WATCHMAN: A WATer CHerenkov Monitor for ANtineutrinos

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The WATCHMAN collaboration

The
WATCHMAN
Collaboration

- Atomic Weapons Establishment
- Brookhaven National Laboratory
- Iowa State University
- Lawrence Livermore National Laboratory
- Pennsylvania State University
- Science Technology Facilities Council– Boulby
- University of California, Berkeley
- University of California, Davis
- University of California, Irvine
- University of Hawaii
- University of Michigan
- University of Pennsylvania
- University of Sheffield
- University of Tennessee

32 collaborators
10 Universities
4 National Laboratories

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

Neutrinos and antineutrinos

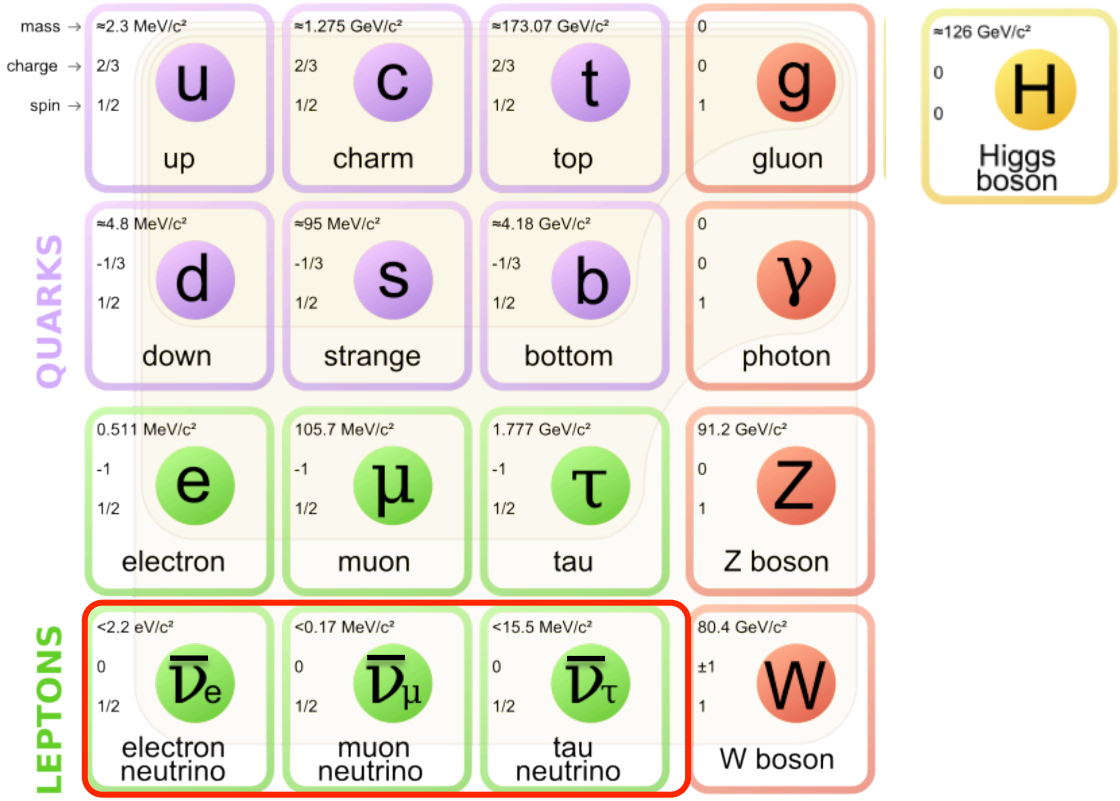
Fundamental particles in the Standard Model of Particle Physics

Neutrinos:

Exactly three types or flavors couple to matter
<u>via the weak interactions</u>

- ✓ stable
- ✓ elementary
- ✓ have no electric charge
- ✓ do have a <u>weak charge</u>

All of this is also true of antineutrinos except: opposite weak charge

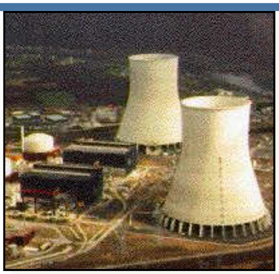


Millennial discovery: neutrinos change flavors or ‘oscillate’ as they move through space, and have mass (~10 meV)

Sources of neutrinos (and antineutrinos)

✓ Nuclear Reactors (power stations, ships)

antineutrinos (fission)

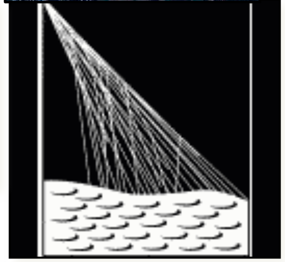


✓ Particle Accelerators

both

✓ Earth's Atmosphere (Cosmic Rays)

both

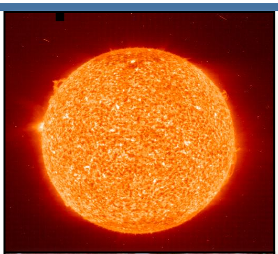


✓ Earth's Crust (Natural Radioactivity)

antineutrinos

Sun ✓

neutrinos (fusion)



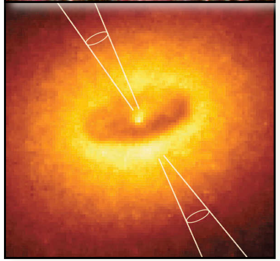
Supernovae (star collapse) ✓

SN 1987A

both

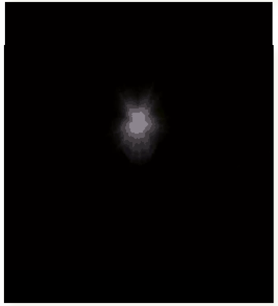
Astrophysical Accelerators

both



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

both



slide adapted from J Learned, AAP 2007

Huge numbers of antineutrinos from reactors

Very small interaction cross-section

$\sim 6 \quad \times \quad \sim 10^{21} \quad \rightarrow \quad \sim 10^{22} \quad \rightarrow \quad \sim 6$

