The Near-Field and the Far-Field

Current and Future Trends in Applied Antineutrino Physics

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Outline

- Rare neutral particles
- Antineutrinos
- IAEA safeguards
- reactor antineutrinos from core to detector
- Applications of possible interest to the IAEA
    - Plutonium disposition
    - Remote monitoring of reactors - **WATCHMAN**

Rare neutral particle detection underlies certain important nuclear security and fundamental nuclear science problems

Fissile Material Search and Monitoring

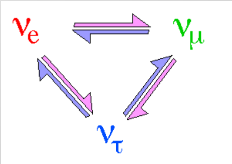
Rare Event Detection

Dark Matter and Neutrino Physics

Reactor antineutrino signature

1-10 MeV antineutrinos

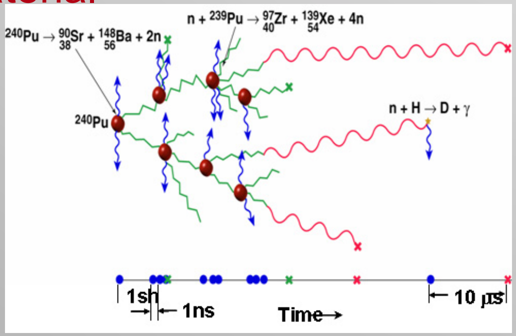
Neutrino Physics:
oscillations and neutrino mass

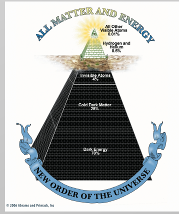


Gammas/neutrons from fissile material

1 keV to 10 MeV Neutrons and Gamma-rays

Dark Matter physics:
Axions and WIMPS





Nuclear Security and Nuclear Science both depend on sensitive keV to MeV-scale neutral particle rare event detectors

Neutrinos and antineutrinos

Neutrinos are:
- stable elementary particles
- with no electric charge
-small mass (10^{-6} m_e)

3 types or flavors are known to couple to matter via the weak interactions

electron (ν_e)
muon (ν_μ)
tau (ν_τ)

All of this is also true of antineutrinos except they have opposite weak charge of neutrinos

Where do antineutrinos and neutrinos come from ?

✓ Nuclear Explosions

antineutrinos (fission weapon)

✓ Nuclear Reactors (power stations, ships)

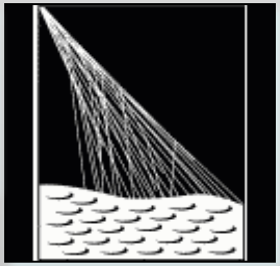
antineutrinos

✓ Particle Accelerators

both

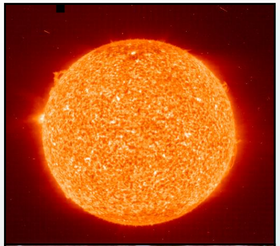
✓ Earth's Atmosphere (Cosmic Rays)

both



✓ Earth's Crust (Natural Radioactivity)

antineutrinos



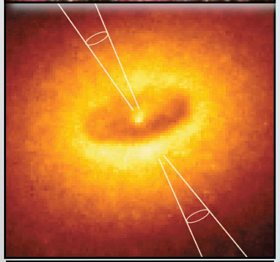
Sun ✓

neutrinos (fusion)

Supernovae (star collapse)

SN 1987A ✓

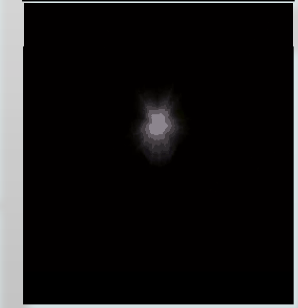
both



Astrophysical Accelerators

Soon ?

both



Big Bang ($330\ \nu/cm^3$)

Indirect Evidence

both

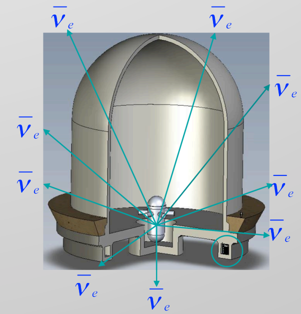
Why do we insist on the word antineutrino ?

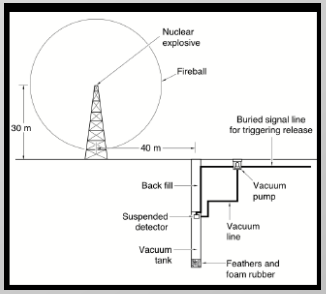
- Antineutrino and neutrinos are as unlike as positrons and electrons
  - <u>weak charges are opposite</u>

$$Q_{electric}(e^{+}) \Leftrightarrow -Q_{electric}(e^{-})$$

$$Q_{weak}(\nu) \Leftrightarrow -Q_{weak}(\bar{\nu})$$

- Fission reactors and fission explosions produce only <u>antineutrinos</u>





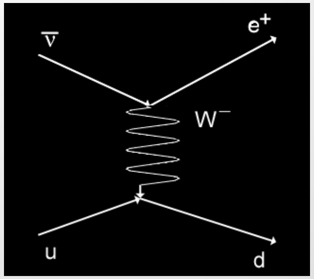
- At the energy scales that matter here, antineutrinos have <u>much higher interaction probabilities, and a more specific experimental signature</u>

Some common antineutrino interactions

1.Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

The gold standard for antineutrino detection

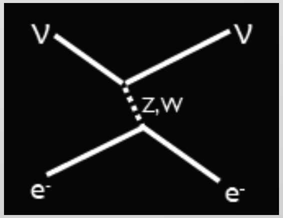
A robust time-coincident signal from positron and neutron
'*good old inverse beta*' - Petr Vogel
Neutrinos *are not* a background for this process



$$\sigma \sim 10^{-42} \mathrm{cm}^2 \, E_{\bar{\nu}}^{\,2}$$

2.Antineutrino-electron scattering $\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$

only the final state electron is detected
Neutrinos *are* a background for this process



$$\sigma \sim 10^{-44} \mathrm{cm}^2 \, E_{\bar{\nu}}$$

3. Coherent antineutrino-nucleus scattering

(100-1000x **larger** cross section than inverse beta decay)

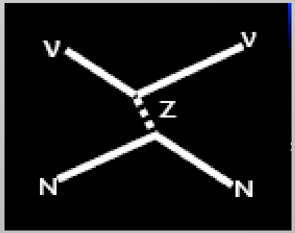
But - a very weak signal (10s-100s of eV nuclear recoils)

May be interesting for reactor monitoring out to a few km

Neutrinos *are* a background for this process

$$\sigma_{\mathrm{coh.}} \approx 0.4 \times 10^{-44} \mathrm{cm}^2 N^2 \, E_{\bar{\nu}}^{\,2}$$

Enhanced by square of neutron number



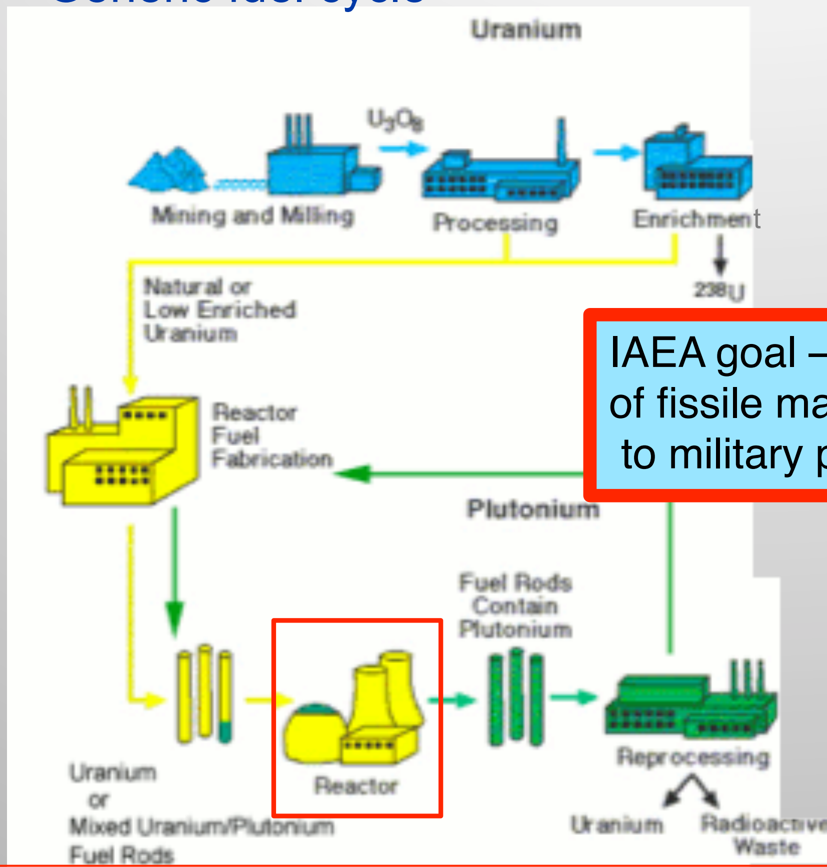
The International Atomic Energy Agency - IAEA - verifies nonproliferation in non-nuclear weapons states, and promotes nuclear power as part of the Treaty on the Nonproliferation of Nuclear Weapons

