The Myriad Wonders and Challenges of Gadolinium Loading in WC Detectors

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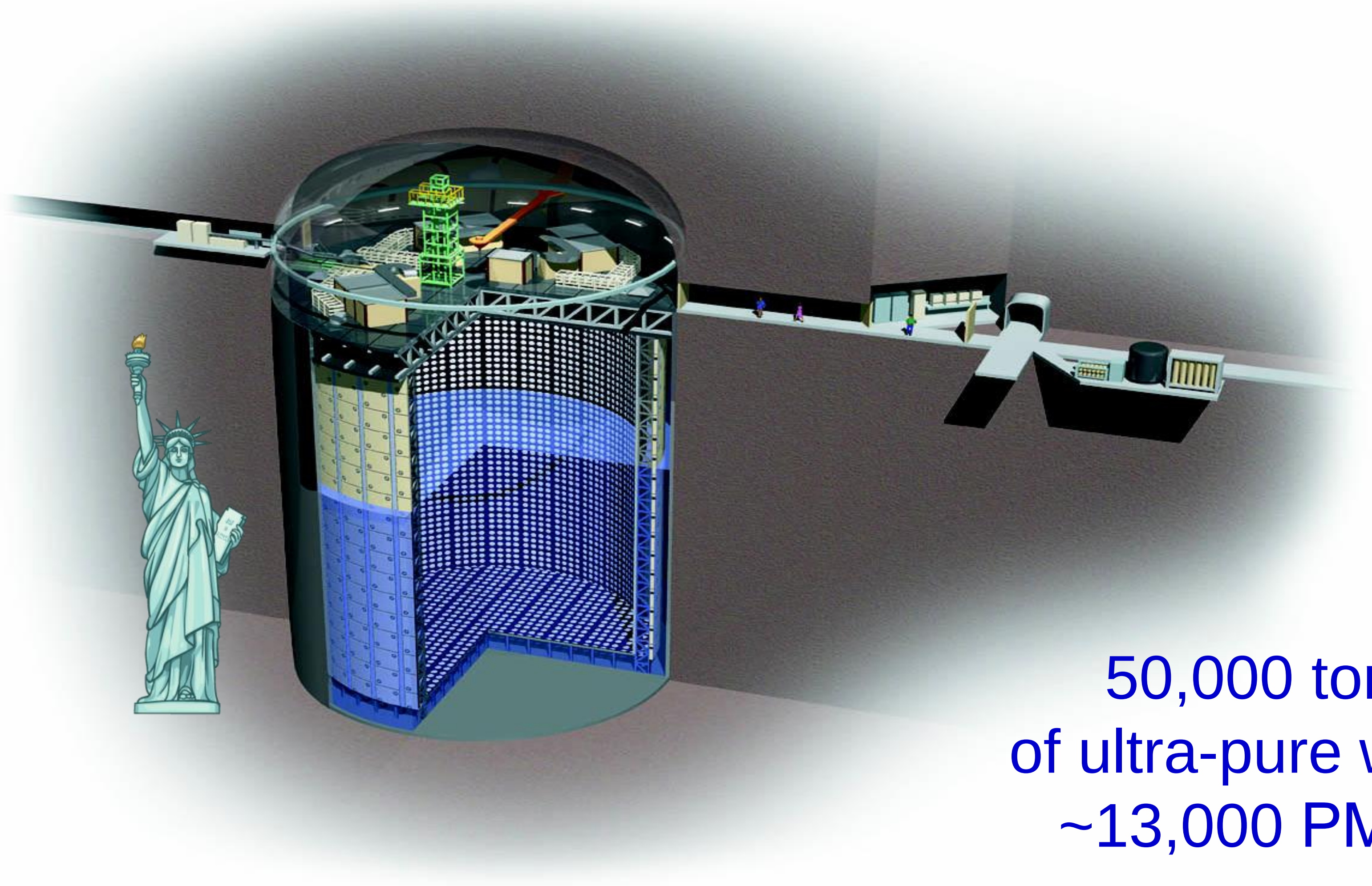
My beloved Super-Kamiokande
– already the best supernova ν detector in the world –
has been taking data, with an occasional interruption,
for over twenty years now… but no SN neutrinos so far!



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

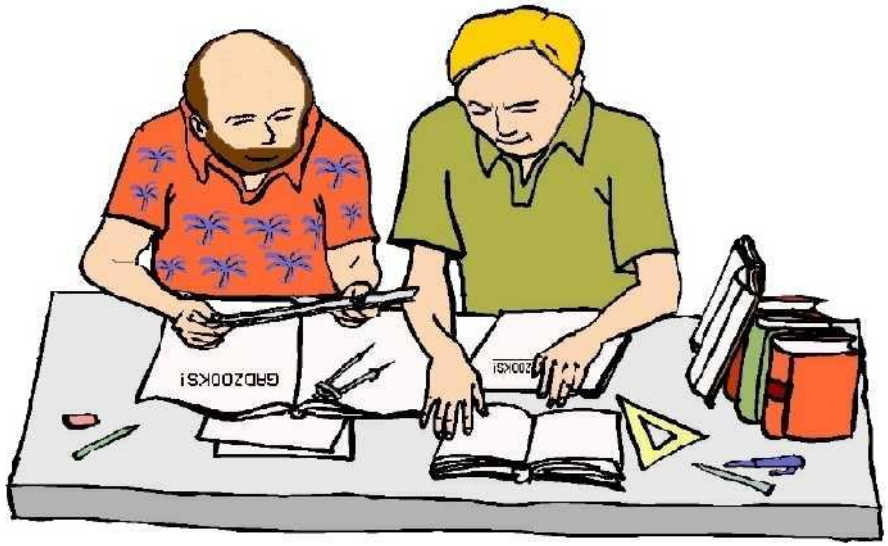
Super-K has been taking data many years.
But what does the future hold?

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

"We <u>must</u> 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.

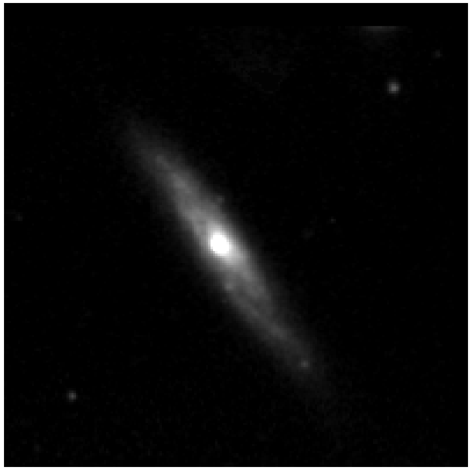
It proposed loading big WC detectors, specifically Super-K, with water soluble gadolinium, and evaluated the physics potential and backgrounds of a giant antineutrino detector.

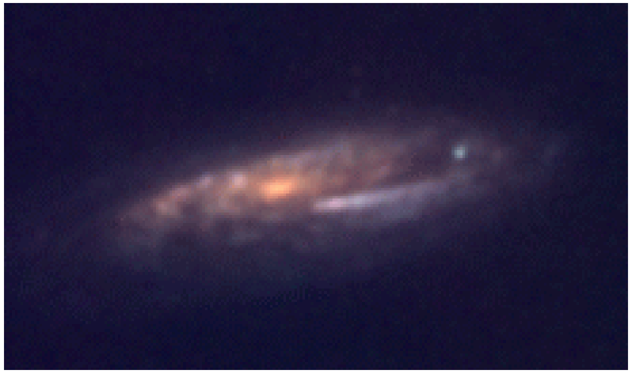
[Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

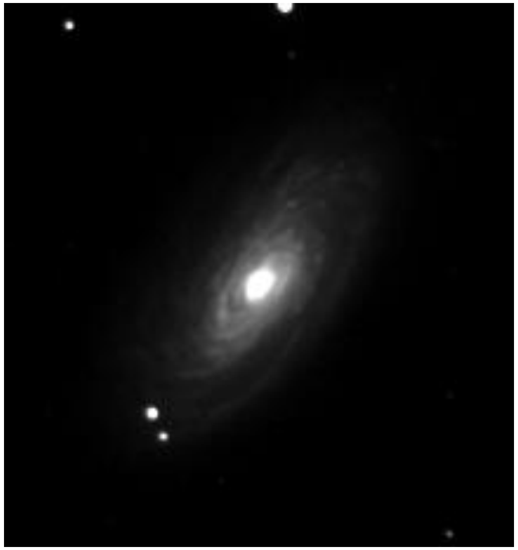
(330 citations → one every 15 days for fourteen years)

This is not the typical view of a supernova! Which, of course… is good.