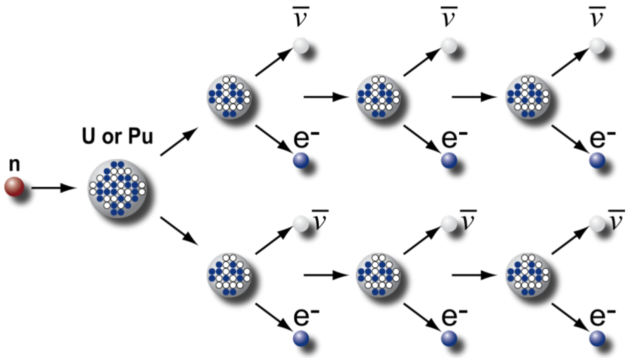
antineutrinos per fission

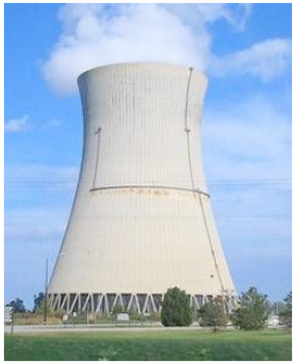
fissions per second in a 3,000-MWt reactor

antineutrinos per second from a typical PWR - unattenuated and in all directions

antineutrinos interactions per day per 1000 tons

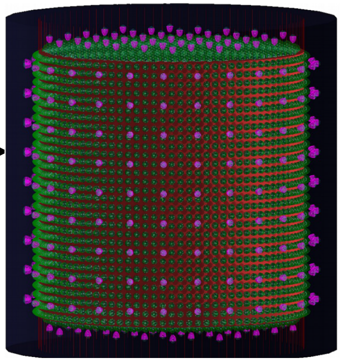
at 25 km standoff





~ 25 kilometer

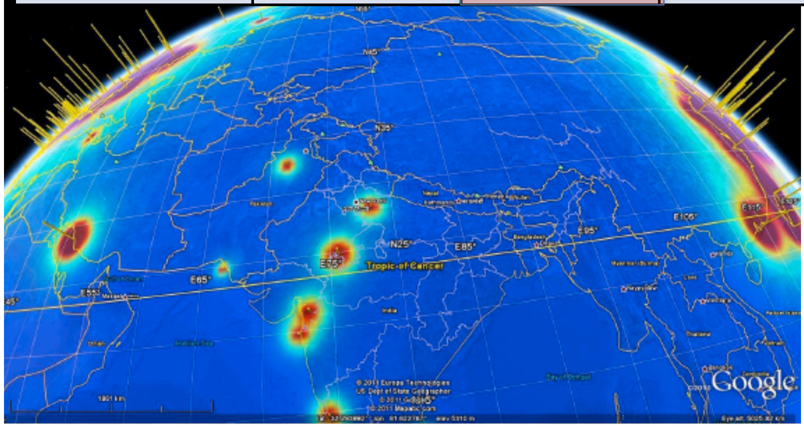
1000 tons of water instrumented with PMTs



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

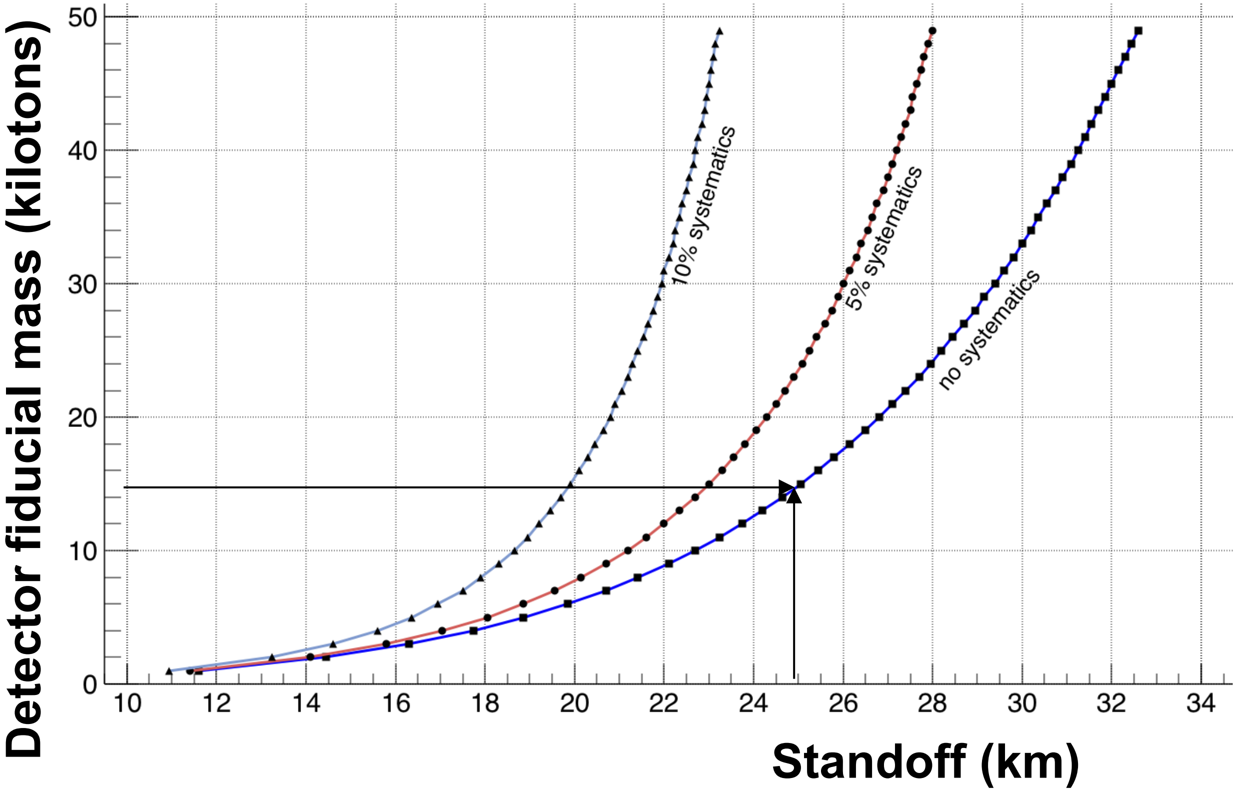
Large detectors are essential for statistics

