Antineutrino Detection based on ^{6}Li-doped Pulse Shape Sensitive Plastic Scintillator

or more generally…
New Techniques in antineutrino detection

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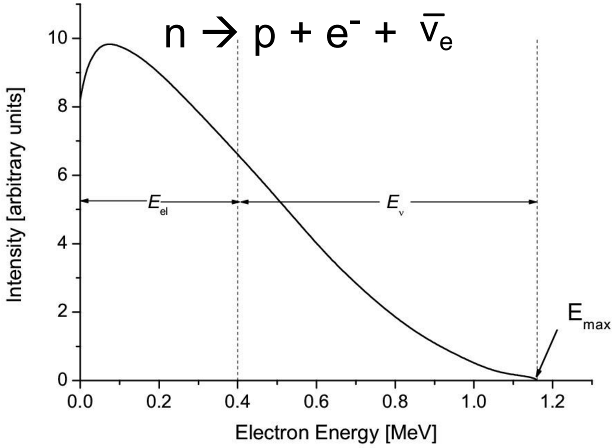
Antineutrino detectors for science – short history

“I have done a terrible thing,
I have postulated a particle
that cannot be detected”

1930 – neutrino (called the neutron here) was proposed by Wolfgang Pauli in a famous letter

Dear radioactive ladies and gentlemen,
As the bearer of these lines [...], I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, […]. The continuous *β*-spectrum would then become understandable by the assumption that in *β* decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant……..



Division of energy between electron
And antineutrino

But it was detected 26 years later
(Reines and Cowan – 1956)

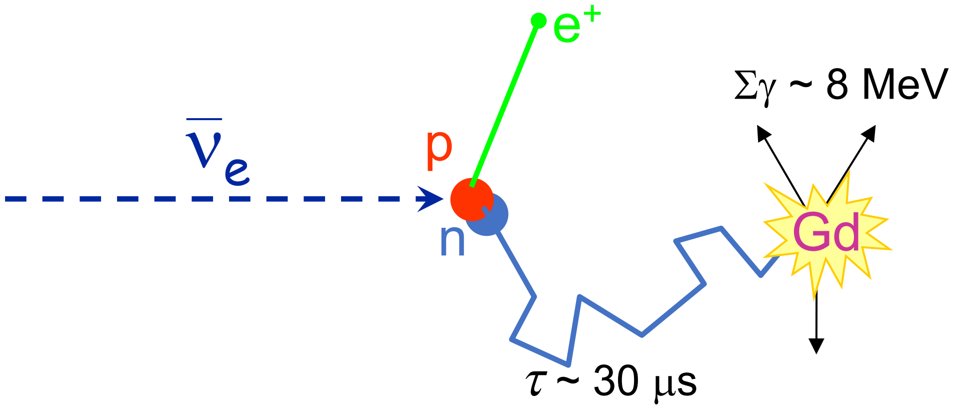
Signal/background ~ 3:1
~3GWth “P” reactor at Savannah river
Baseline 11 meters