Yes, nearby supernova explosions may be rare, but supernova explosions are extremely common.



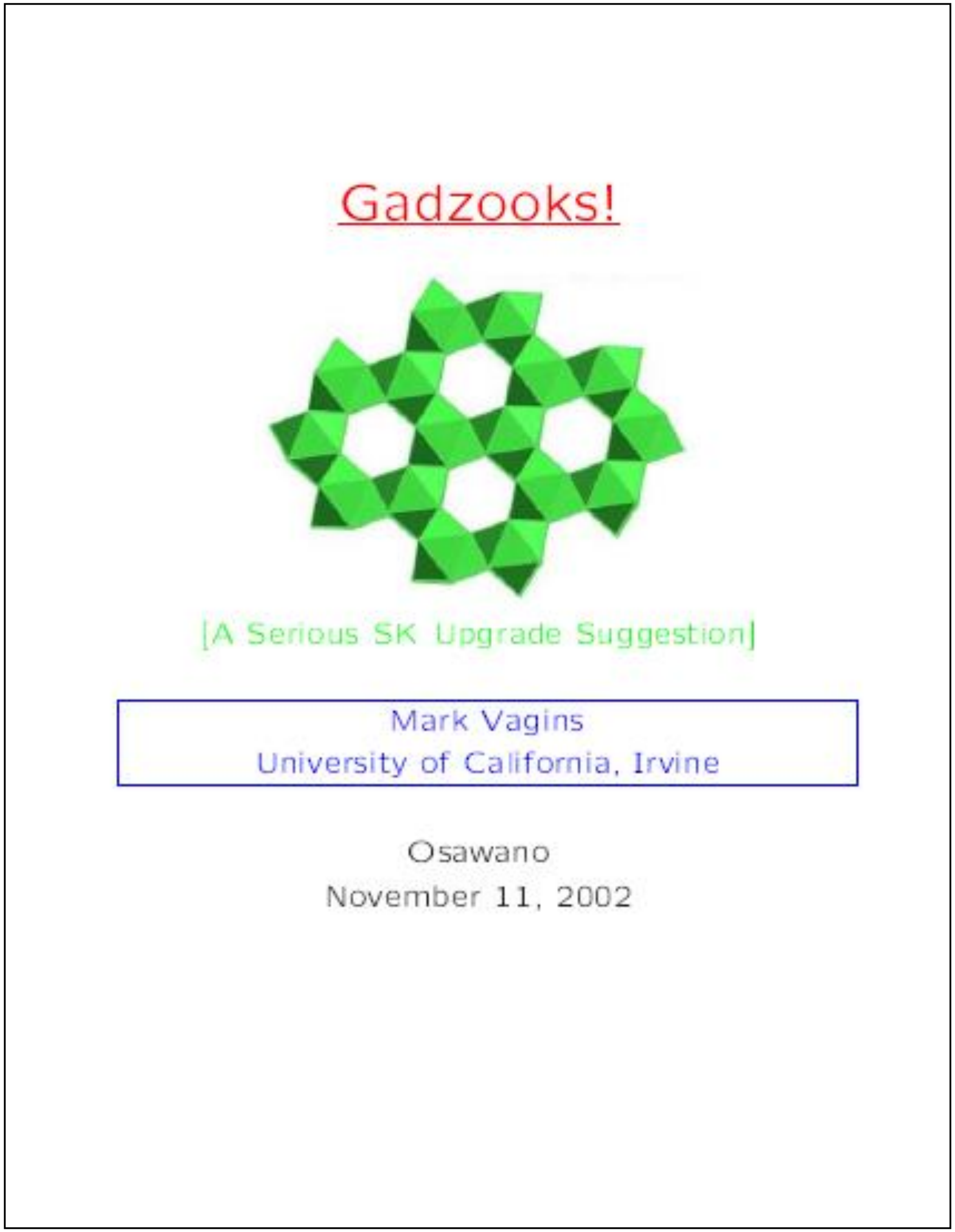




Here's how most of them look to us (video is looped).

There are *thousands of supernova explosions per hour* in the universe as a whole!

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

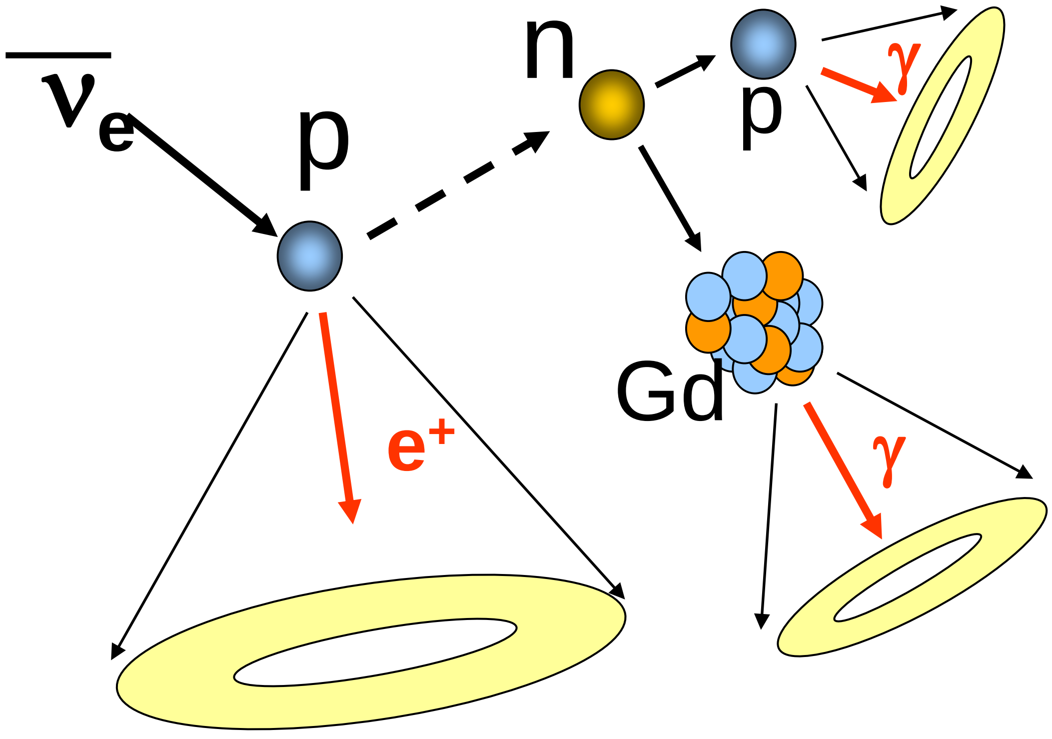


Here's the very first transparency (i.e., what we older folks used before PowerPoint but after glass slides) I ever showed on the topic… over fifteen years ago.

Please note the subtitle:

"A Serious SK Upgrade Suggestion"

