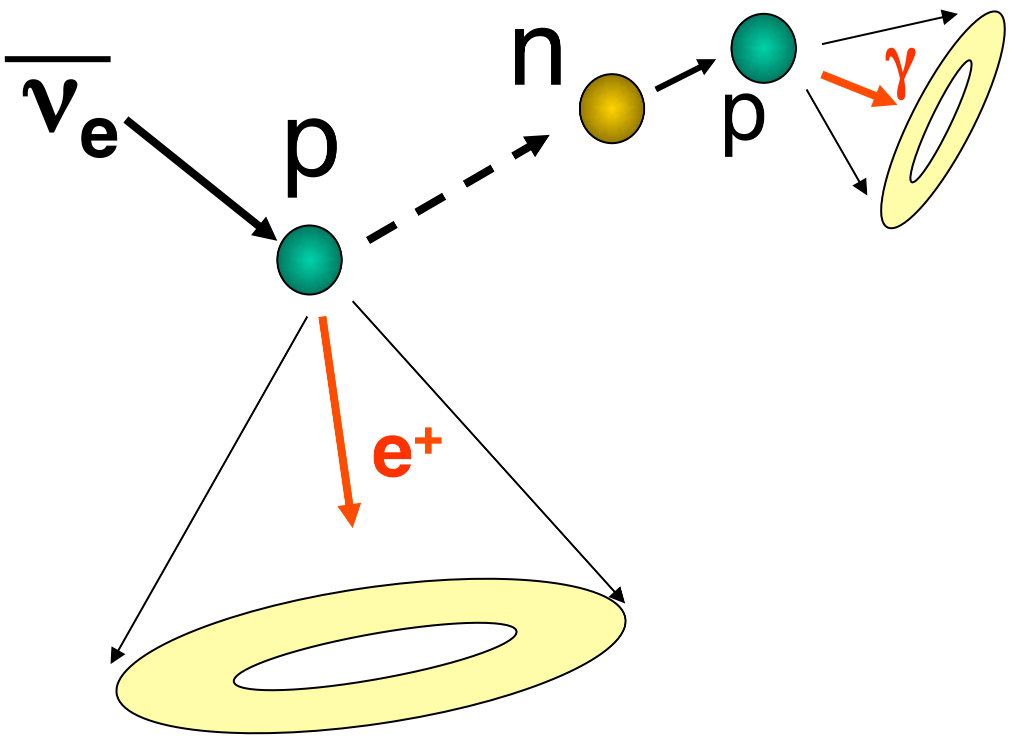
Inspired by this call to action, theorist John Beacom and I wrote the original GADZOOKS!

(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.

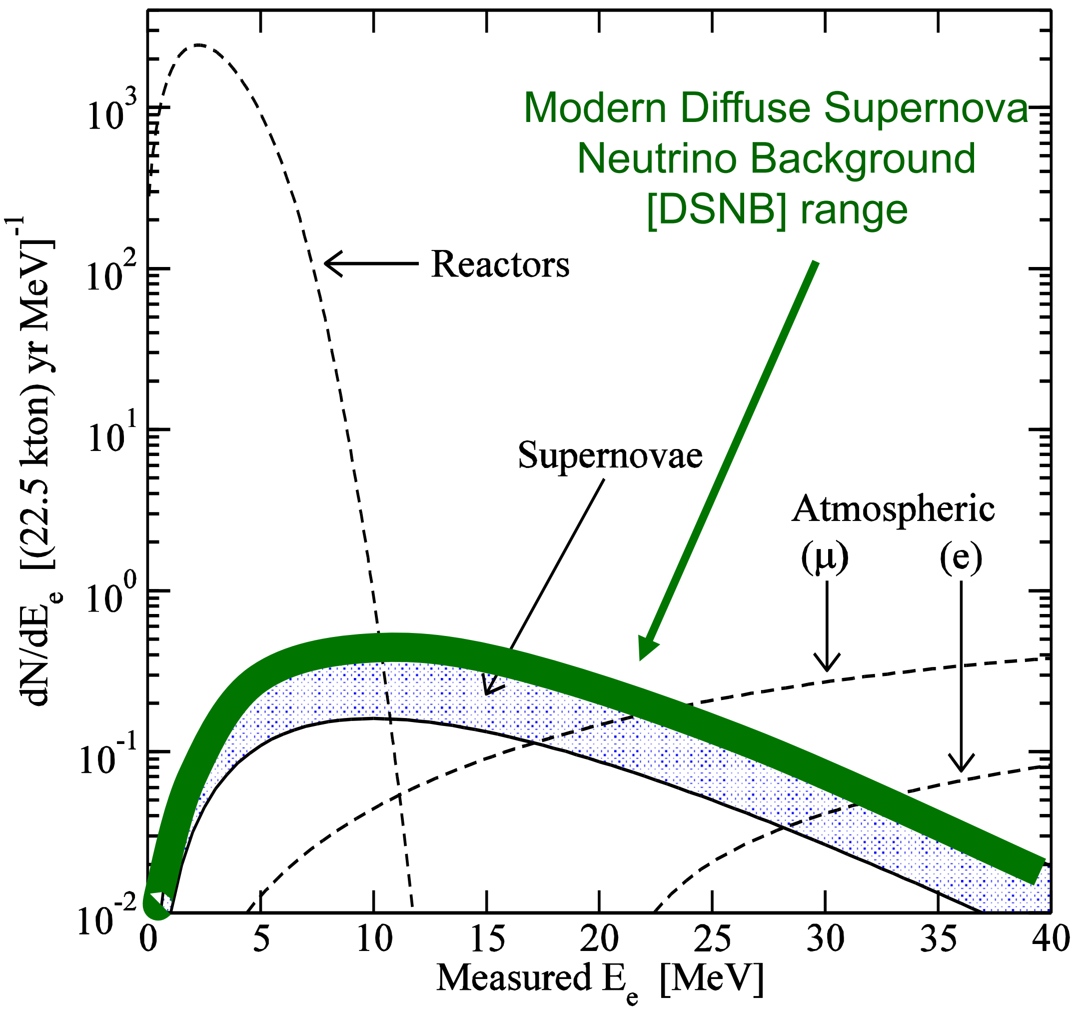
[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

Basically, we said, "Let's add 0.2% of a water soluble gadolinium compound to Super-K!"



Positron and gamma ray vertices are within ~50cm.

Here's what the coincident signals in Super-K with $GdCl_3$ or $Gd_2(SO_4)_3$ will look like (energy resolution is applied):



$\bar{\nu}_e + p \rightarrow e^+ + n$

spatial and temporal separation between prompt e^+ Cherenkov light and delayed Gd neutron capture gamma cascade:

$\lambda = \sim 4\text{cm}, \tau = \sim 30\mu s$

A few clean SN events/yr in Super-K with Gd

In addition to two guaranteed new ν signals - SN and reactor - adding gadolinium to a big WC would provide a variety of other interesting possibilities:

- Sensitivity to very late-time black hole formation
- Full de-convolution of a galactic supernova's ν signals
- Early warning of an approaching SN ν burst
- Proton decay background reduction (5X)
- New long-baseline flux normalization (T2K)
- Matter- vs. antimatter-enhanced atmospheric ν samples

All of this would work even better in a much larger detector.

Indeed, any such massive (and massively expensive) new project will _need_ to have many new physics topics to explore!

[Snowbird photo by A. Kusenko]

Suggesting a major upgrade of one of the world's leading neutrino detectors is not always the easiest route… we have to make certain the plan will work.

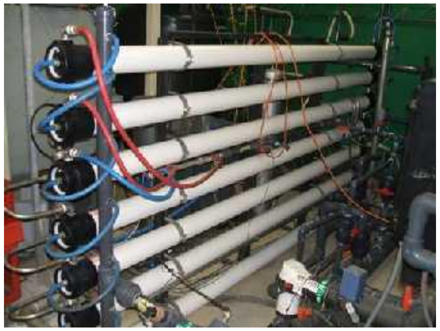
<u>Now, to make GADZOOKS! work, we will have to:</u>

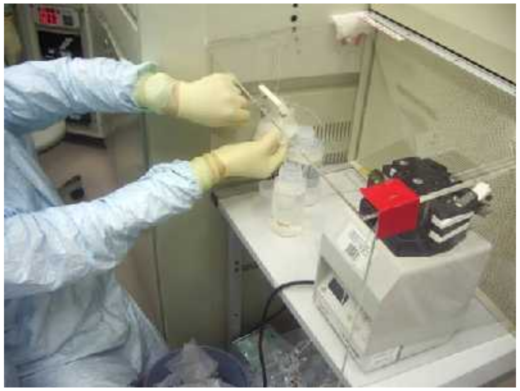
Dissolve the gadolinium sulfate in the water
→ Easy and fast (pH control)

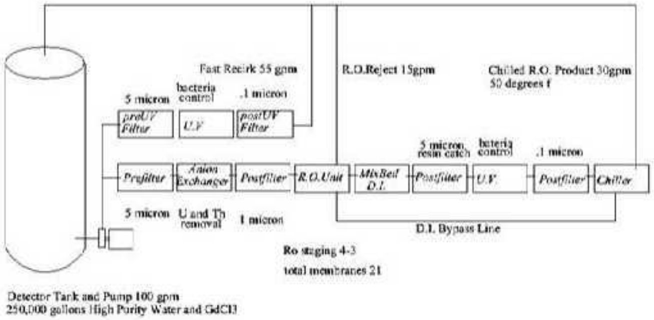
Remove the gadolinium efficiently and completely when desired
→ Also easy and fast (pH control)

Keep pure water pure yet retain gadolinium in solution
→ The tricky part; need a <u>selective</u> Gd filtration system

Over the last eight years there have been a large number of Gd-related R&D studies carried out in the US and Japan:



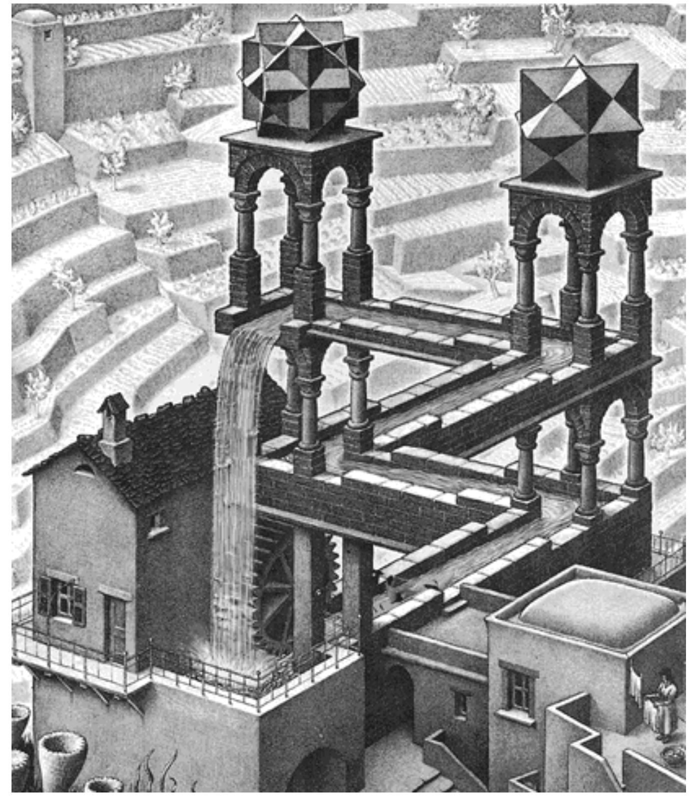




The Essential Magic Trick

→ 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!