Beyond ~100 km, directionality is essential to reject backgrounds

A 15 kton water detector can confirm the absence of operating reactors in a wide geographical region

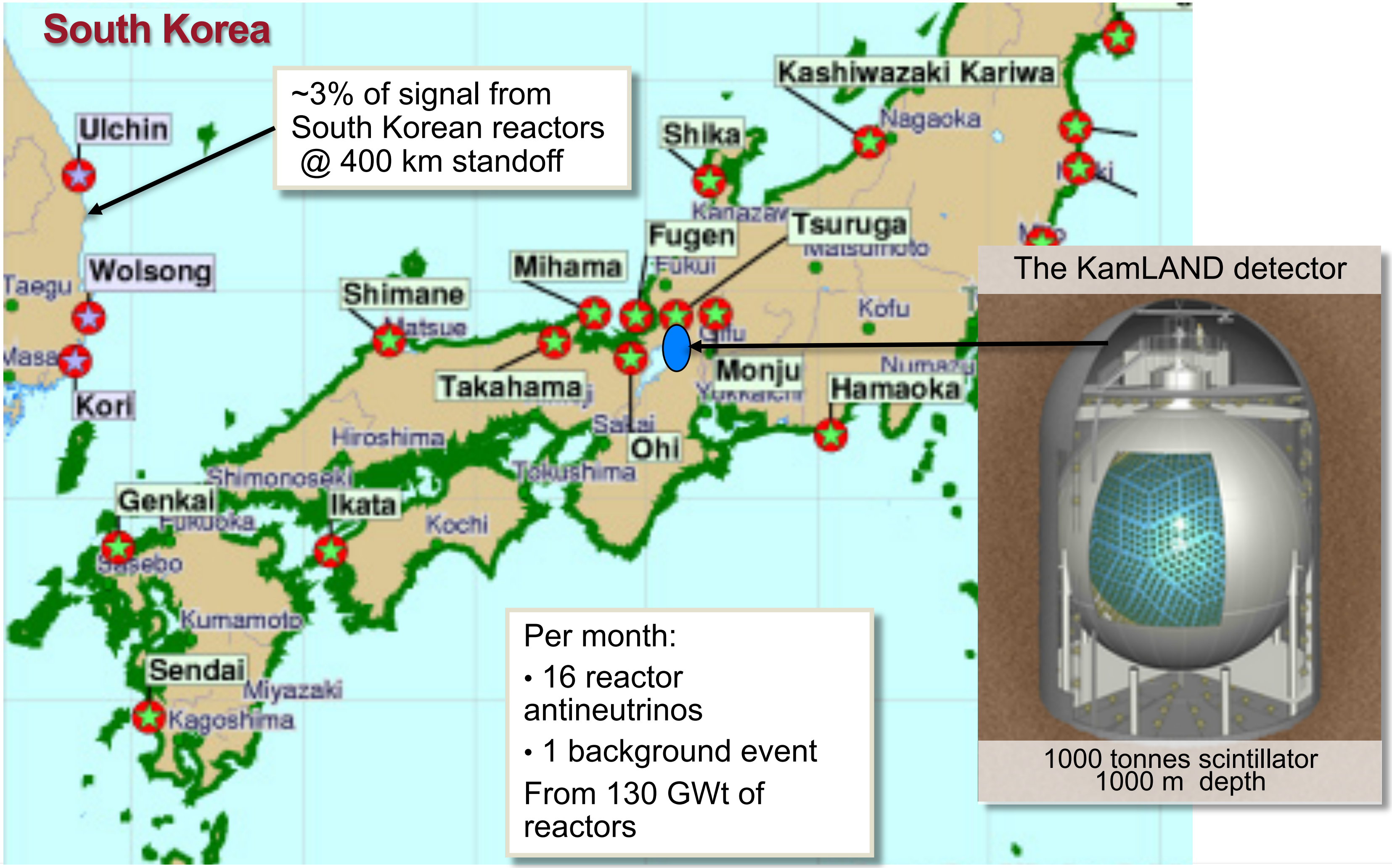
Example:

- A **15 kton** fiducial WATCHMAN-like detector:
- excludes **a 40 MWt reactor**
- in **6 months**
- with **2 sigma confidence**
- to **25 kilometers**



Possible use: Iran agreement calls for verified elimination of reactors and engagement of Iranian nuclear scientists in peaceful research