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



Possibility 1: 10% or less

$n + p \rightarrow d + \gamma$

2.2 MeV γ-ray

Possibility 2: 90% or more

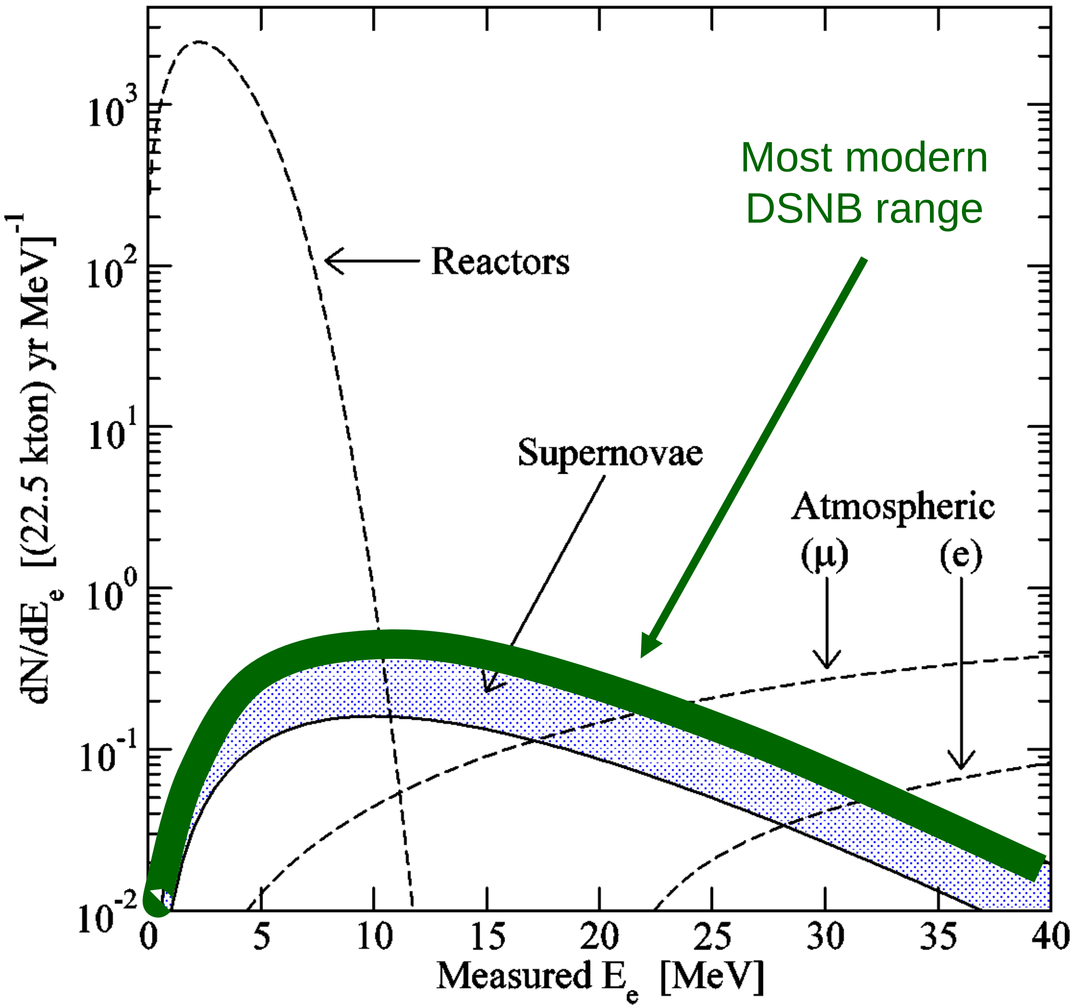
$n + Gd \rightarrow \sim 8 MeV\ \gamma$

$\Delta T = \sim 30\ \mu sec$

Positron and gamma ray vertices are within ~50cm.

$\overline{\nu}_e$ can be identified by delayed coincidence.

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):



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

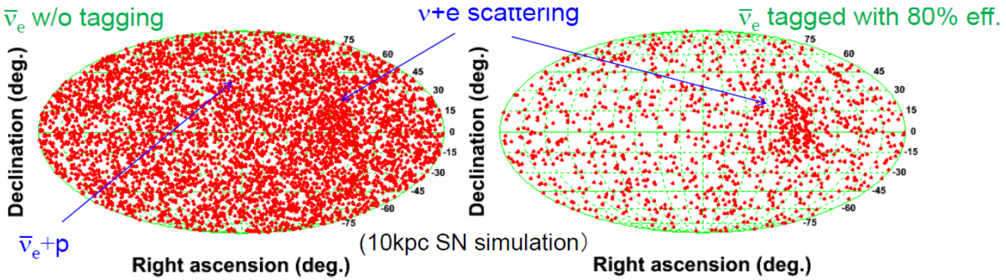
spatial and temporal separation between prompt e^+ Cherenkov light and delayed Gd neutron capture gamma cascade:

λ=~4cm, τ=~30μs

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

In the case of a galactic supernova, having $Gd_2(SO_4)_3$ in Super-K will provide many important benefits:

- Allows the exact $\bar{\nu}_e$ flux, energy spectrum, and time profile to be determined via the extraction of a tagged, pure sample of inverse beta events.
- Instantly identifies a burst as genuine via “Gd heartbeat”.
- Doubles the ES pointing accuracy. Error circle cut by 75%.



- Helps to identify the other neutrino signals, especially the weak neutronization burst of ν_e.
- Enables a search for very late time black hole formation.
- Provides for very early warning of the most spectacular, nearby explosions so we can be sure not to miss them.

In addition to our “guaranteed” new DSNB signal and greatly improved response to a galactic supernova, it is likely that adding gadolinium to SK will provide a variety of other interesting possibilities:

- Proton decay background reduction
- New long-baseline flux normalization for T2K
- Reduction of low energy neutrino spallation backgrounds
- Matter- vs. antimatter-enhanced atmospheric ν samples

All of this could work even better in an much larger detector.

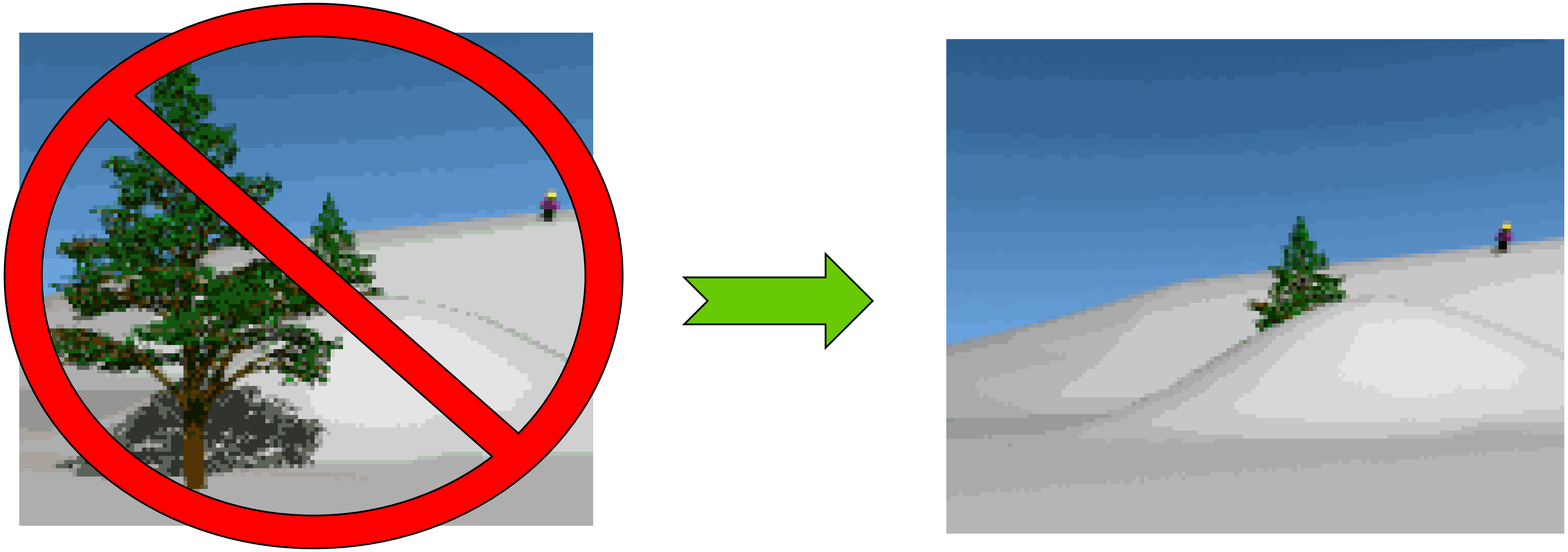
Indeed, any such massive new project will *need* to have some new physics topics to study!

Now, Beacom and I never wanted to merely propose a new 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 may not be the easiest route…

…and so to avoid wiping out, some careful hardware studies are needed.