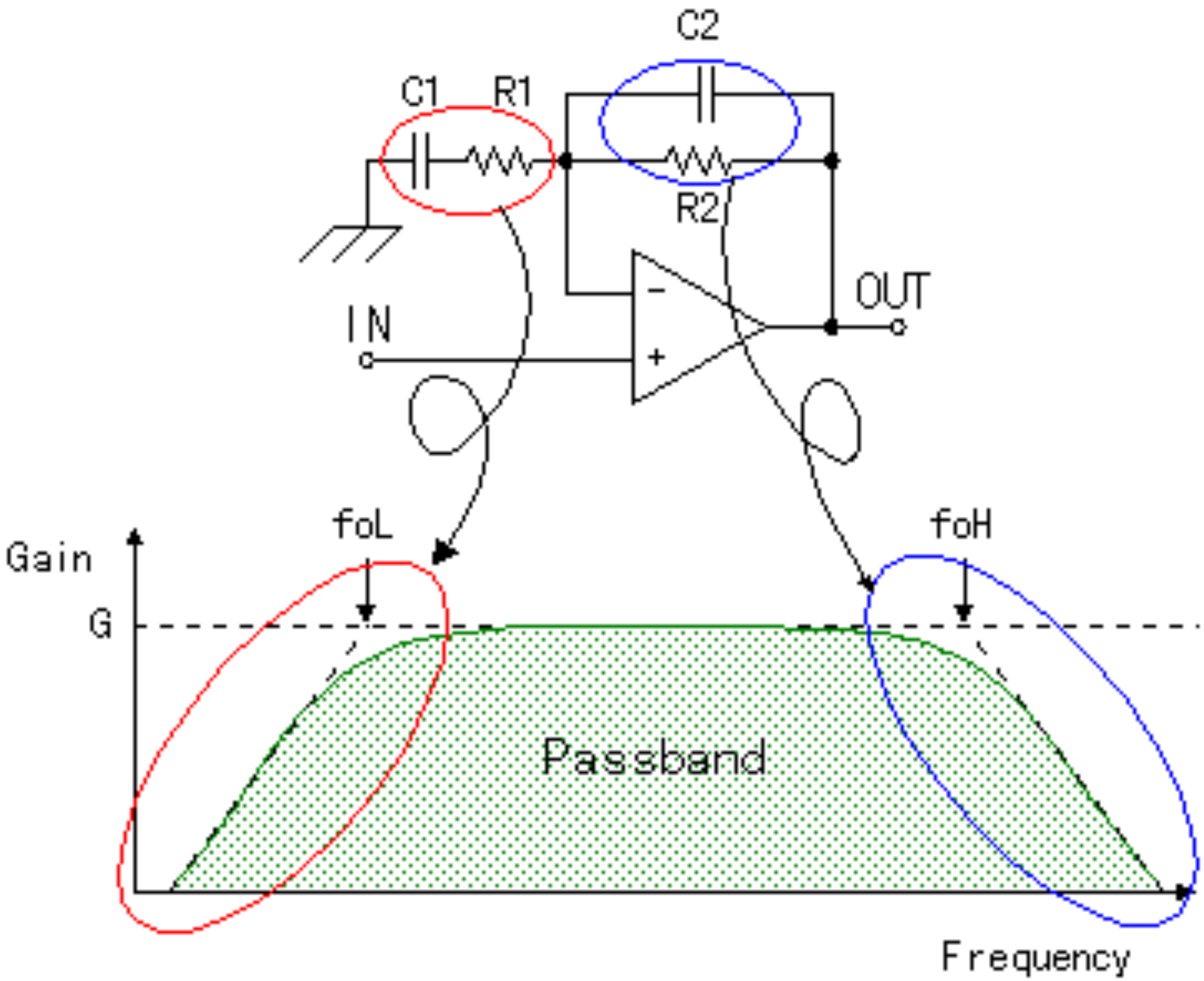
This technology will support a variety of applications, such as:

→ Supernova neutrino and proton decay searches

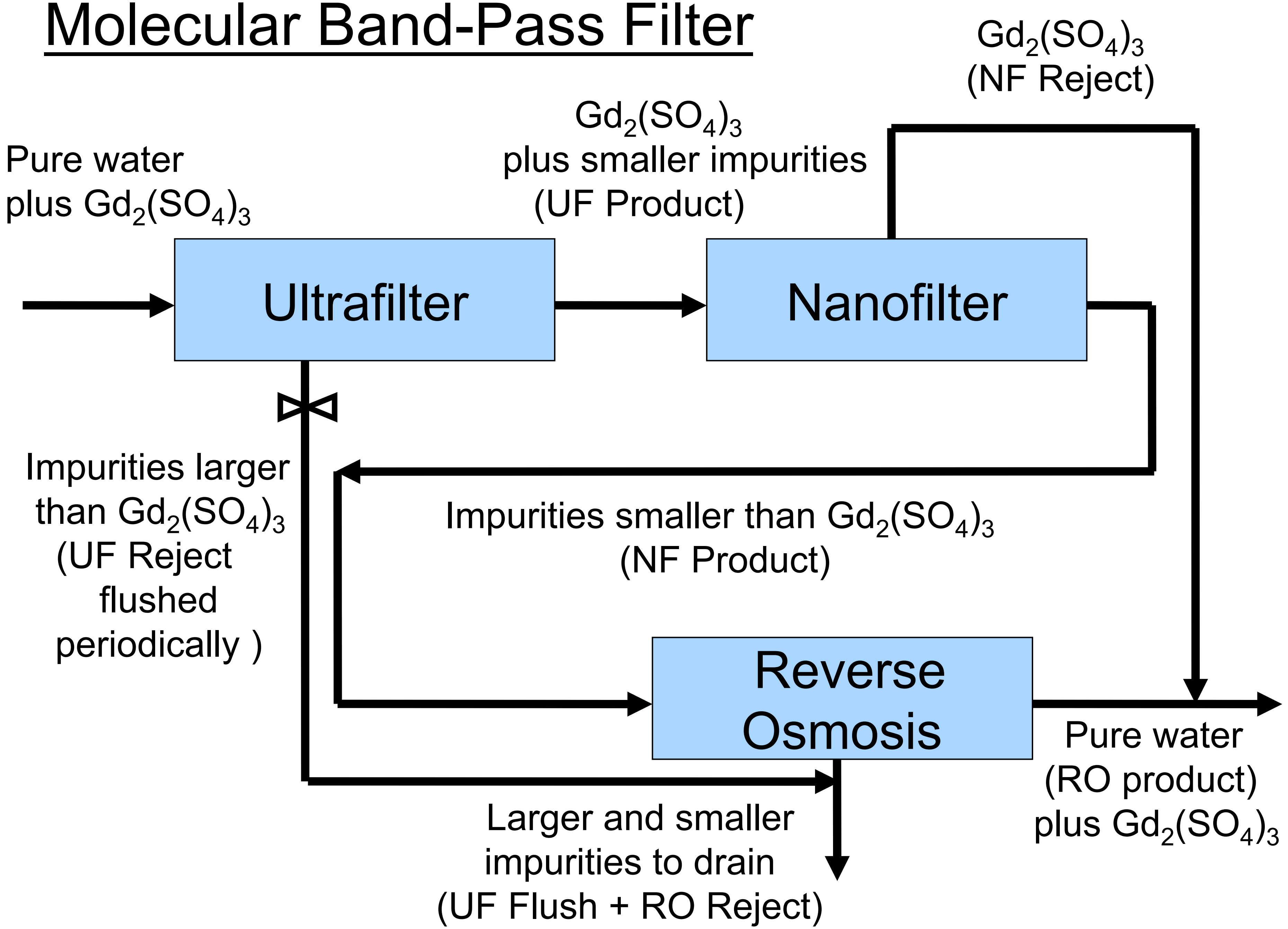
→ Remote detection of clandestine fissile material production

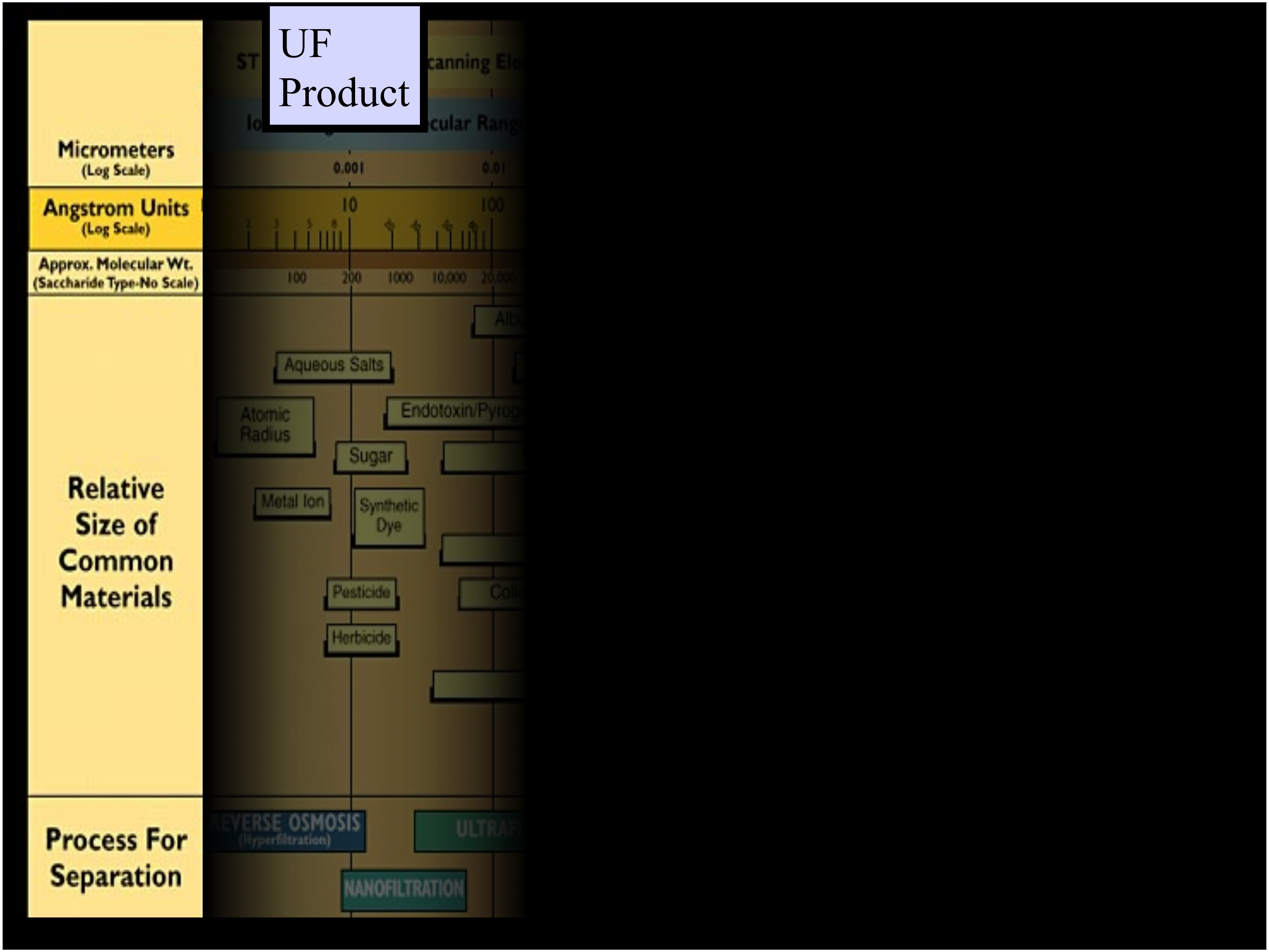
→ Efficient generation of clean drinking water without electricity

