Neutrinos for Peace
or
Applied Antineutrino Physics

History of the Neutrino Conference September 5-7 2018, Paris France

Lawrence Livermore
National Laboratory

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Foreshadowing and a look back..

"I don't say that the neutrino is going to be a practical thing, but it has been a time-honored pattern that science leads, and then technology comes along, and then, put together, these things make an enormous difference in how we live."

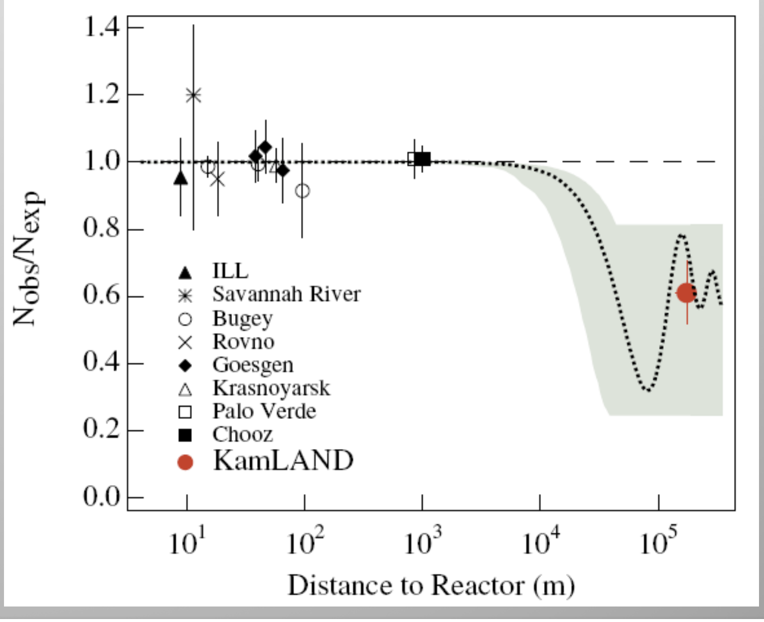
Fredrick Reines, winner of the Nobel Prize and co-discoverer of the neutrino
NYT interview, 1997

http://library.lanl.gov/cgi-bin/getfile?00326606.pdf

A practical thing: near-field reactor monitoring

- Monitor reactor operational status, power and fuel consumption and composition
- 'Near': less than 1 km, typically 10-100 meters – <u>access granted by operators</u>
- 'High' statistics: a few thousand events per day per ton sufficient to populate a spectrun
- Reactor power > ~20 MWt, but main focus has been on > 1000 MWt

<u>Rovno</u> and numerous other detector provided detector technology even with null oscillation results



The origin of this idea: L.A. Mikaelyan – Neutrino '77 conference, Baksan

3. I want to talk about the development of the new technique of the remote reactor diagnostics by the neutrino radiation. Due to the novelty of the problem the consideration naturally will be incomplete and limited by two questions only:

- determination of the reactor power production and in prospect
- determination of the dynamics of the fissing isotopes burning-out and accumulation (mainly ^{235}U and ^{239}Pu).

The principle promises of the proposed technique seem to be the remote analysis and fixing the plutonium accumulation immediately in the place of its production. This technique (if developed successfully) will be sufficiently important from the point of view of the control on the leakage of fissing materials and on the non-proliferation of nuclear weapons, and also for the economics of nuclear fuel recycling. More detail consideration of these problems on this conference seems to be irrelevant.

R&D Timeline for Near-field Monitoring

2004:Early (the first ?) workshop on Neutrinos and Arms control, UH

Applied Antineutrino Physics workshops France, Japan, US, Brazil, India, UK,

1980 1990 2000 2010 2020

The Rovno era

All basic ideas explored

Birth of the idea: Neutrino '77, Baksan (maybe '75 ?)

Gd-scintillator donated by F. Boehm/Caltech/Palo Verde experiment

SONGS

basic ideas re-explored - minor simplifications and attention of the IAEA

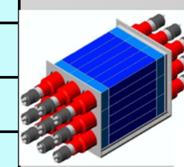
Theoretical case studies (Huber, others)

Solide, CHANDLER,NuLAT PROSPECT… reactor SBL expts.

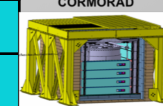
'Cambrian explosion' for monitoring detectors

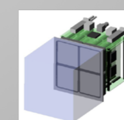
precursor to reactor short baseline experiments

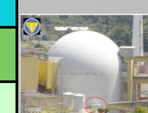
Group	Country
SNL/LLNL	USA
'PANDA'	Japan
'Mars'	UK
'CORMORAD	Italy
'Nucifer'	France
Tohoku U.	Japan
AECL	CA/US
Angra	Brazil
Niigata U.	Japan
U. Hawaii	USA
ISMRAN	India