IAEA

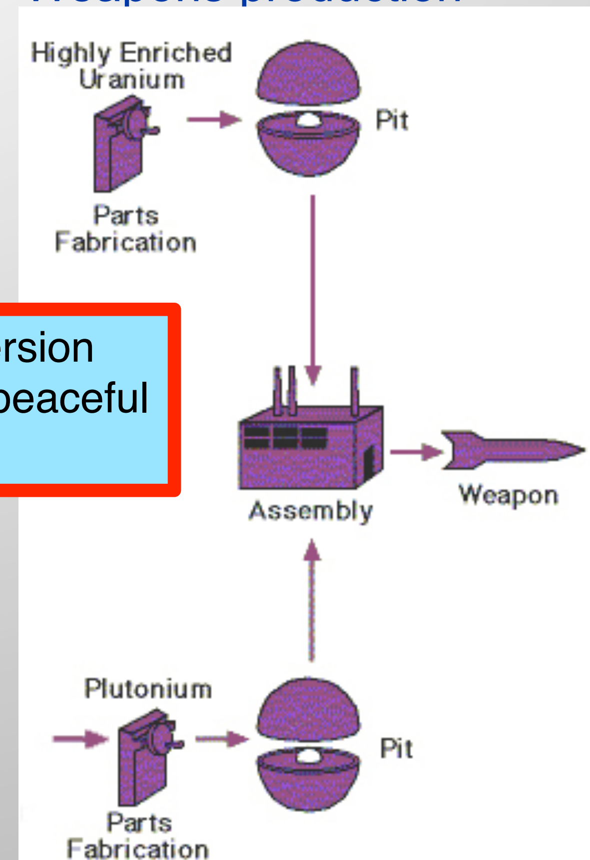
International Atomic Energy Agency

The IAEA 'Safeguards' regime monitors the flow of fissile material through the nuclear fuel cycle in 170 countries

Generic fuel cycle



Weapons production

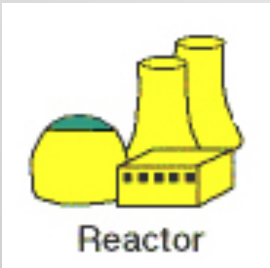


IAEA goal – detect diversion of fissile material from peaceful to military programs

Goal for antineutrino measurements - track fissile inventories in operating reactors

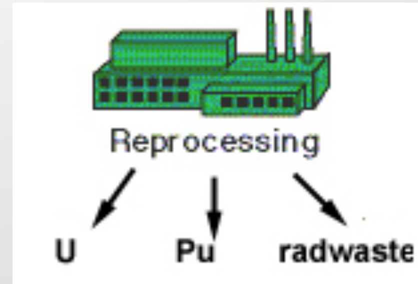
IAEA monitors about 220 reactors worldwide – but never directly measures in-core fissile content

(1-1.5 years)



(months to years)

(months)



(forever)

1. Check Input and Output Declarations
2. Verify with Item Accountancy
3. Containment and Surveillance

1 'Gross Defect' Detection
2 Continue Item Accountancy
3. Containment and Surveillance

1 Check Declarations
2 Verify with Bulk Accountancy:

Some possible concerns:

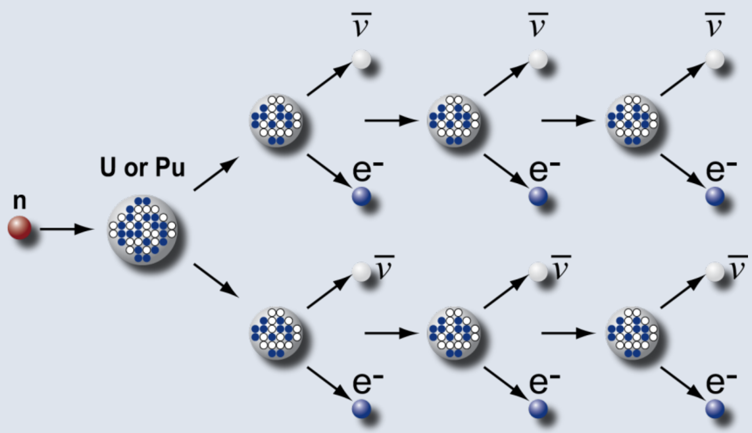
Operators **Report** Fuel Burnup and Power History

No Direct Pu Inventory Measurement is Made Unless and Until Fuel is Reprocessed

Monitoring nuclear reactors with antineutrinos

Reactors emit huge numbers of antineutrinos

- 6 antineutrinos per fission from beta decay of daughters
- 10^{21} fissions per second in a 3,000-MWt reactor



About 10^{22} antineutrinos are emitted per second from a typical PWR unattenuated and in all directions

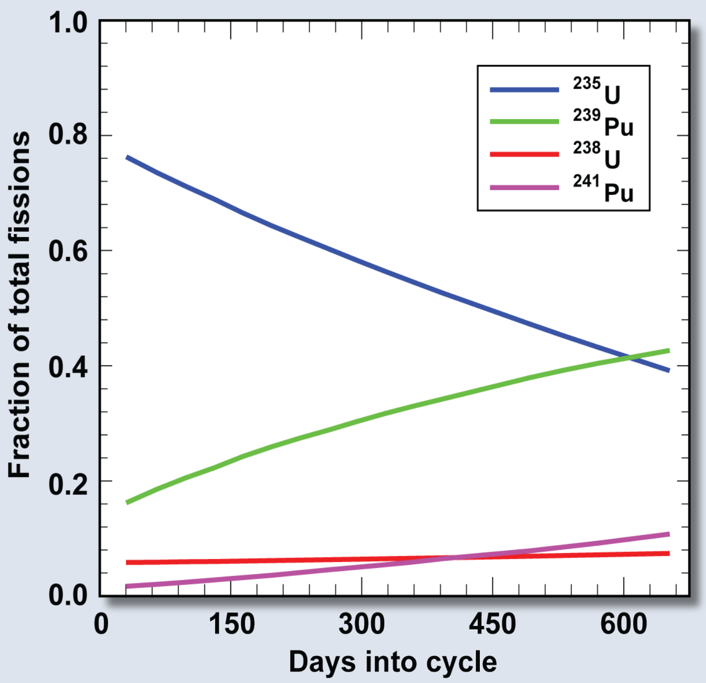
Detected rates are quite reasonable

- 10^{17} antineutrinos per square meter per second at 25-m standoff
- 6,000 events per ton per day with a perfect detector
- 600 events per ton per day with a simple detector (e.g., SONGS1)

Example: detector total footprint with shielding is 2.5 meter on a side at 25-m standoff from a 3-GWt reactor

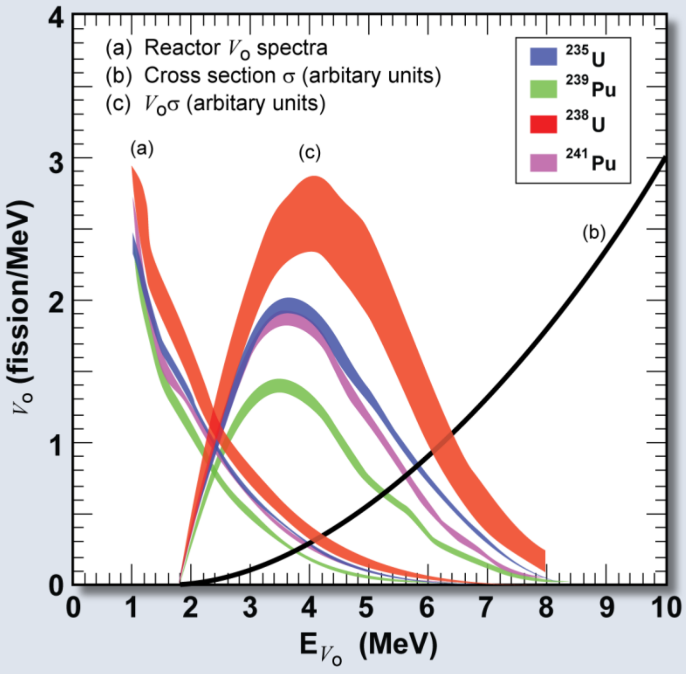
Antineutrino rate and spectrum are both sensitive to the fissile content of the reactor

