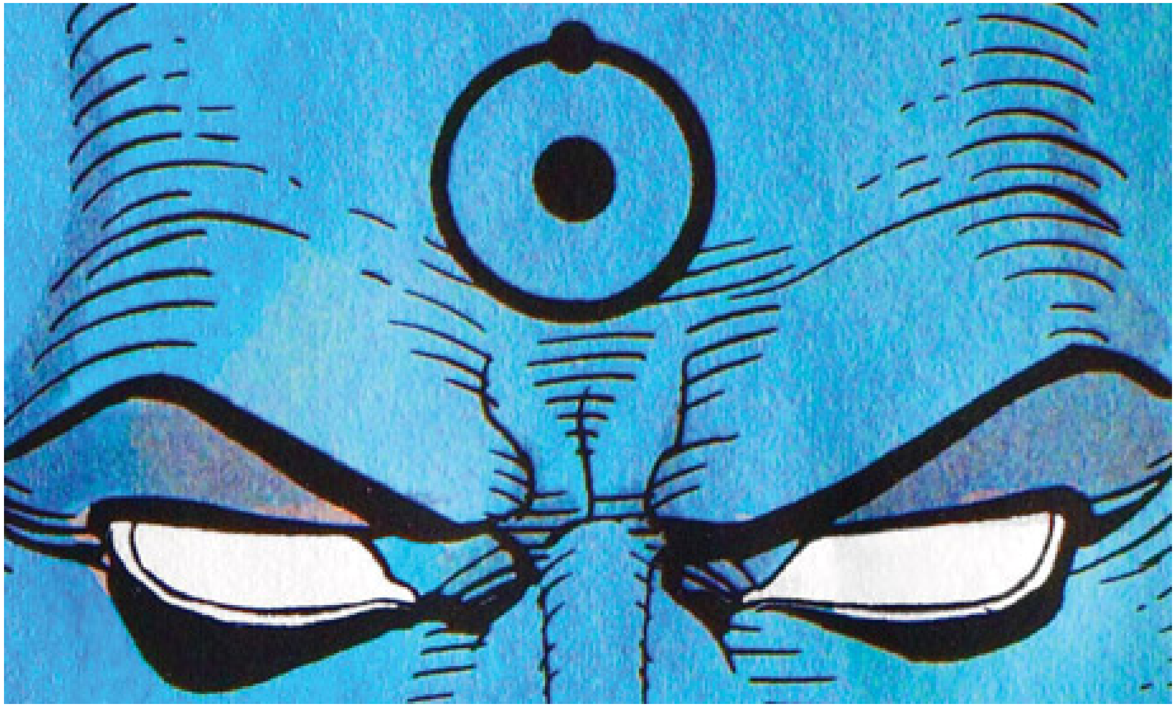
<u>WATCHMAN</u>: <u>WAT</u>er <u>CH</u>erenkov <u>M</u>onitoring of <u>A</u>nti-<u>N</u>eutrinos



Mark Vagins

Kavli IPMU, University of Tokyo/UC Irvine

5th Open Meeting for the Hyper-Kamiokande Project

Vancouver July 20, 2014

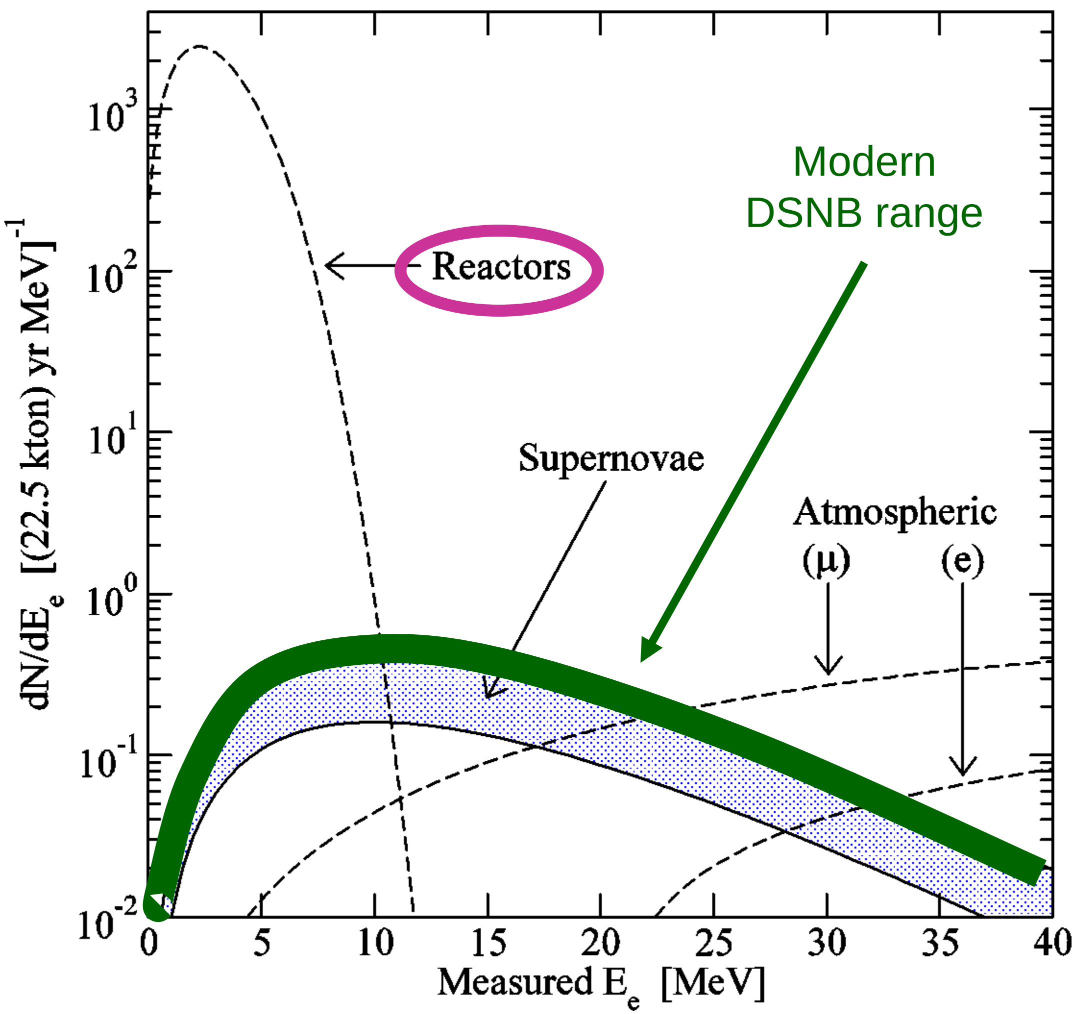
Those who know me are well aware that for the last decade I have been going around the world spreading a certain message:

Super-Kamiokande
1KT @ KEK
LBNE WC
EGADS
ANNIE
nuPRISM
TITUS
Hyper-Kamiokande
.
.
.

Of course, the detector I've spent most of this time preparing to gadiate is my beloved Super-Kamiokande.