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

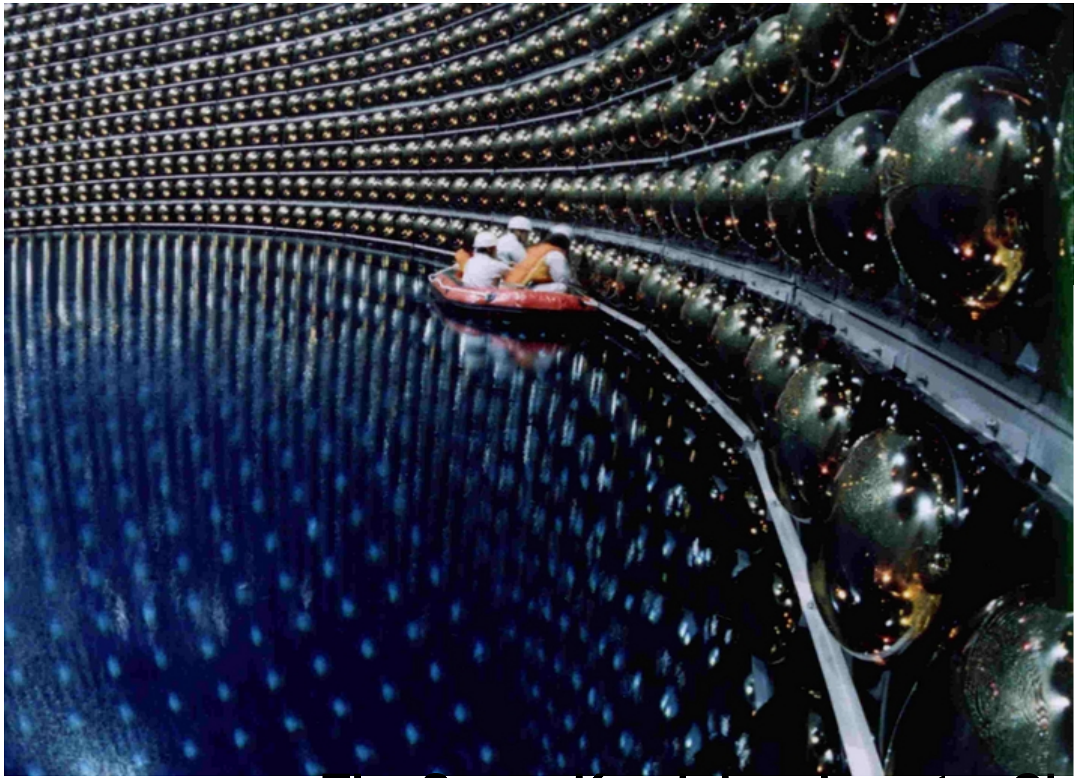
$\bar{\nu}_e + p = e^+ + n$

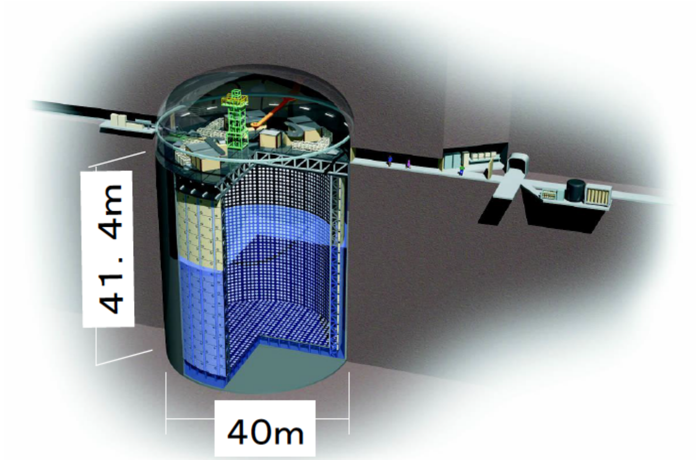
Inverse beta decay
from reactor $\bar{\nu}_e$

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

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

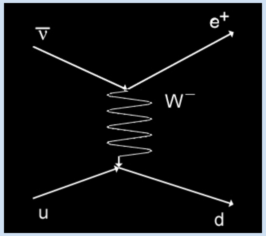
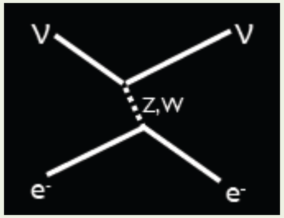
Elastic scatter
(solar neutrinos, reactors)





The Super-Kamiokande water Cherenkov detector

Two kinds of interactions for MeV-scale antineutrinos (and neutrinos)

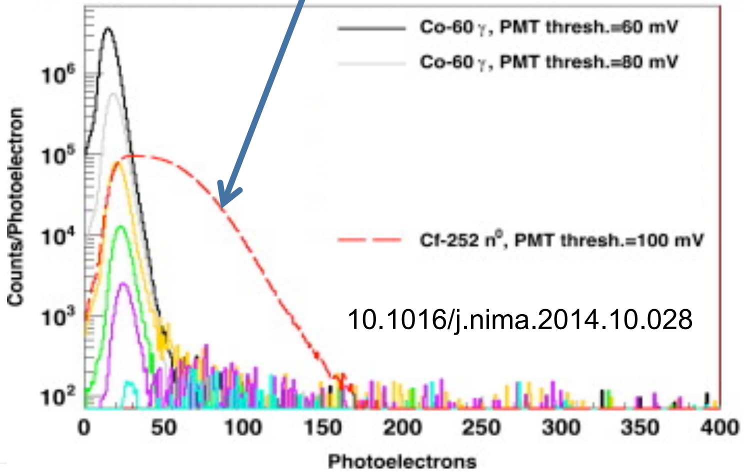
Feynman diagram		
Name	Antineutrino-proton (Inverse beta decay)	antineutrino-electron or neutrino-electron
Initial/final states	$\bar{\nu} + p \rightarrow e^+ + n$	$\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$
Cross section	$\sigma \sim 10^{-42}\,\mathrm{cm}^2\, E_{\bar{\nu}}^{2}$	$\sigma \sim 10^{-44}\,\mathrm{cm}^2\, E_{\bar{\nu}}$
Experimental signature	• Two MeV scale energy depositions • Δt ~ 100 μsec • Δr ~ 5 cm	Any MeV scale energy deposition
Backgrounds	Rare cosmogenic neutrons and radionuclides - **easy**	Solar neutrinos, ambient gamma-rays, muons… **hard**
Industry opinion	'*good old inverse beta*' - Petr Vogel	

If this neutron is undetected, these interactions appear nearly identical and background rejection becomes much harder

Large water Cherenkov antineutrino detectors require efficient water-based neutron detection