Detection method
Inverse beta decay

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

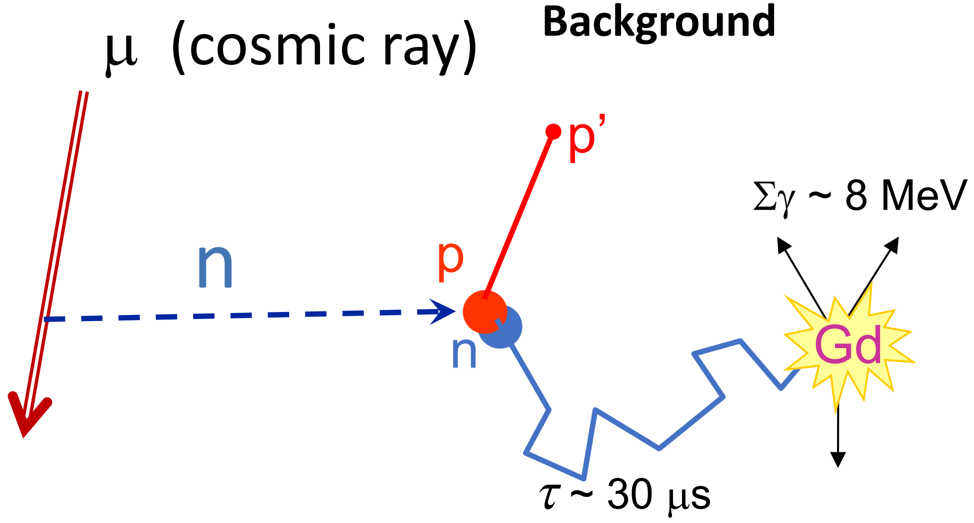
Inverse beta decay - Backgrounds

Signal



prompt e^+ signal + n capture on Gd

Background

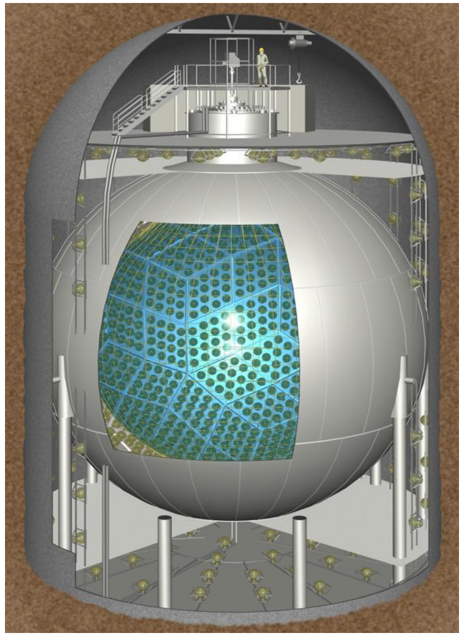


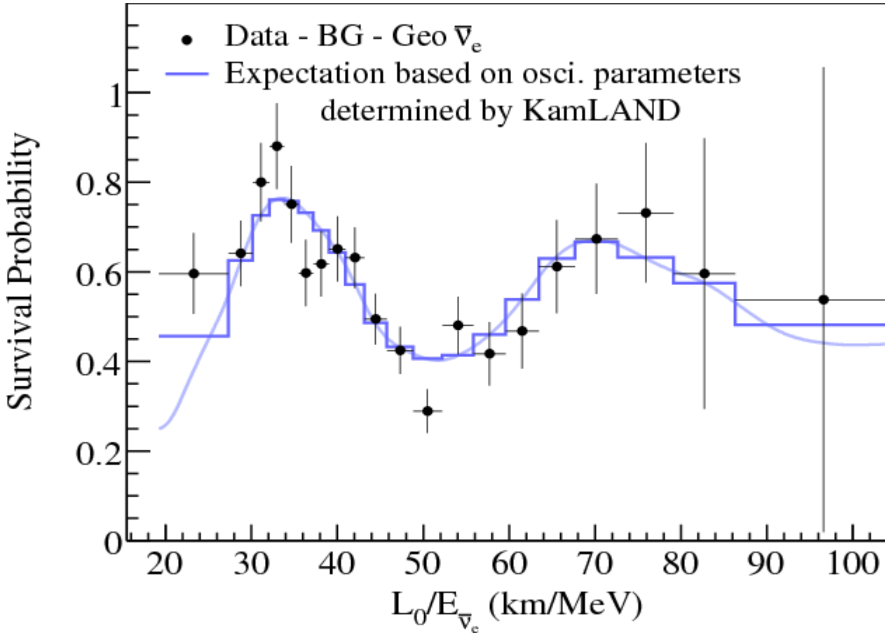
Prompt recoil signal + n capture on Gd

- Problem:
  - High-energy muogenic neutrons are a key background for all antineutrino detectors
- Present day solution:
  - Detector **UNDERGROUND**
  - **most of detector volume is neutron shielding**

Antineutrino detectors for science – short history

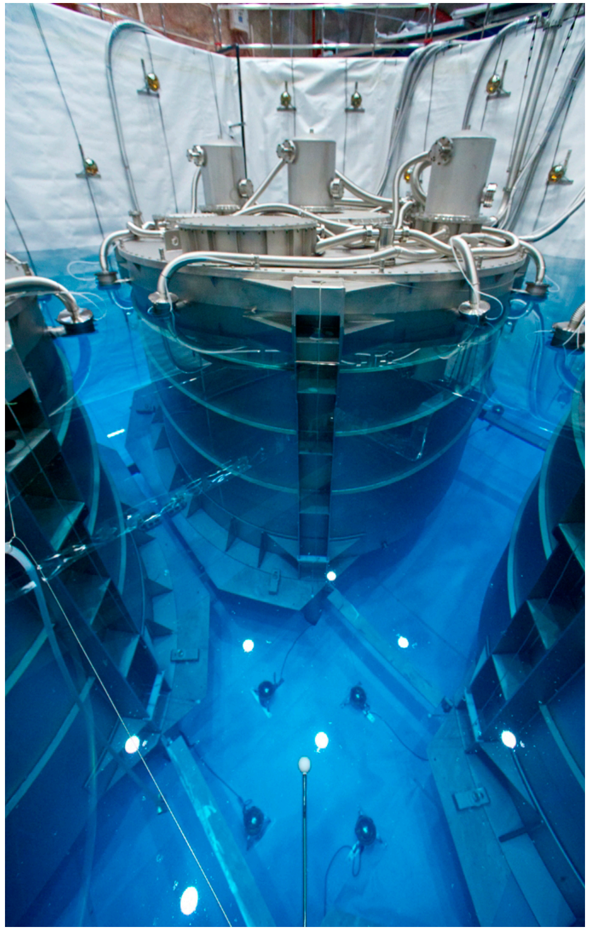
KamLAND – 1kton
First measurement of $\boldsymbol{\theta}_{12}$ oscillation



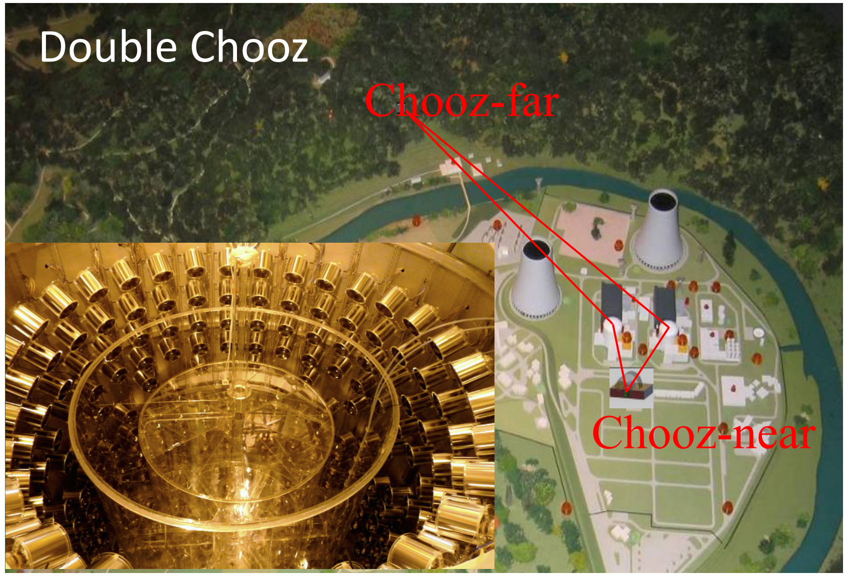


KamLAND – First successful long baseline (~100 km) detection of reactor antineutrinos
Signal/background ~50:1