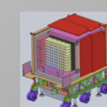

CORMORAD


PANDA


NUCIFER

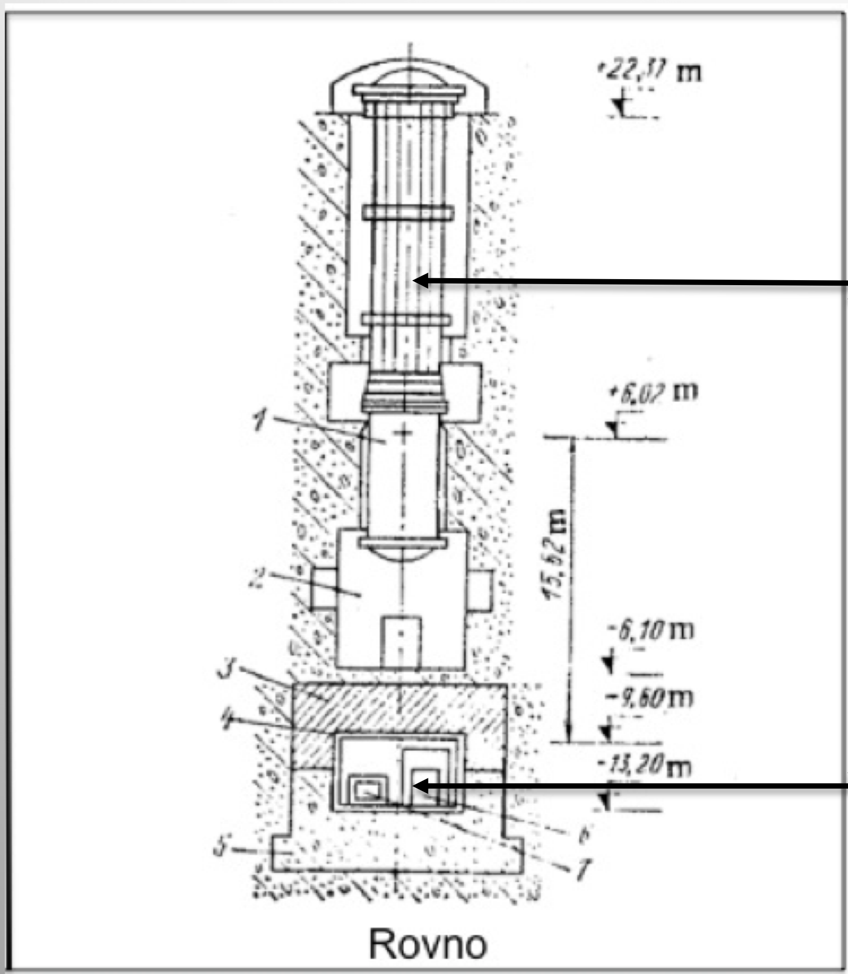

Mini-TimeCube


ANGRA


ISMRAN

IAEA workshops on antineutrino-based monitoring

1980s - the remarkable deployment at Rovno



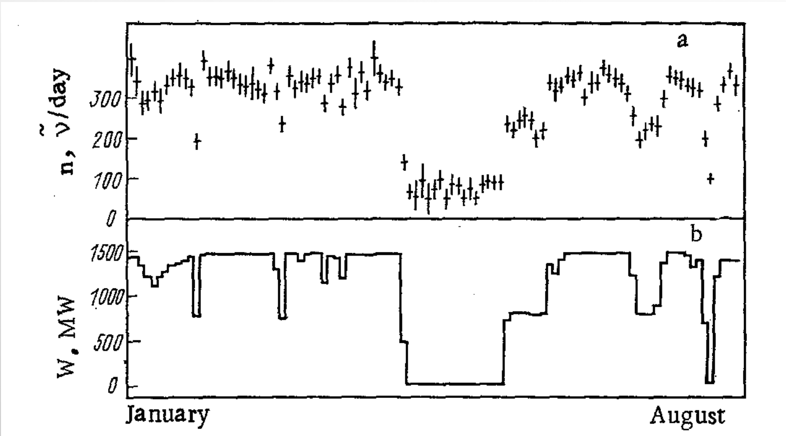
- 1400 MWt reactor (VVER 440)
- 18 m from core
- 18 m of overburden
- 500 l liquid scintillator (Gd-doped)
- 84 PMTs

The ideal monitoring experiment !

Reactor and Earth shield cosmics

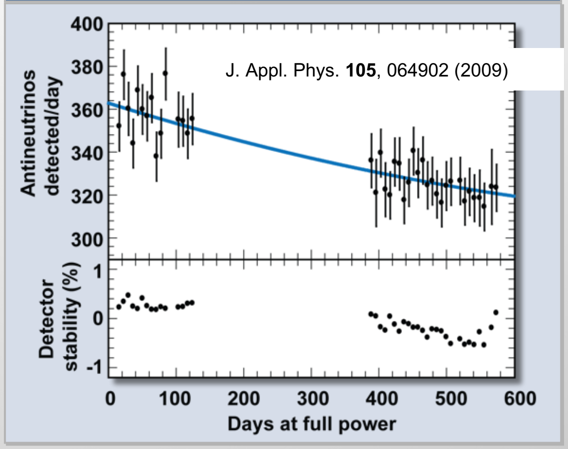
Detector is close to the core but in a relatively low radiation environment

The antineutrino rate measured over months and years) tracks power and fissile inventory "burnup effect"



2 months of data show reactor power/operational status tracking 2-3% precision – not so much worse than operator's own estimates

Detect burnup of 250 kg U, 50 kg Pu with known power and initial fuel content



SONGS '06 (Rovno '84 also measured this)

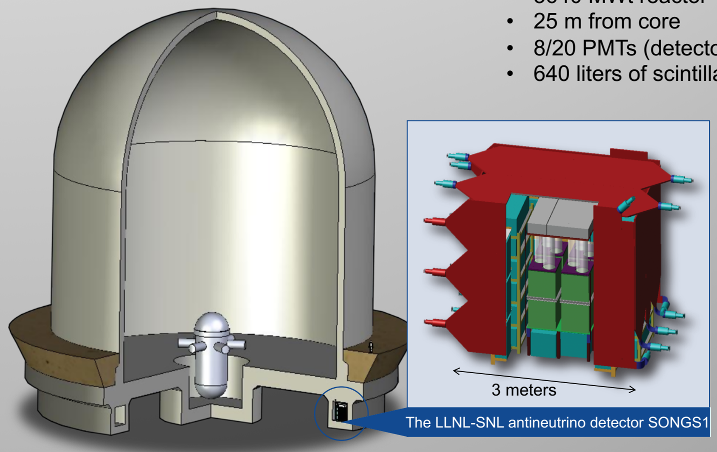
L. A. Mikaeiyan, "Neutrino laboratory in the atomic plant," in: Proceedings of the International Conference "Neutrino 77," Vol. 2, Nauka, Moscow (1978), pp. 383-385.

A. A. Borovoi and L. A. Mikaelyan, "Possibilities of practical applications of neutrinos," At. Energ., 44, No. 6, 508-511 (1978).

V. A. Korovkin, S. A. Kodanev, A. D. Yarichin, et al., "Measurement of nuclear fuel burnup in a reactor according to neutrino emission," At. Energ., 56, No. 4, 214-218 (1984).

V. A. Korovkin, S. A. Kodanev, N. S. Panashchenko, et al., "Measurement of power generation of a power reactor by the method of neutrino detection," At. I~nerg., 65, No. 3, 169-173 (1988).
Yu. V. Klimov, V. I. Kopeikin, L. A. Mika~lyan,, K. V. Ozerov, and V. V. Sinev, "Neutrino Method Remote Measurement of Reactor Power and Power Output, Atomic Energy, Vol. 76, No. 2, 1994

- 3640 MWt reactor
- 25 m from core
- 8/20 PMTs (detector/veto)
- 640 liters of scintillator



The LLNL-SNL antineutrino detector SONGS1

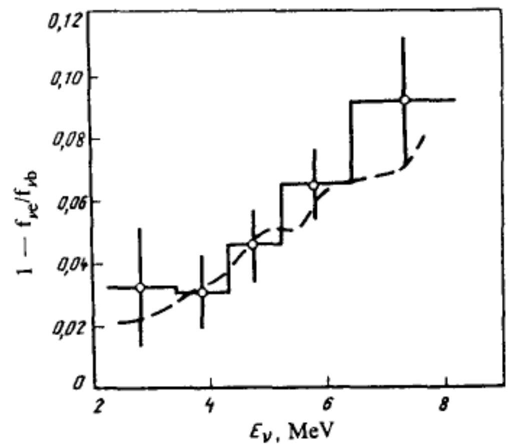
Antineutrino spectral evolution at measured at Rovno

Spectral information increases independence
from inputs (daily power levels) provided by the reactor operator

Plot shows the ratio of
energy spectra from beginning
and the end of the reactor cycle

Uranium hardens the spectrum, plutonium softens it

Klimov et. al, 1994, Atomic Energy



. 2. Ratio of the spectra of antineutrinos from the reactor at the beginning $f_{\nu b}$ and $f_{\nu e}$ of the period between reloadings.