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

- The signal is two flashes of Cerenkov light, close in time (~100 μsec) and location (~5 cm) – the “antineutrino heartbeat”
- Reduces backgrounds by several orders of magnitude
- Gadolinium doped Water Cerenkov technology offers path to 100-1000 kiloton antineutrino detectors
- LLNL was first to demonstrate this neutron detection capability, in ton-scale detectors



Neutron signal in
4 tons of Gd-doped water

10.1016/j.nima.2014.10.028

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

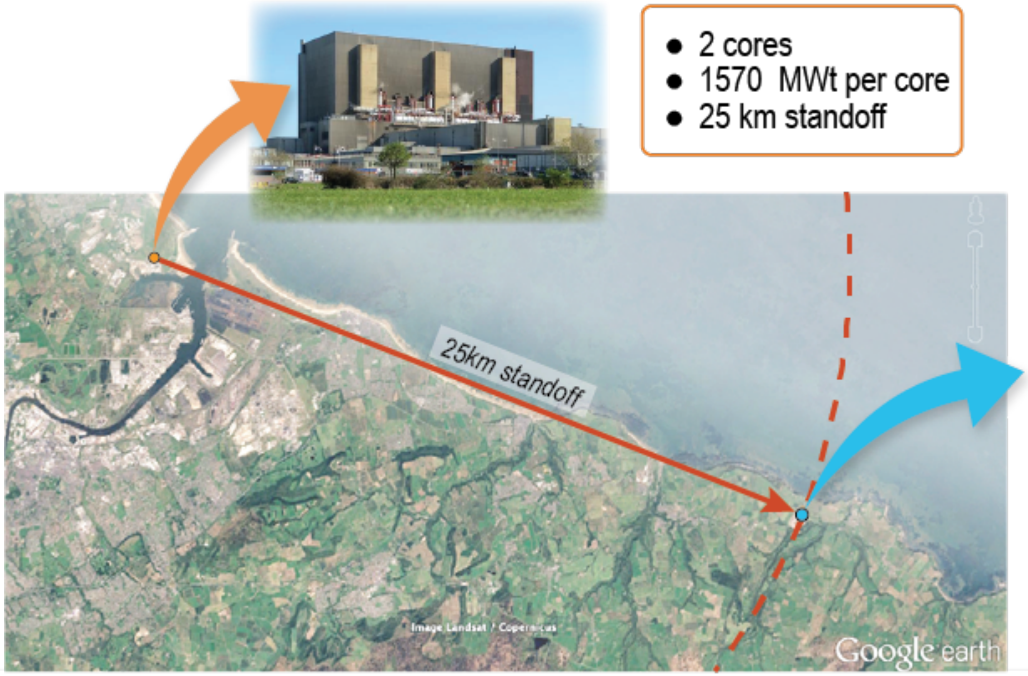
WATCHMAN: A WAter CHerenkov Monitor of Antineutrinos

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

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

UK deployment option

HARTLEPOOL REACTORS



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

WATCHMAN detector at the Boulby mine

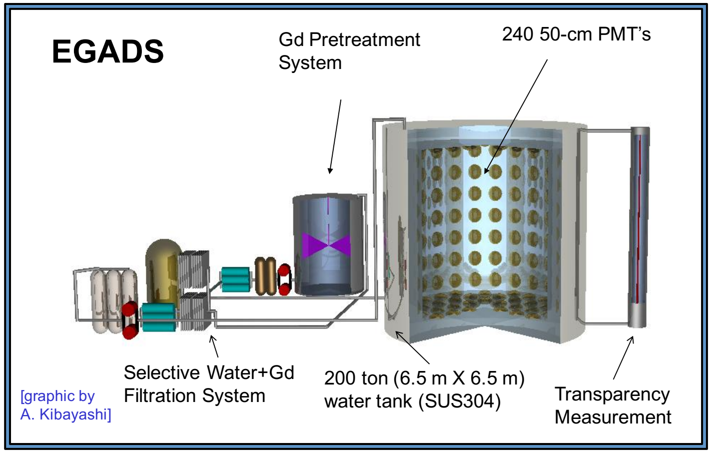
- 3500 tons, ~3000 photomultiplier tubes
- Water Cherenkov detector, doped with gadolinium

Site and configuration choices

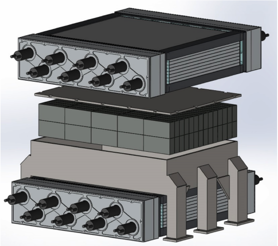
	Option 1	Option 2
Reactor Location	Perry, Ohio, United States	Hartlepool, England, United Kingdom
Thermal Power (MWt)	1 x 3875	2 x 1500
		
Detector Location	Morton Salt/IMB mine Painesville, Ohio	Boulby underground science lab, Boulby, England
Standoff	~13 km	~25 km
Overburden (mwe)	~1500	~3000
Signal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

Preliminary studies in 2012-2017 that demonstrate key aspects of the WATCHMAN demonstration

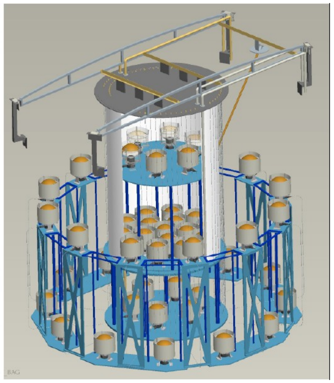
- ✓ **EGADS**: Continuous in situ purification of water in the presence of Gd, without removing the Gd
- ✓ **LLNL detector:** First neutron detection with Gd-doped water
- ✓ **WATCHBOY/MARS**:Direct measurement of relevant backgrounds versus depth
- ✓ **RAT-PAC, WATCHMAKER, web-based tool for background predictions**: High-fidelity signal and background simulations;
- ✓ **Boulby site**: Confirmation of the geologic suitability of cavern space;
- ✓ **PMT studies**: Identification of suitable low activity, high efficiency photomultiplier tube meeting all requirements for deployment



[graphic by A. Kibayashi]