Antineutrino detectors for science – short history



Daya Bay experiment



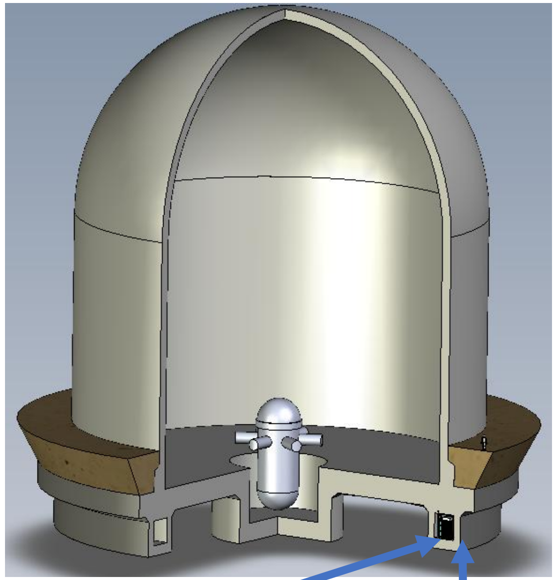
RENO experiment

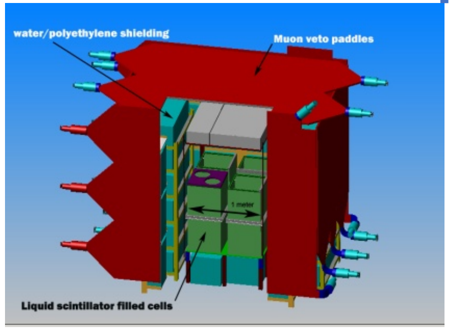
Double Chooz, Daya Bay, RENO

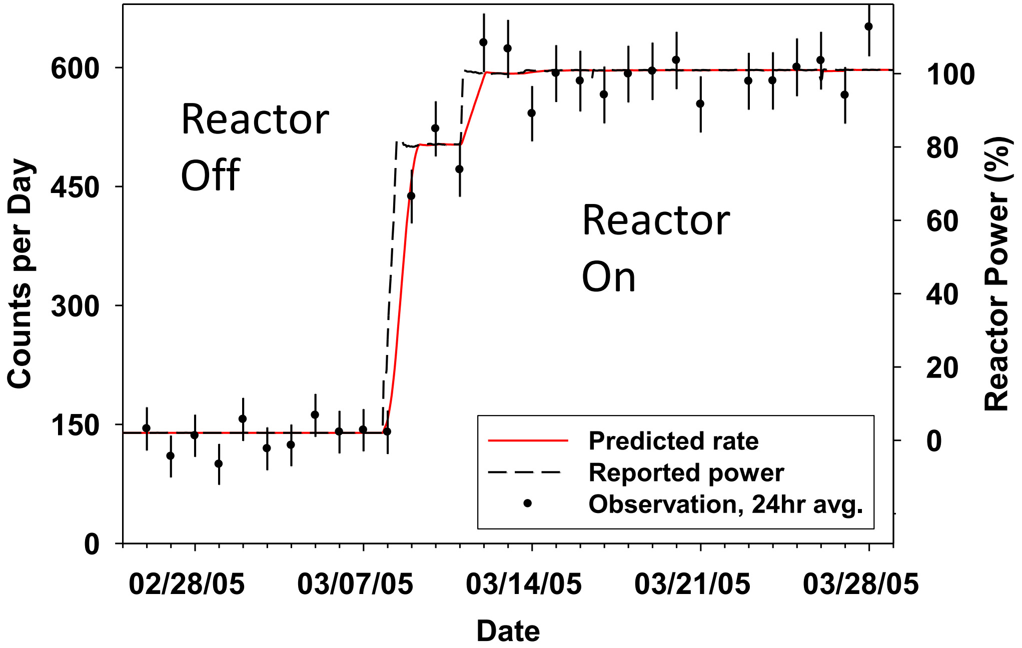
- Simultaneous measurements of reactor antineutrino fluxes from multiple baselines
- “near” and “far” – where “far” = ~1km
- Systematic differences between “near” and “far” detectors ~ 0.1%
- $\boldsymbol{\theta}_{13}$ oscillations discovered and measured to remarkable accuracy
- Signal/background levels remarkably good – ~45:1 (at Double Chooz). Others similar
- Experiments protected from cosmic ray induced neutrons by depth (~few hundred m.w.e.)

Antineutrino detectors for reactor monitoring

SONGS experiment





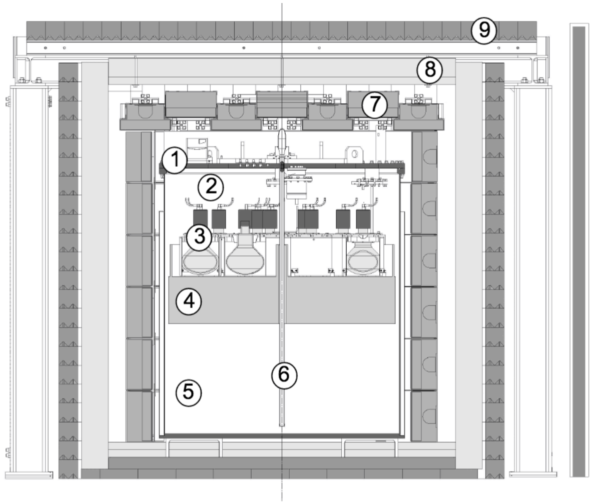


Note:

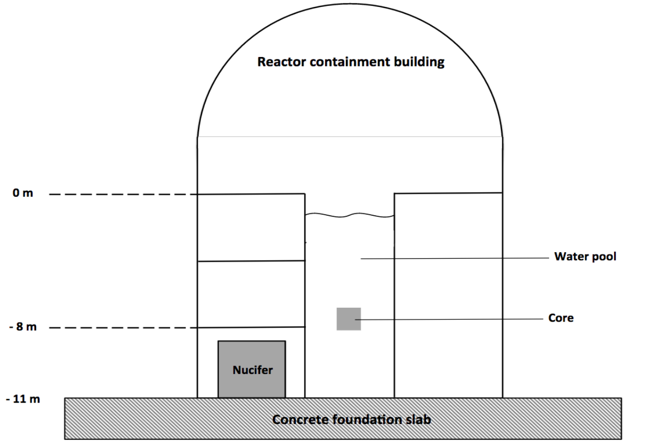
- 25m from a 3.5 GWt core. Situated just outside containment
- 0.6 ton active volume
- 20 meters water equiv. shielding against cosmic ray induced fast neutrons
- Signal/Background ~ 4/1

Antineutrino detectors for reactor monitoring

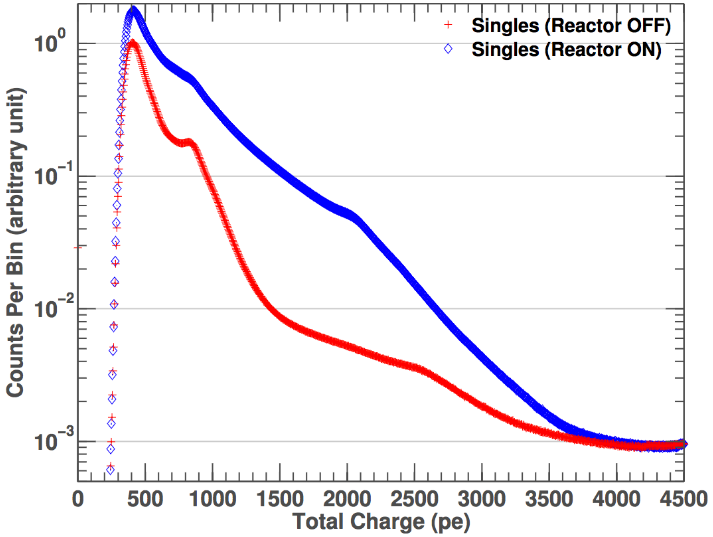
Nucifer – research reactor (@65 MWth). (arXiv:1509.05610)