Nuclear Engineering 101



Fission rates vary in time

Antineutrino Engineering 101

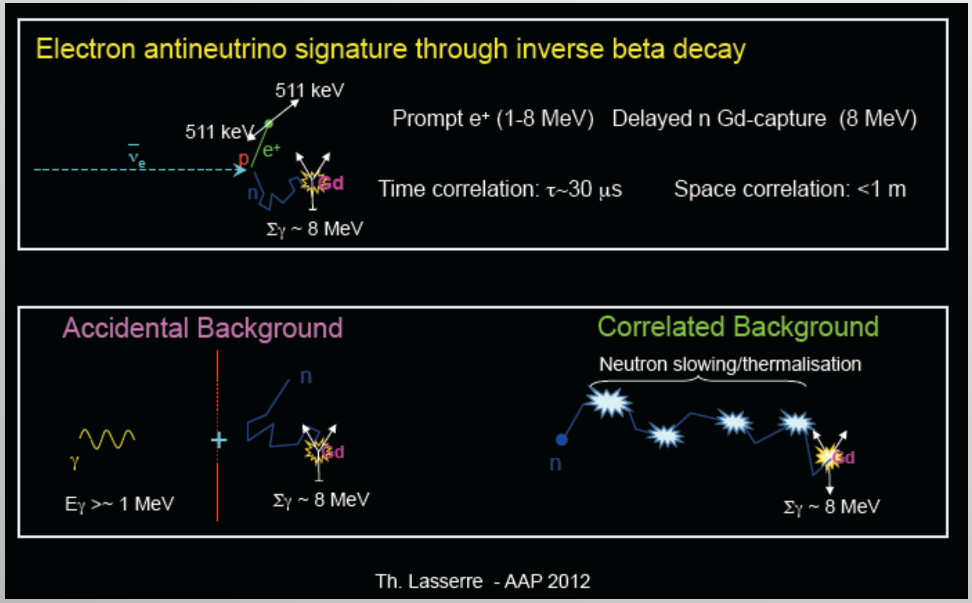


Antineutrino rates vary with isotope

Detecting reactor antineutrinos

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

prompt e^+ signal + n capture on GD



Two intense flashes of scintillation light:

1) Positron absorbs most of antineutrino energy

First flash of blue light: e^+ ionizes the medium and annihilates on a positron: excited atoms and recombining ions induce scintillation

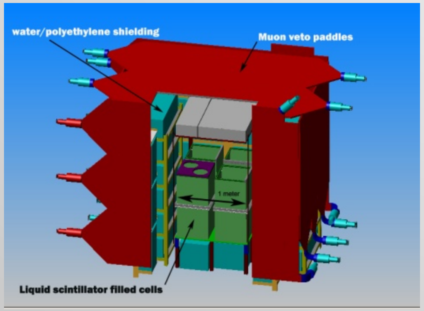
2) Neutron loses energy, wanders through scintillator and finds a Gd nucleus in about 28 microseconds

Second flash of blue light:
Gamma rays from neutron capture create Compton electrons, which induce scintillation

Number of photons in flash is proportional to the deposited energy

A neutrino detector menagerie

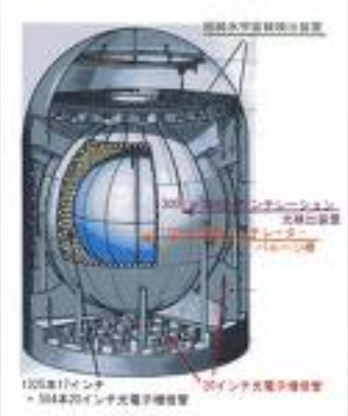
SONGS1
Antineutrino **detector**



2.5 m liquid scintillator
0.6 ton detector
Depth 35 feet
30 m.w.e
Cost 250K

250 m standoff

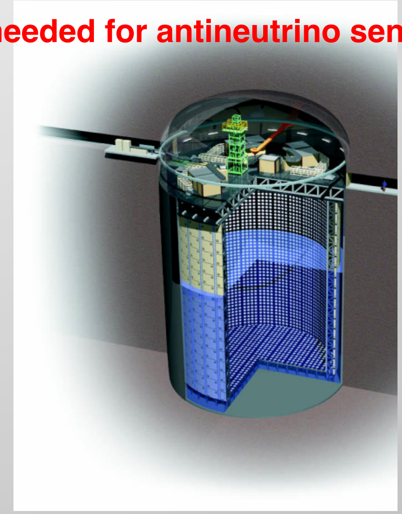
KamLAND
Antineutrino **detector**



12.5 m liquid scintillator
600 ton detector
Depth about 1 kilometer
2700 m.w.e.
Cost 20 M$ (est.)

6 km standoff

SuperKamiokande
Neutrino* **detector**
*Research needed for antineutrino sensitivity

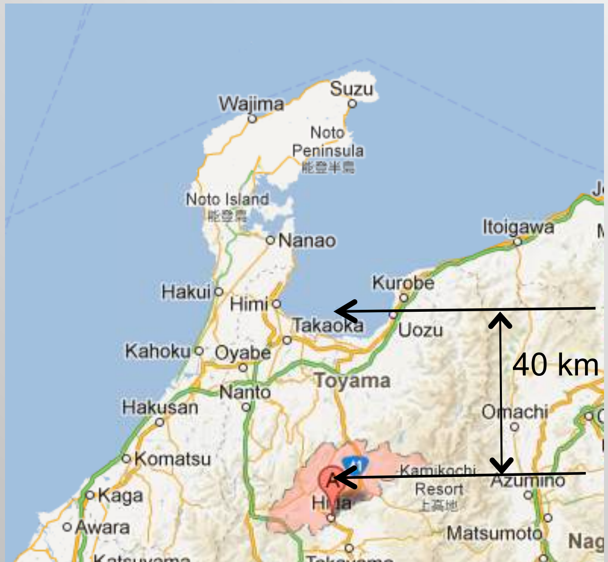


45 m pure water
32000 ton detector/shield
Depth about 1 kilometer
2700 m.w.e.
Cost 100 M$ (est.)

30 km standoff

16 events, 1 year, 10 MWt reactor, no bg.

For a seagoing reactor, well… forget about it



Stanford paper: A ~400 MWt Typhoon class submarine at 40 km could affect a 1000 tonne detector like Kamland

arXiv:hep-ex/0207001 v1 29 Jun 2002

2 antineutrinos per week, 10% of total KamLAND signal

But it's worse than that..

Either:

- **The sub is in port → reactor off, no antineutrinos**

Or:

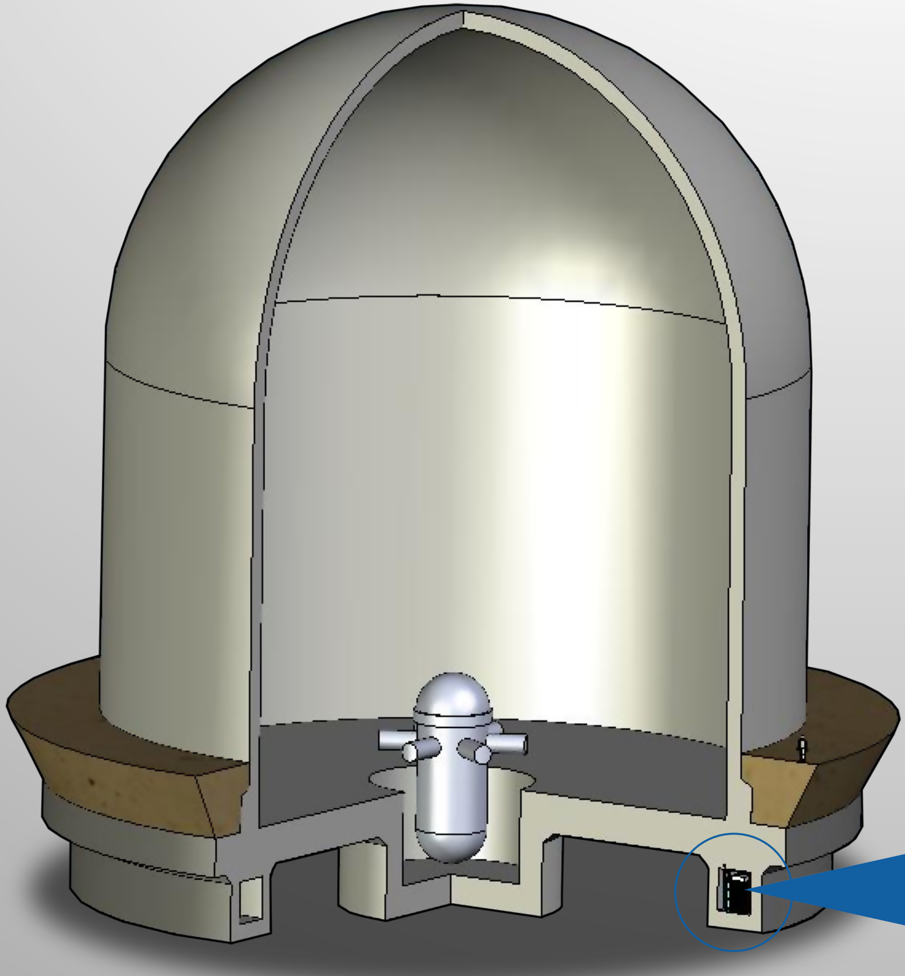
- **The sub is in the open ocean → far from the detector, dwell time of minutes**