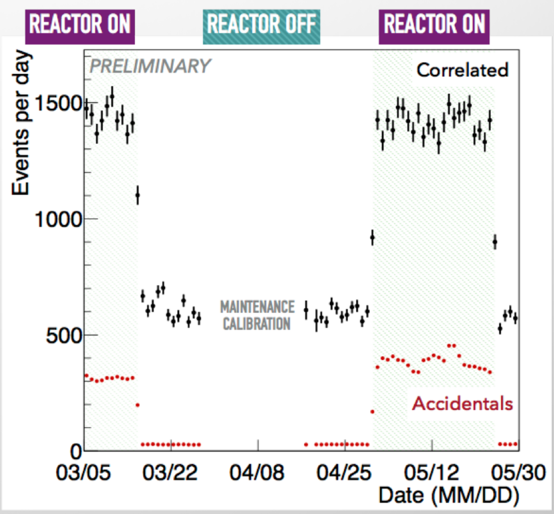
Theoretical expectation with modern detectors: **sensitive to a change of 7 kg of Pu at > 5 sigma for a 40 MWt reactor**

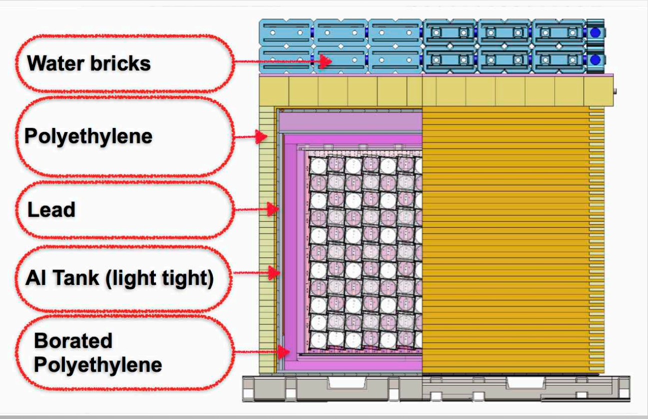
P. Huber - arxiv:1403.7065

Recent history: Above-ground spectral sensitivity demonstrated in 2018

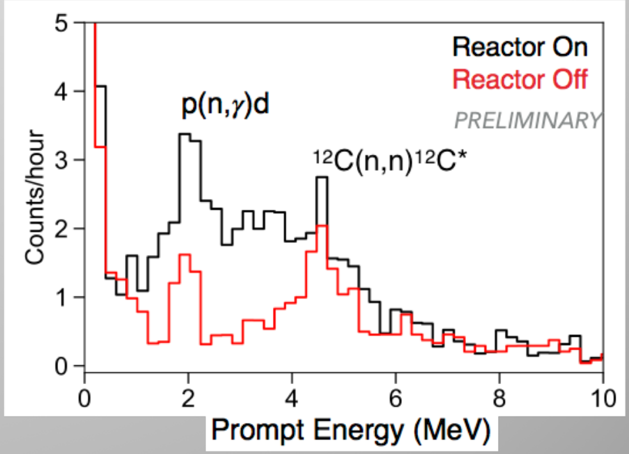
- Short baseline (5-10 m) oscillation searches demand near-surface operation – as does monitoring
- Highly segmented detectors, optimized shields permits above-ground rate and spectral measurements

750 ν/day with <1m overburden





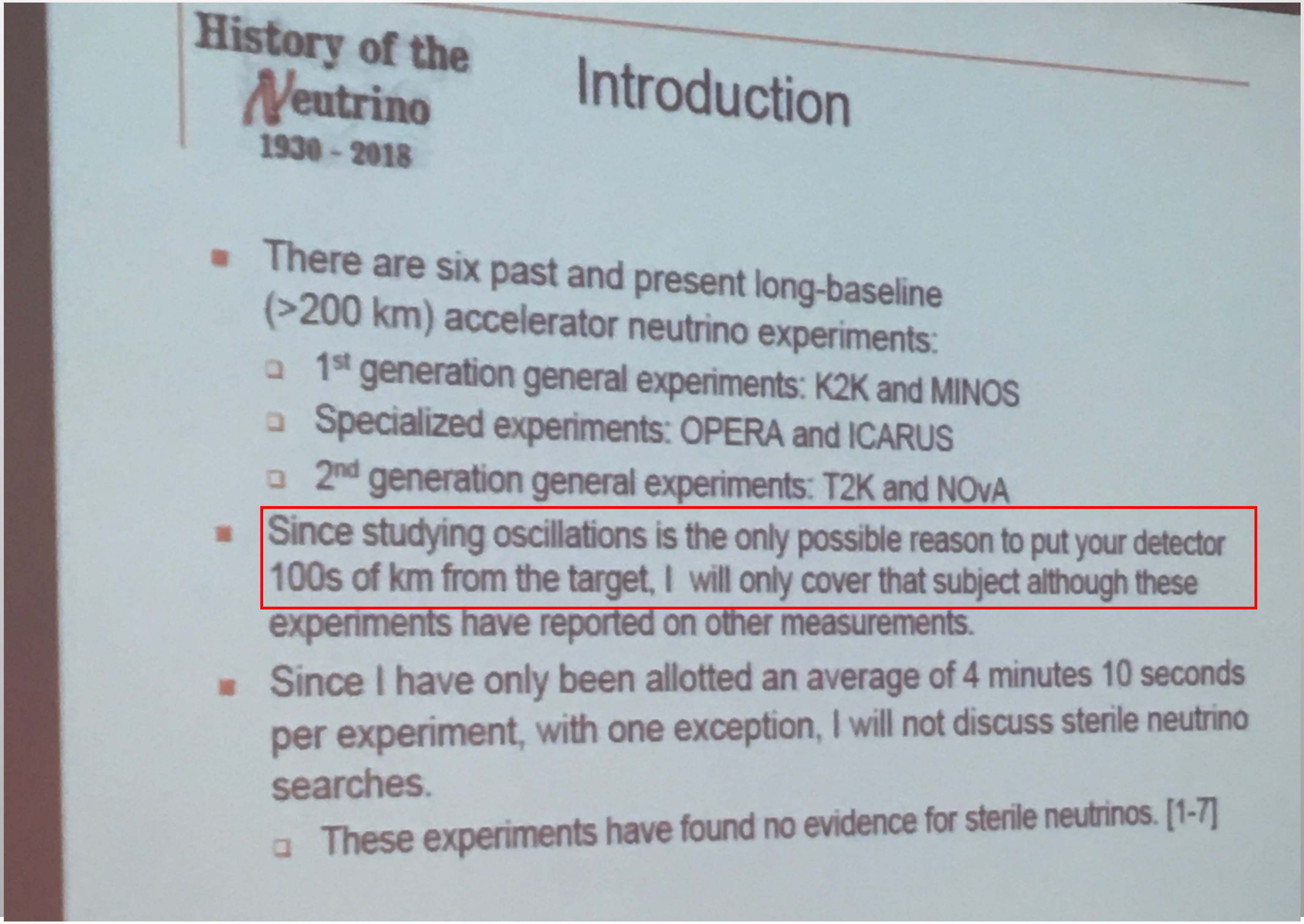
PROSPECT
PRECISION REACTOR OSCILLATION AND SPECTRUM EXPERIMENT



PROSPECT, NuLAT, CHANDLER, Solide and others will simplify monitoring deployments

From Gary Feldman's talk ..