① Stainless steel tank Teflon coated
② Nitrogen atmosphere
③ 16 PMTs
④ Acrylic buffer
⑤ Target Liquid (0.8 m³)
⑥ Calibration tube
⑦ Cosmic ray veto
⑧ 14 cm B-doped polyethylene
⑨ 10 cm Lead



Nucifer
7.2 m from core inside containment



Pairs (/day)	ON	OFF
Candidates	4903 ± 7	1223.5 ± 3.4
Accidentals	3476.3 ± 0.7	69.1 ± 0.1
Correlated	$1426 \pm 7 \pm 18$	$1145.4 \pm 3.4 \pm 2.5$
R_ν^{obs}	$281 \pm 7(\mathrm{stat}) \pm 18(\mathrm{syst})\, \overline{\nu}_e/\mathrm{day}$	

Note (much more challenging measurement than SONGS):

- Detector above ground – unprotected from fast neutrons
- Inside containment (high reactor correlated gamma ray backgrounds)
- Reactor was a low power research reactor

Remarkable that despite low power and difficult background environment, the antineutrino signal was **still** detectable
Nevertheless, the low signal to background ratio (~1:4) highlights the challenges involved

Takeaway – Status of Current Technology

Short Baseline:

- We need detectors with better signal/background (near reactor and unprotected from fast neutrons on surface)
- Cooperative reactor monitoring (IAEA) may not become widely used until these background issues are solved
- Need to enable consistent performance at any location

Long Baseline:

- Deep detectors have very good signal/background
- But there is an important limitation of current technology

Next-gen Short Base-line Sensitivity Improvements

(Focus: directionality and neutron-gamma-ray discrimination)

aim: use new PSD sensitive plastic scintillator to provide antineutrino flux directionality, and improve background discrimination

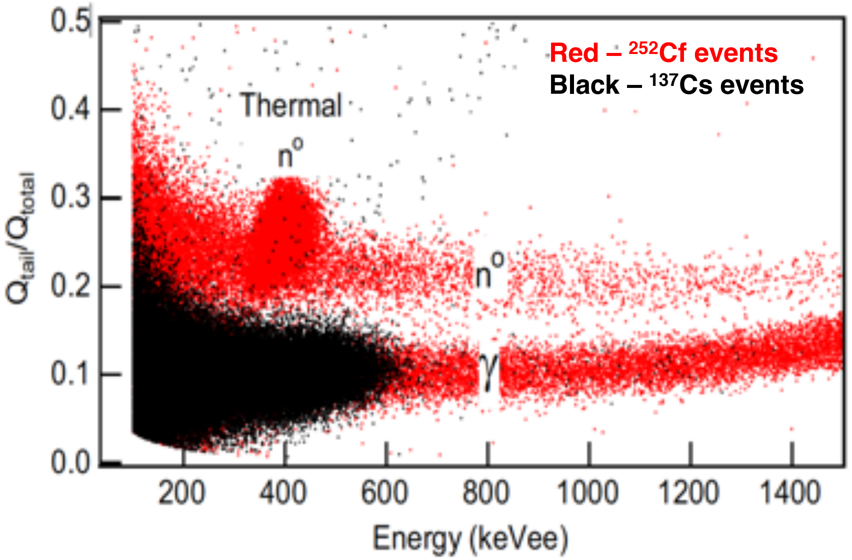
New PSD plastic scintillators are disruptive. They enable:

- Neutron-like/gamma-ray-like PSD differences
- Particle track length sensitivity
- High-fidelity position sensitivity
- antineutrino direction sensitive
- annihilation gamma-ray identification

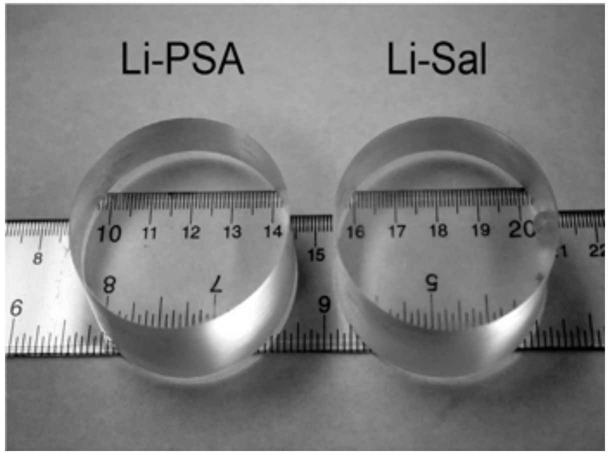
ALL-OF-THE-ABOVE strategy is now possible

Project aim: Develop both scintillator and data readout needed to make this concept a reality. Then test it.

N. Cherepy et al. NIMA,
V778, P126, (2015)



A. Mabe et al. NIMA
V806, P80, (2016)



Next-gen – Improving Short Base-line Sensitivity

(directionality and neutron-gamma-ray discrimination)

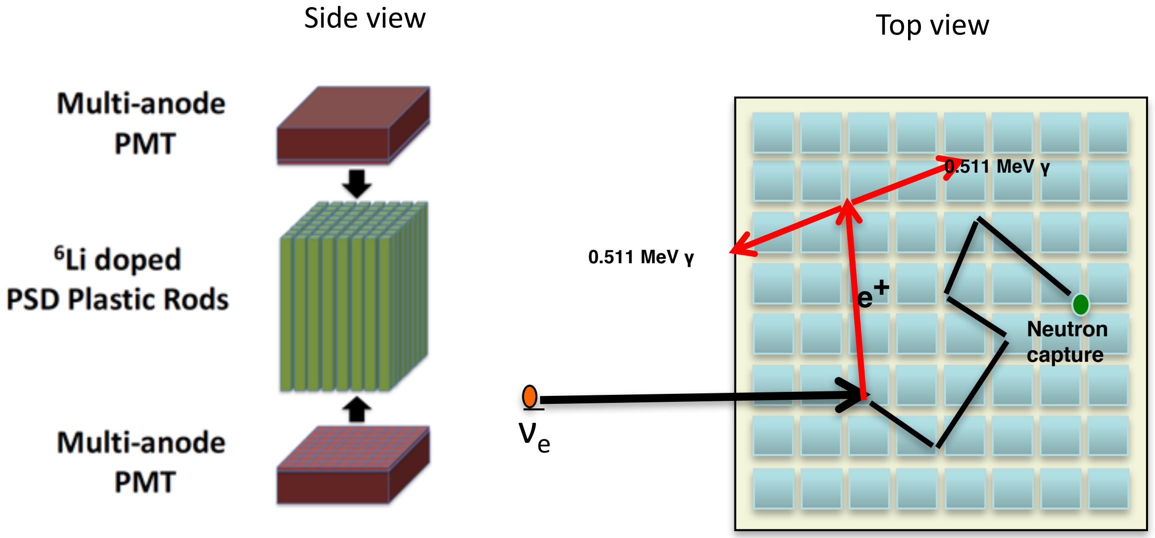
Concept:

Above ground reactor antineutrino detection with less shielding using new scintillator materials developed at LLNL

Antineutrino inverse beta decay (IBD) interaction

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

Detector Concept



Plastic form of ^{6}Li PSD scintillator enables a highly segmented, position sensitive readout.
Which is excellent for antineutrino detection, also for neutron imaging

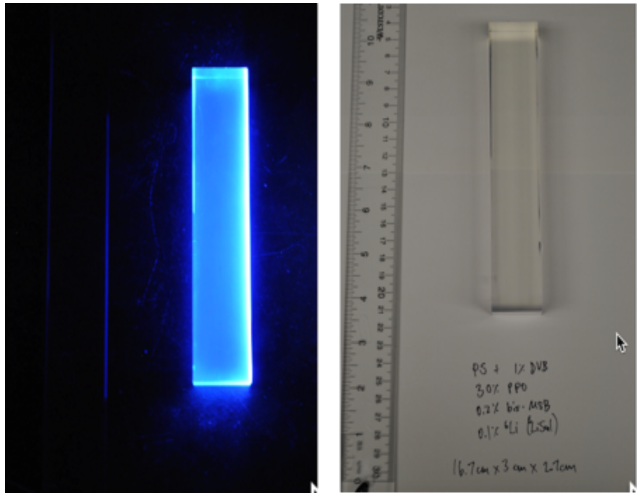
IBD event topology

Positron → multiple contiguous rods
.511 MeV gamma-rays → small non contiguous energy deposits
Neutron capture → single rod event, PSD also indicates neutron capture

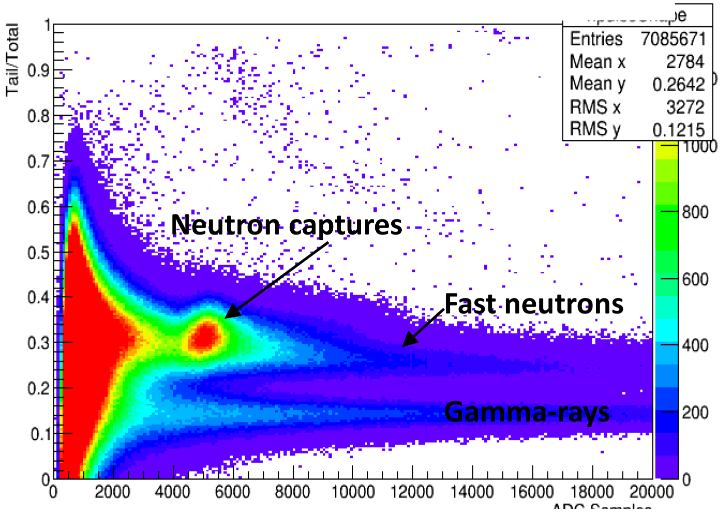
PSD plastic R&D Status

(need longest possible sections of PSD plastic to enable large detector volumes)

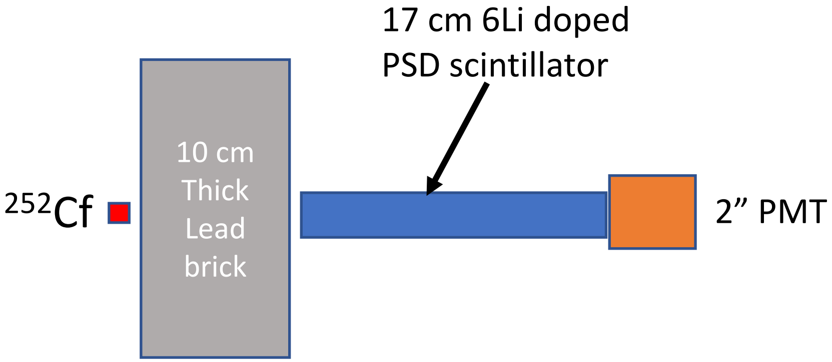
First ^{6}Li doped sample (Sample #9126)



Neutron/gamma-ray Pulse shape



Light propagating from end to end
Light levels are sufficient for PSD at 17 cm



17 cm 6Li doped PSD scintillator

^{252}Cf

10 cm Thick Lead brick

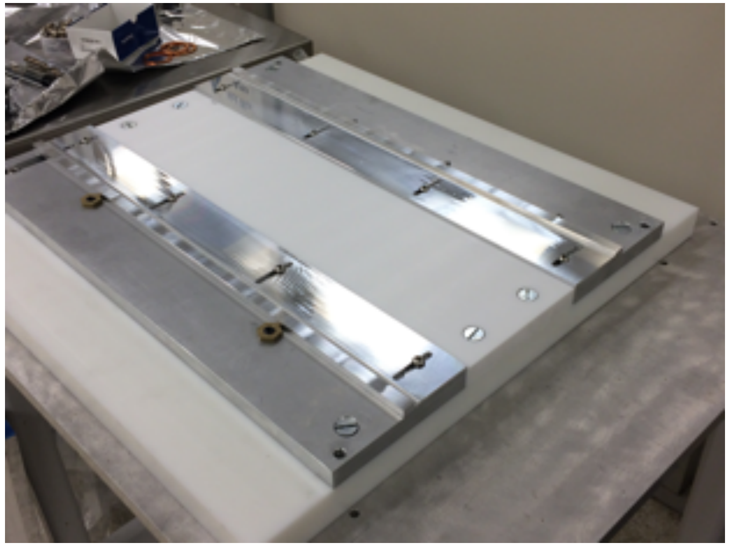
2” PMT

First 17 cm samples of ^{6}Li doped PSD plastic have been produced → Light propagation is okay (better than expected at this stage) improving with every sample.