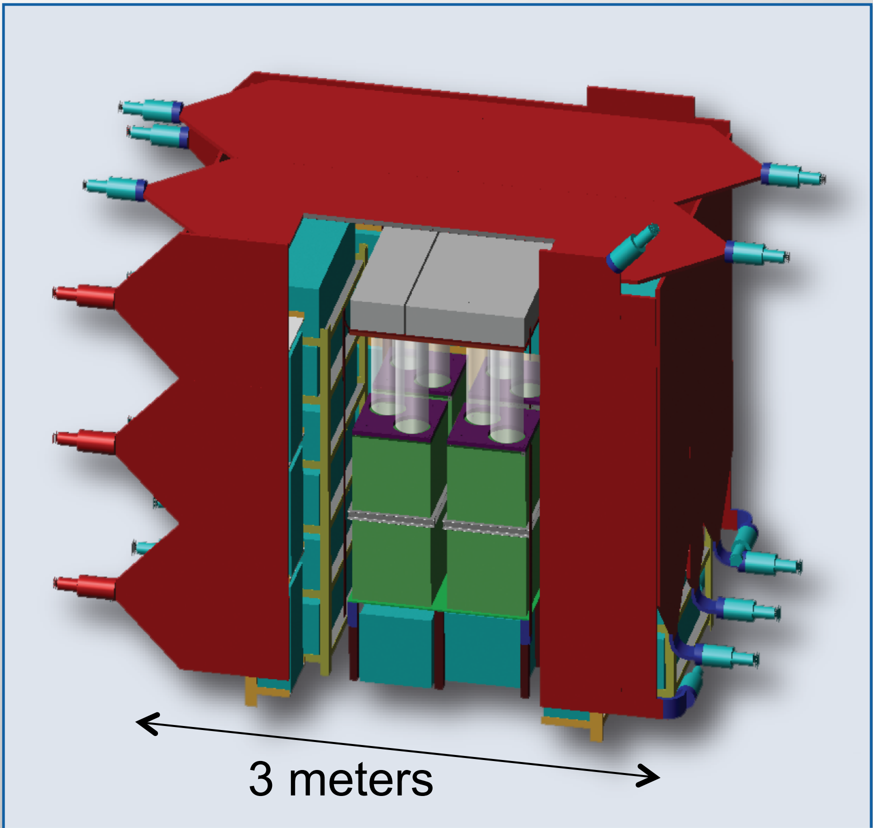
A factor of 1000 scale-up in mass → 12 events in 1 hour

The detector need substantial overburden to suppress backgrounds

The detector can't be on a nuclear submarine or it will 'drown' in its own signal

A deployment at the San Onofre nuclear generating station

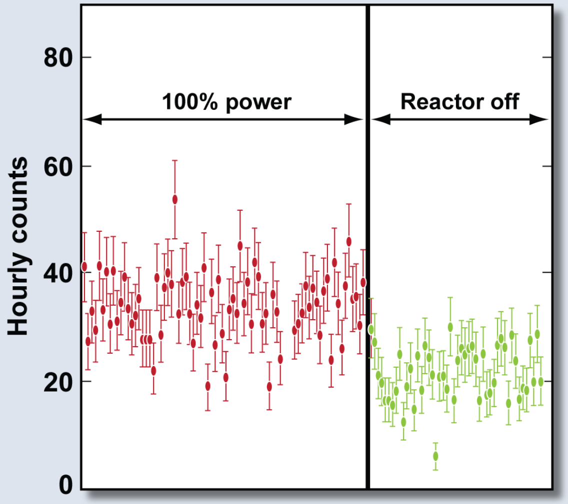


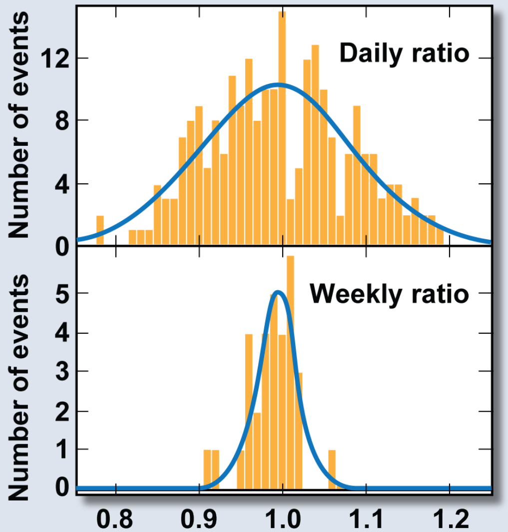


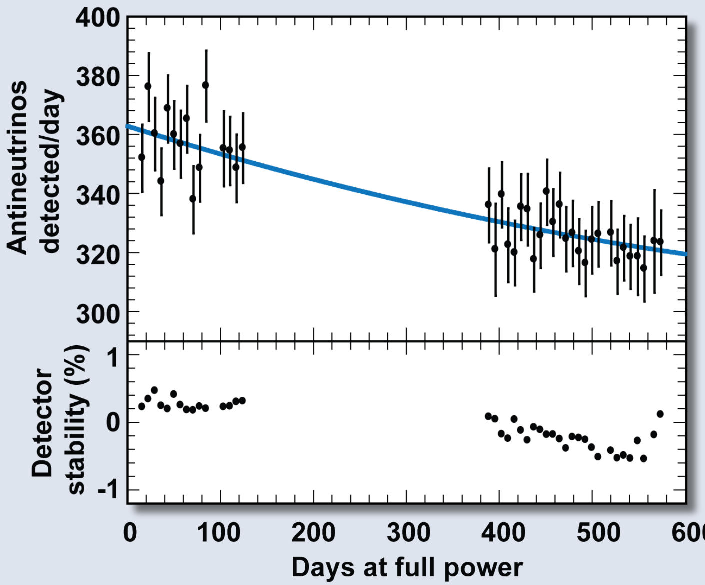
The LLNL-SNL antineutrino detector SONGS1

Our LLNL/SNL collaboration has helped create the field of applied antineutrino physics for nonproliferation

Determine reactor on/off status within 5 hours with 99.9% C.L.	Measure thermal power to 3% in one week	Detect burnup of 250 kg U, 50 kg Pu with known power and initial fuel content







According to Julian Whichello, a safeguards technology specialist at the IAEA, the agency had not taken an active interest in antineutrino technology for years, because earlier detectors were too large and had not been tested in a real setting.

"The American group has done the first practical demonstration, and its detector is promising, because it is not much bigger than other systems the IAEA currently deploys at reactors," Whichello says.

IEEE Spectrum, April 2008

Current IAEA attitudes towards antineutrino detection

- We are introducing a disruptive technology to an agency that prizes stability, continuity, and economy
- IAEA sees no immediate utility in reactors – existing methods are sound, costs modest, politics of changing are difficult
- Still, there are some areas of interest…
  1. Monitoring the irradiation of plutonium-based ‘MOX’ fuel to ensure the material is hard to recover without reprocessing
  2. Improve knowledge of input plutonium mass at reprocessing facility or repository – currently no bettter than 5-10%
  3. Long range monitoring or exclusion of reactors
- IAEA also remains interested in further R&D and ongoing demonstrations – many ongoing worldwide

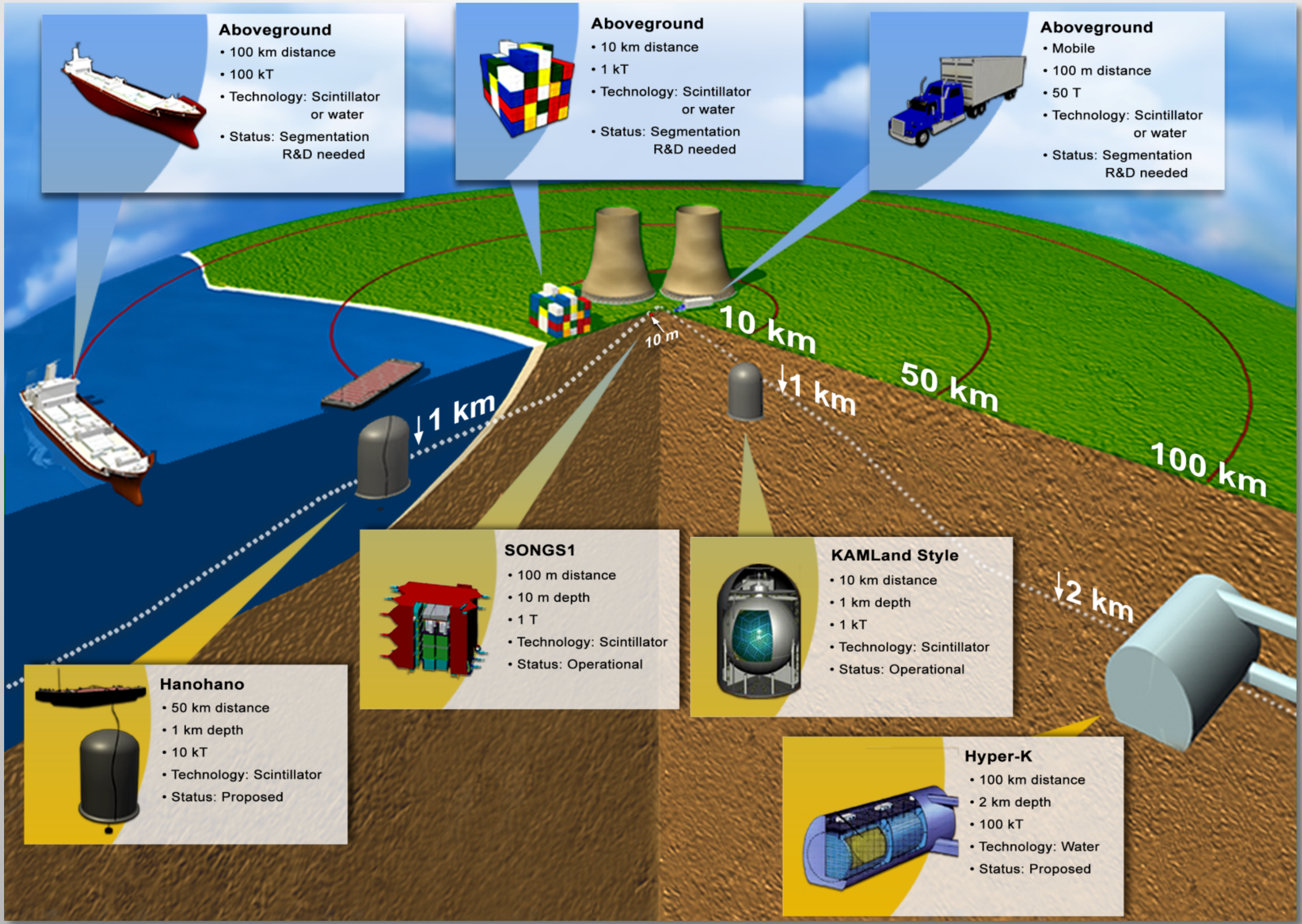
A groundswell of experimental activity worldwide