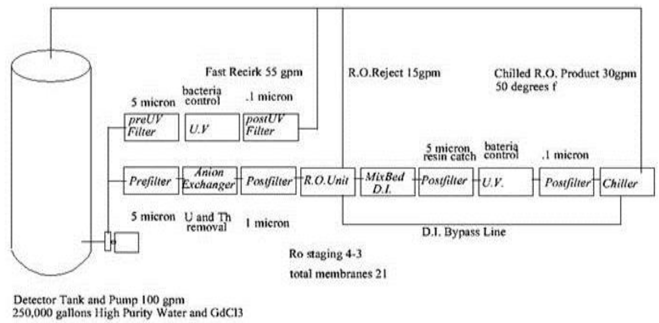


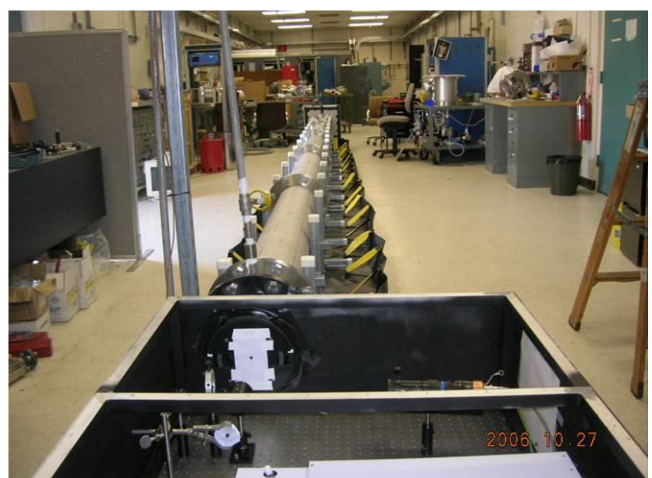
- What does gadolinium do the Super-K tank materials?
- Will the resulting water transparency be acceptable?
- Any strange Gd chemistry we need to know about?
- *How will we filter the SK water but retain dissolved Gd?*

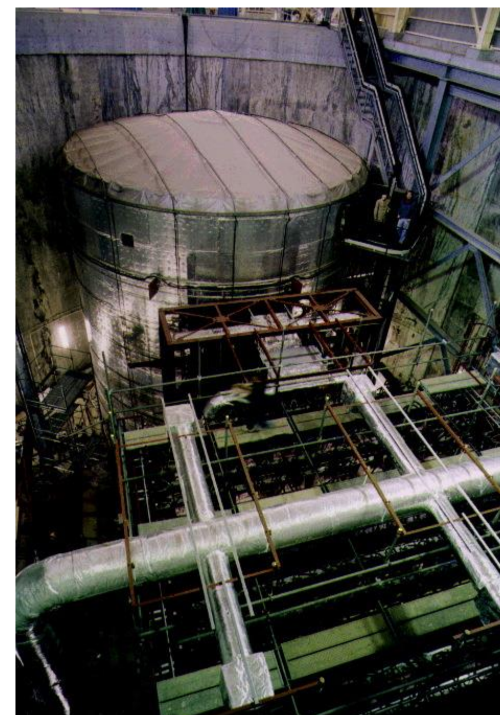
As a matter of fact, I very rapidly made two discoveries regarding $GdCl_3$ while carrying a sample from Los Angeles to Tokyo:

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

Over the last fifteen years there have been a large number of Gd-related studies carried out in the US, Japan, UK, and Spain:







We tried using electrodeionization (EDI) to selectively remove gadolinium. It worked, but EDI unfortunately had two problems:

1) It split $GdCl_3$ into gaseous chlorine…

Highly toxic!

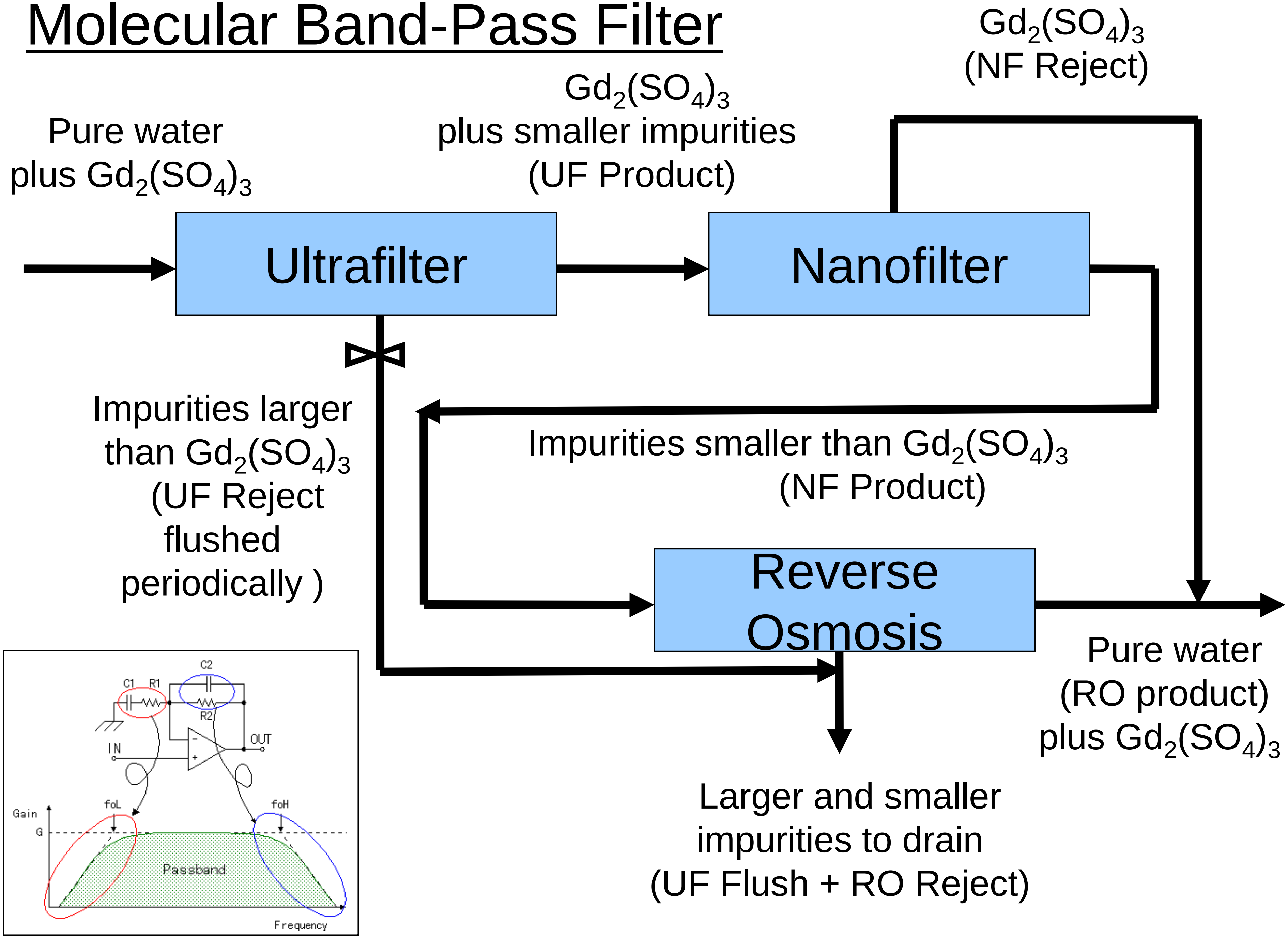
1) It split H_20 into gaseous hydrogen…

Highly explosive!

So we were forced to abandon our EDI studies (and $GdCl_3$) and invent an entirely new technology:

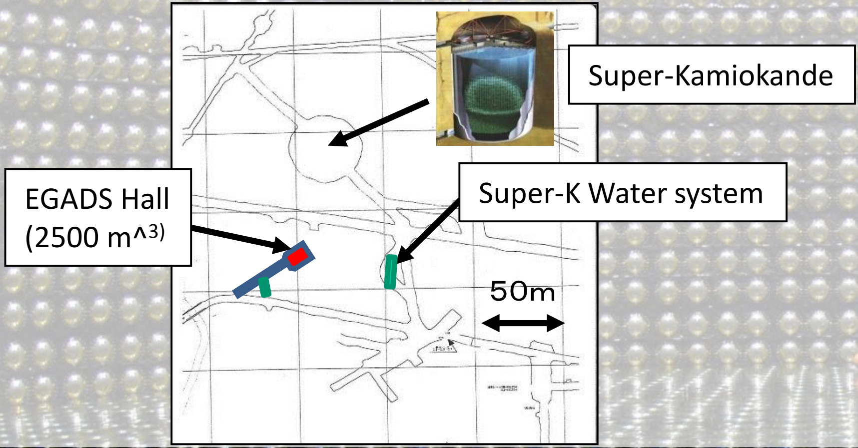
"Molecular Band-pass Filtration"