Problems/Issues:

1. Cloudy lithium complex – slight improvement with every sample so far
2. edge bubbles – testing possible mitigations.
3. Slightly soft plastic – will tackle this after above issues

Polishing table: for batches of scintillator rods
(max length 50 cm)



Deployment Plans (tentative)

3GWt Reactors at North Anna in Virginia

- Deployment → ~ early 2019.
- ~5 modules → 2-5 liters of central detector

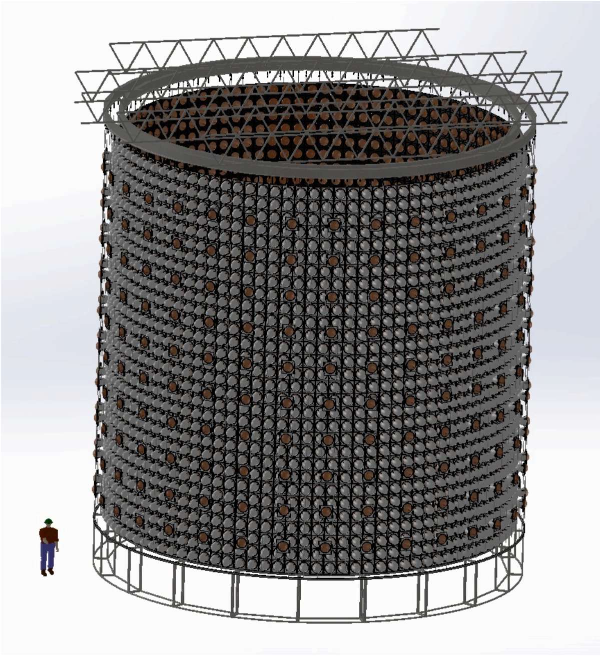
  plus a full moderating shield
- Possible in same container as NULAT experiment
- Deployment above ground

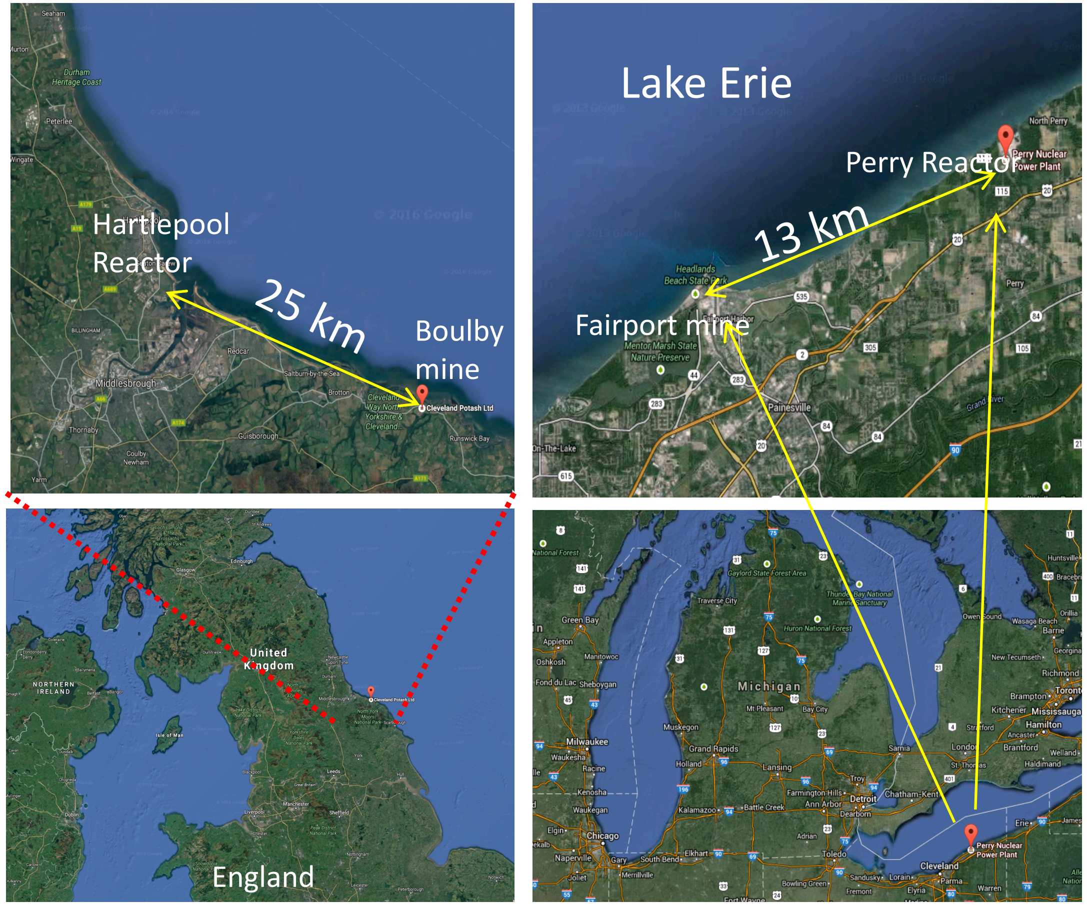
Virginia, USA

Long baseline experiments (WATCHMAN). See Adam Bernstein's talk next…

Aim: demonstrator for a technology scalable to megaton size range
(which would be needed for >100 km reactor detection)