World Activities

| Done | Running | Proto | In construction |

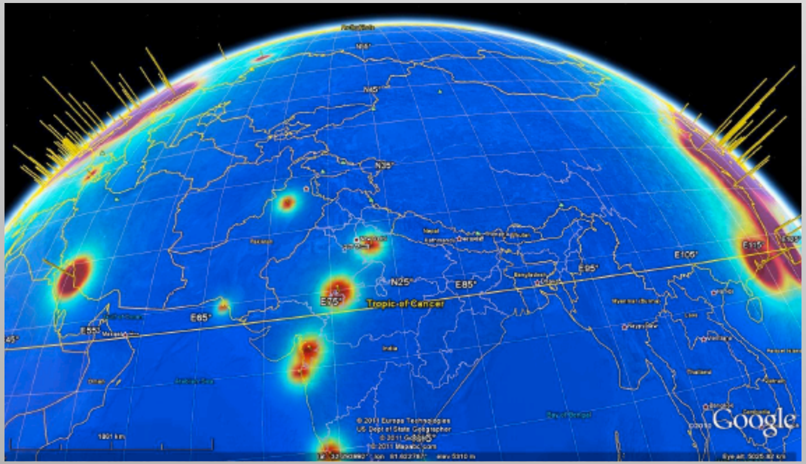
	Site	Techno	Comment
SANDS	San Onofre, US	0.5 t LS @20mwe	Done
SANDS	San Onofre, US	PS & Gd-H2O @20mwe	On Going
ANGRA	Angra, Brazil	LS	On Site R&D
DANSS	KNPP, Russia	Plastic	In construction
Kaska	Joyo, Japan	Gd-LS	Prototype
Panda	Japan	Plastic, Gd foil	Prototype
NUCIFER	Osiris	Gd-LS	Just Funded
Texono	Taiwan	HPGe	On Going – CNS –
Pt Lepreu	Canada	Gd-LS	CANDU, with USA
Cormorad	Italy	Plastic	Prototype
MARS	ILL	Plastic + ^{6}Li	Prototype

What about long range monitoring or discovery of reactors ?



This is a very hard problem for a stationary reactor

Goal	Detector mass	standoff	Required reduction in bg rate relative to KamLAND
16 events in 1 year from a 10 MWt reactor, (25% accurate thermal power)	10 kiloton	~40 km	10x
	1 Megaton	~400 km	100x



Global reactor antineutrino fluxes

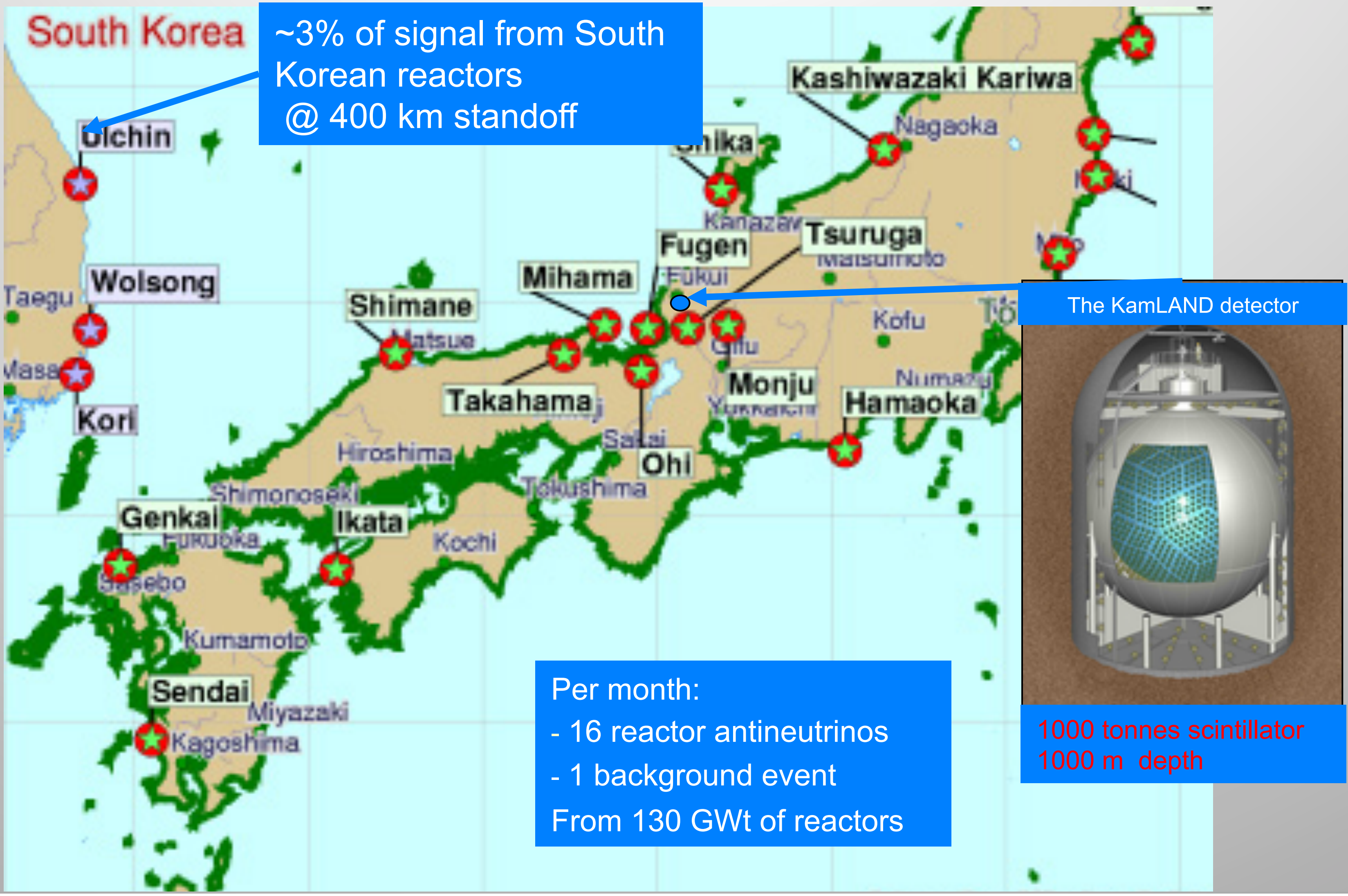
Bernstein, et. al,
Nuclear Security Applications of Antineutrino Detectors: Current Capabilities and Future Prospects

http://arxiv.org/abs/0908.4338
Science & Global Security, 18:127–192, 2010

Advantages of antineutrino detection for remote discovery and monitoring of reactors

1. Cross border detection – ultimate limit is perhaps ~800 km
2. Persistent surveillance
3. Power measurement and constraint on Pu production rate
4. Reactor localization with improved directionality or spectral measurement
5. With long range capability, no cueing information required