Molecular Band-Pass Filter

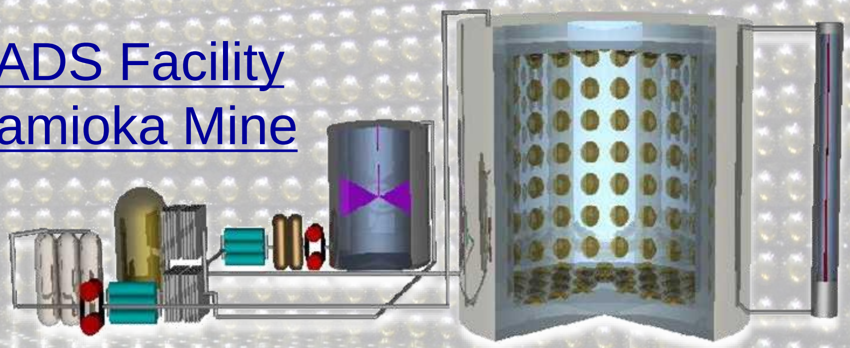


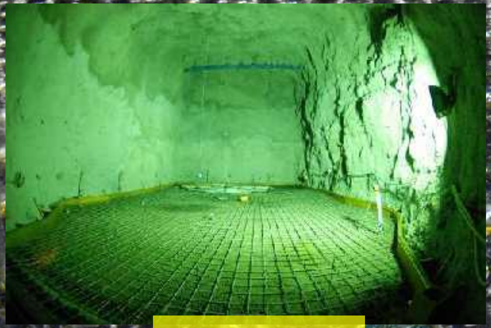
EGADS → Gd-loaded Super-K

To show everything was going to work as expected, we built **EGADS** (Evaluating Gadolinium's Action on Detector Systems), a dedicated Gd demonstrator which includes a working 200-ton scale model of SK.