Electrical Band-Pass Filter



Molecular Band-Pass Filter

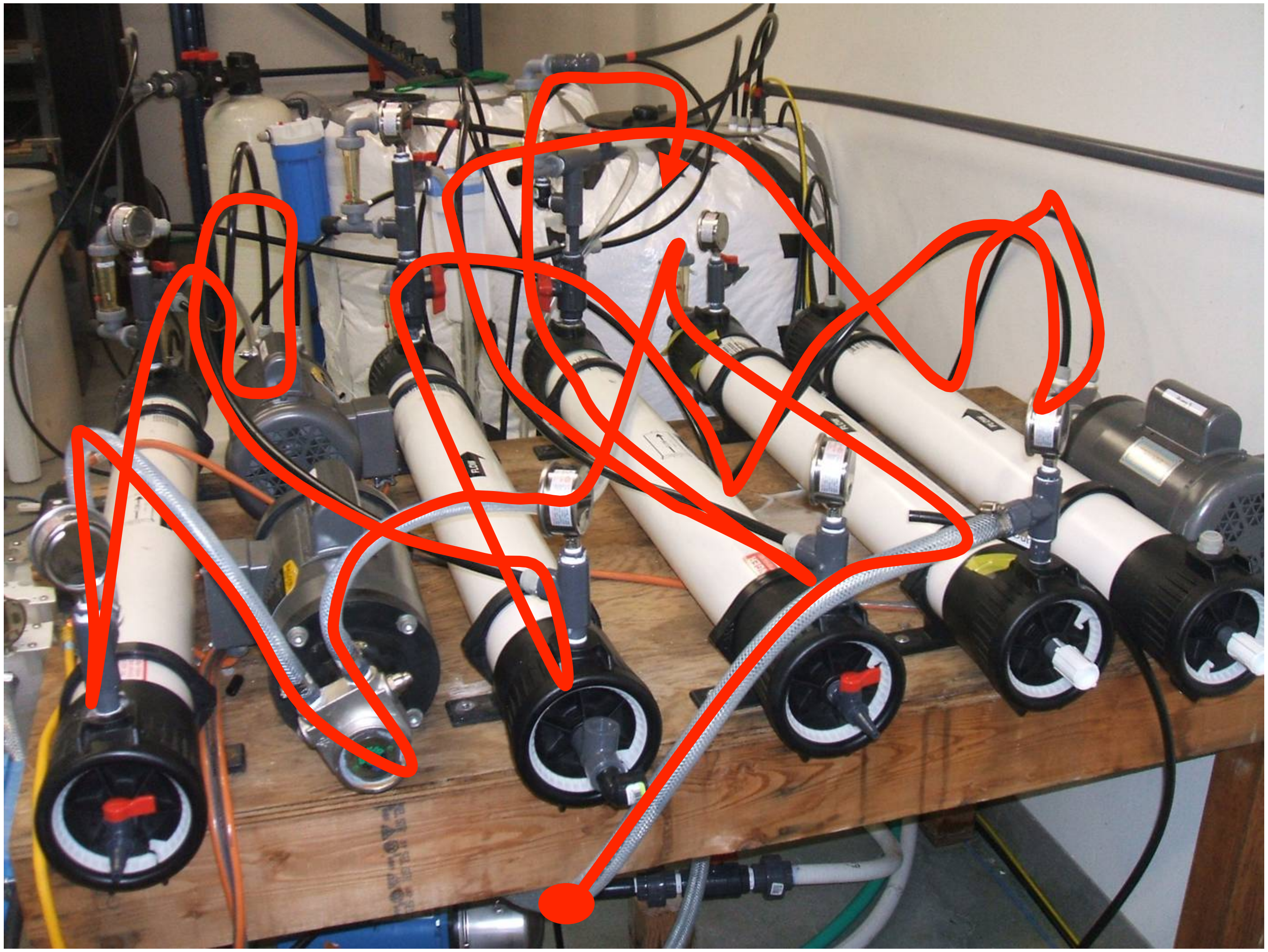




UF
Product
Micrometers
(Log Scale)
0.001
0.01
Angstrom Units
(Log Scale)
10
100
Approx. Molecular Wt.
(Saccharide Type-No Scale)
100
200
1000
10,000
20,000
Relative Size of Common Materials
Aqueous Salts
Atomic Radius
Endotoxin/Pyrog
Sugar
Metal Ion
Synthetic Dye
Pesticide
Herbicide
Process For Separation
REVERSE OSMOSIS
(Hyperfiltration)
NANOFILTRATION

Band-Pass Window

At UCI: World's 1st Molecular Band-Pass Filter



Nanofilter #1 Nanofilter #2 Reverse Osmosis Ultrafilter

In 2008 I underwent a significant transformation…

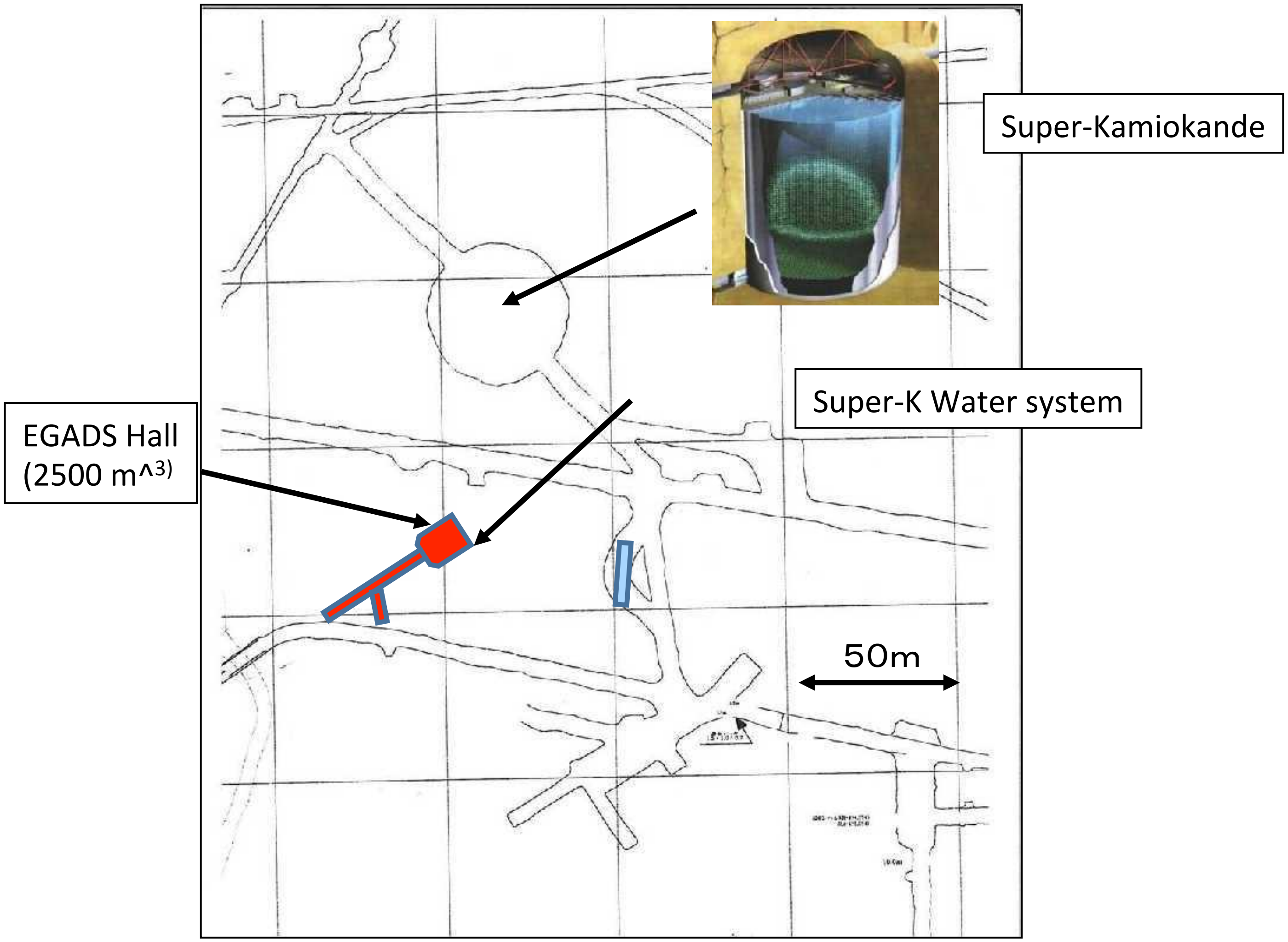
I joined UTokyo's newly-formed IPMU as their first full-time *gaijin* professor, though I still retain a "without salary" position at UC Irvine and continue Gd studies there.

I was explicitly hired to make gadolinium work in water!