Long-range reactor monitoring is going on right now – but only for GWt reactors



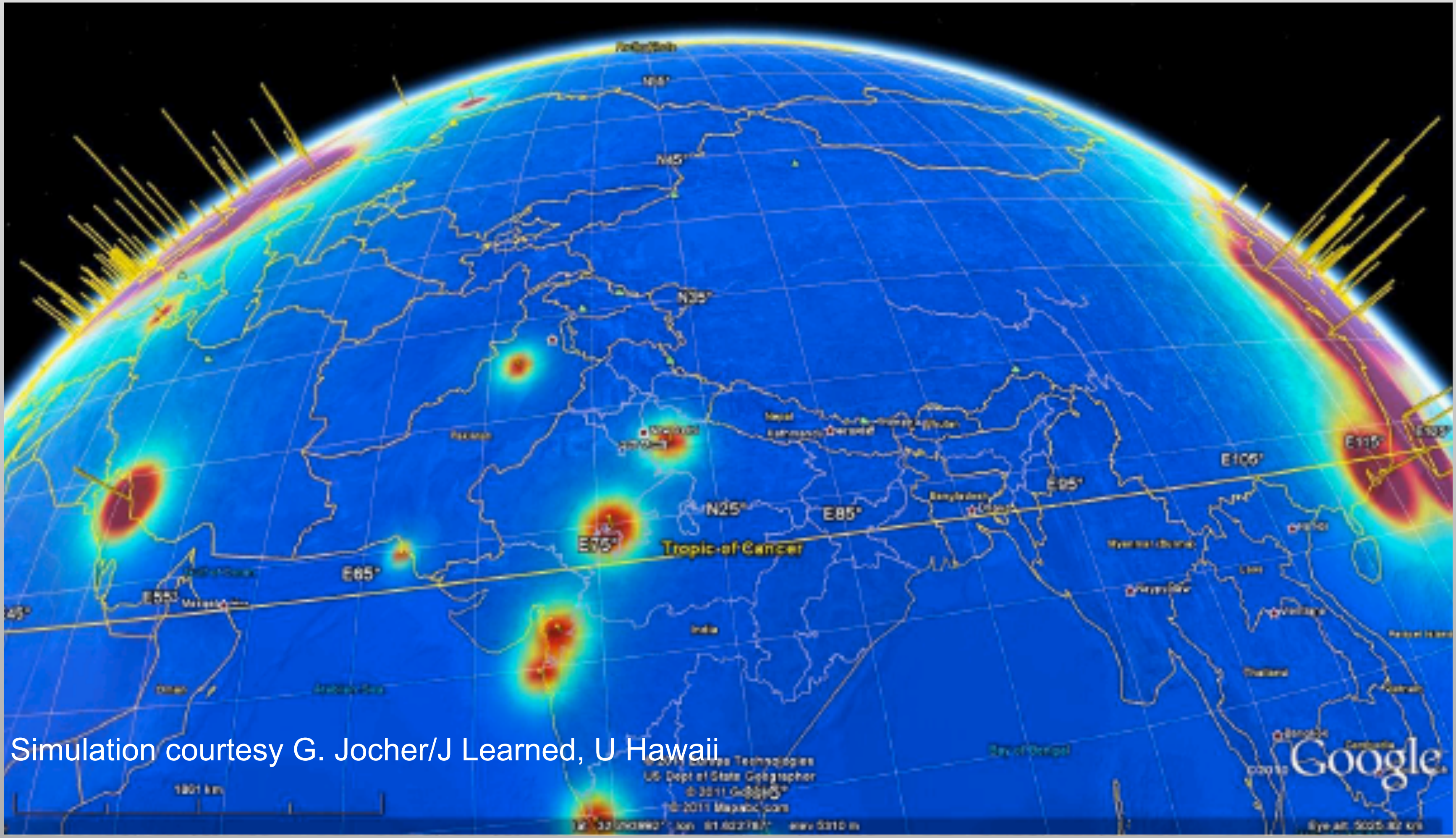
~3% of signal from South Korean reactors
@ 400 km standoff

Per month:
- 16 reactor antineutrinos
- 1 background event
From 130 GWt of reactors

The KamLAND detector

1000 tonnes scintillator
1000 m depth

WATer CHerenkov Monitor using AntiNeutrinos (WATCHMAN)



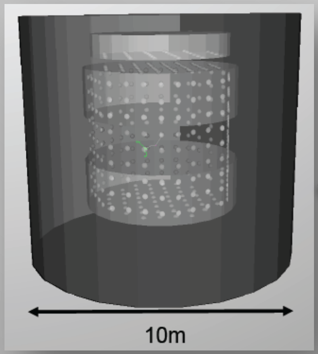
Overall Project Goal

- First ever demonstration of sensitivity to reactor antineutrinos using a gadolinium-doped water detector
- ~1-10 km standoff distance
- 100-1000 MWT scale US reactor.

0.1 - 10 km standoff

Research or power reactor

30-200 meters overburden



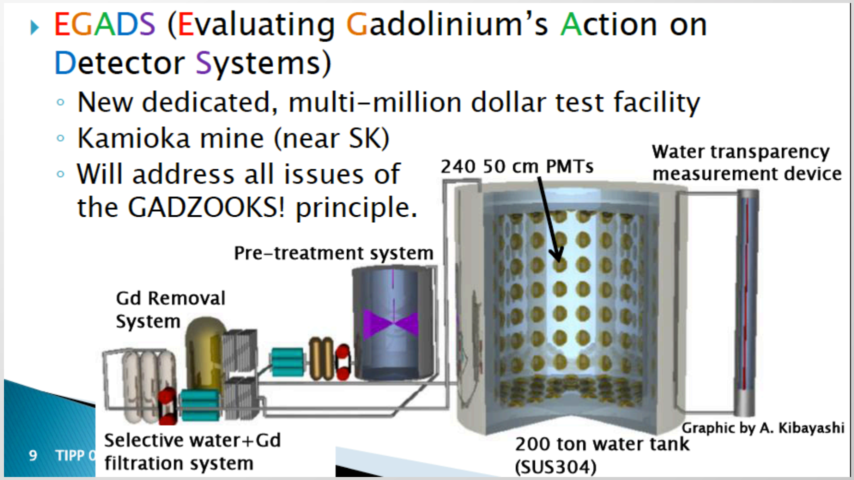
Kiloton scale detector

Complementary activities worldwide

EGADS- 200 ton deeply buried detector
to evaluate Gd-doped antineutrino detection

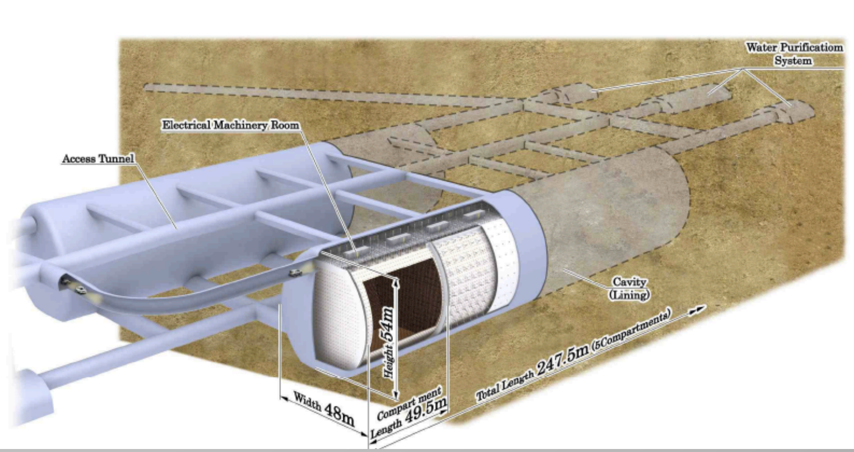
- backgrounds
- materials
- energy thresholds

<u>This detector volume is too small for direct demonstration of sensitivity</u>



- **HyperKamiokande**

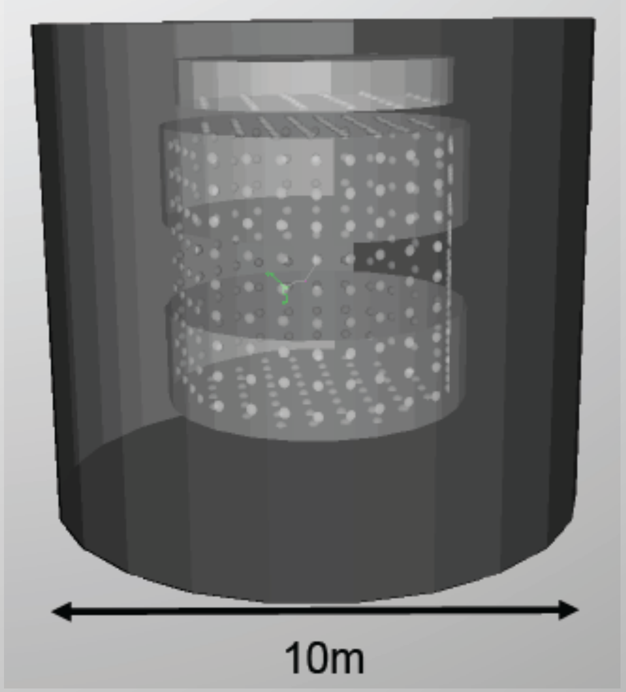
- 560,000 ton multipurpose water detector being planned by Japan
- Time scale: ~12 years
- Interest in U.S. science community in participation will lead to further R&D in this area
- Gd an option but not guaranteed



<u>Our demonstration would give strong confidence for exercising the Gd option</u>