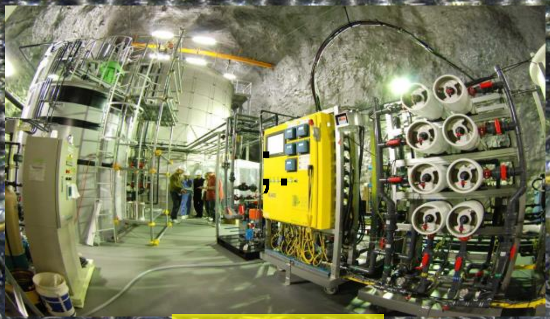


EGADS Facility in Kamioka Mine



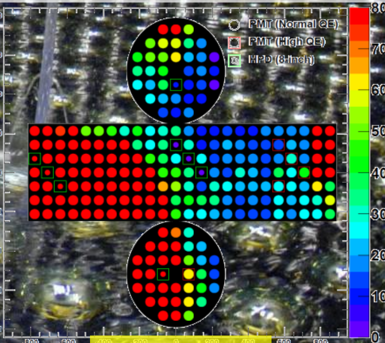


12/2009



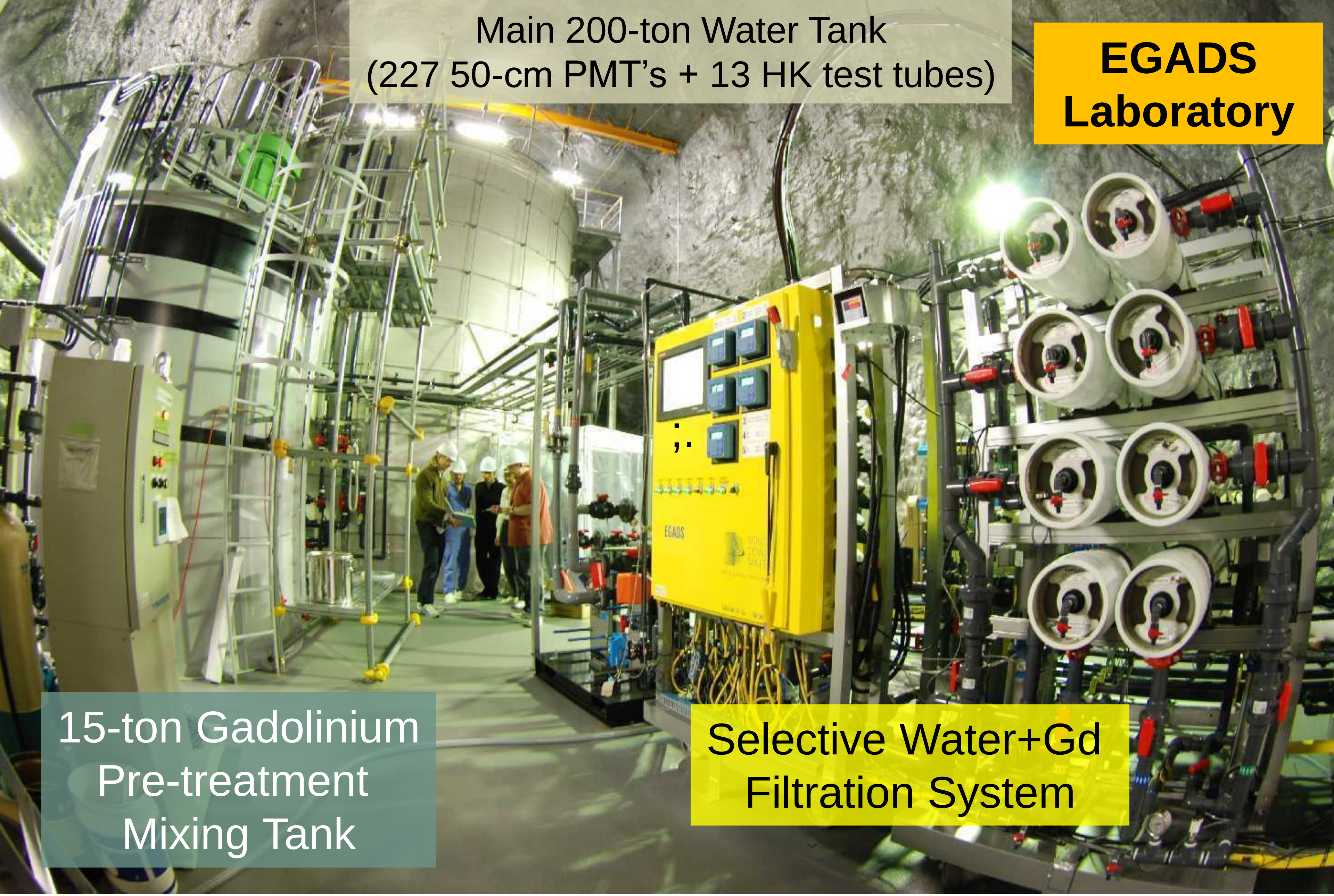
11/2011

8/2013



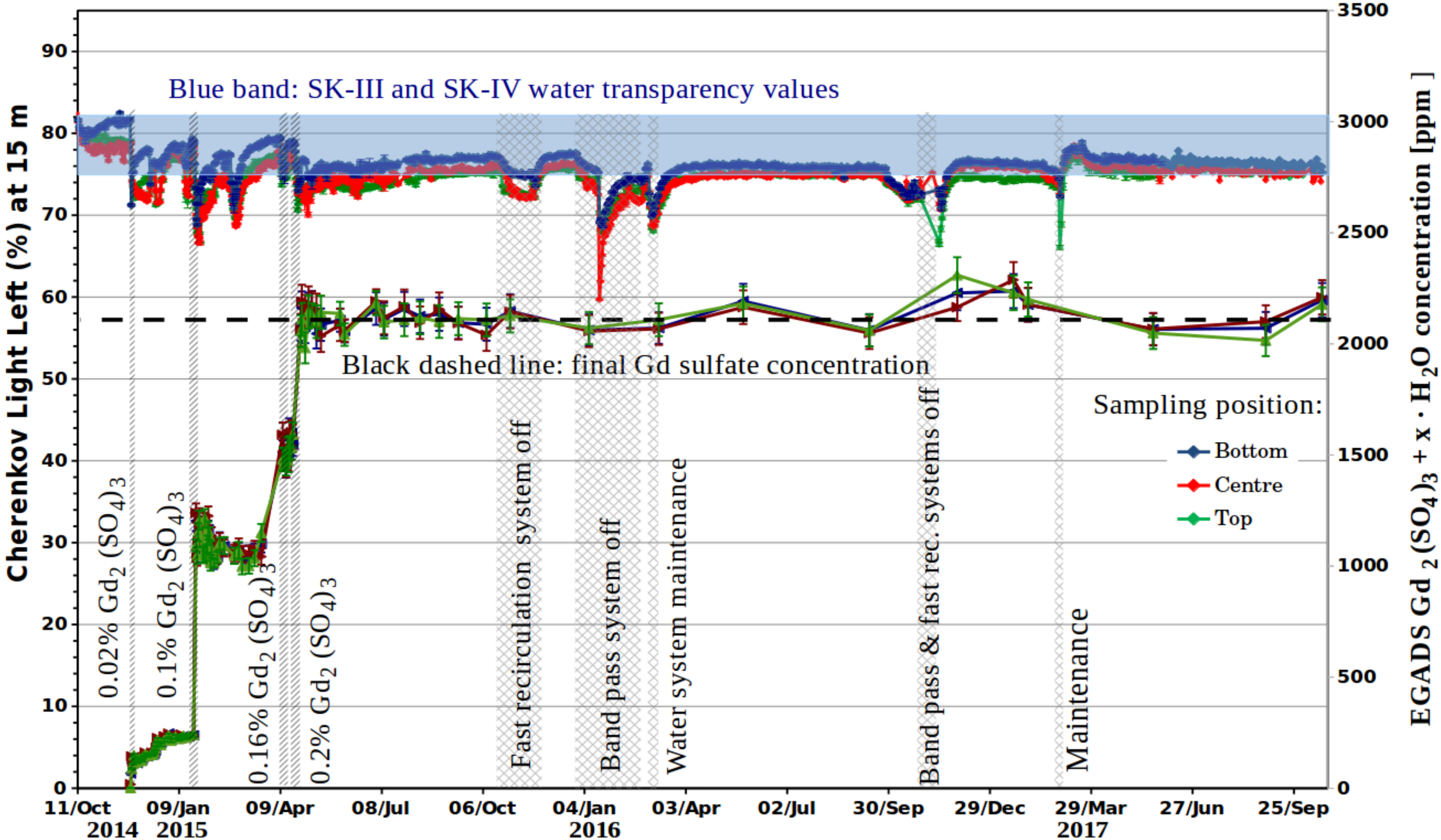
6/2015

Between April 2015 and October 2017, the EGADS detector was fully loaded (0.2%) with gadolinium sulfate, and functioned perfectly.



Well over $10,000,000 (1.1B yen) - <u>not</u> counting salaries - has been spent developing and proving the viability of the Gd-in-water concept.

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



After two and a half years at full Gd loading, during stable operations <u>EGADS water transparency remains within the SK ultrapure range</u>.

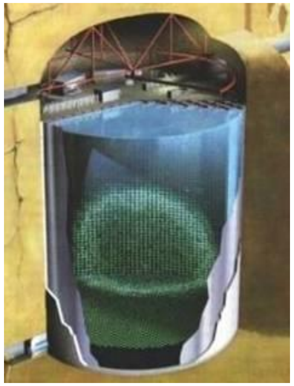
→ No detectable loss of Gd after more than 650 complete turnovers. ←

November 6th, 2017; This view is directed up the side wall from the bottom of the 200-ton tank. Looks great after 2.5 years of exposure to 0.2% $Gd_2(SO_4)_3$ water!

After years of testing and study

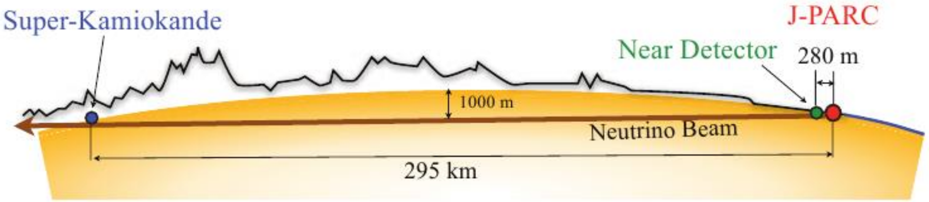
– culminating in these powerful EGADS results –

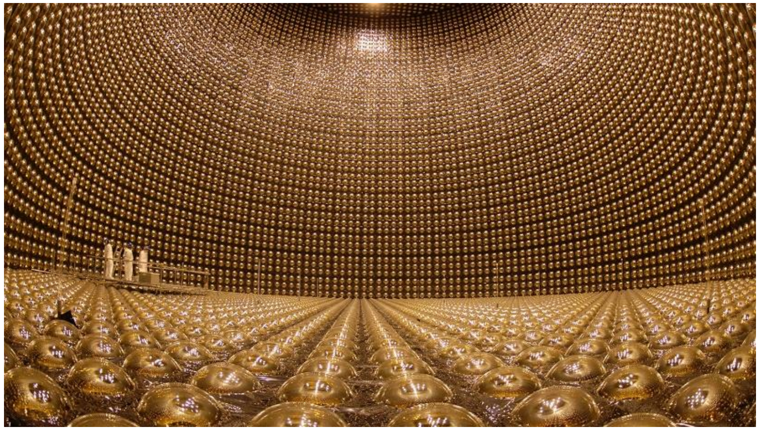
no technical showstoppers have been encountered. And so…



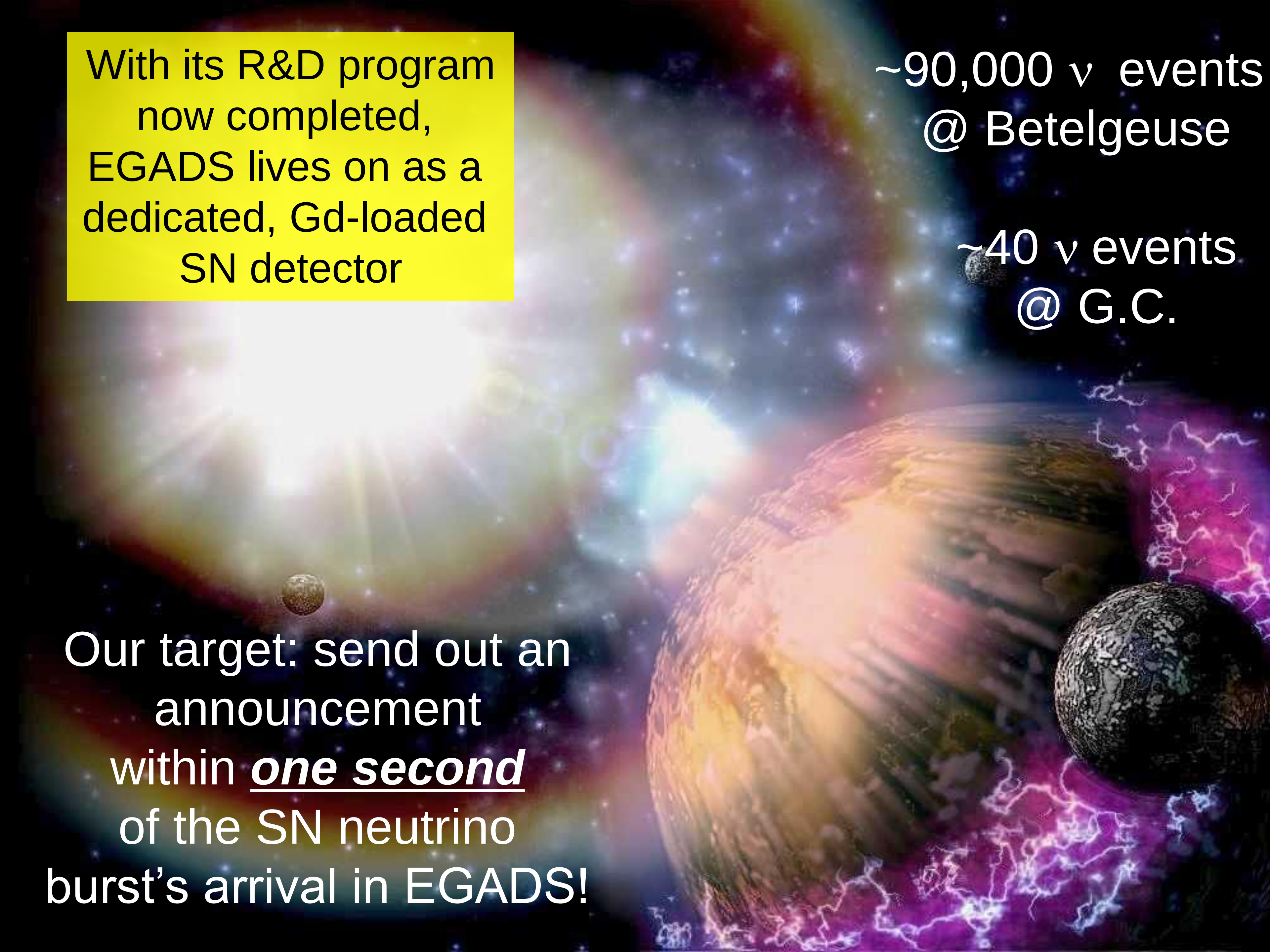
June 27, 2015: The Super-Kamiokande Collaboration approved the addition of gadolinium to the detector, pending discussions with T2K.