(see or download my talk tomorrow)

Here are the expected coincident signals with $Gd_2(SO_4)_3$:

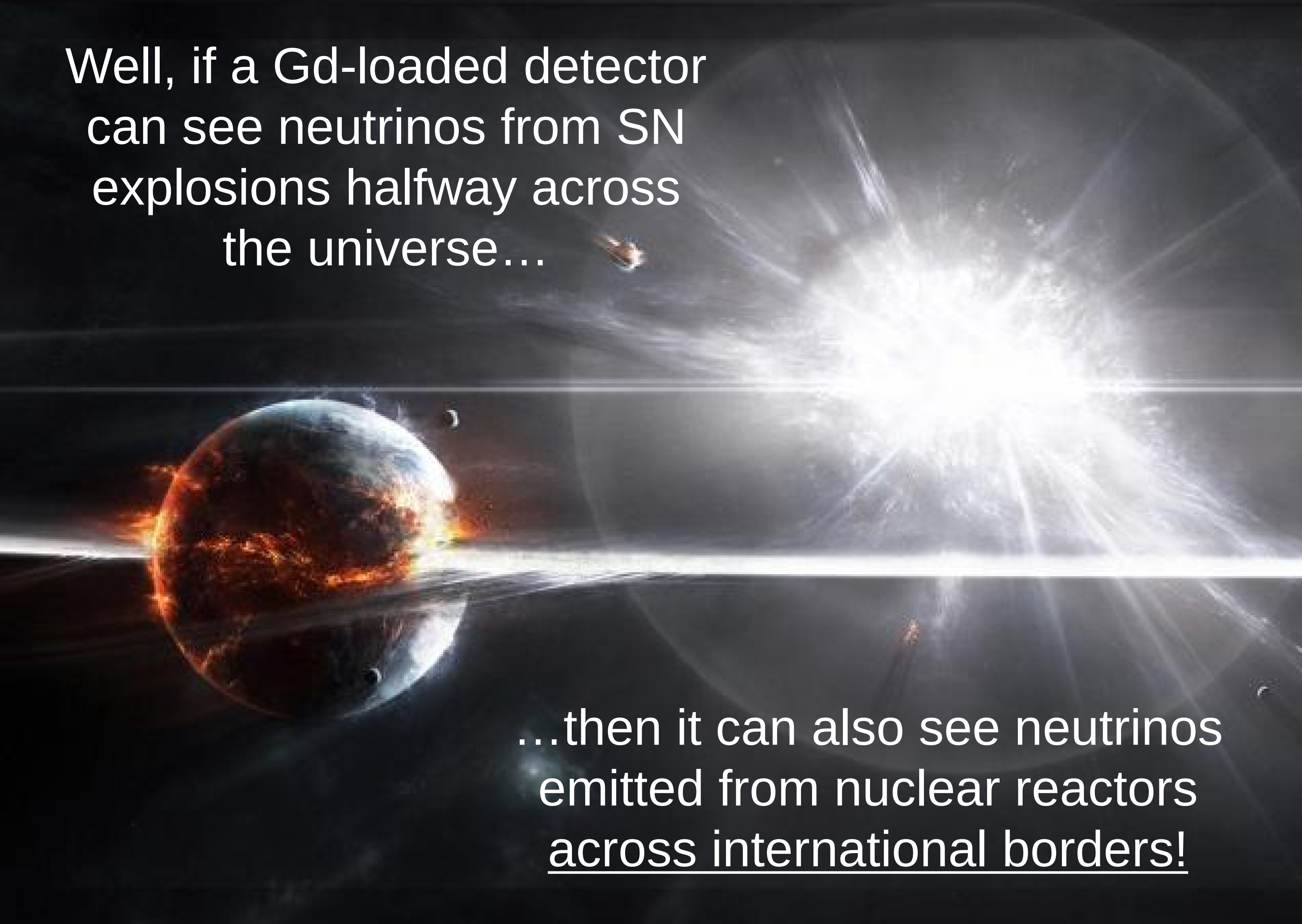


$\bar{\nu}_e + p \rightarrow e^+ + n$

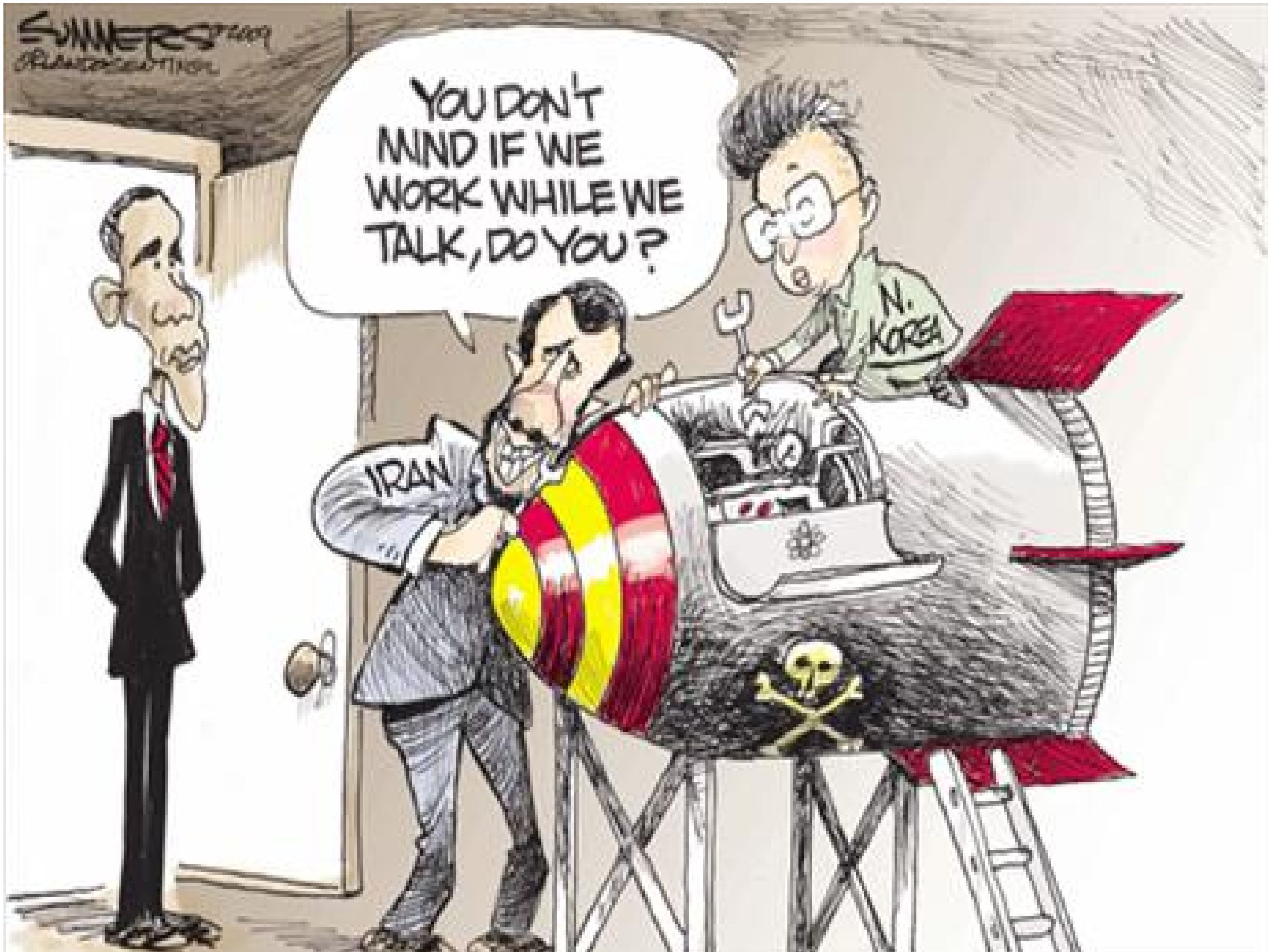
spatial and temporal separation between prompt e^+ Cherenkov light and delayed Gd neutron capture gamma cascade:

λ=~4cm, τ=~30μs

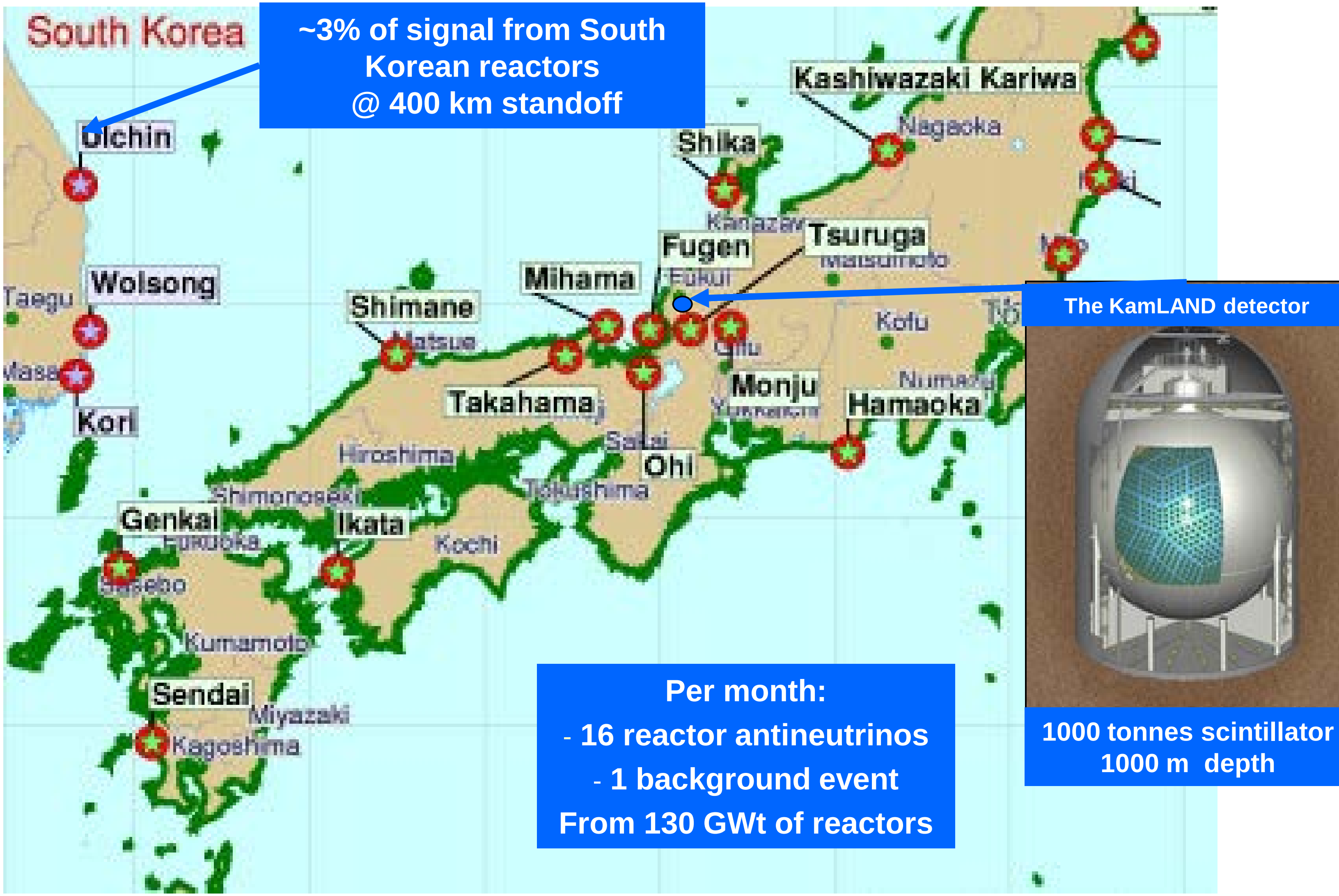
→ But what about that *big* reactor signal?


Well, 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!

So very large scale anti-neutrino detection just might have another application or two…



But hold on a minute… what about KamLAND?