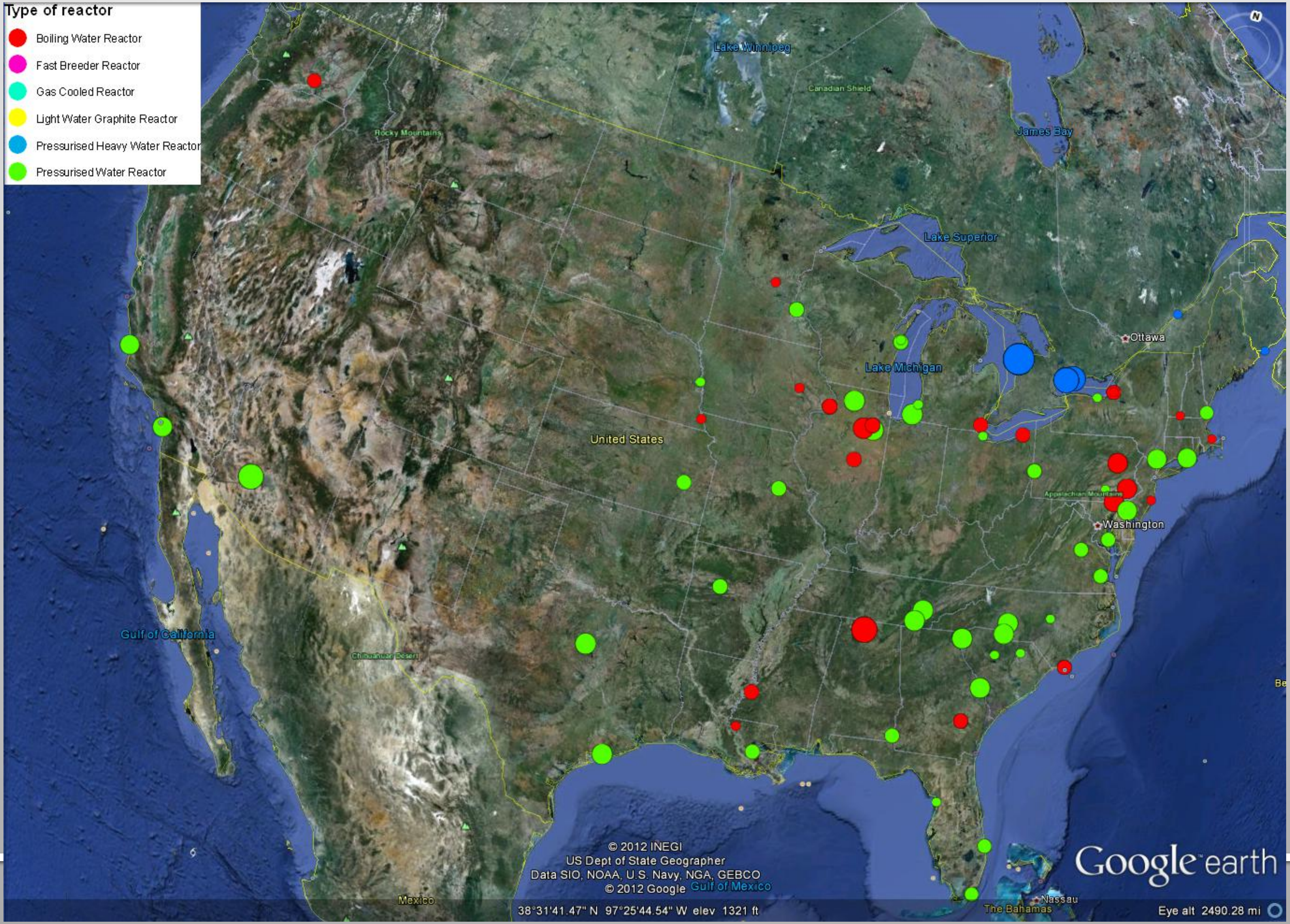
The choice of location is essential

1. **Remote Monitoring implies low event rates:**
   - The detector must be able to detect up to no greater than 10 reactor ν events per day.
2. **Sensitivity: 99.7% detection confidence (3σ) of the presence of the reactor in <1 month.**
   - For 10 events per day → tolerable background of 340 events per day.
   - Deployments at greater standoff may be compensated by greater overburden

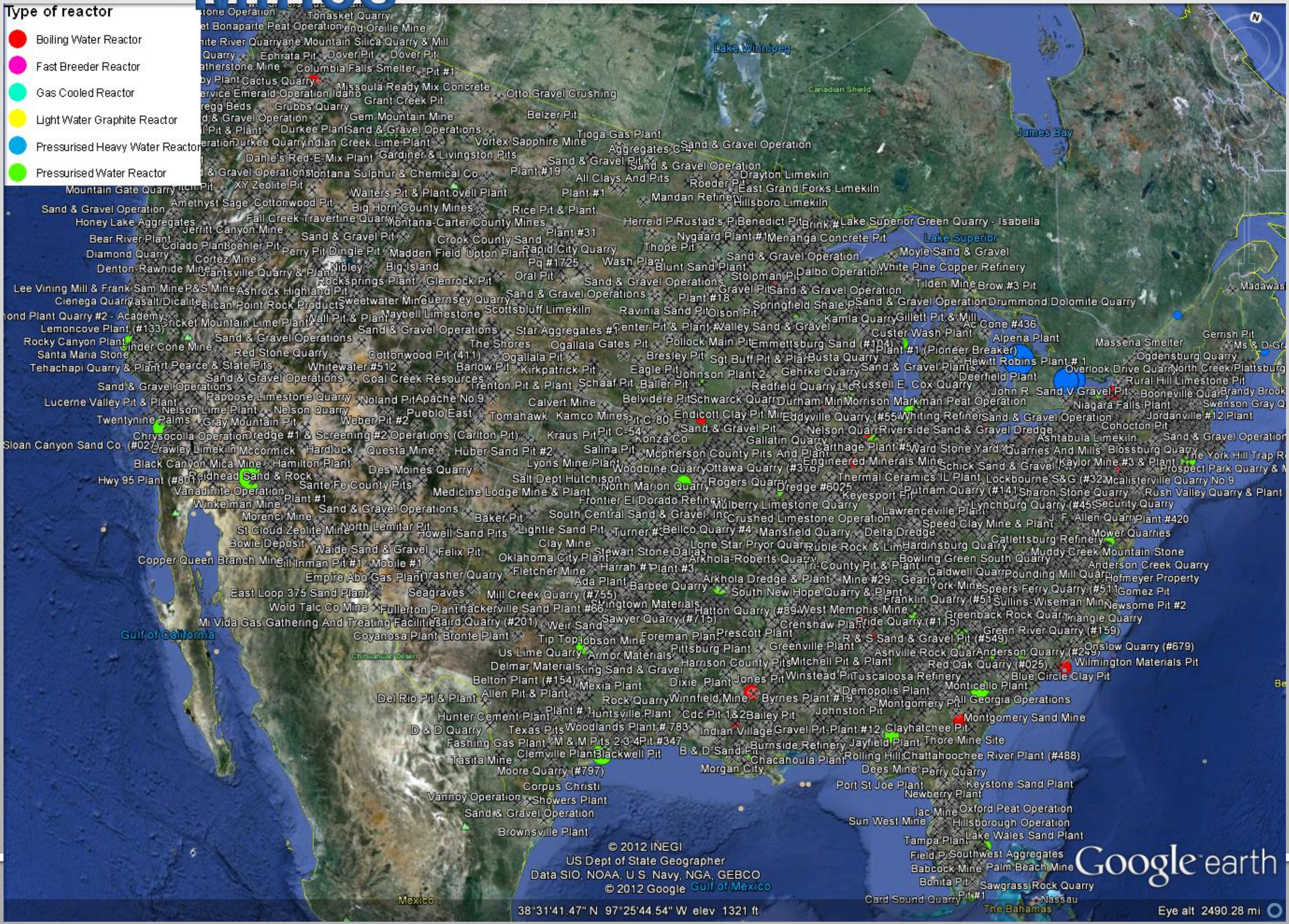


3. **Overburden:**
   - For reasons of cost, sites with existing overburden are preferred.
4. **Reactor Power:**
   - Other factors being equal, a research reactor deployment is preferred compared to a power reactor, owing to the greater similarity with the ultimate intended use.

Map of US Power Reactors



Map of US Reactors + Active Mines



Perry Nuclear Generating Station

Perry Reactor Nuclear Generating Station to IMB cavern in the Fairport Salt Mine (Ohio)

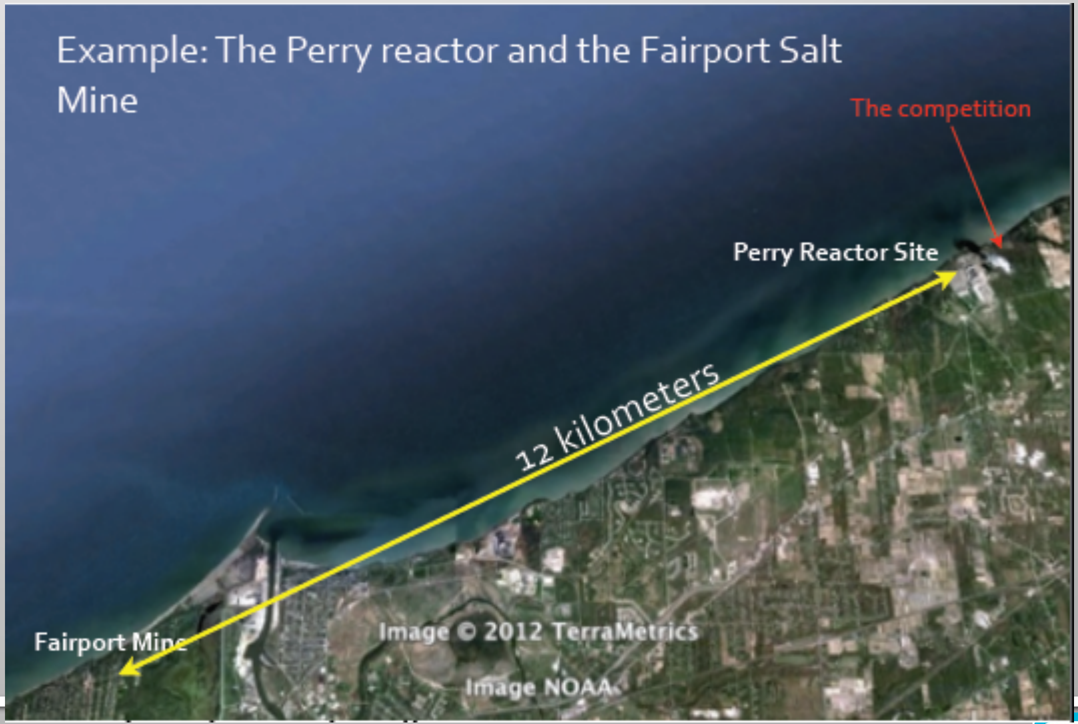
- 1570 m.w.e.
- cavity was 18m x 17m x 22.5m
- ~13 km standoff
- 3875 MWth

Pros

- Existing cavern in active mine.
- Large depth for low background.