There is one other possible reason…



A somewhat less practical thing: ‘far-field’ or ‘remote’ reactor and explosion monitoring

- Discover, or exclude the existence of, operating reactors
- Confirm the nuclear nature and measure yield of nuclear explosions
- ‘Far’: more than 1 km, out to perhaps 1000 km ? – varying degrees of access
- ‘low’ statistics: a few events per week month, year or explosion
- Reactor power ~50 MWt – roughly generating 8 kg/one Significant Quantity per year
- Explosive yield – difficult to achieve for less than 10 kton at reasonable standoff

Technology: Variations on KamLAND, Super-Kamiokande, Borexino and other large detectors used as models by a number of authors

Timeline for Far-field Monitoring concepts

relevant experiments

KamLAND
'03 - clearly demonstrates Remote reactor monitoring with 1 kton of scintillator

EGADS
200 ton Gd-H2O engineering demonstrator

WATCHMAN:
1 kT Gd-doped water devoted to reactor monitoring

Super-K_Gd:
50 kT Gd-doped water

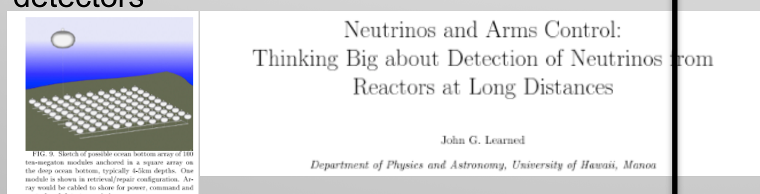
2000 2005 2010 2015 2020

relevant analyses

'01: Bernstein et. al.
Gd-doped water
for CTBT monitoring
applications

Conclusion: not worth it
for the 1 G$ price of entry

'03: Dreaming big: John Learned considers the benefits of a gigaton array of monitoring detectors

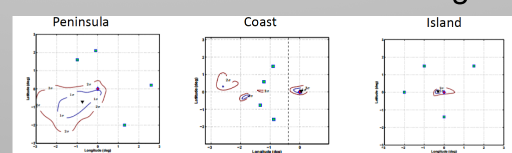

Neutrinos and Arms Control:
Thinking Big about Detection of Neutrinos from Reactors at Long Distances

John G. Learned

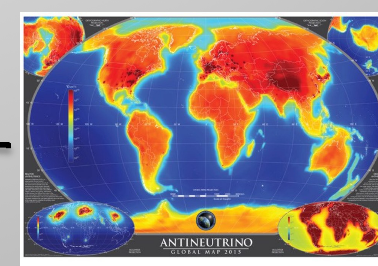
Department of Physics and Astronomy, University of Hawaii, Manoa

'08: Gullian –
Far-Field Monitoring of
Rogue Nuclear Activity

'10: Lasserre et. al – PRC
'Secret Neutrino Interaction Finder'
marvelously detailed treatment of
reactor and non-reactor backgrounds

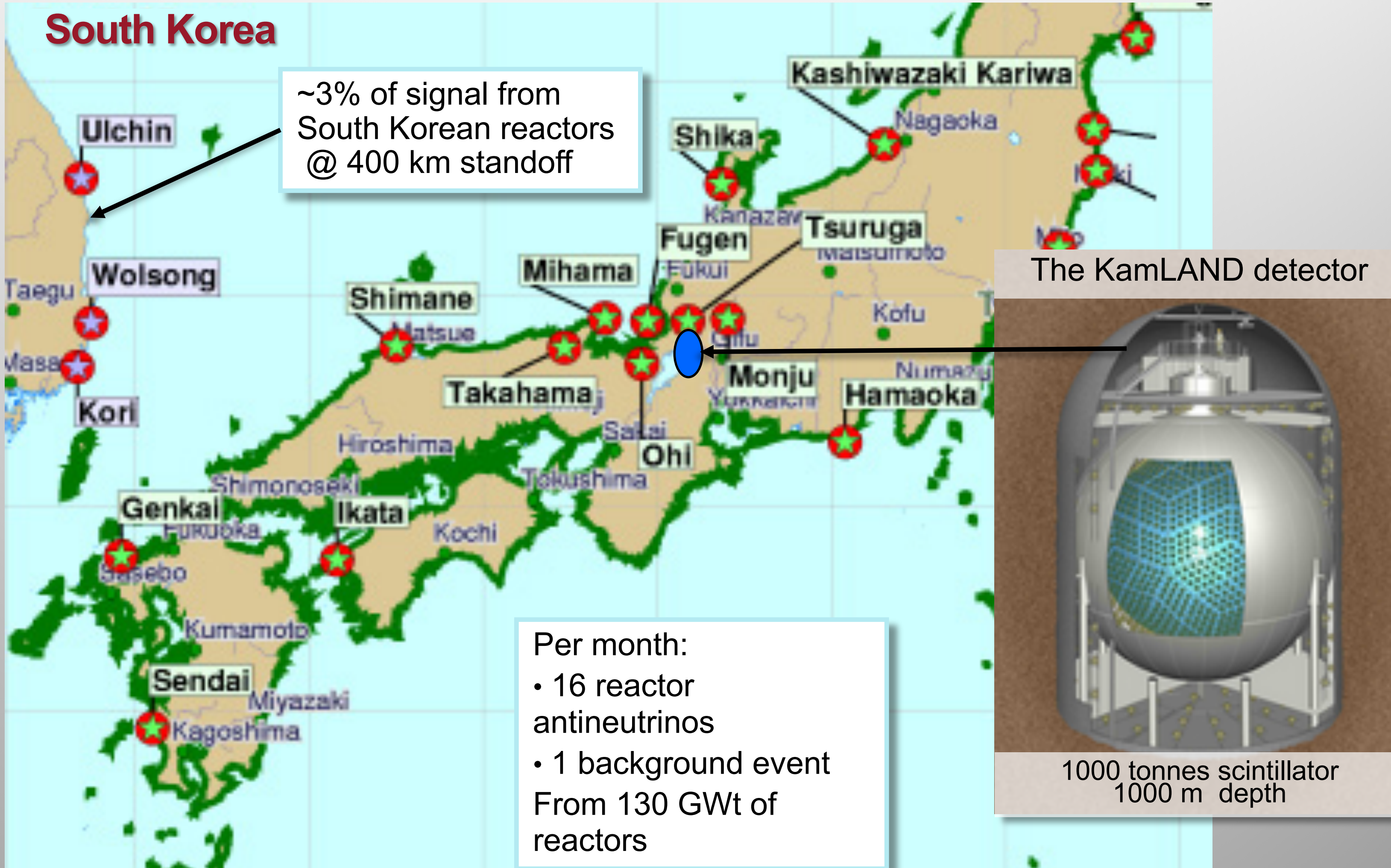


'17: Carr et. al – PR Appl. 10
'Seismically cued antineutrino detectors'
Modest improvement on '01 results