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

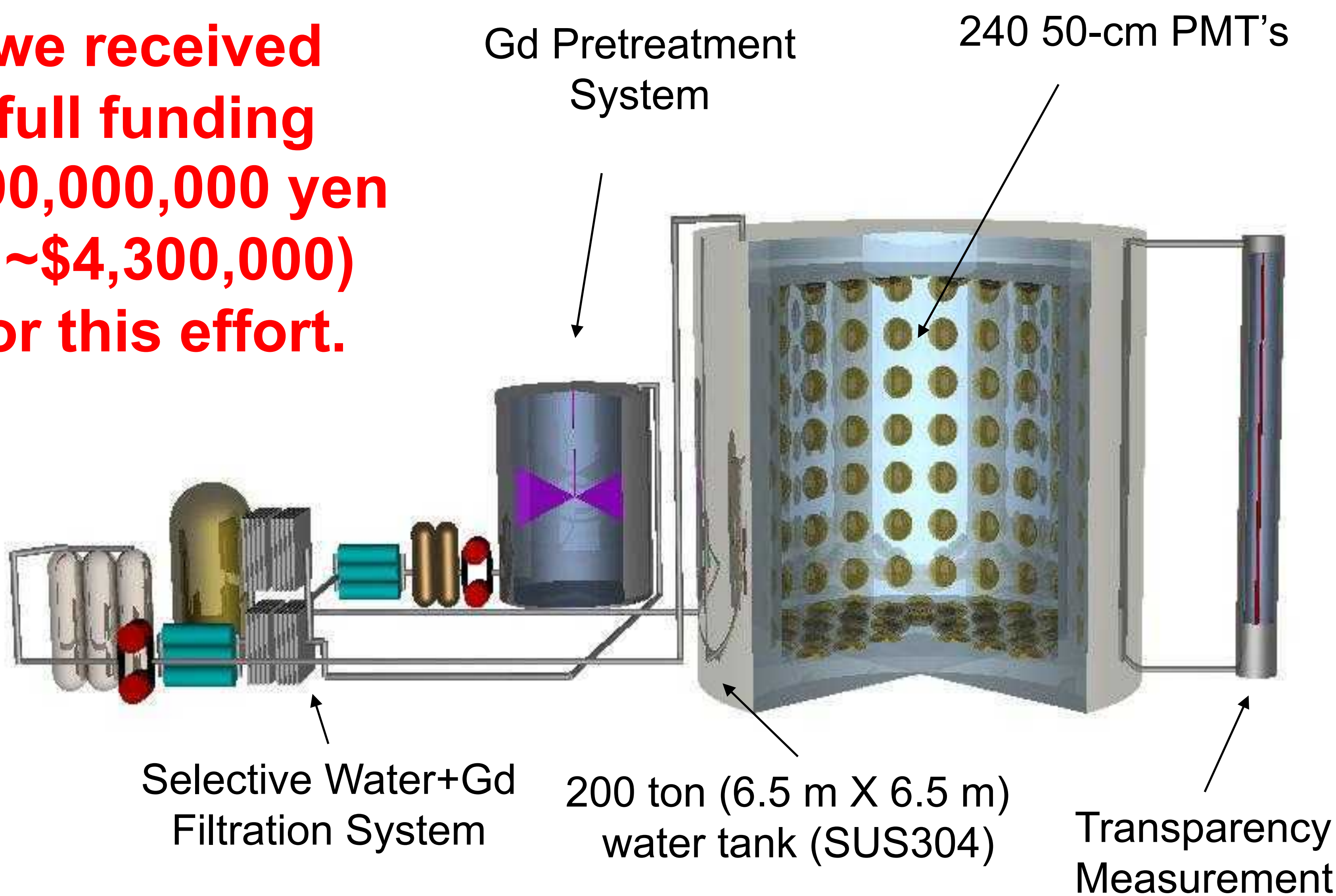
In Japan we've built a dedicated Gd test facility, complete with its own water filtration system, 50-cm PMT's, and DAQ electronics.

This 200 ton-scale R&D project is called EGADS – Evaluating Gadolinium's Action on Detector Systems.



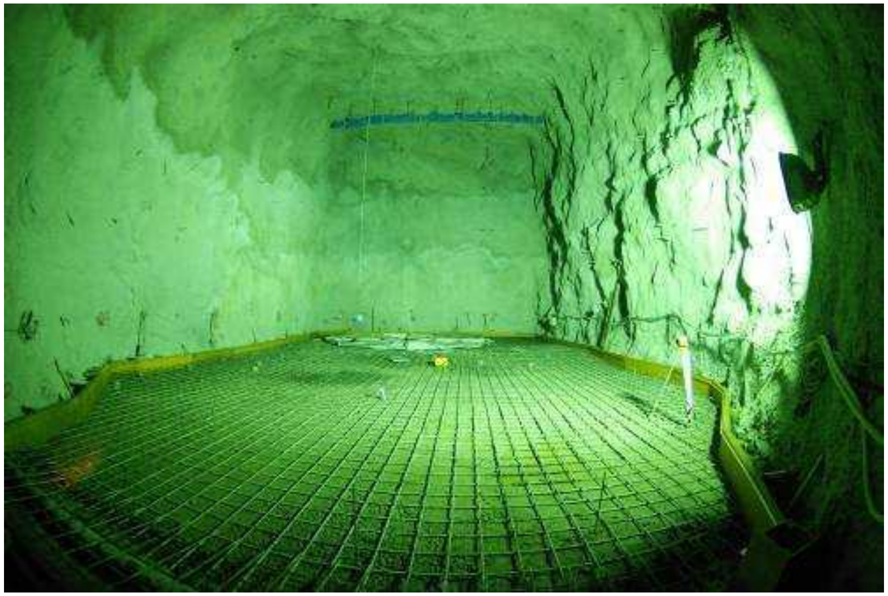
EGADS Facility

In June of 2009 we received full funding (390,000,000 yen = ~$4,300,000) for this effort.