2 deployment options under active consideration





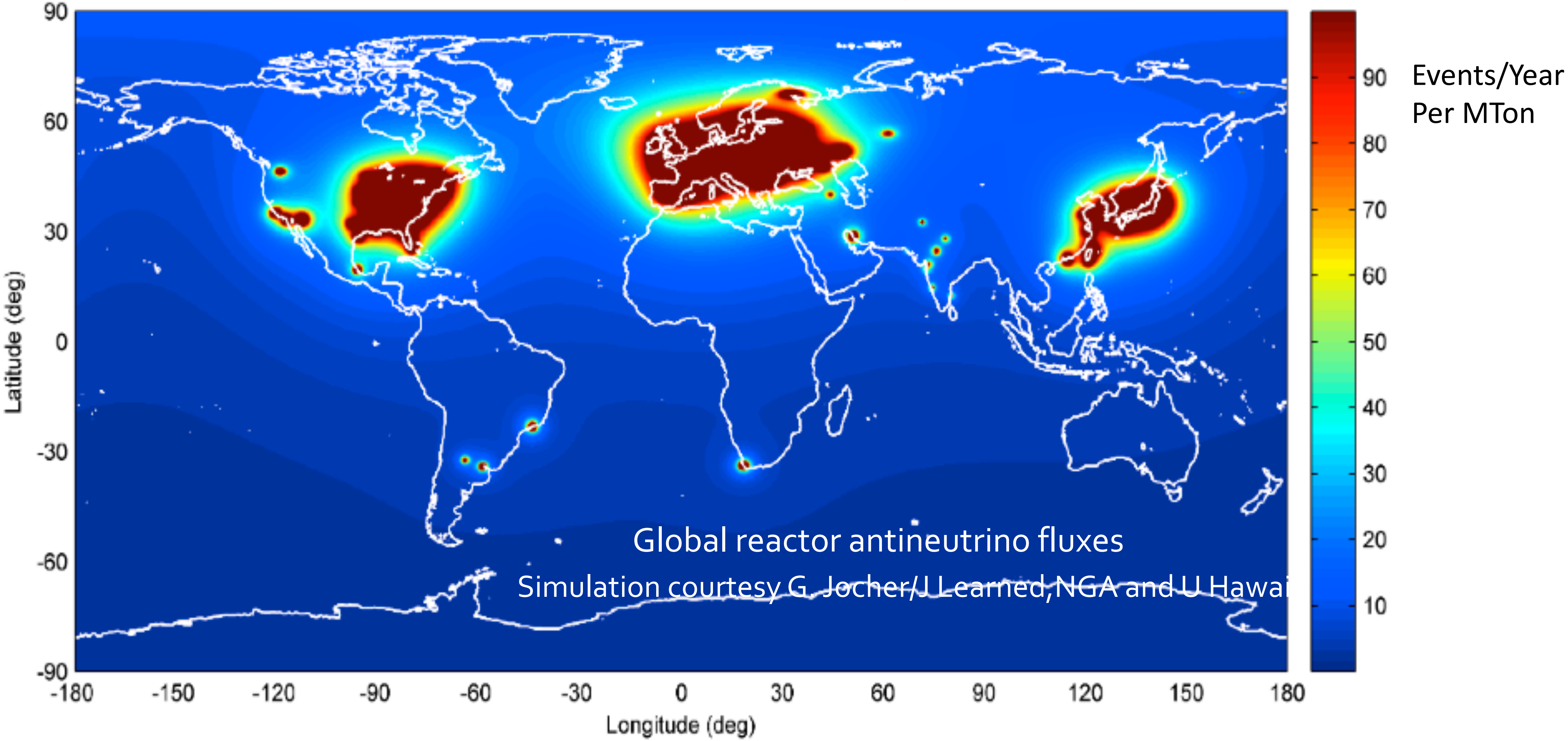
- 15.8 meter total diameter.
  3.1 ktons Gd-doped water
- PMT support structure 13.8 meter diameter
    - 2.1 kiloton target
    - 1 kiloton fiducial
    - 1.5 meter buffer
    - low-background PMTs

At Fairport, OH, USA:
- 1500 m.w.e. overburden
- 13 km standoff, 3.758 GWth reactor

At Boulby, England:
- 2800 m.w.e. overburden
- 25 km standoff, 2 x 1.5 GWth reactor

Why Directionality is Important at Long Baselines

(KamLAND results indicate that main source of backgrounds will in fact be other nearby reactors)

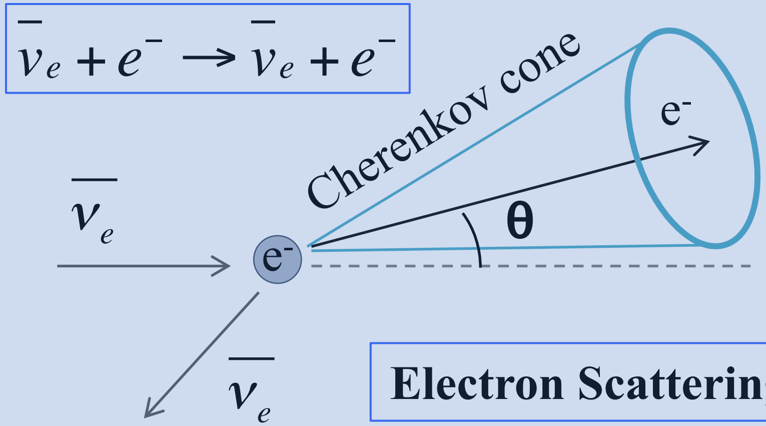


Global reactor antineutrino fluxes

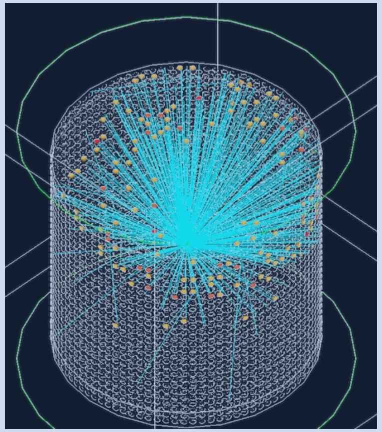
Simulation courtesy G. Jocher/J Learned,NGA and U Hawai

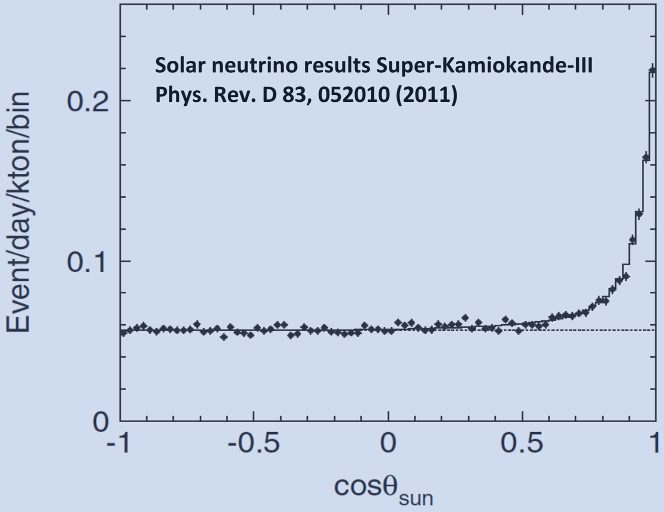
Long range Directionality

$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$



Electron Scattering



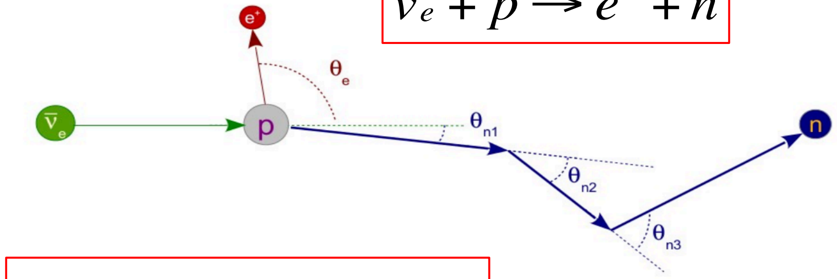


Solar neutrino results Super-Kamiokande-III
Phys. Rev. D 83, 052010 (2011)