AGM 2015 Usman/Learned
geoneutrino.org/reactors S. Dye

Long-range reactor antineutrino detection is feasible now but only for relatively high power reactors and with a hard-to-scale technology



~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

Today's Water Cherenkov detectors are 50x larger than scintillator detectors, but can't distinguish neutrino from antineutrino

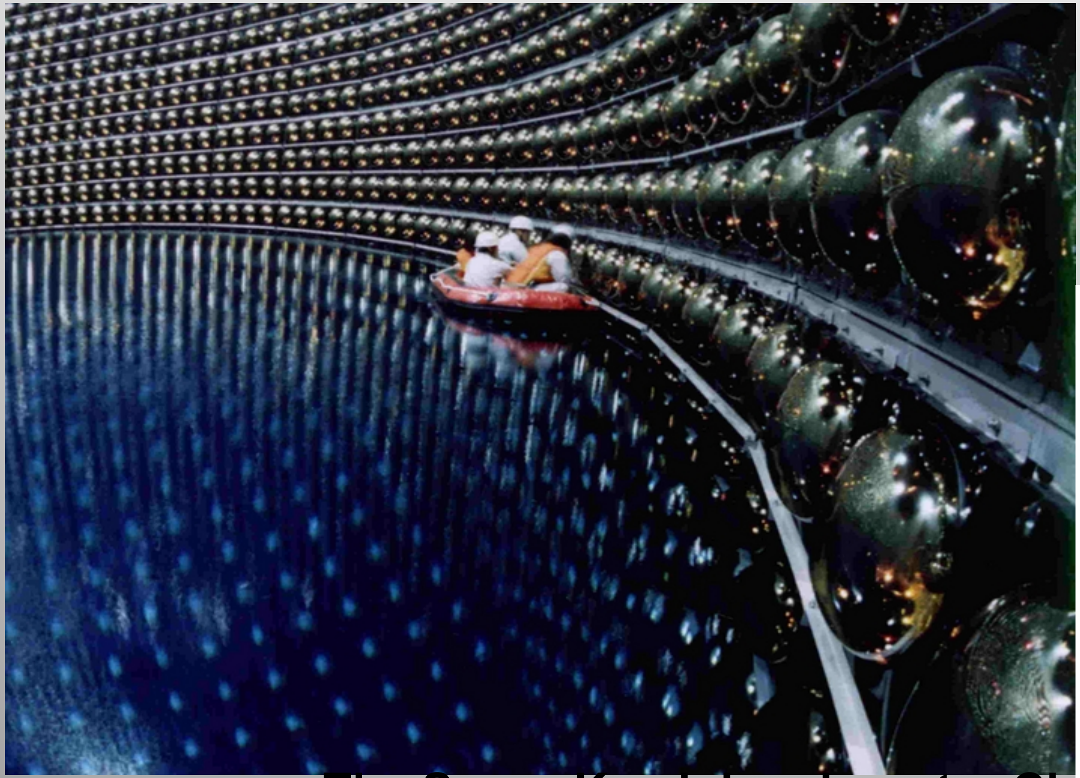
$\overline{\nu}_e + p = e^+ + n$

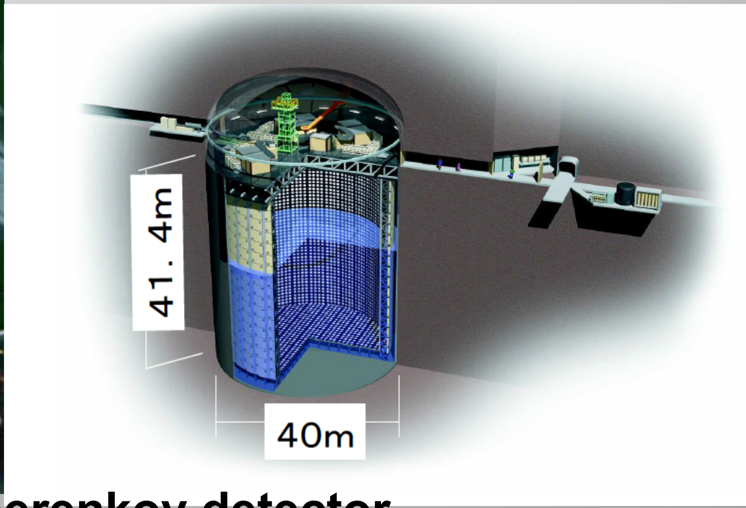
Inverse beta decay from reactor $\overline{\nu}_e$

Identical signals from both processes:
a single flash of Cerenkov light

$\nu_e + e^- = \nu_e + e^-$

Elastic scatter (solar neutrinos, reactors)





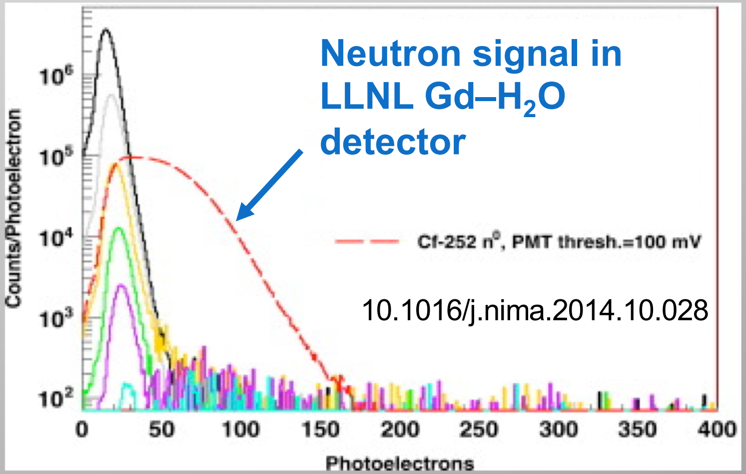
The Super-Kamiokande water Cherenkov detector

In 2009, LLNL and the Super-K collaboration both demonstrated water-based neutron detection using gadolinium as a trace additive – a natural extension from gd-scintillator

$$\overline{\nu_e} + p = e^+ + n$$

- Gadolinium nucleus captures neutrons with high efficiency and creates an intense flash of Cherenkov light
- The signal is two flashes of Cherenkov light, close in time (~100 μsec) and location (~5 cm)—the "antineutrino heartbeat"
- Method reduces backgrounds by several orders of magnitude
- Gadolinium-doped Water Cherenkov technology offers path to 100–1000 kiloton antineutrino detectors
- First proposed by Bernstein in 2001
  Science & Global Security **9,** 235 (2001)
- Experimental verification in 2009

LLNL: *NIMA* **607** (3), 21 (August 2009)
Super-K: *Astroparticle Physics* **31**(4), 320–328 (May 2009)



The WATCHMAN demonstration

Main Project Objective:

Detect the ON/OFF power cycle of a single reactor:

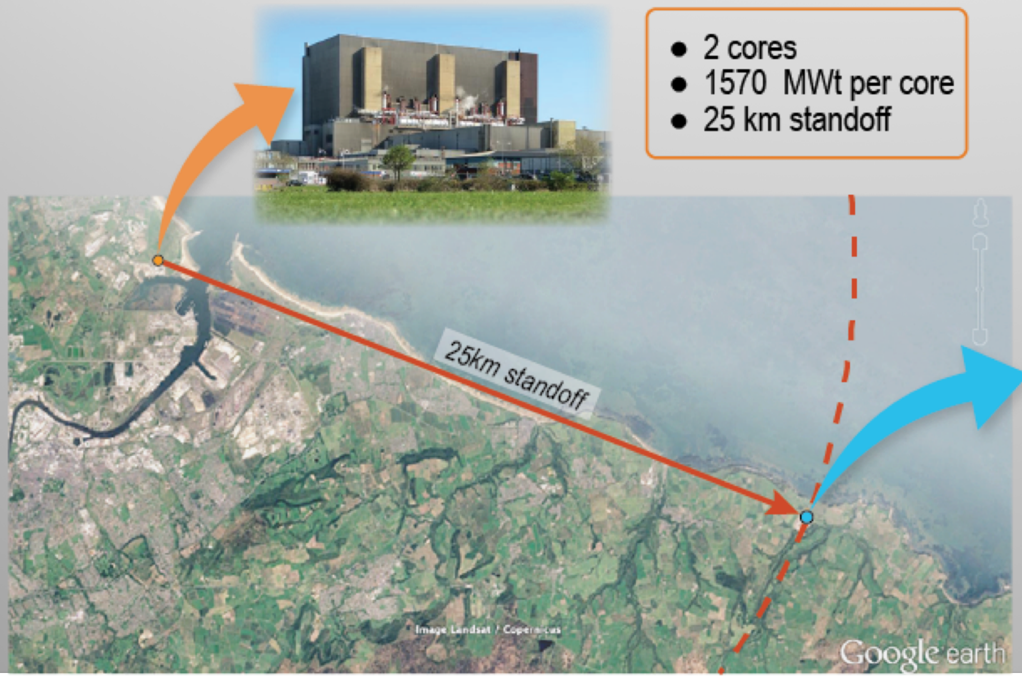
- at 10-25 km standoff
- with a kiloton-scale Gd-H2O detector
- at 3 sigma confidence level
- Choose water based on cost and scalability

WATCHMAN: A WAter CHerenkov Monitor of Antineutrinos

Doping the water with gadolinium greatly increases sensitivity to inverse beta interactions of antineutrinos

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

HARTLEPOOL REACTORS



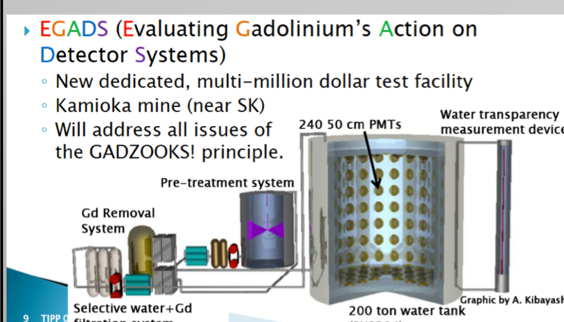
- 2 cores
- 1570 MWt per core
- 25 km standoff

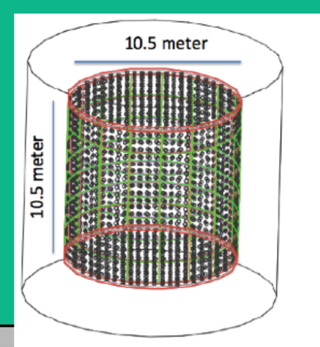
WATCHMAN detector at the Boulby mine

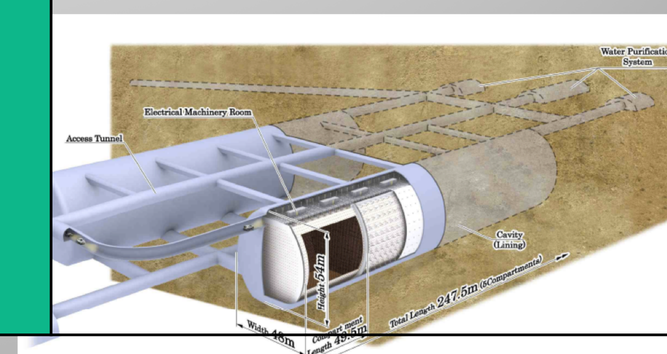
- 3500 tons, ~3000 photomultiplier tubes
- Water Cherenkov detector, doped with gadolinium

Other relevant activities worldwide

Detector	EGADS	WATCHMAN	Super-K-GD →Hyper-K
Status	Ongoing	2018	Now
Mass (ton)	200	5000	50,000 → 500,000
Type	Gd-WCD	Gd-WCD	Pure H2O or Gd-WCD
Purpose	Measure background materials,energy threshold Too small to see reactor antineutrinos	Remotely detect reactor antineutrinos	Neutrino oscillations, proton decay, supernovae… and maybe reactors and explosions







Penultimate remarks…

- In the near-field (<100 m or so) it has been proven since Rovno/1980's that antineutrino detectors can be used to determine issile inventories and power levels at reactors – easily deployable detectors are now approaching realization
- Far-field detection at hundreds of kilometers has already been demonstrated at one level by KamLAND – SuperK and WATCHMAN will demonstrate the scalable water-based technology
- In all cases, the technology has a natural overlap with detection for particle physics and the two communities should plan accordingly
- Apologies to the many ideas and people I didn't talk about – coherent scatter, JUNO, fast phototubes and water-based scintillator…

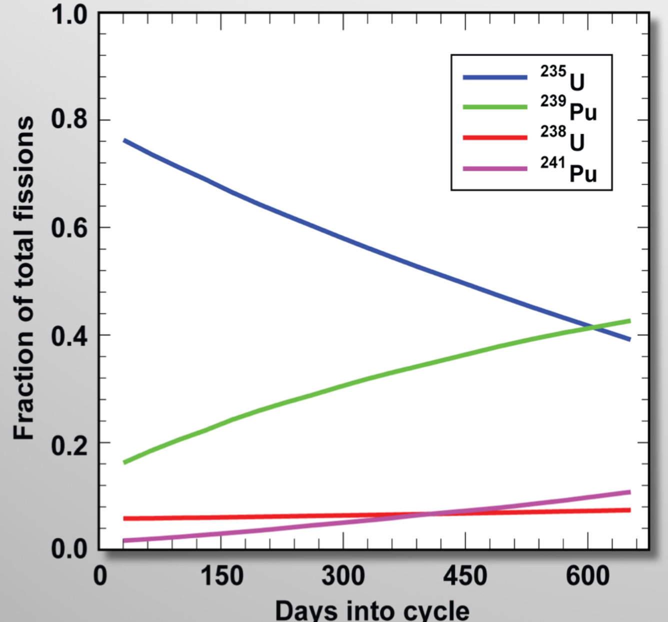
Another origin story for applied antineutrino physics – Moliere, Le Bourgeois Gentilhomme, Paris ’70 (1670)

MONSIEUR JOURDAIN.— Par ma foi, il y a plus de quarante ans que je dis de la prose, sans que j'en susse rien; et je vous suis le plus obligé du monde, de m'avoir appris cela.