Hall E and EGADS

12/2009

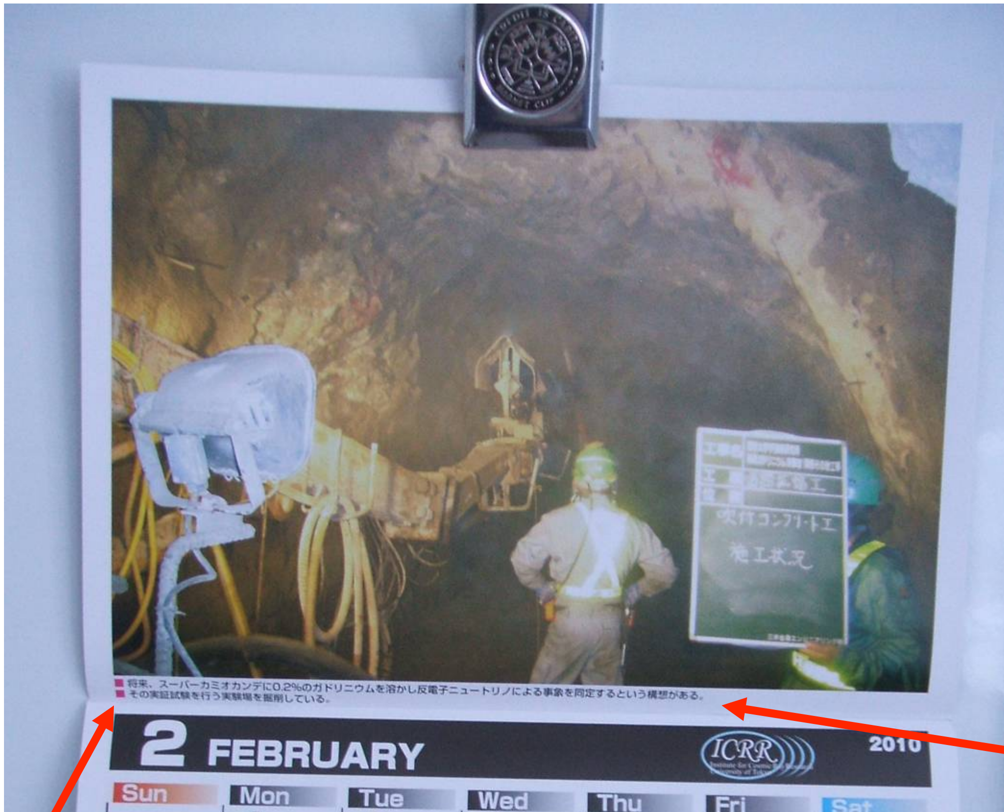


2/2010

6/2010

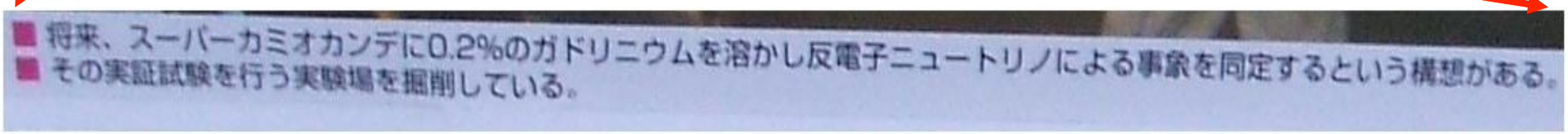
12/2010

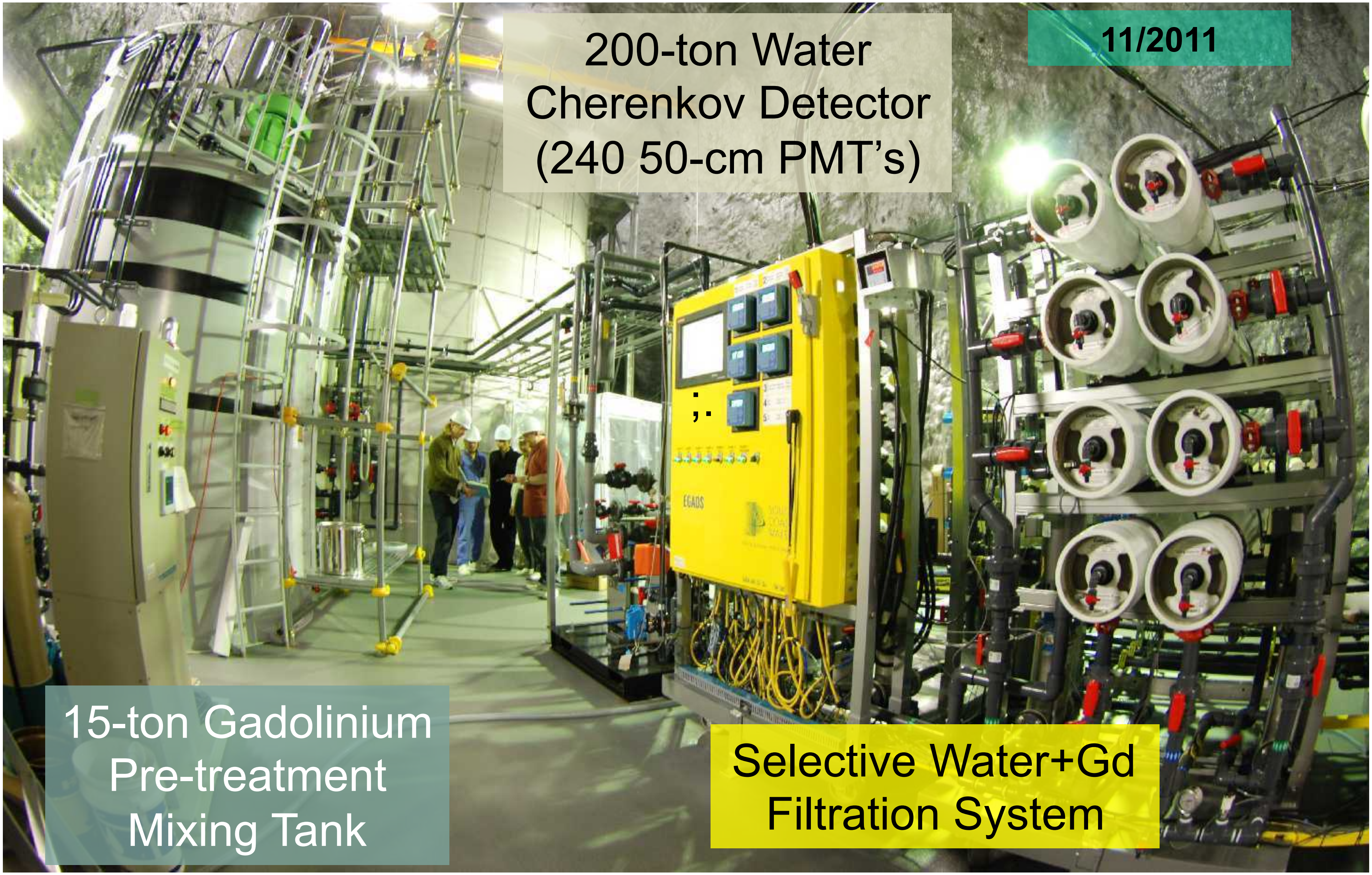
Just another Thanksgiving weekend; Nov. 25th, 2011



Here's the official Institute for Cosmic Ray Research [ICRR] calendar:

EGADS was Miss February in 2010, and Miss March in 2012!

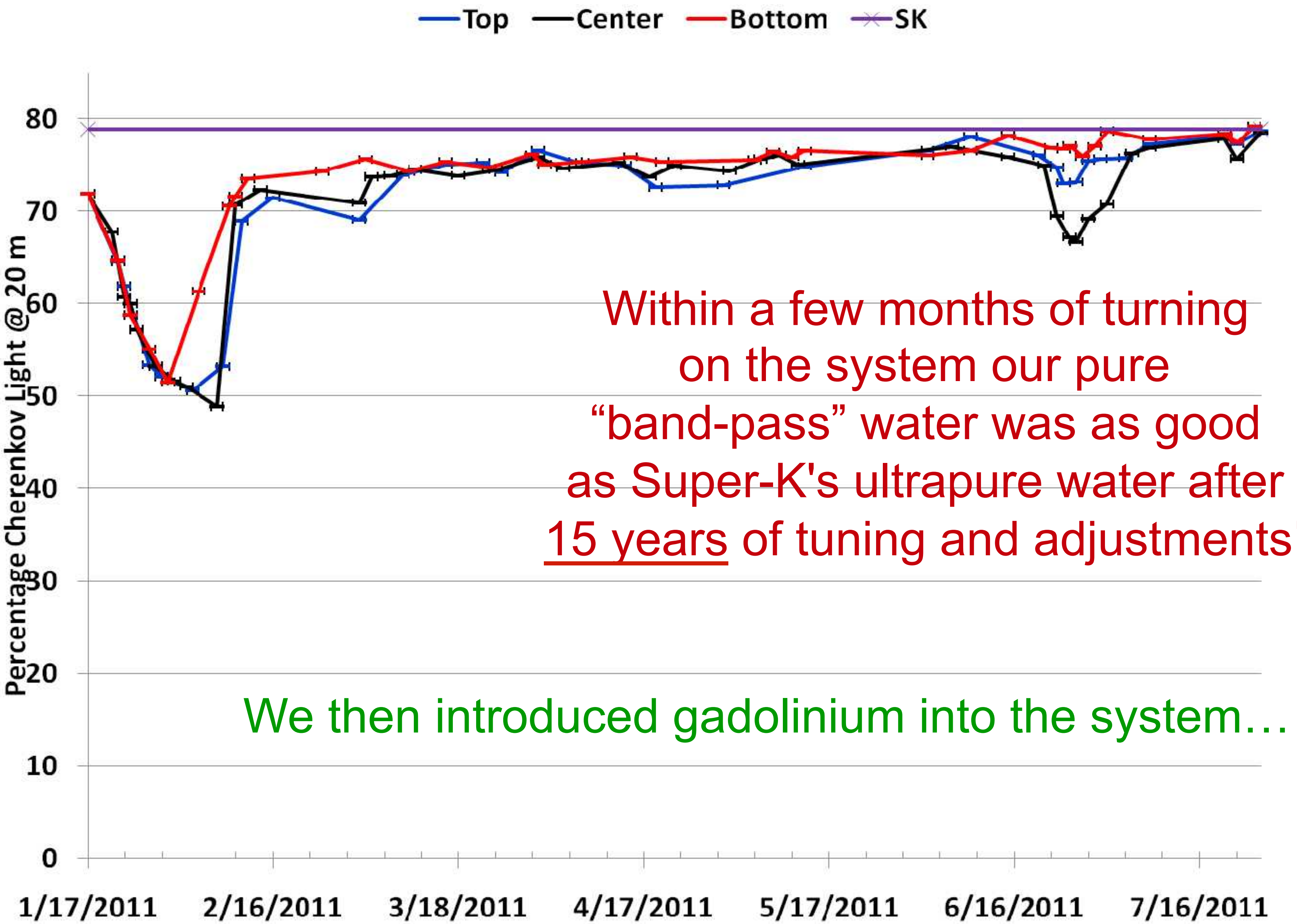




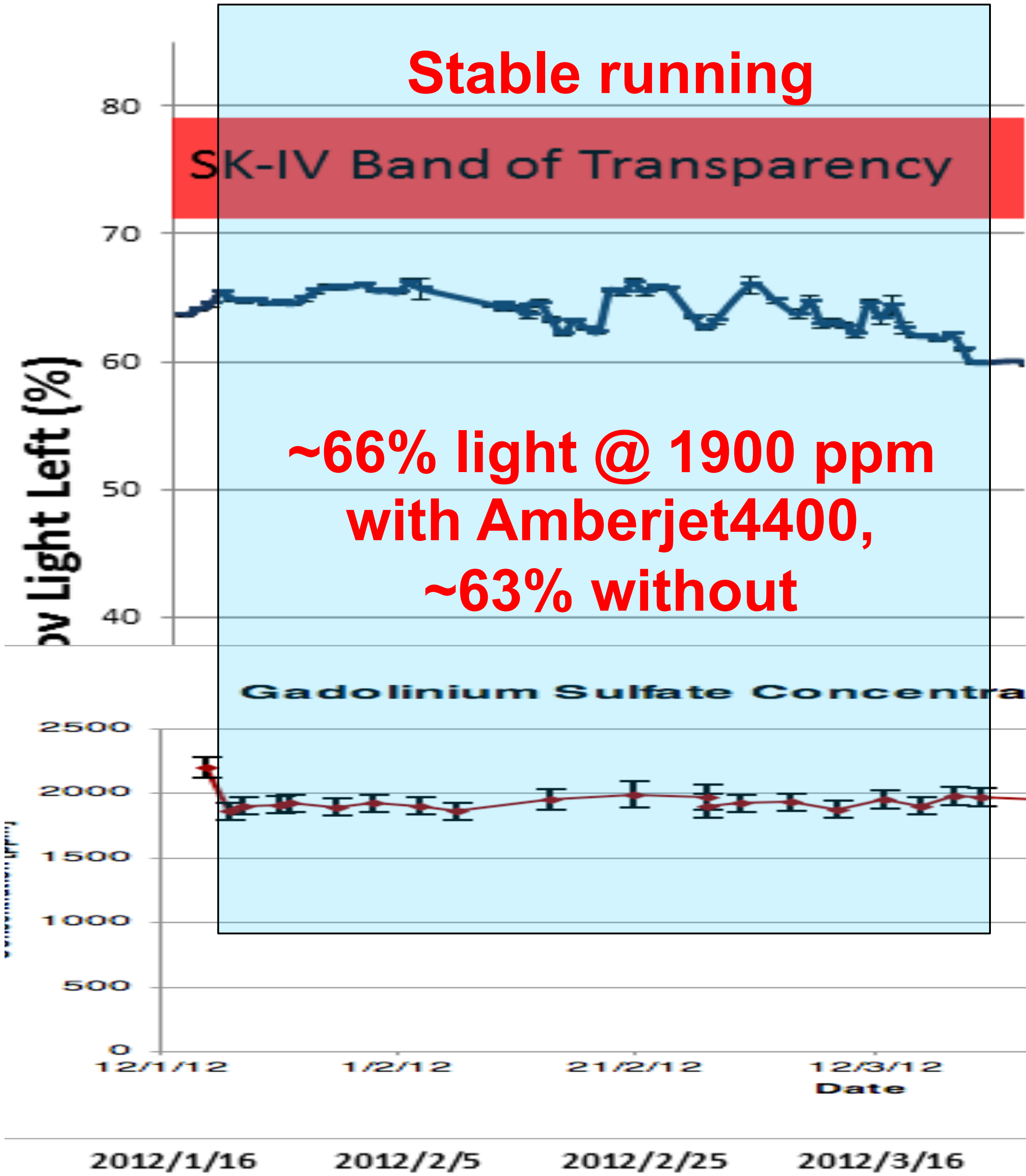
By next year, EGADS will have shown conclusively whether or not gadolinium loading of Super-Kamiokande will be safe and effective.

If so, this is the likely future of *all* water Cherenkov detectors.

Cherenkov Light Remaining at 20 m (200-ton tank)



Cherenkov Light Left at 20 m for Gd Water in 15 m³ Tank



Studies continue, but we have already achieved stable light levels of 66% at 20 meters with fully Gd-loaded water.

This should be compared to a range of 71%→79% for "perfect" pure water in SK-IV.