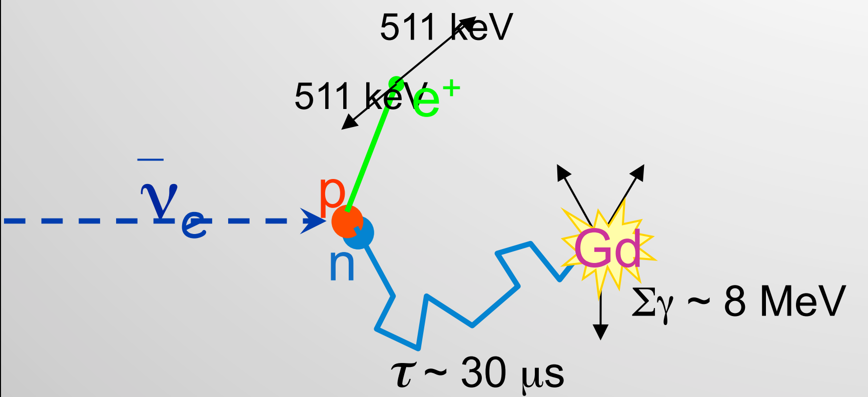
Cons

- Large stand-off will give low signal rate (0.5-1.0 per day).
- Old cavern likely to require renovation.



We must also must know what backgrounds to expect – by measuring them

Signal in 1 kiloton of water



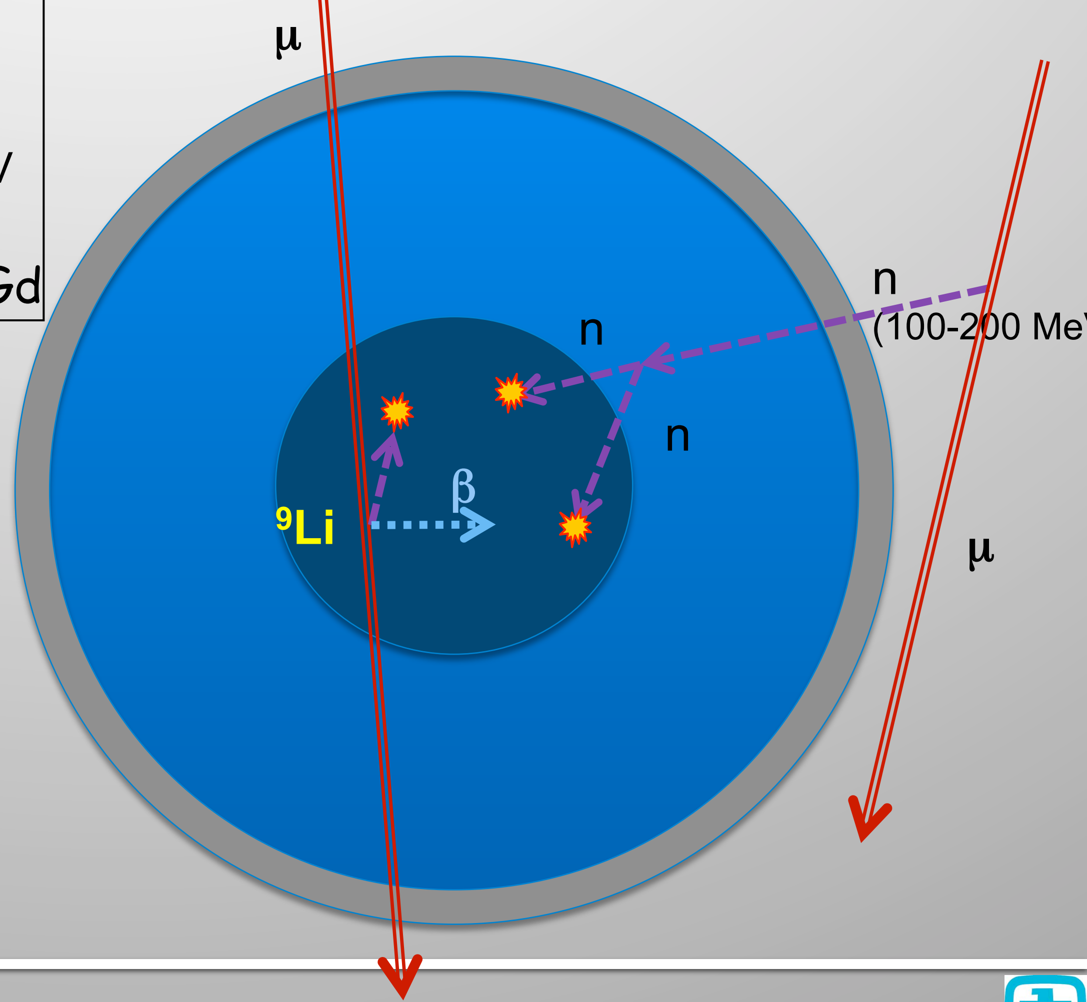
prompt e^+ signal + n capture on Gd

- Exactly two Cerenkov flashes
- within ~100 microseconds
- Within a cubic meter voxel

'The antineutrino heartbeat'

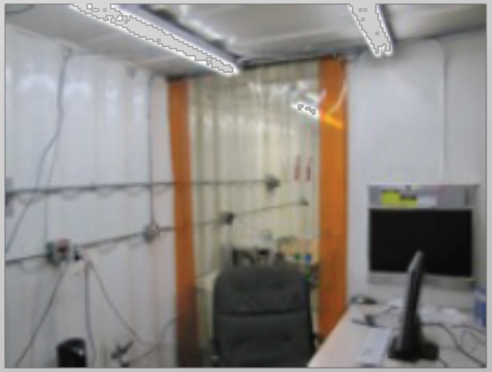
Backgrounds:

1. Real antineutrinos
2. Accidental coincidences.
3. Muon induced fast neutrons
4. Long-lived (~ 1 sec) radionuclides



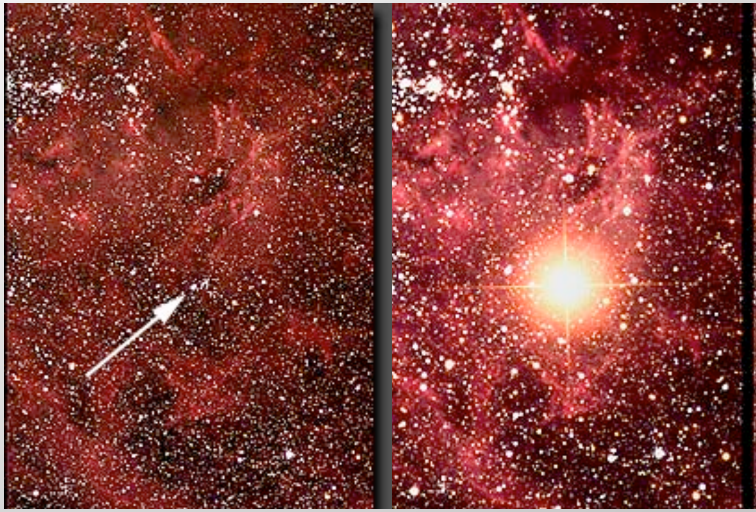
Background Measurements using ton-scale detectors at the Kimballton Underground Research Facility in Virginia

- Drive in access
- Can deploy from 100 feet to 1400 feet of overburden
- Use of the same detector at multiple depths ensures reliable comparison of results
- First-ever continuous measurement as a function of depth



WATCHMAN will also be one of the world's largest supernova watch detectors

- A 1000 ton detector with moderate shielding (few 100 m.w.e.) could detect ~700 events from a supernova at the galactic center. Any detector capable of detecting reactor antineutrinos can do this by default (SN antineutrinos are higher energy and easier to detect).



Pre-1987 1987

WATCHMAN would see antineutrinos from a supernova like 1987a, shown here in the visible

Conclusions

- Antineutrino detectors deployed a few hundred meters from reactors detect operational status, thermal power and Pu production

- This information may be useful for future safeguards regimes and future reactor types

- Attempts at the far more ambitious long-range capability are underway in both the nonproliferation and scientific communties

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