~3% of signal from South Korean reactors @ 400 km standoff

Per month:
- 16 reactor antineutrinos
- 1 background event

From 130 GWt of reactors

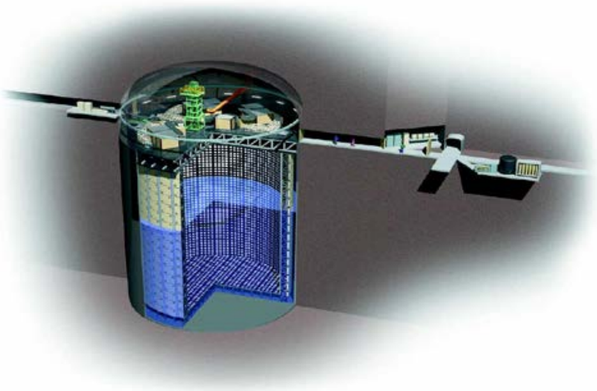
The KamLAND detector

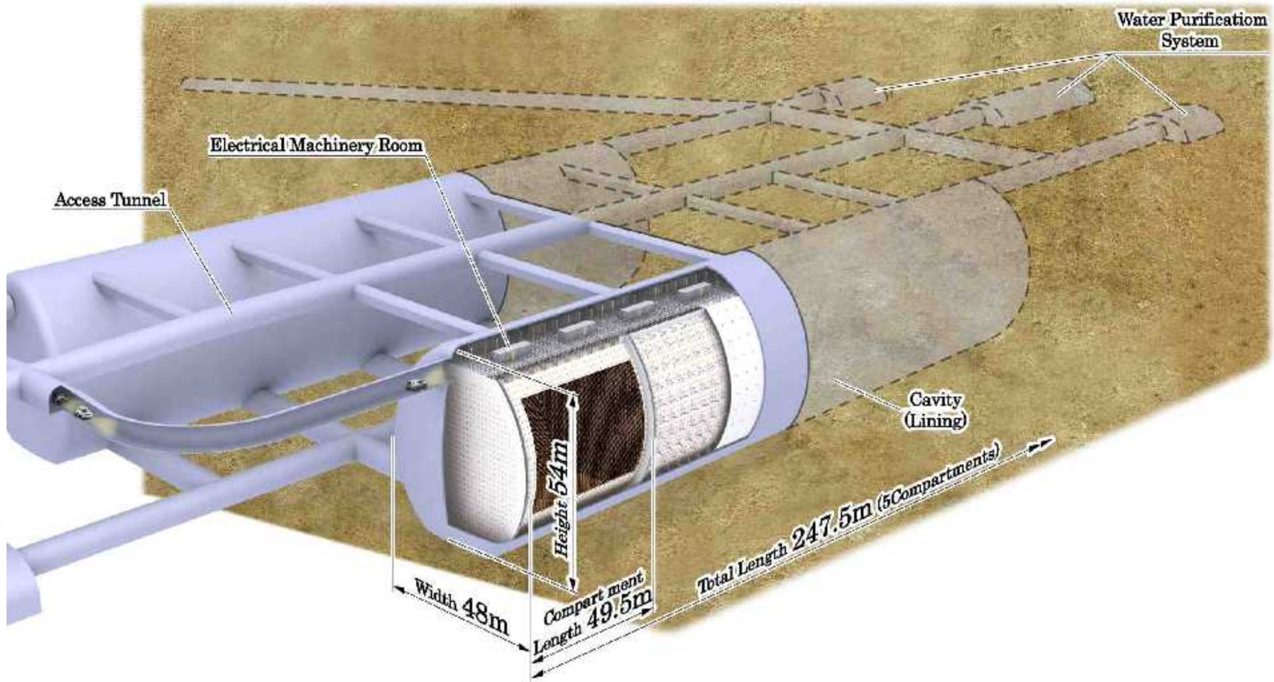
1000 tonnes scintillator
1000 m depth

KamLAND saw neutrinos from huge power reactors (>1 GWt)
but this must be compared with
tiny clandestine plutonium production reactors (~10 MWt).
Plus, considerably more rate will be needed to spot shenanigans.

→ Scaling KamLAND up 1000X is not going to happen! ←

In contrast, based on all our work so far scaling Gd-loaded WC technology appears to be entirely feasible:





Now a new player in the game is aiming to find out for sure… and *soon.*

U.S. DEPARTMENT OF ENERGY
GTRI
REMOVE
CONVERT
PROTECT
DEFENSE NUCLEAR NONPROLIFERATION
NATIONAL NUCLEAR SECURITY ADMINISTRATION

NNSA
National Nuclear Security Administration

WATCHMAN is an initiative to demonstrate standoff detection of hidden reactors in a non-proliferation context for NNSA, while also doing physics for HEP.

The WATCHMAN Collaboration

Livermore

Sandia

BROOKHAVEN NATIONAL LABORATORY

Brookhaven

UC Berkeley

UChicago

UC Davis

A. Bernstein, N. Bowden,
S. Dazeley, D. Dobie

P. Marleau, J. Brennan,
M. Gerling, K. Hulin, J. Steele,
M. Sweany

M. Yeh

K. Van Bibber, G. Gann,
K. Vetter, C. Roecker, T. Shokair

M. Wetstein

R. Svoboda, M. Askins,
M. Bergevin, Daine Danielson

Students getting WATCHMAN-related Ph.D. s
Undergraduate

U of Hawaii

Hawaii Pacific

UC Irvine

Virginia Tech

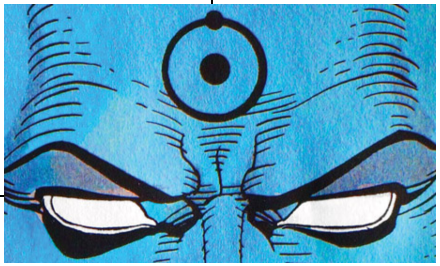
J. Learned, J. Maricic

S. Dye

M. Vagins, M. Smy

S.D. Rountree, B. Vogelaar,
C. Mariani, Patrick Jaffke

3 National Laboratories
7 Universities
28 Collaborators
18 Physicists
5 Engineers
2 Post-docs
3 Ph.Ds
1 Undergrad



WATCHMAN Construction/Operation Phase contingent on full project approval

National Nuclear Security Administration
Defense Nuclear Nonproliferation

Goals for Construction/Operation Phase:

- **See reactor ON/OFF transition in 30 days or less @ 99% confidence**

- **Demonstrate innovative, scalable, cost-effective Gd-H_2O Cherenkov technology, pioneered by WATCHMAN collaborators**

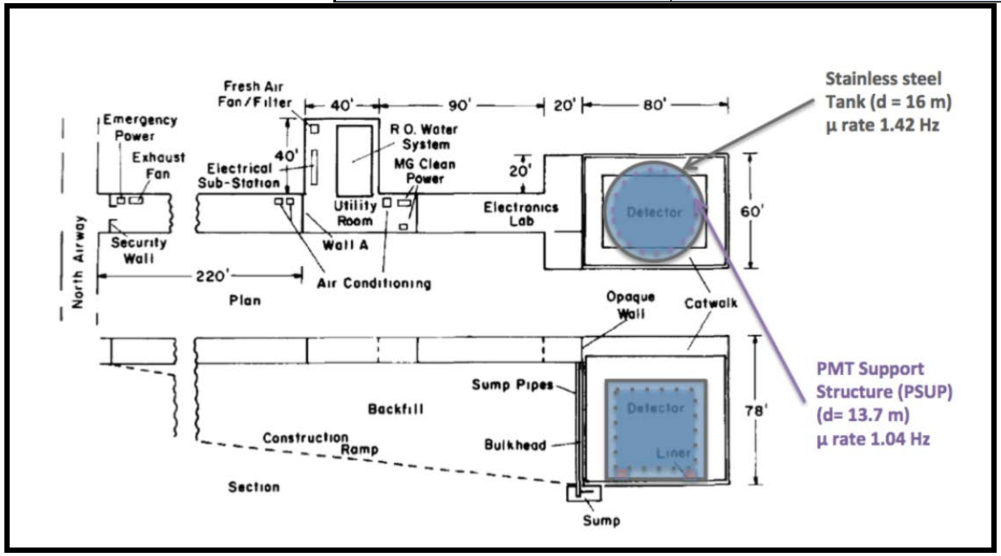
- **Provide a data-sharing and joint funding model for the scientific community**
(currently envisioned: $50,000,000 total, split ~60% NNSA/~40% HEP)

- **Hand off to science agencies at the end of nonproliferation demonstration**

Lawrence Livermore National Laboratory
BROOKHAVEN NATIONAL LABORATORY
Virginia Tech
Sandia National Laboratories