January 30, 2016: The T2K Collaboration approved addition of gadolinium to Super-Kamiokande, with the precise timing to be jointly determined based on the needs of both projects.

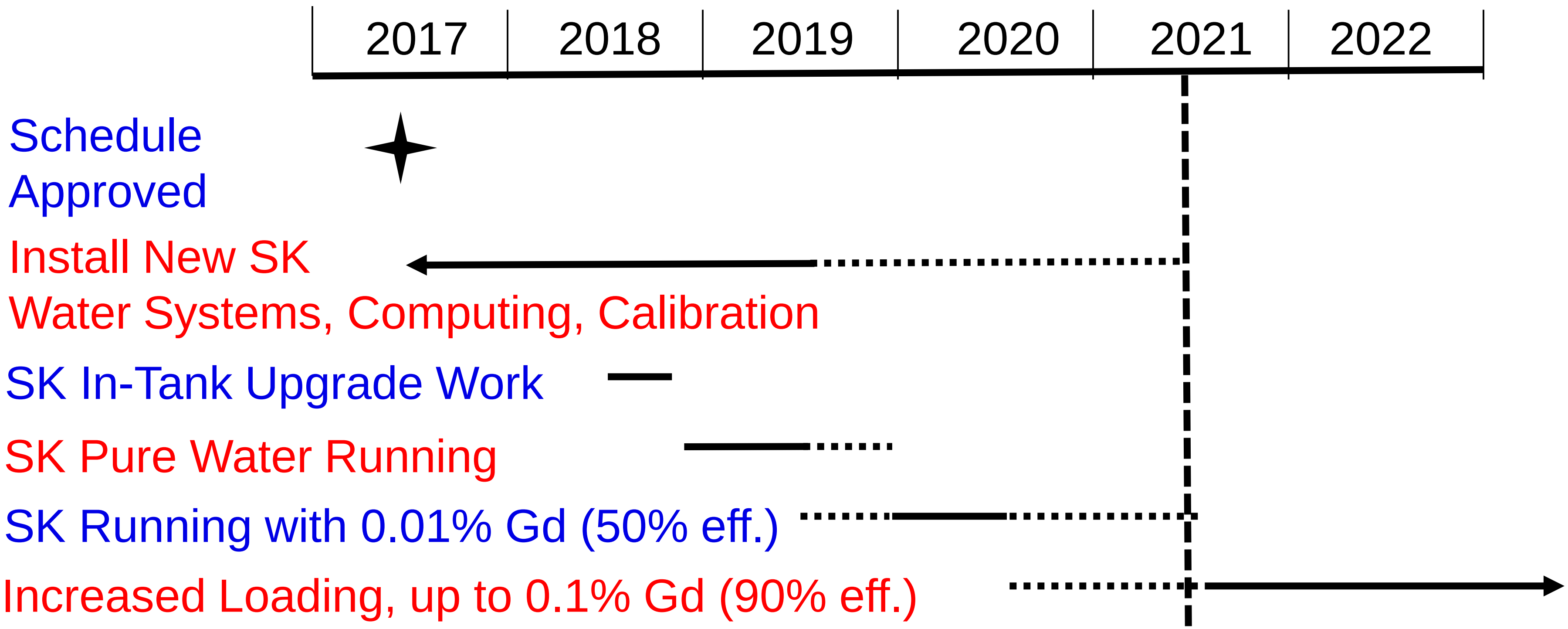




July 26, 2017: The official start time of draining the SK tank to prepare for Gd loading is decided to be June 1, 2018.


With its R&D program now completed, EGADS lives on as a dedicated, Gd-loaded SN detector
~90,000 ν events @ Betelgeuse
~40 ν events @ G.C.
Our target: send out an announcement within ***one second*** of the SN neutrino burst's arrival in EGADS!

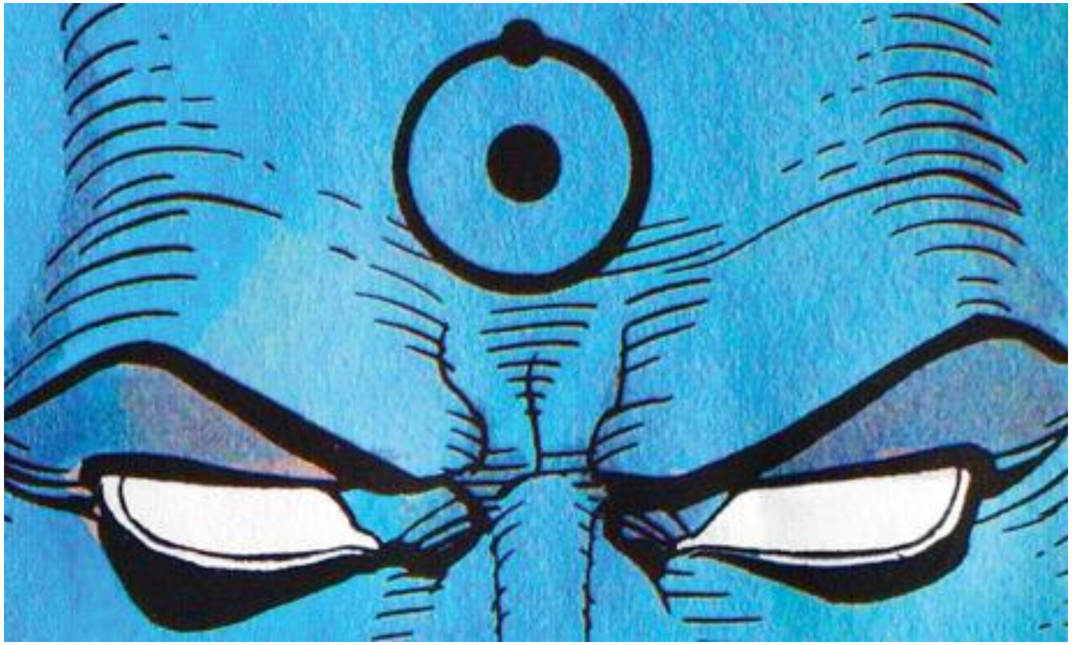
Expected timeline for SK-Gd



We should have collected some new supernova neutrinos within three years from today!

<u>Oh, and one more thing</u>:
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 <u>across international borders!</u>



First applied use of neutrinos!

WATCHMAN: WATer CHerenkov Monitoring of Anti-Neutrinos

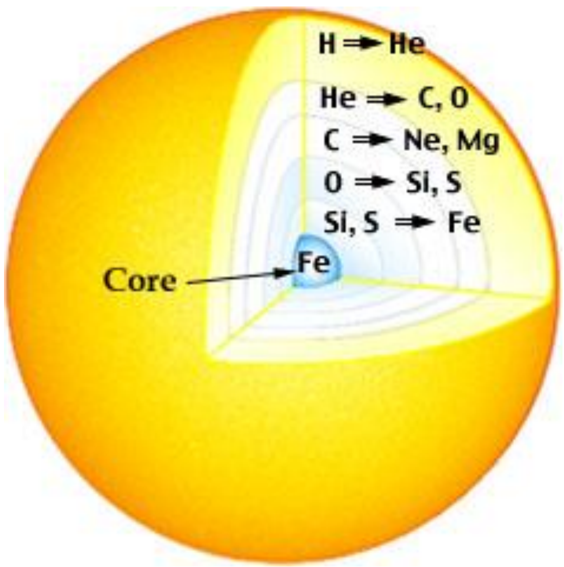
NNSA
National Nuclear Security Administration