→ No detected Gd loss after >100 complete turnovers.←

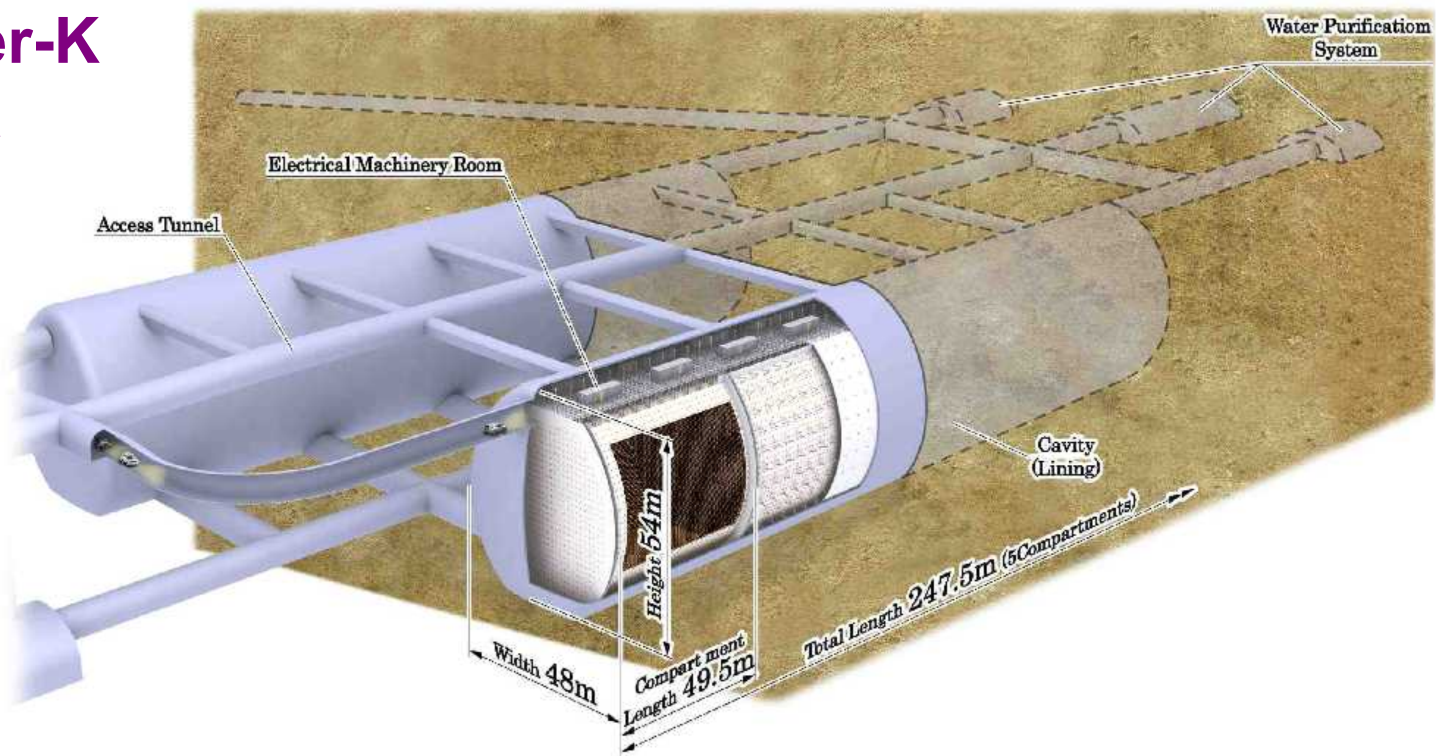
Gadolinium loading is part of the executive summary!

Last year, the official Hyper-Kamiokande Letter of Intent appeared on the arXiv:1109.3262

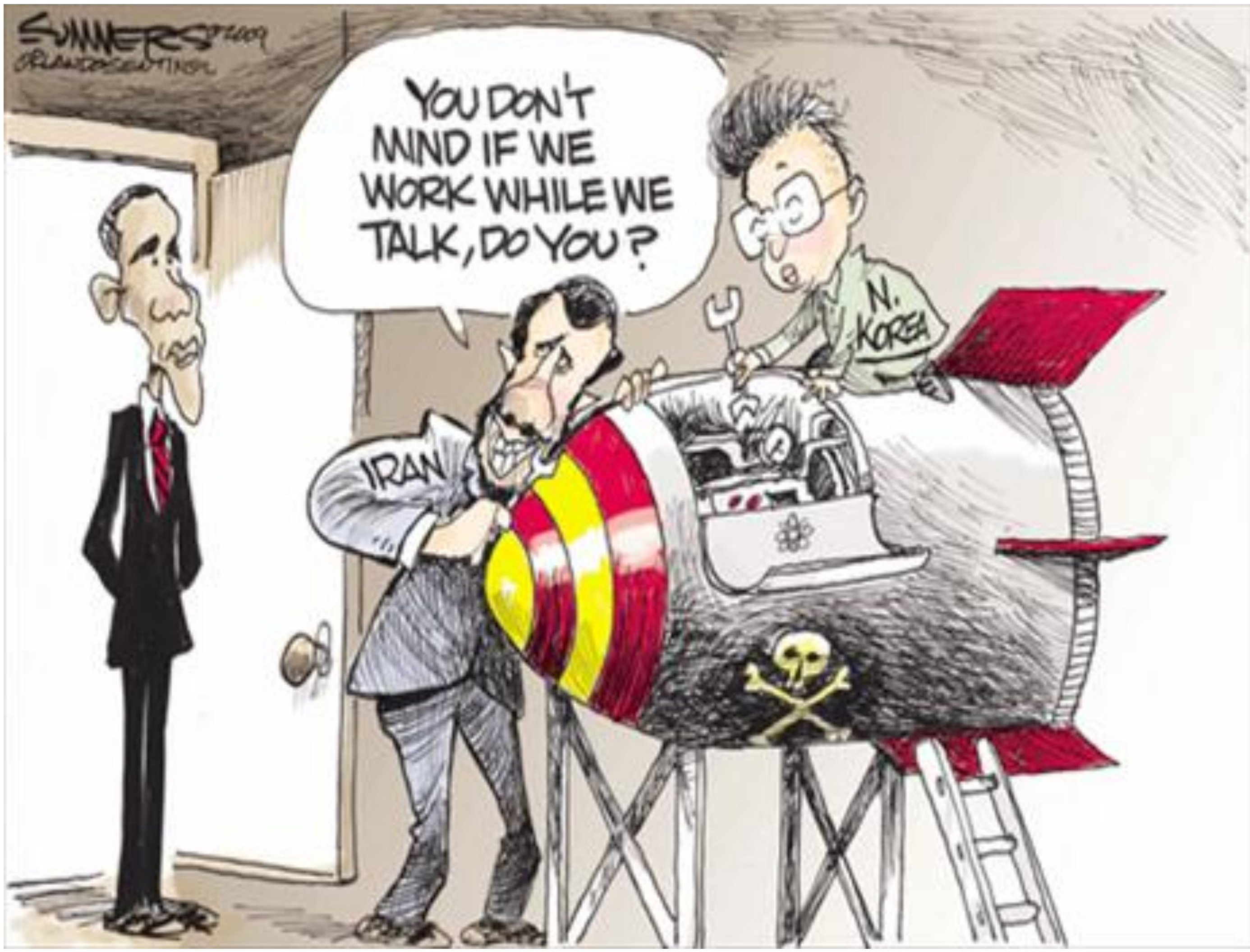
1.0 Mton total water volume

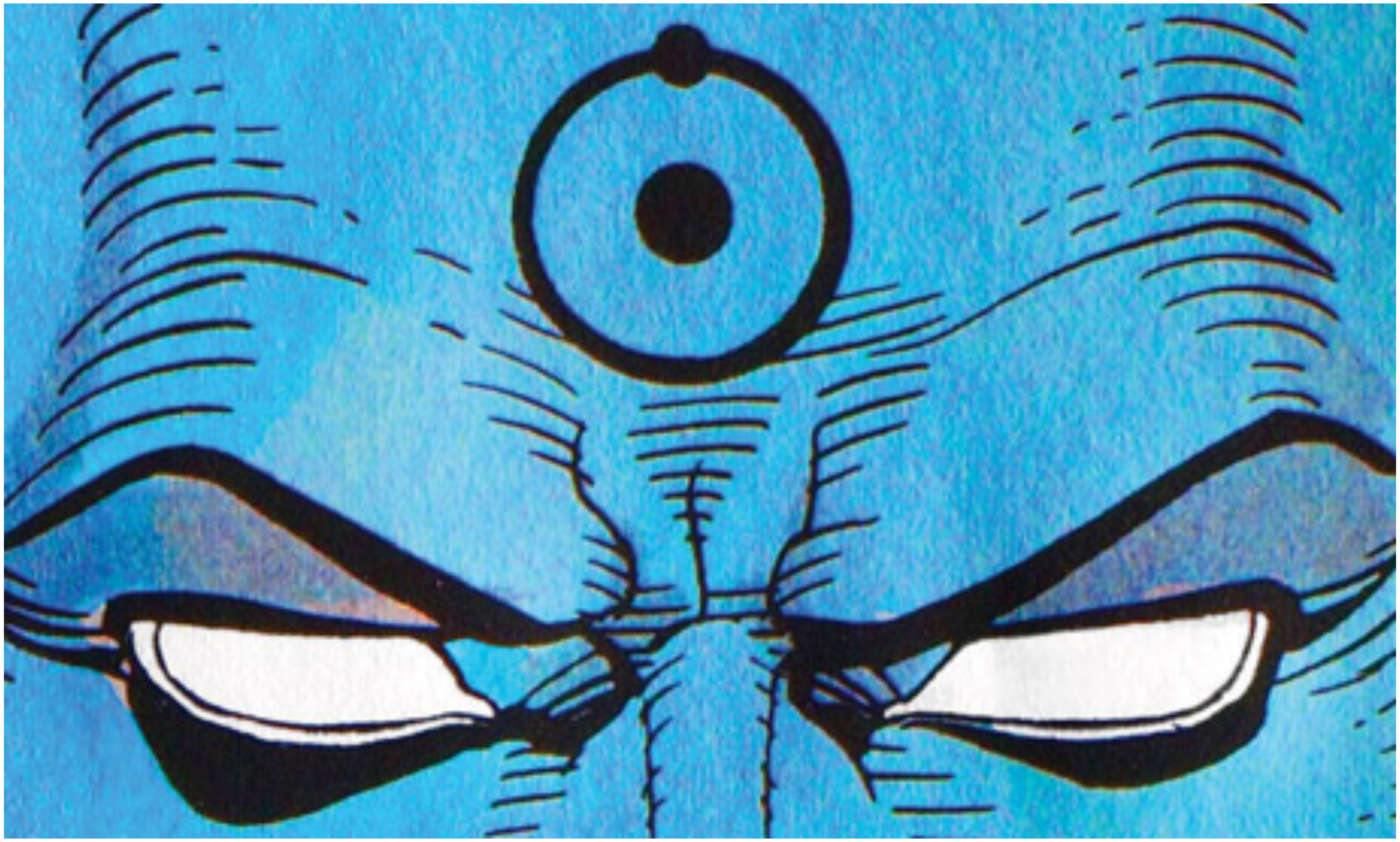
0.56 Mton fiducial volume (25 X Super-K)

With Gd, Hyper-K should collect SN1987A-like numbers of supernova neutrinos... *every month!*



Of course, very large scale anti-neutrino detection just might have another application or two…





WATCHMAN: WATer CHerenkov Monitor of Anti-Neutrinos

A newly-funded US National Security initiative

Also newly funded: Multi-messenger Supernova Astronomy

X-ray, γ-ray, Optical, Infrared, GW, and Neutrino

Approved - June 2012
~$1.2M for EGADS/IPMU

計画研究 A03：なんとかかんとかの研究

Special features of SN neutrinos and GW's

- Provide image of core collapse itself (identical t=0)
- Only supernova messengers which travel without attenuation to Earth (dust does not affect signal)
- Guaranteed full-galaxy coverage

What is required for maximum SN ν information?