Existing IMB lab only 13 km from commercial nuclear reactor

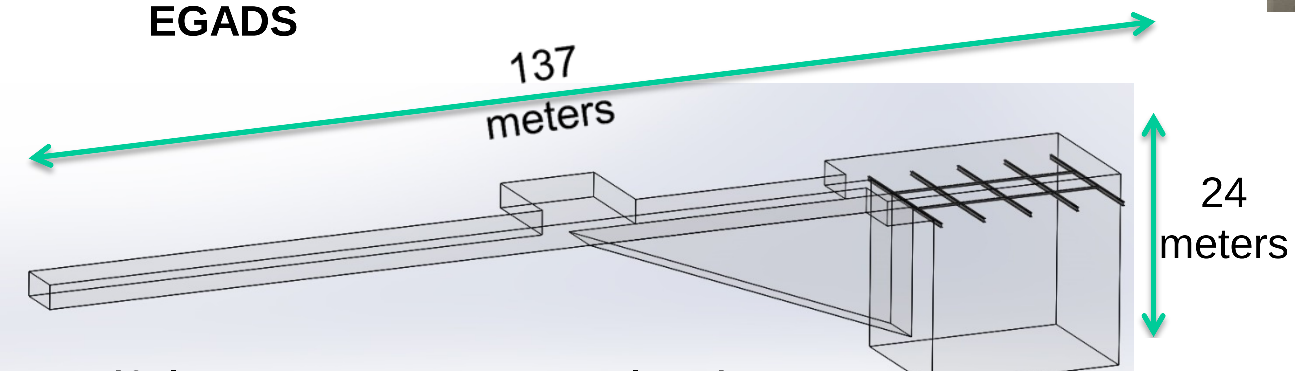
Reactor Location	Perry Ohio
Thermal Power	3875 MWt
Detector Location	Morton Salt/IMB mine (!) Painesville, Ohio
Standoff	13 km - the only reactor in the US at a suitable distance from a deep mine
Overburden	1670 mwe
Approval status	Morton Salt has approved installation – assuming cost-neutral and no disruption to mining activities



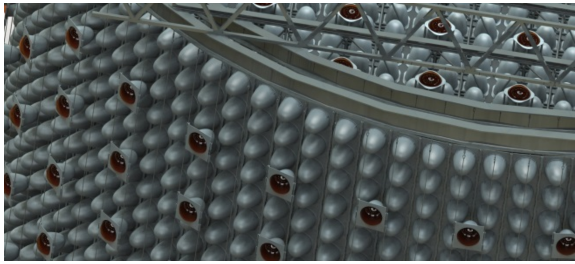
The IMB cavern in late 1970's. Used by DOE HEP until 1991 for the IMB detector and other smaller experiments

Current 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**
  - **DOE feels now an established technology due to EGADS**



Drift layout at Morton Salt Mine

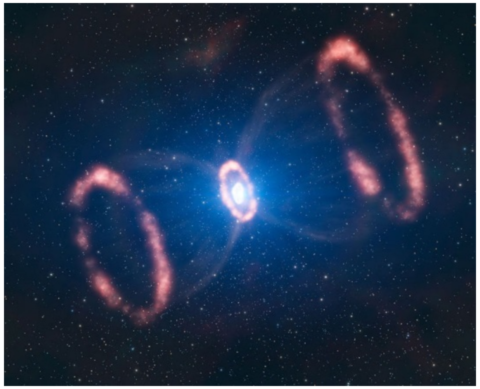


Close-up of Veto PMT Wall

Physics with WATCHMAN

National Nuclear Security Administration
Defense Nuclear Nonproliferation

The Baseline (Gd-loaded water) WATCHMAN will provide:

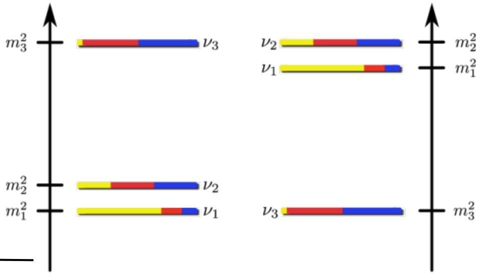


- **The U.S.'s only world-class supernova neutrino detector**
- **A test facility for future large neutrino detectors (an LAPPD test deployment will be part of initial design)**

An upgraded WATCHMAN may also provide:

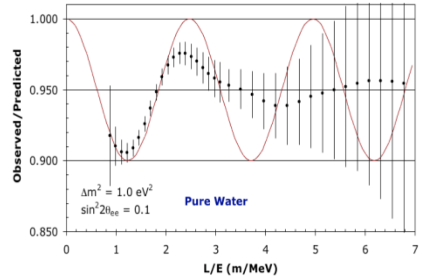
- **A measurement of the ordering of the neutrino masses**

Requires upgrade with (Wb) scintillator



- **A search for a proposed 4th neutrino flavor e, μ, τ … ?**
- **A search for non-standard neutrino interactions**

Requires nearby neutrino beam



Science benefit strengthens case for remote monitoring applications

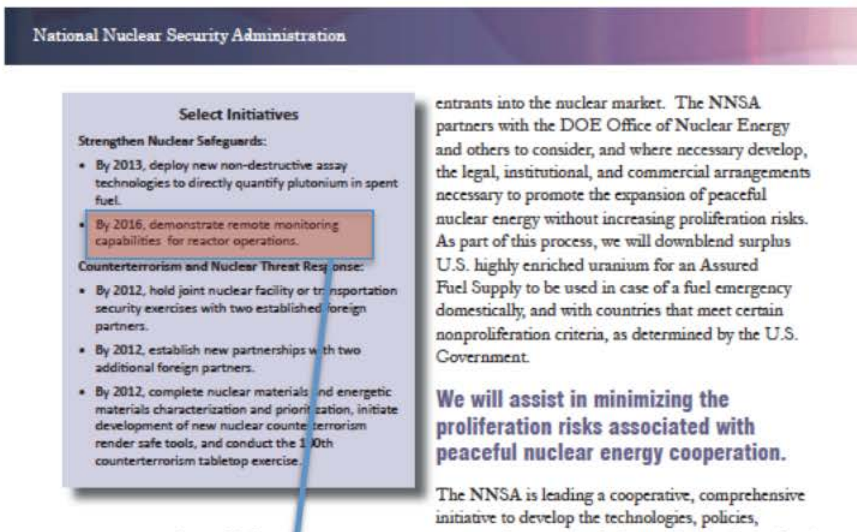
Lawrence Livermore National Laboratory
BROOKHAVEN NATIONAL LABORATORY
Virginia Tech
Sandia National Laboratories

Physics in three possible stages

			NNSA-led	NNSA/OHEP/NSF	OHEP/NSF-led
2014 2016	Non-accelerator Physics – 2016-2020	Natural source	Pure Gd-H_2O "WATCHMAN-H_2O"	Gd-H_2O + 1% scintillator "WATCHMAN-WBLS"	Pure scintillator "WATCHMAN –LS"
			Supernova	Supernova	Supernova
2018			Proton Decay	Proton Decay	Proton Decay
2020		Reactor	Neutrino Mass Hierarchy	Neutrino Mass Hierarchy	Neutrino Mass Hierarchy
2022	Accelerator-based physics 2019-2024	ISODAR beam	Sterile Neutrinos	Sterile Neutrinos	Sterile Neutrinos
2024			Non-Standard Interactions	Non-Standard Interactions	Non-Standard Interactions

A Remote Reactor Monitoring Demonstration is in the NNSA Strategic Plan

- 2012-2014: 3 year scoping project finishes this September
- 2014-15: Decision point to deploy WATCHMAN demonstrator at the old IMB site in Ohio
- Proposed joint funding with Office of Science, High Energy Physics (DOE-SC-HEP)


National Nuclear Security Administration

Select Initiatives

Strengthen Nuclear Safeguards:

- By 2013, deploy new non-destructive assay technologies to directly quantify plutonium in spent fuel.
- By 2016, demonstrate remote monitoring capabilities for reactor operations.