Multiplicity and Recoil Spectrometer (MARS) (Sandia) submitted to PRL



WATCHBOY 40 ton water detector

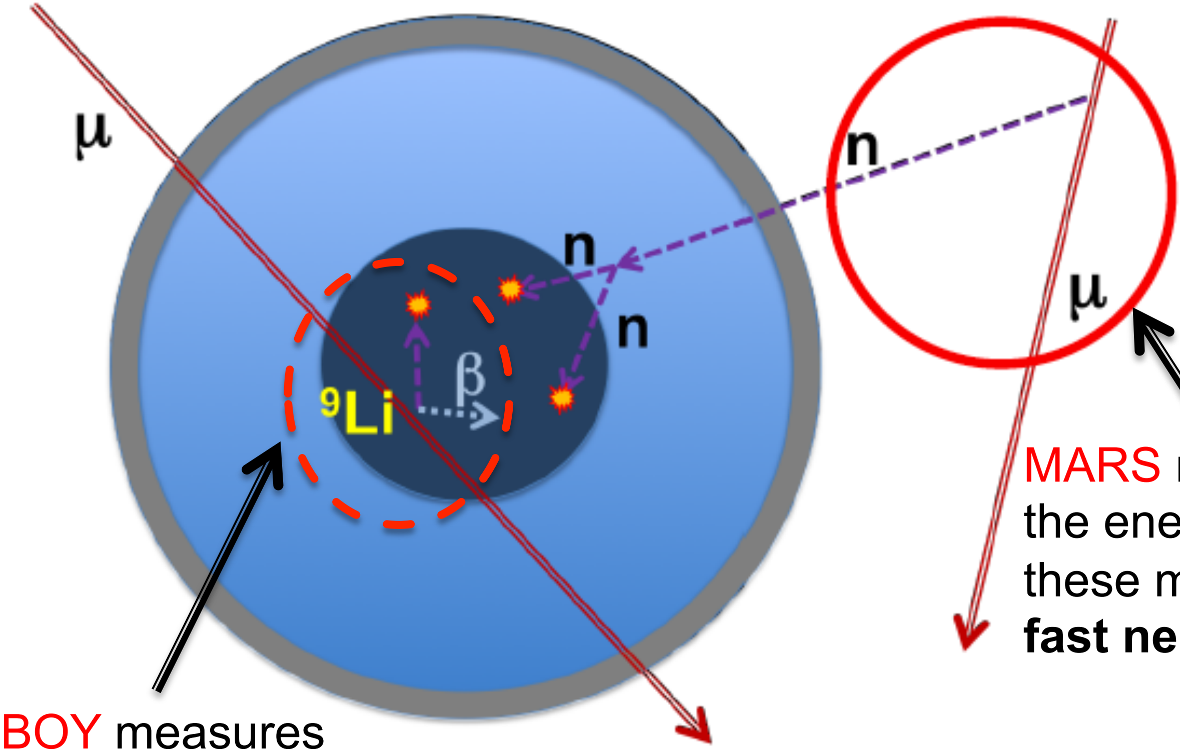
Backgrounds in large gadolinium doped water detectors – how else can we get two flashes of Cherenkov light in ~100 μsec ?

1: long lived radionuclides

2: fast neutrons

3: coincidences of:

single gamma-rays,
neutrons,
muons,
radon...



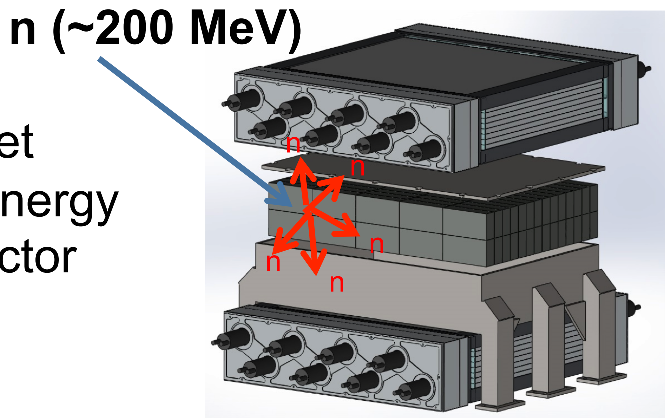
MARS measured the energy of these muogenic **fast neutrons**

WATCHBOY measures the production rate in water of these muogenic **long-lived radionuclides**

Our depth-dependent measurements of high energy neutrons have shown these backgrounds are manageable

MARS:

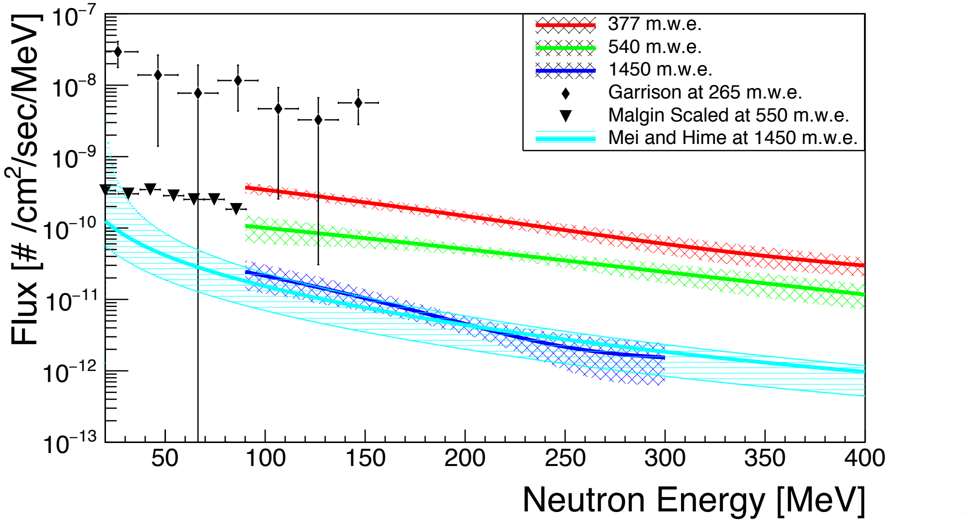
- Multiplicity and Recoil Spectrometer
- Measures **muogenic neutron spectrum**
- Fast neutrons induce multiple neutrons in a lead target
- Neutron multiplicity correlates with incident neutron energy
- First ever variable depth measurement with one detector
- Necessary to understand backgrounds in large water detectors like WATCHMAN