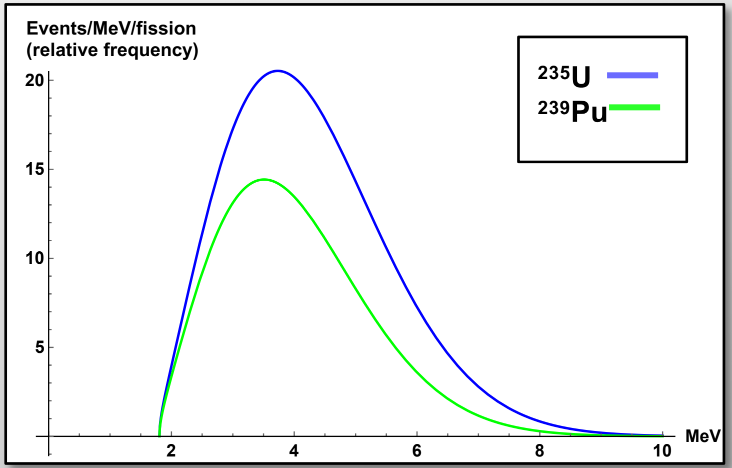
By my faith! For more than forty years I have been speaking prose without knowing anything about it, and I am much obliged to you for having taught me that.

Reactor antineutrino energy spectra, convolved with changing fission fractions, produce the "burnup effect"

For each isotope, fission rates vary with time



Energy spectra vary with isotope
Plutonium emits fewer detectable events for IBD interactions and spectrum is 'softer'



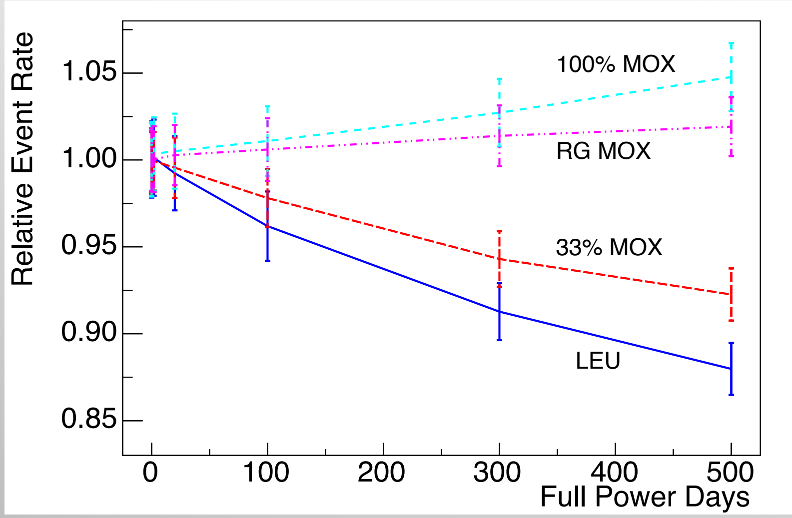
$$N_{\bar{\nu}} = \gamma \cdot (1 + k(t)) \cdot P_{th}(t)$$

Zeroth order: reactor power

First order: ~10%
Varying contributions from Pu/U isotopes

Antineutrino rate and shape measurements reveal properties of the core

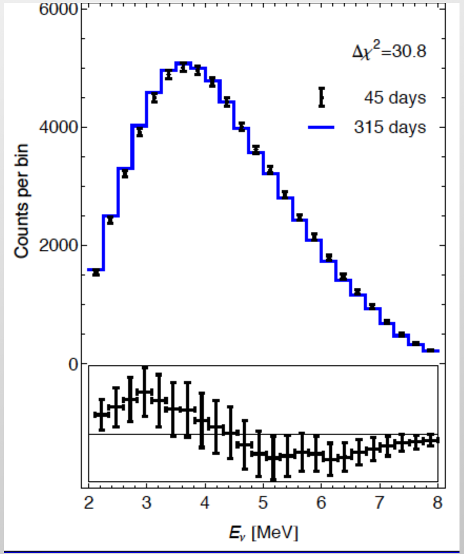
Comparison of relative nubar rates versus time for different core types



- 5 ton detector
- 3 GWt core
- 25 m standoff
- **Sensitive to an 8% change in MOX composition in 150 days**

arxiv:1612.00540

Comparison of two spectra with midpoints on cycle day 45 and day 315



- 5 ton detector
- 40 MWt core
- 17.5 m standoff
- **Sensitive to a change of 7 kg of Pu at > 5 sigma**

arxiv:1403.7065

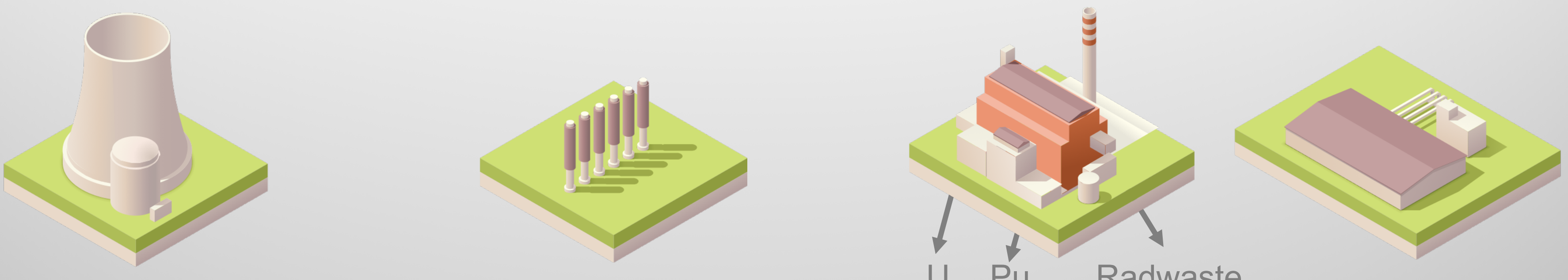
The International Atomic Energy Agency - IAEA - verifies nonproliferation in non-nuclear weapons states, and promotes nuclear power as part of the Treaty on the Nonproliferation of Nuclear Weapons

IAEA

International Atomic Energy Agency

Current IAEA safeguards practice at reactors (220 worldwide)

Reactor (1–1.5 years) | **Onsite Fuel Storage** (months to years) | **Reprocessing** (months) | **Waste Repository** (forever)



Reactor
- Check declarations
- Item accountancy
- Containment and surveillance

Onsite Fuel Storage
- Gross defect detection
- Item accountancy
- Containment and surveillance