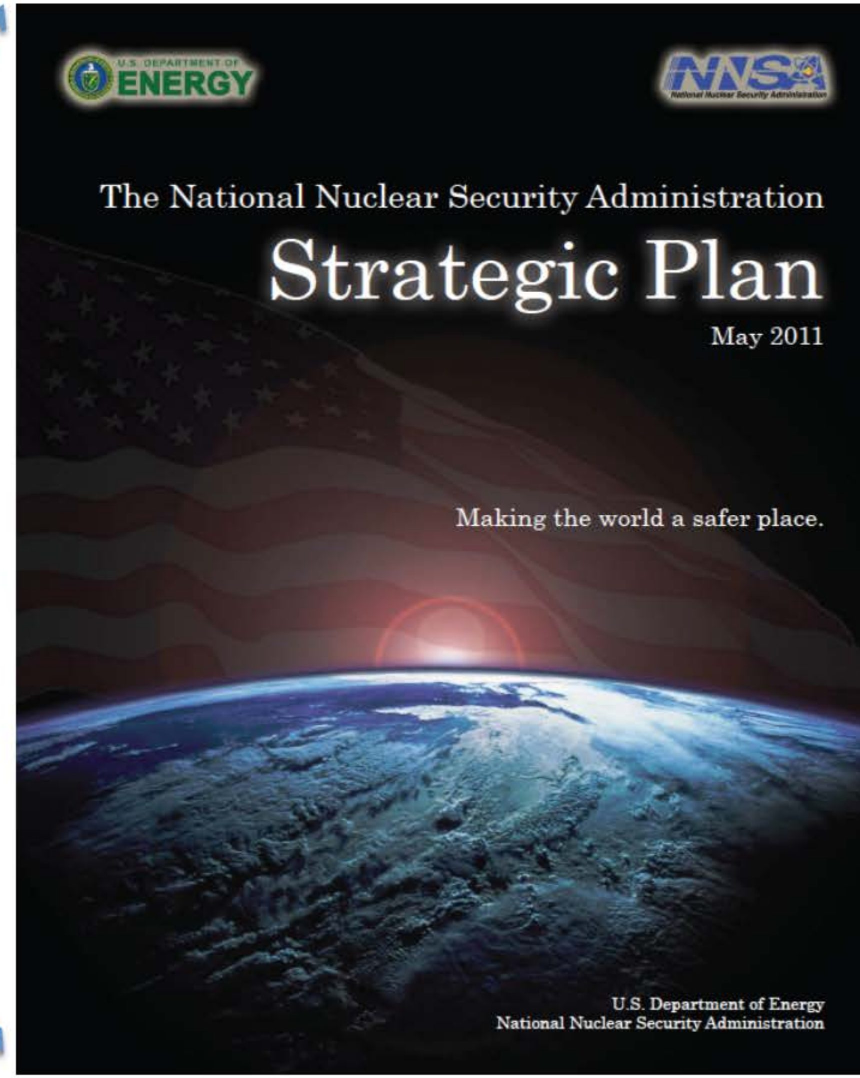
Counterterrorism and Nuclear Threat Response:

- By 2012, hold joint nuclear facility or transportation security exercises with two established foreign partners.
- By 2012, establish new partnerships with two additional foreign partners.
- By 2012, complete nuclear materials and energetic materials characterization and prioritization, initiate development of new nuclear counterterrorism render safe tools, and conduct the 10th counterterrorism tabletop exercise.

entrants into the nuclear market. The NNSA partners with the DOE Office of Nuclear Energy and others to consider, and where necessary develop, the legal, institutional, and commercial arrangements necessary to promote the expansion of peaceful nuclear energy without increasing proliferation risks. As part of this process, we will downblend surplus U.S. highly enriched uranium for an Assured Fuel Supply to be used in case of a fuel emergency domestically, and with countries that meet certain nonproliferation criteria, as determined by the U.S. Government.

We will assist in minimizing the proliferation risks associated with peaceful nuclear energy cooperation.

The NNSA is leading a cooperative, comprehensive initiative to develop the technologies, policies,



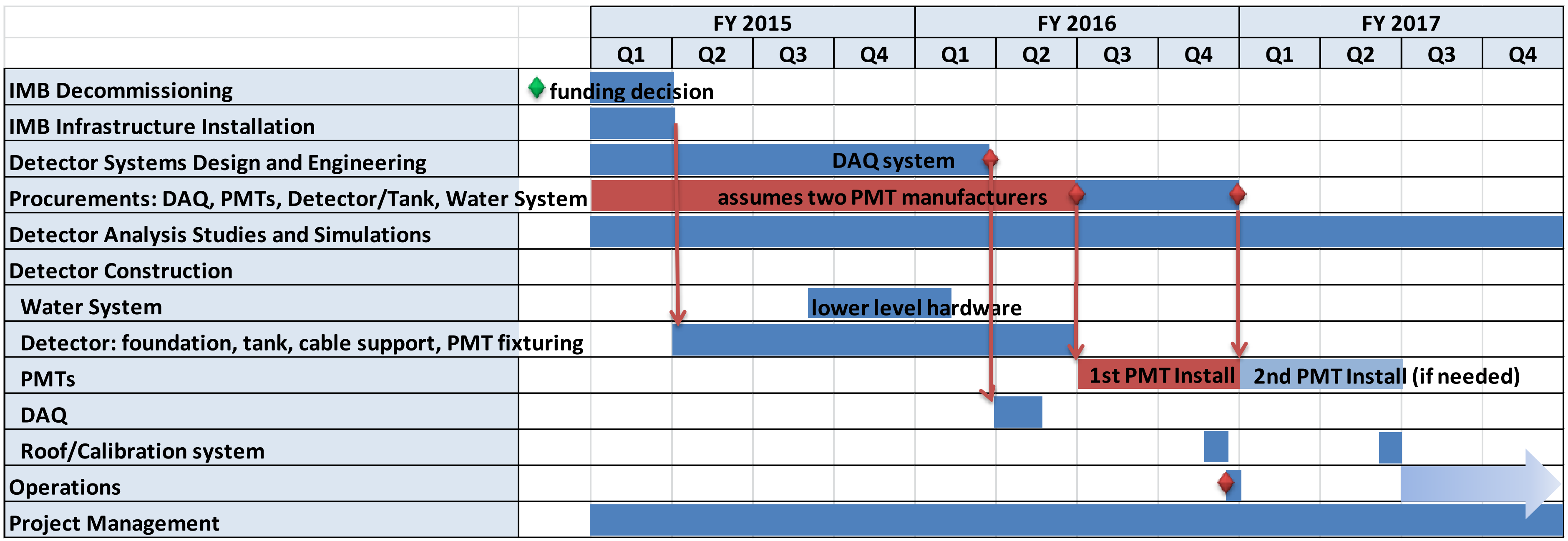
- By 2016, demonstrate remote monitoring capabilities for reactor operations.