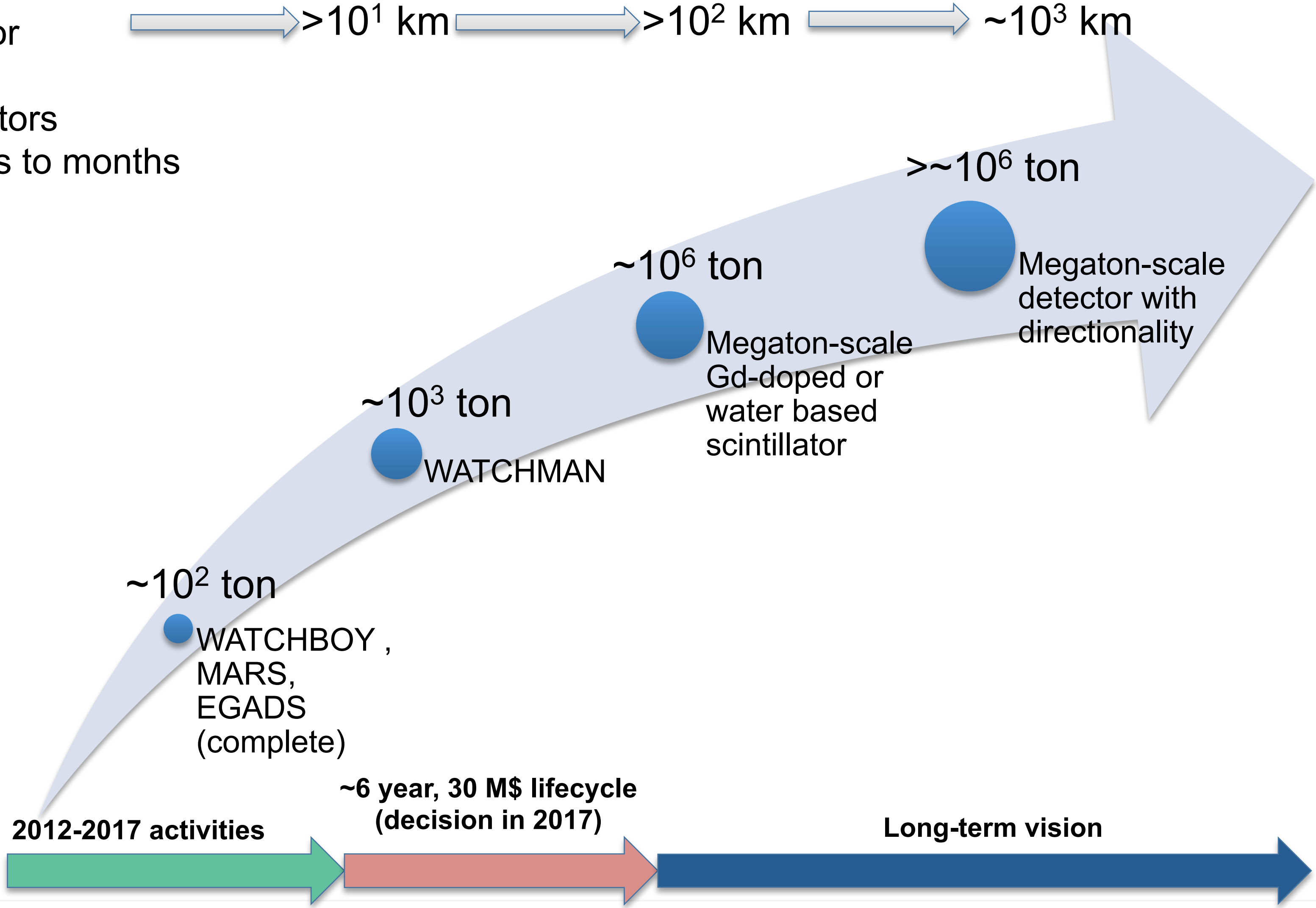
Key result: benchmarks the “industry standard” Mei and Hime model

(PRD 73 (2006) 053004)

Paper submitted to PRL May 2017



Long term vision



Standoff for
finding
small reactors
within days to months

$>10^1$ km → $>10^2$ km → $\sim10^3$ km

$\sim10^2$ ton

WATCHBOY ,
MARS,
EGADS
(complete)

$\sim10^3$ ton

WATCHMAN

$\sim10^6$ ton

Megaton-scale
Gd-doped or
water based
scintillator

$>\sim10^6$ ton

Megaton-scale
detector with
directionality

2012-2017 activities

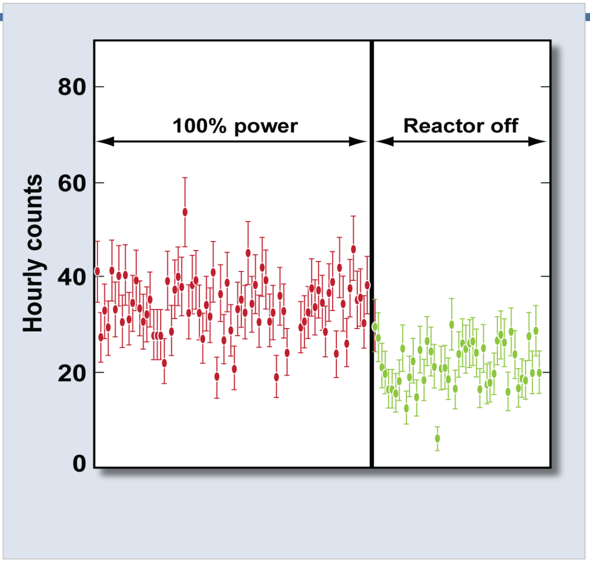
~6 year, 30 M$ lifecycle
(decision in 2017)