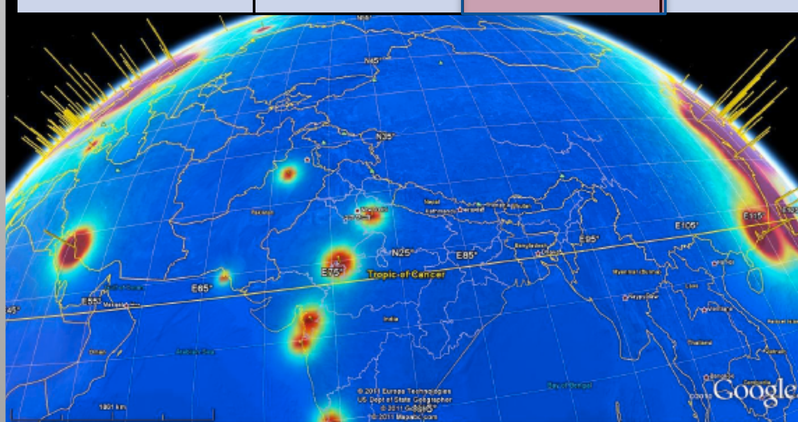
Reprocessing / Waste Repository
- Check declarations
- Bulk accountancy

- Operators only declare fuel burn up and power history
- No direct Pu inventory measurement is made unless the fuel is reprocessed
- **Can antineutrino detectors provide real-time inventory estimates?**

Existing reactor backgrounds form the ultimate limit on discovery of unknown reactors

					Dwell times for different reactor backgrounds		
Reactor Thermal power (MWt)	**Standoff (km)**	**Detector Mass (Megatons)**	**Confidence of detection**	**Total number of signal events**	**suppressed (1 evt./mo./MT)**	**Medium (300 evt./mo./MT)**	**High (2000 evt./mo./MT)**
40	100	1	95%	~8	4 days	45 days	9 months
40	1000	2	68%	~9	7 months	-	-
100	1000	2	95%	~20	6 months	-	-

Science & Global Security, 18:127–192, 2010



Global reactor antineutrino fluxes

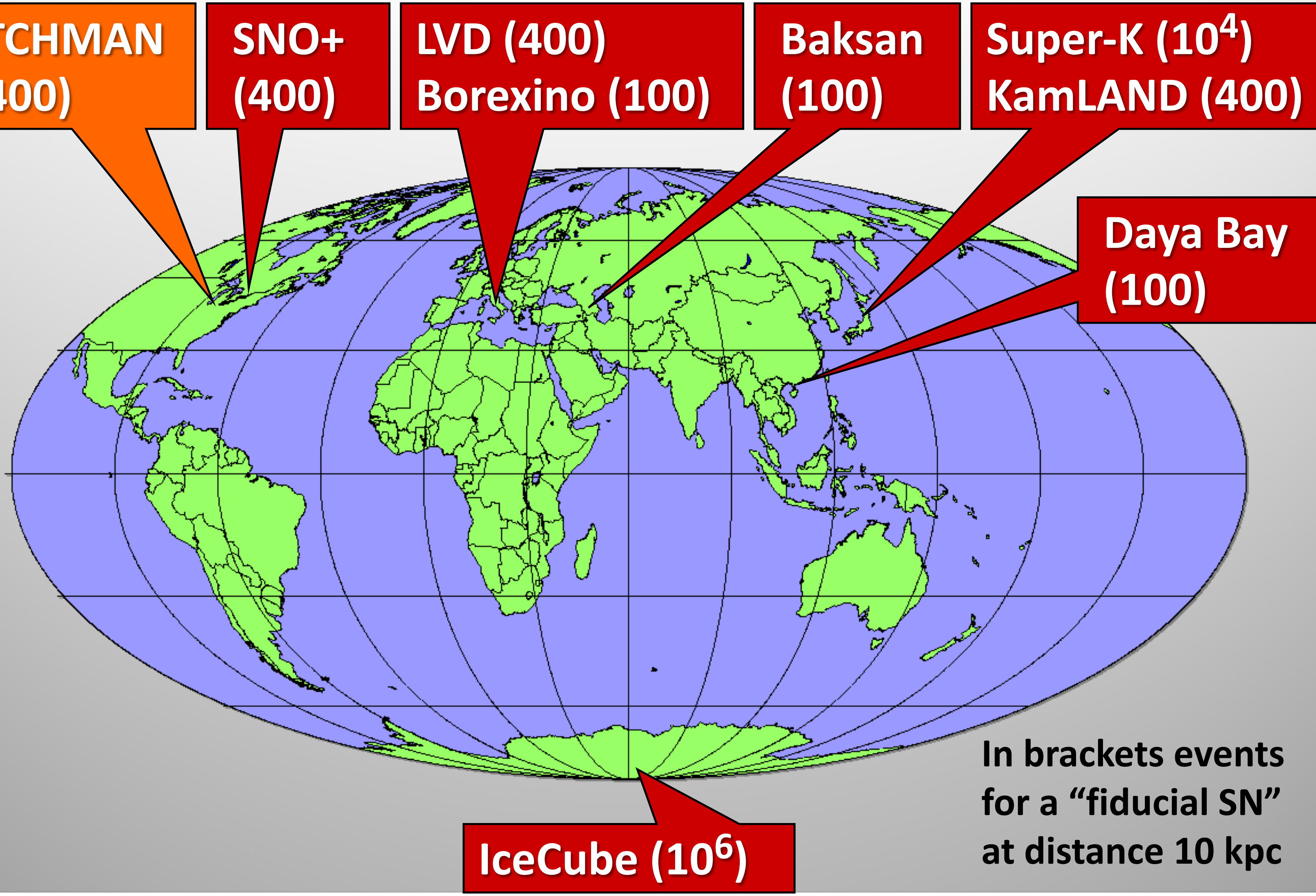
simulation courtesy Jocher/Learned/Usman NGA/UH

Large masses are essential for statistics

(More efficient configurations are possible)

Beyond ~100 km, directionality is essential to reject backgrounds

Supernova Neutrino Antineutrino Detectors



The AIT-WATCHMAN collaboration

The WATCHMAN Collaboration

32 collaborators
9 Universities
4 National Laboratories

Co-spokespersons:
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Mark Vagins, UC Irvine/Tokyo University

AWE
- J.Burns

LLNL
- A. Bernstein
- M. Bergevin
- S. Dazeley

BNL
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STFC–Boulby
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U. Hawaii
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- J. Learned

U. Michigan
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U. Pennsylvania
- C. Mauger

UC Davis
- R. Svoboda

UC Irvine
- M. Vagins

U. of Sheffield
- M. Malek
- N. Spooner
- L. Thompson

Site and configuration choices

	Option 1	Option 2
Reactor Location	Perry, Ohio, United States	Hartlepool, England, United Kingdom
Thermal Power (MWt)	1 x 3875	2 x 1500
		
Detector Location	Morton Salt/IMB mine Painesville, Ohio	Boulby underground science lab, Boulby, England
Standoff	~13 km	~25 km
Overburden (mwe)	~1500	~3000
Signal Events	110 per month	11 per month
Background Events	50 per month	20 per month

An Historical Artifact: J. Learned Concept for remote monitoring applications, circa 2007-8