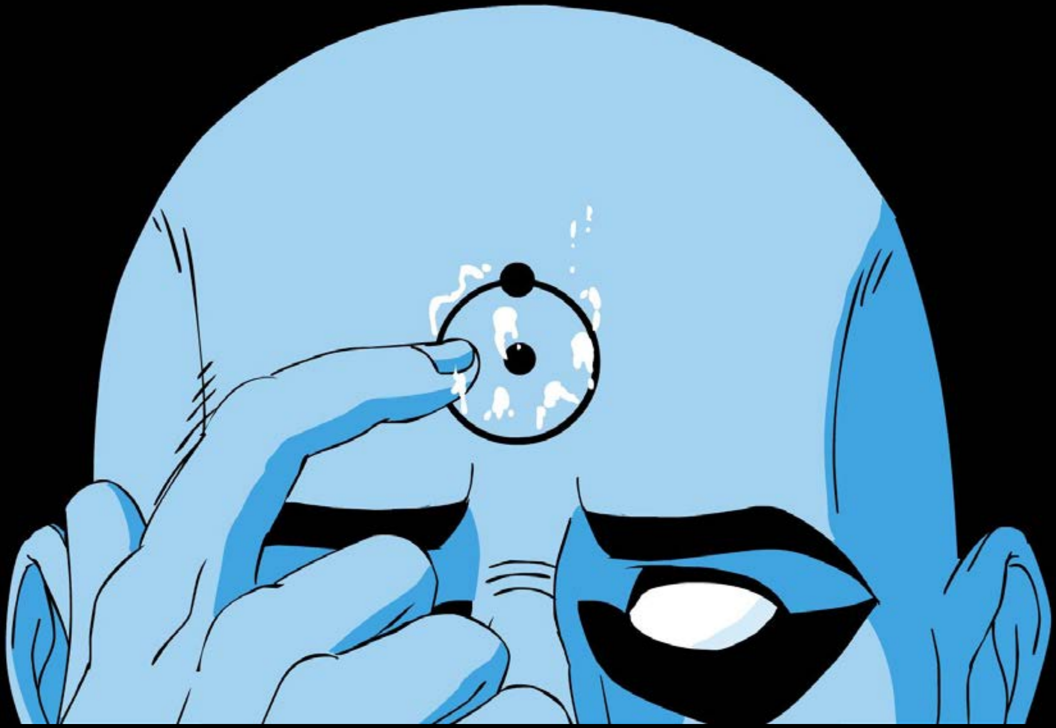
Wait… *2016?* Yes!

At the beginning of last week, we were pressed to submit the full $50M proposal to NNSA and HEP… by the end of July!

In order to meet the 2016 target, if the project is approved it would start less than 11 weeks from today.

(1st Quarter of US FY2015 begins October 1st, 2014)





So if all goes according to plan, it is possible that there will be a new, kiloton scale Gd-doped WC detector in operation <u>in the next two years.</u>

➔ *Keep watching the WATCHMAN!* ➔

Supplemental Slides

After the kiloton demonstrator in Ohio, what then?

Long Term Goals	Detector mass (Fiducial)	standoff
16 events in 1 year (power measured at ±25%) **from a 10 MWt reactor** (3 kg of Pu)	10 kiloton	~40 km
	1 Megaton	~400 km

Examples of greatest interest

- 1000 km - verify reactor exclusion zone
- 10-20 km - ensure only declared reactors are operating

Small reactor standard: 10 MWt yields 4 kg Pu/year

"Gap analysis" for other technologies

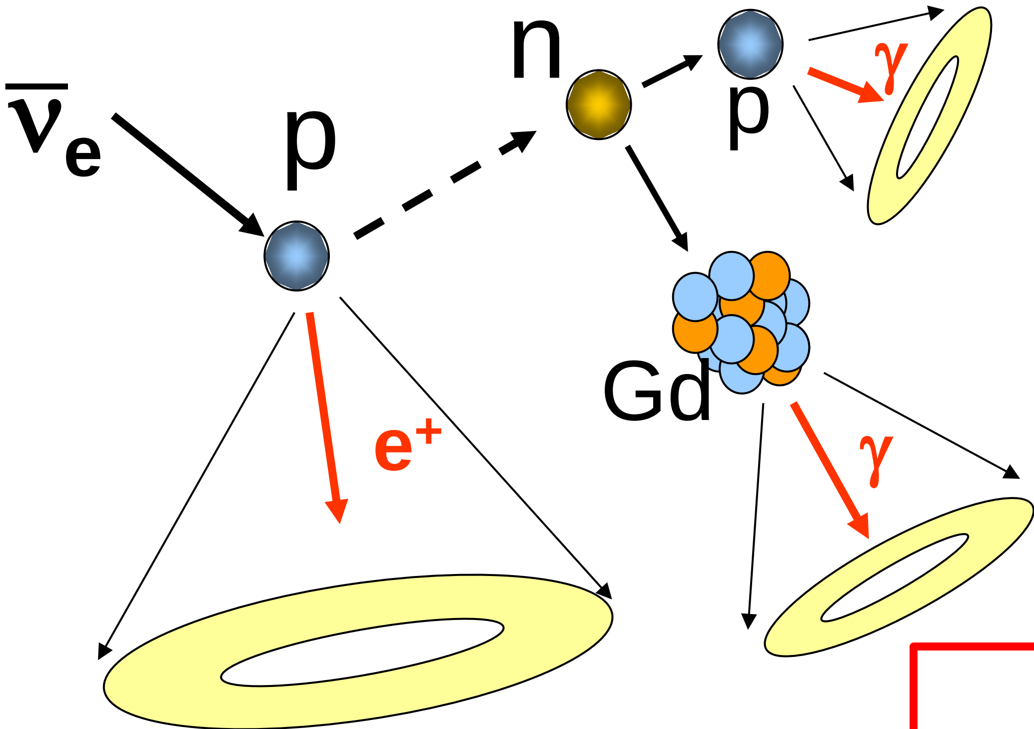
Thermal/visible satellite imagery – requires cueing, hard to cover large areas

Radionuclide detection - needs accidental release from reactor, ambiguity about location