- Sensitivity to nearby explosions (closes gap in Super-Kamiokande's galactic SN ν coverage)
- Deconvolution of neutrino flavors via efficient neutron tagging

By converting an existing R&D facility (EGADS) into the world's most advanced SN ν detector, we could collect

3,690 ν events @ 3,000 light-years

369,000 ν events @ 300 light-years

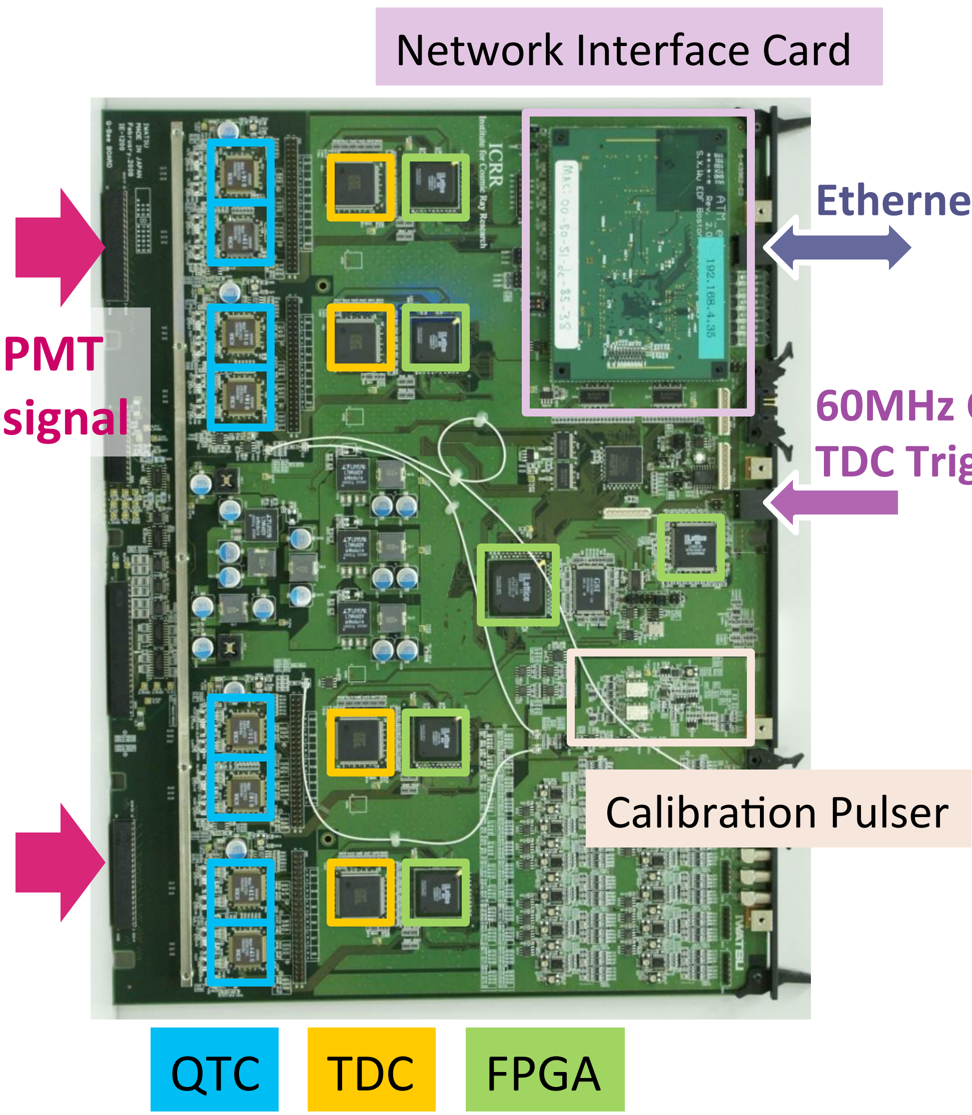
So, what does it take to turn the EGADS R&D facility into a world-class supernova neutrino observatory?

- ✓ Low energy threshold
- ✓ Neutron tagging (unique WC ability)
- ✓ High uptime fraction

This new SN grant will enable:

- ✓ Large dynamic range in electronics and DAQ
- ✓ Instant event reconstruction and alert generation
- ✓ Precision timing
- ✓ Good energy calibration

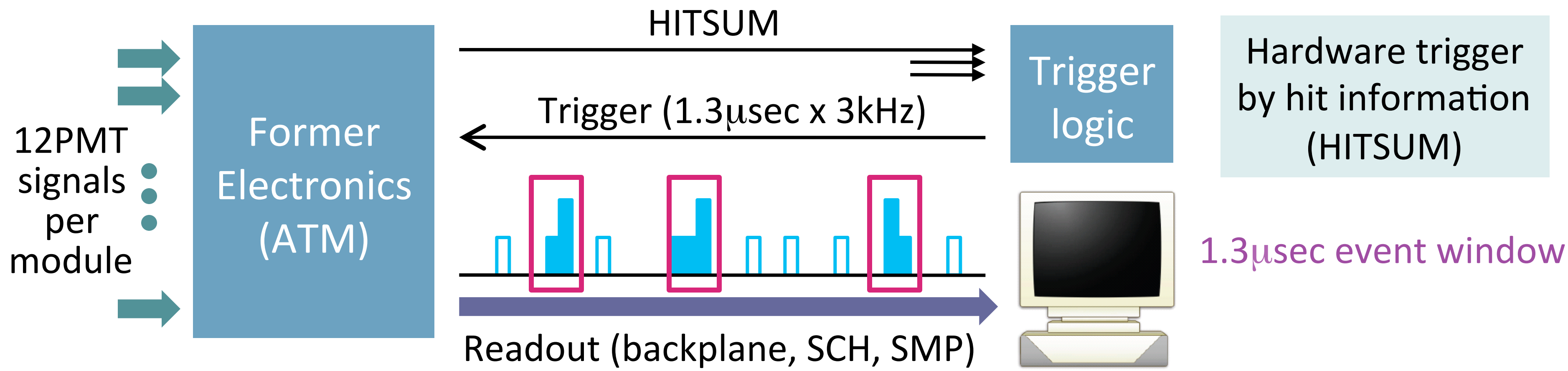
Turning EGADS into a SN detector: New electronics (2013)



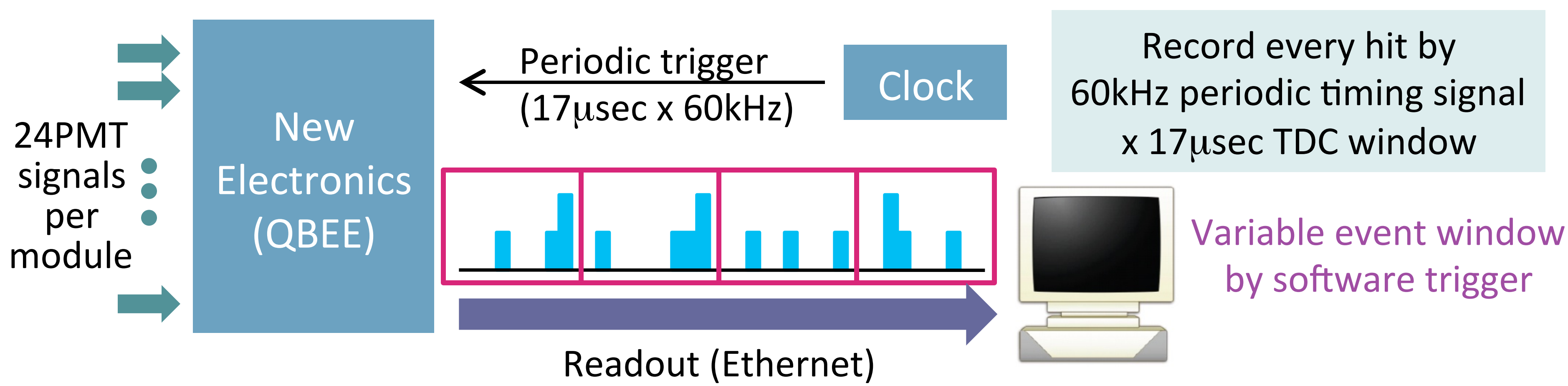
QTC-Based Electronics with Ethernet (QBEE)

- 24channel input
- QTC (custom ASIC)
  - 3 gain stages
  - wide dynamic range (>2000pC)
- Pipelined electronics
  - multi-hit TDC (AMT3)
  - FPGA
- Ethernet readout
- External 60MHz clock input
- On-board calibration pulser
- Low power consumption (< 1W/ch)

New DAQ readout scheme



No hardware trigger. Instead record all hits and apply software triggers.