Long-term vision

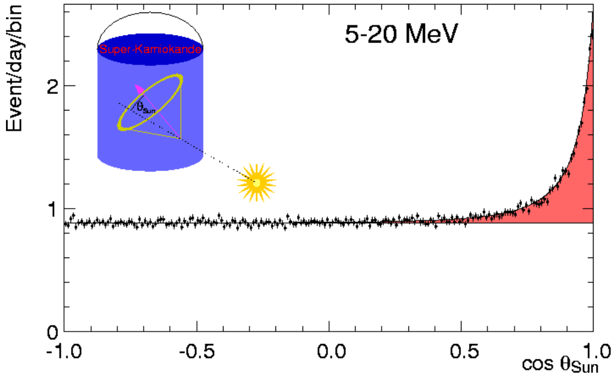
Backup Slides

Detailed characterization of backgrounds could shorten time to discovery

- Baseline goal: observe reactor transition – low risk of failure



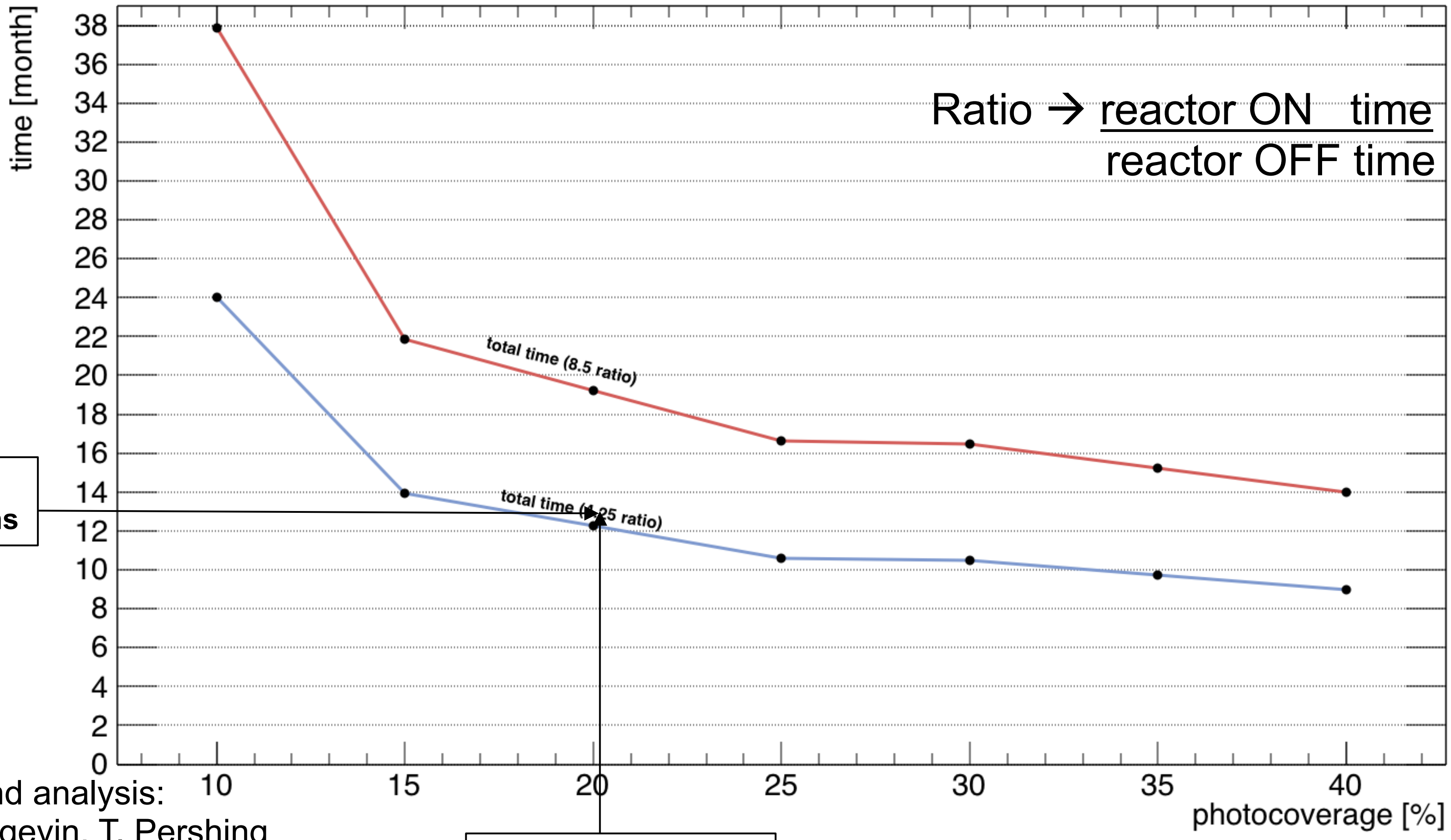
- Opportunity: More nonproliferation impact if we <u>don’t have to wait for a transition</u>
- Stretch goal: calibrate so precisely that a high confidence determination of reactor presence is possible <u>without</u> waiting for a transition
- Worked example: Using directionality, SuperKamiokande, a water-based neutrino detector in Japan, sees the sun in solar neutrinos clearly - without waiting for it to turn off !
- Partially worked example: dark matter detectors operate in an analogous way



time to observe reactor transition depends on PMT count

Average number of months to three sigma observation of transition -

Determined by detection efficiency - and thus by how many photomultiplier tubes we use



Ratio → $\frac{\text{reactor ON time}}{\text{reactor OFF time}}$

12.5 months

20 % PMT coverage

Plot and analysis:
M. Bergevin, T. Pershing