Expected events in WATCHMAN from a Type II supernova

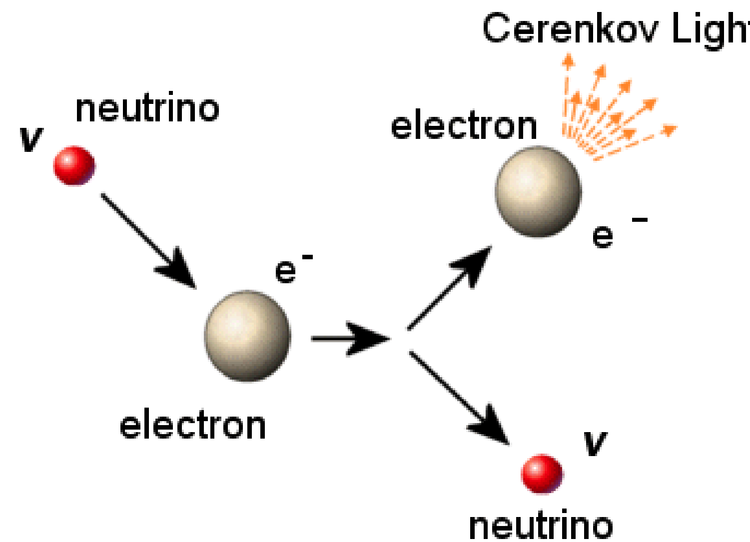
Inverse Beta Decay

(~88% of events)



Elastic Scattering

(~3% → directional)



~1,000,000 total SN
ν events from Betelgeuse

~500 total SN ν events
from galactic center

Mass Hierarchy

- Neutrino mass hierarchy measurements with reactor antineutrinos have been proposed. Fourier analysis to extract a power spectrum, highly sensitive to δm_{13}^2 .
  - Requirements → Energy resolution 3.5%/√E
  - Optimal distance scale 56 ± 7 km
  - Measures δm_{13}^2 to ~1%
  - Small differences in $m_3 - m_2$ and $m_3 - m_1$ show up as features in the power spectrum
- Experiments have been proposed → next-gen RENO (Korea), JUNO (China)
- Watchman site considerations:

  good ----- ~16 x more flux than 56 km

  Fewer spectrum wiggles, E resolution requirements not as stringent (technology less risky)

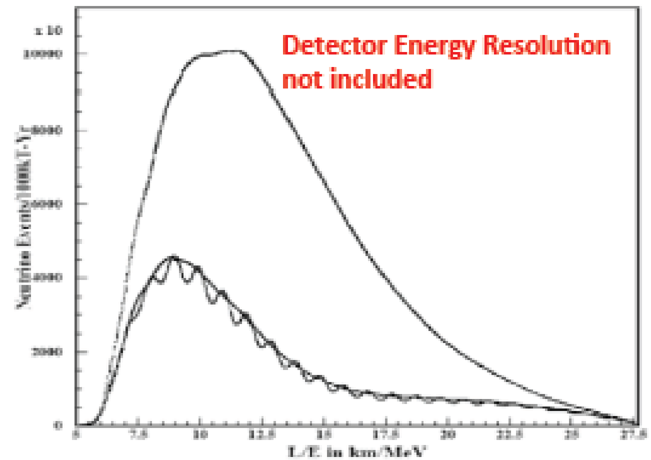
  bad ------- Fewer ν_1 - ν_3 oscillations → so less sensitive to δm^2_{13}

  A larger antineutrino source would help

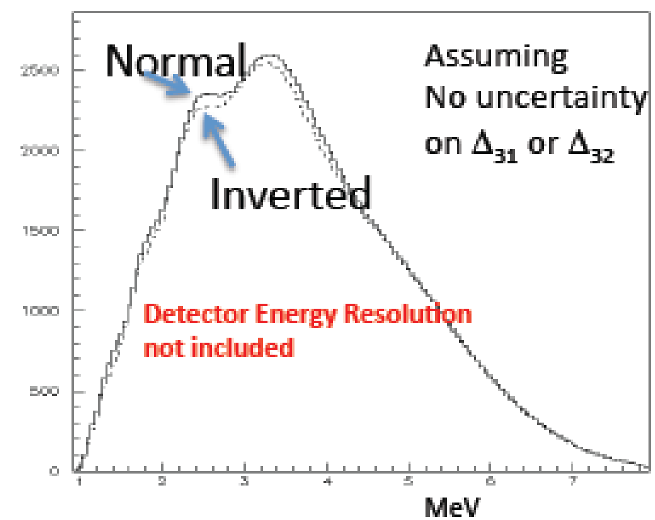
- It is clear that only a 2nd (liquid scintillator) Watchman phase would be capable of making this measurement. Note: PMT coverage is very high → excellent energy resolution
- Liquid scintillator capability must be built into the design from the beginning

A full analysis of the sensitivity of Watchman to mass hierarchy is ongoing.

56km observable



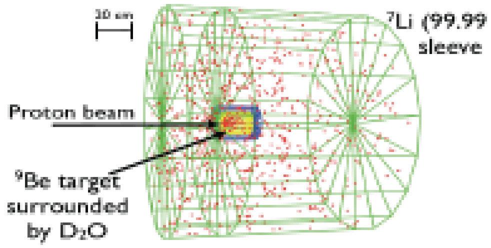
Watchman observable



Sterile Neutrino Search

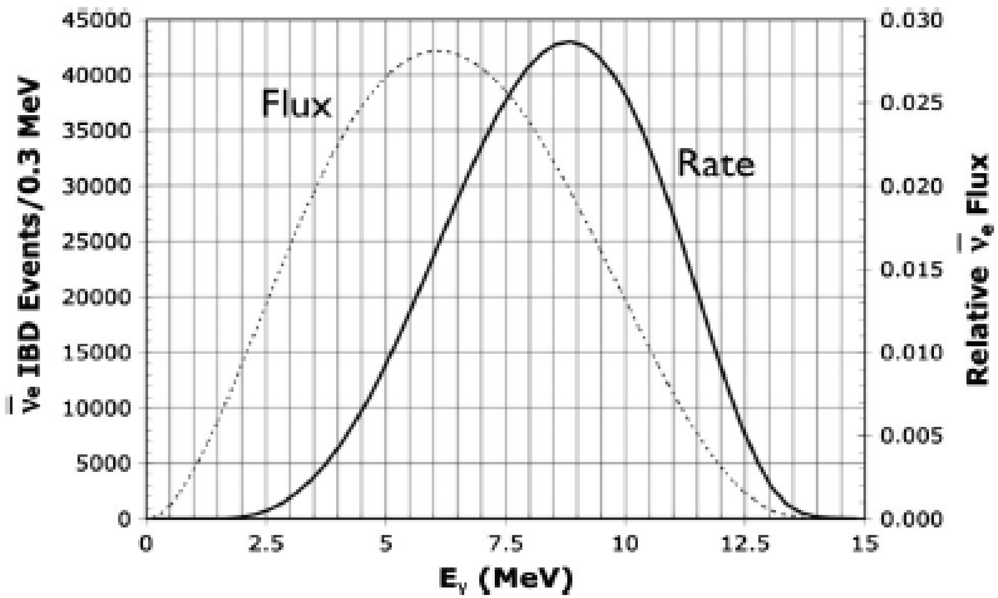
Experimental hints of another neutrino oscillation mode – sterile neutrino

May be tested at Watchman



IsoDAR Beam:

- 4π beam of antineutrinos from ^{8}Li decay at rest
- There is an option to place the IsoDAR antineutrino source near Watchman
- Baseline – 16 meters. Perfect for Sterile neutrino search, NSI search



Installation of accelerator at site required for this experiment

Sterile Neutrino Search – IsoDAR @ Watchman

IsoDAR beam location 16m from center of detector, 3 years