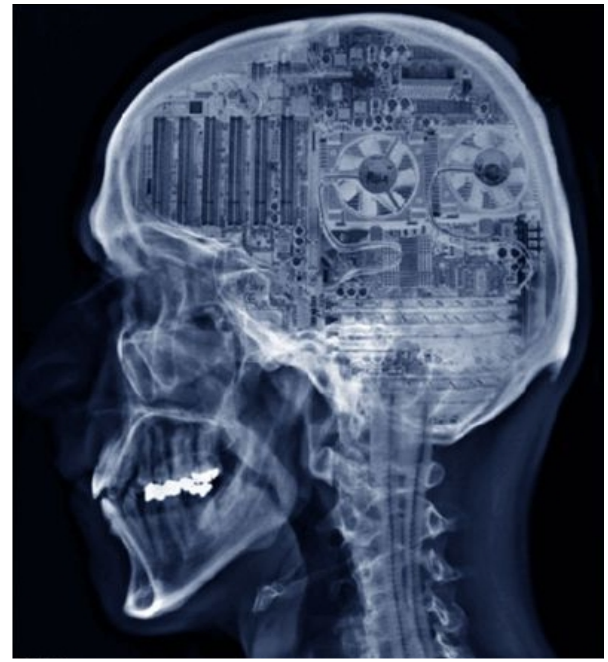


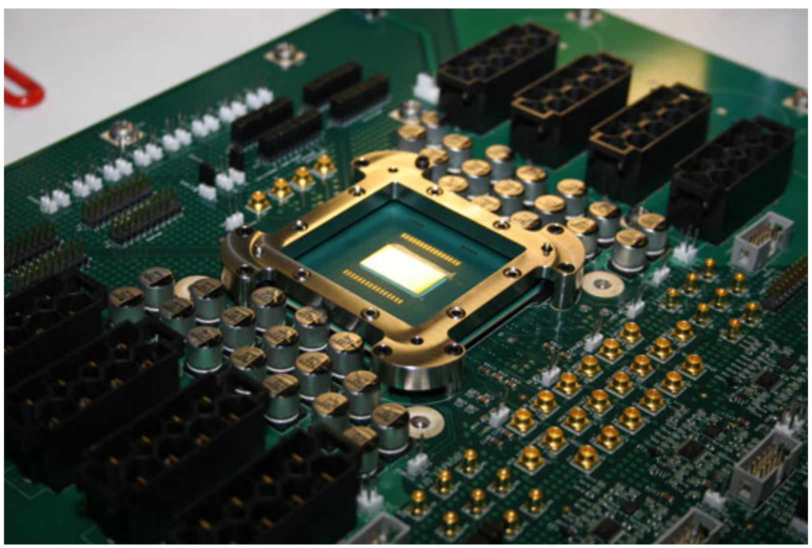
Turning EGADS into a SN detector: New GPS timing (2013)

In addition to adding GSP time stamps to our data, we will make sure – using a portable atomic standard – that time stamps are synchronized between the various observational sites, particularly GW and neutrino

Turning EGADS into a SN detector: Intelligent Trigger (2014)

We want to process every PMT hit and fully reconstruct every event in real time.





One 80-core (experimental) Intel chip = one teraflop

We will buy and install sufficient computing power to do this job.

By 2015 we expect to be ready to detect supernova neutrinos with EGADS from anywhere in our galaxy, and produce immediate alerts to the world.

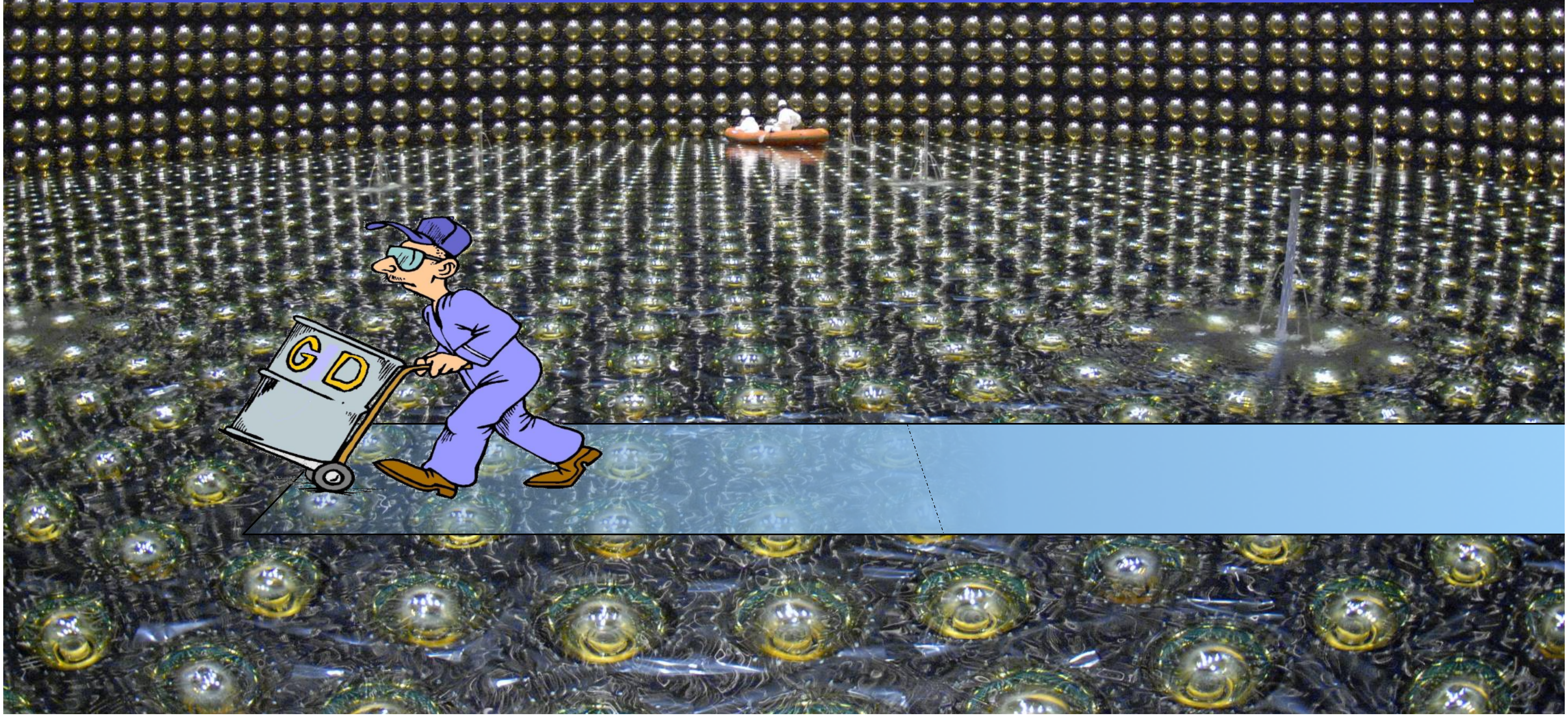
→ **No politics!** ←

By 2016 it is likely we will be adding Gd in Super-K.

In conclusion:

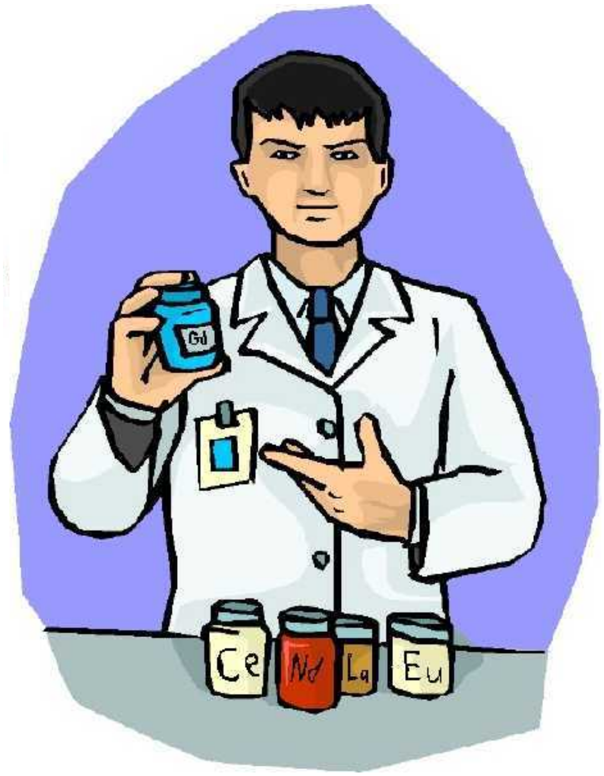
Water Cherenkov detectors have a long, proud history in neutrino physics and proton decay searches.

Now – with EGADS and gadolinium – the <u>next</u> thirty years can be as productive and exciting as the 1st thirty.



Supplementary Slides

But, wait… 0.2% of 50 kilotons is 100 *tons!*
What's <u>that</u> going to cost?



In 1984: \$4000/kg –> \$400,000,000
In 1993: \$485/kg –> \$48,500,000
In 1999: \$115/kg –> \$11,500,000
In 2006: \$6/kg –> \$600,000

These low, low prices are for real.

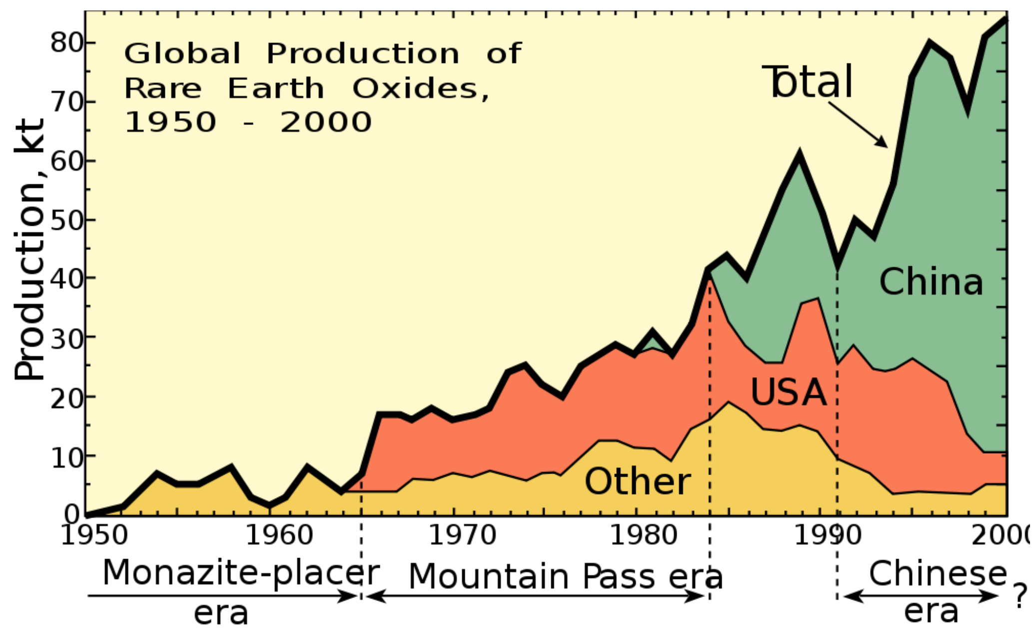
Back in 2005, $24,000 bought me 4,000 kg of $GdCl_3$.

Shipping from Inner Mongolia to Japan was included!

But since China dominates the world's rare earth production, what if they cut off the supply of gadolinium or force up its price?

Although China currently produces >90% of the world's rare earths, they control only 37% of the proven reserves. In fact, the Mountain Pass mine in California was the world's main source of rare earths for decades:

After China undercut prices in the 1990's, the California plant was shuttered. However, given the strategic importance of various rare earth elements, it is now expected to reopen. In addition, major new rare earth mines are in the process of coming online in Australia, Canada, and Vietnam.



<u>The fact is that the so-called "rare" earths are not rare at all.</u>
They are about as abundant on Earth as are "common" elements such as zinc, copper, nickel, and tin. With healthy international competition, there is no need to be concerned about their long-term supply or cost.