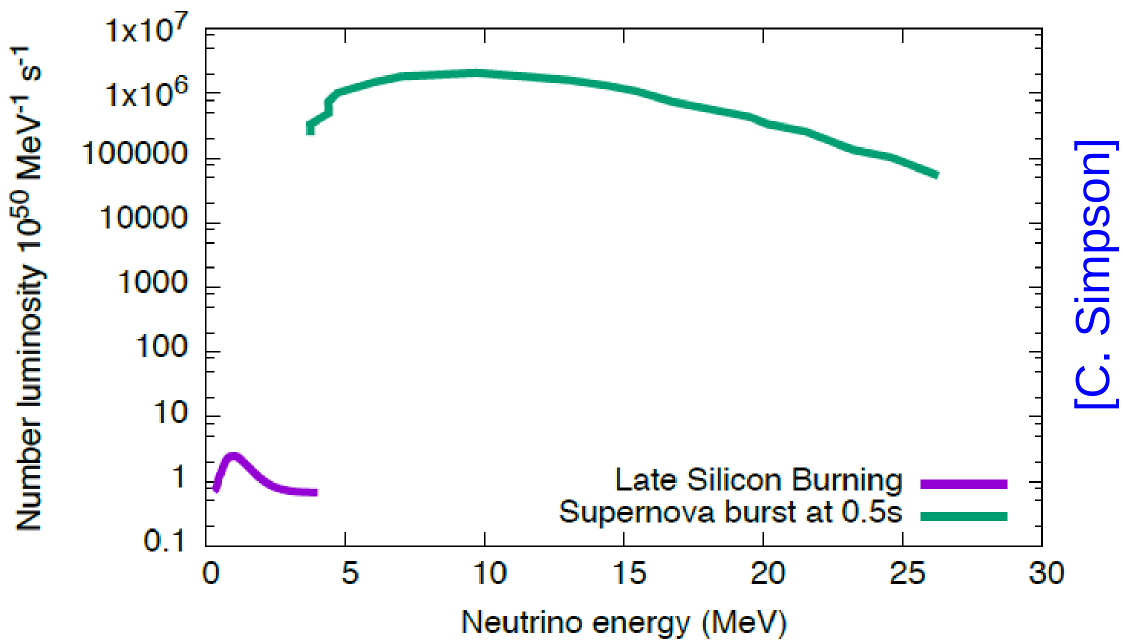
A US NNSA demonstrator project to find small, hidden nuclear reactors in uncooperative nations from a distance using gadolinium-enriched water Cherenkov detectors.

So that's it from me for today.
Back to traveling the globe, to spread my message:

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

Odrzywodek *et al.* were the first to suggest that late-stage Si burning in very large, very close stars could provide useful early warning of a core collapse supernova in a Gd-loaded Super-Kamiokande.





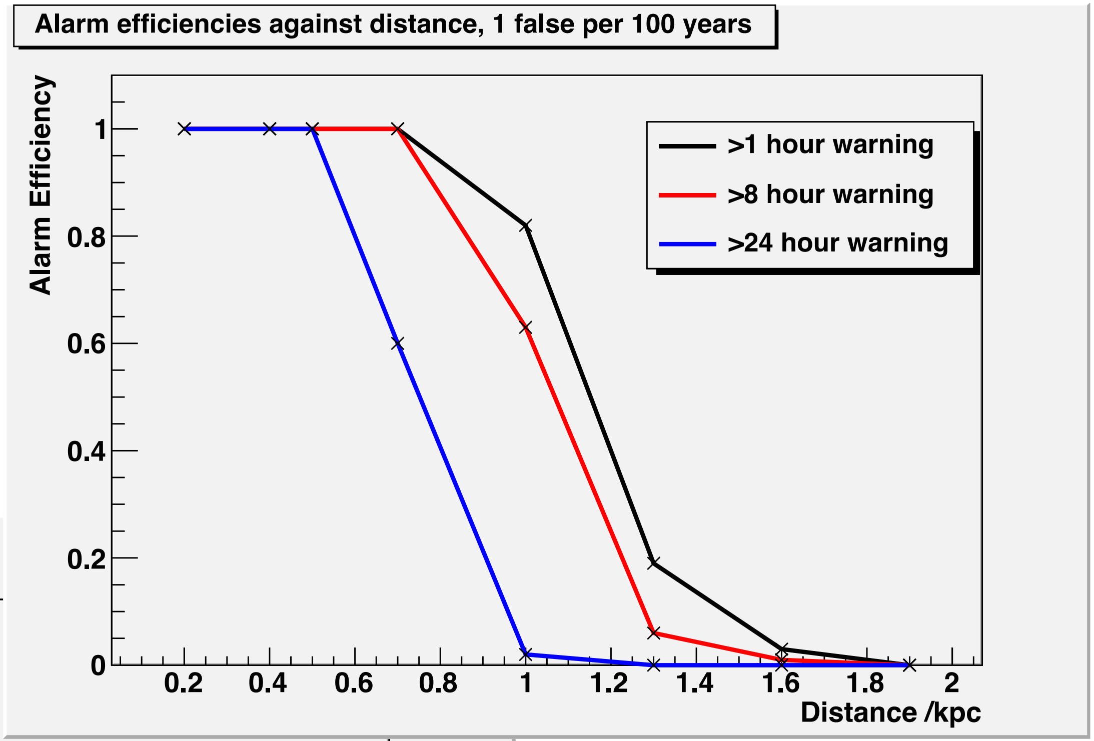
$e^+ + e^- \rightarrow \bar{\nu}_e + \nu_e$ (just above inverse beta threshold)

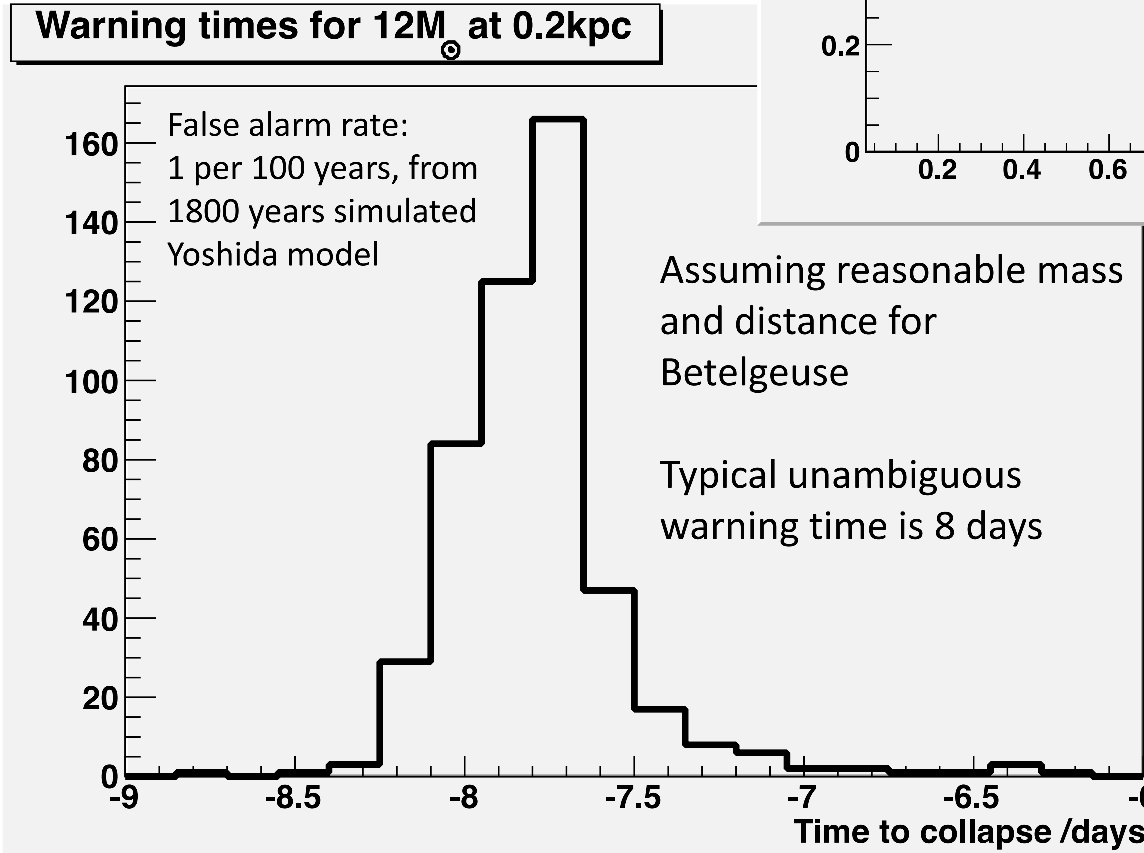
$\hookrightarrow \bar{\nu}_e + p \rightarrow e^+ + n$ (e^+ barely relativistic)

[Odrzywodek, Misiaszek, and Kutschera, *Astropart.Phys.* 21:303-313, 2004]

Gd-loaded Super-Kamiokande's Sensitivity to pre-SN ν's

(Super-K internal study)





Assuming reasonable mass and distance for Betelgeuse

Typical unambiguous warning time is 8 days

[C. Simpson]