Water-Cherenkov + gadolinium is minimum requirement

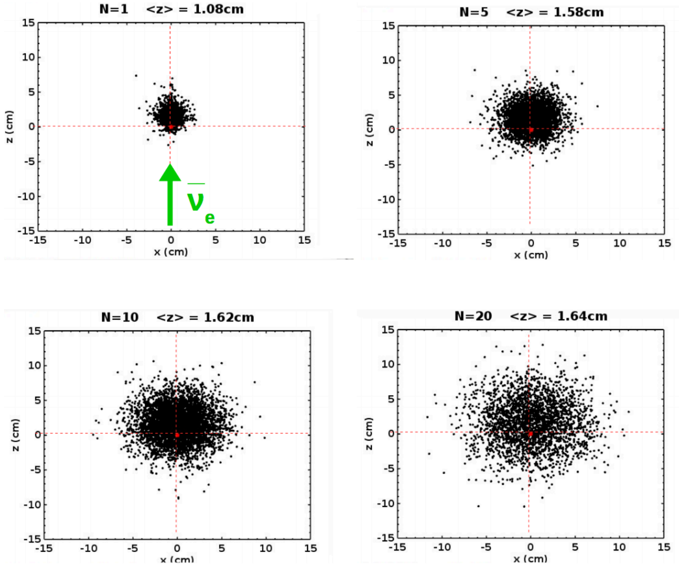
Testable at WATCHMAN !!

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



Inverse Beta Decay

E. Caden (AAP, 2012)



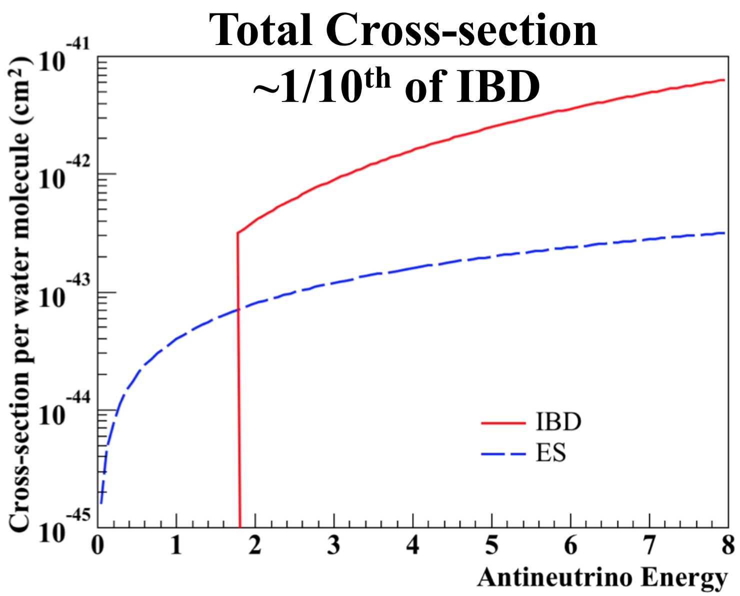
Very accurate position resolution (~1 cm) is minimum requirement

Expected Reactor ES Signal

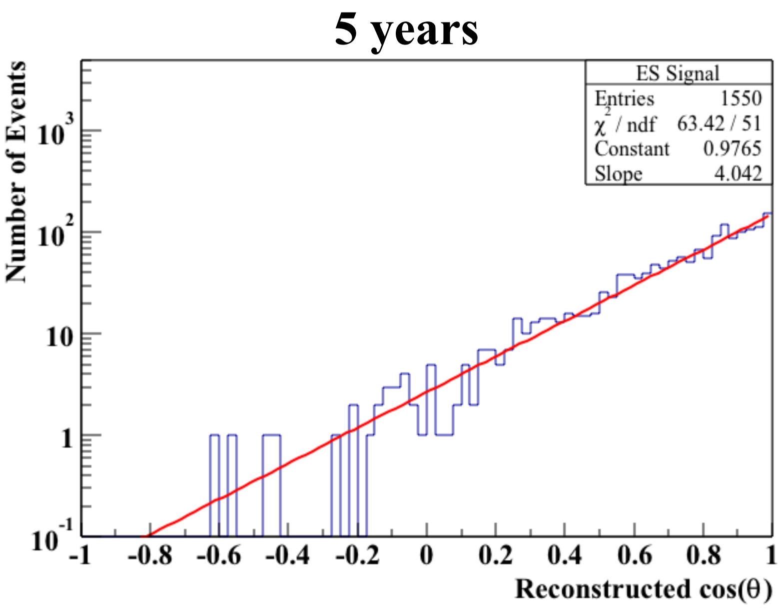
$$R_{\bar{\nu}_e/e^-} = \frac{N_e}{4\pi d^2} \sum_i f_i \int \phi_i(E_{\bar{\nu}_e})\sigma(E_{\bar{\nu}_e})dE_{\bar{\nu}_e}$$

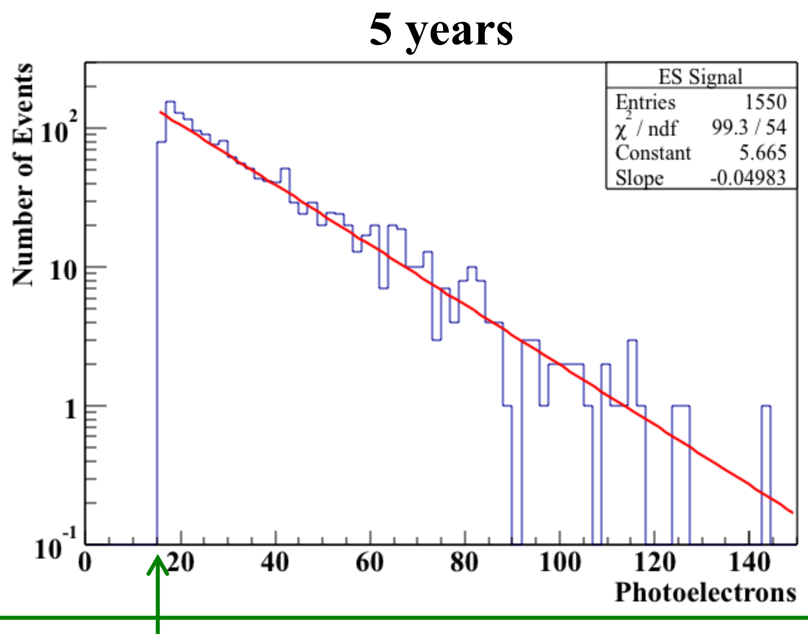
(~ 9270 events/5 years)

- Simulations done with GEANT4 simulation **RMSim**
    - Event reconstruction done with **BONSAI**


Total Cross-section

~1/10th of IBD


5 years


5 years

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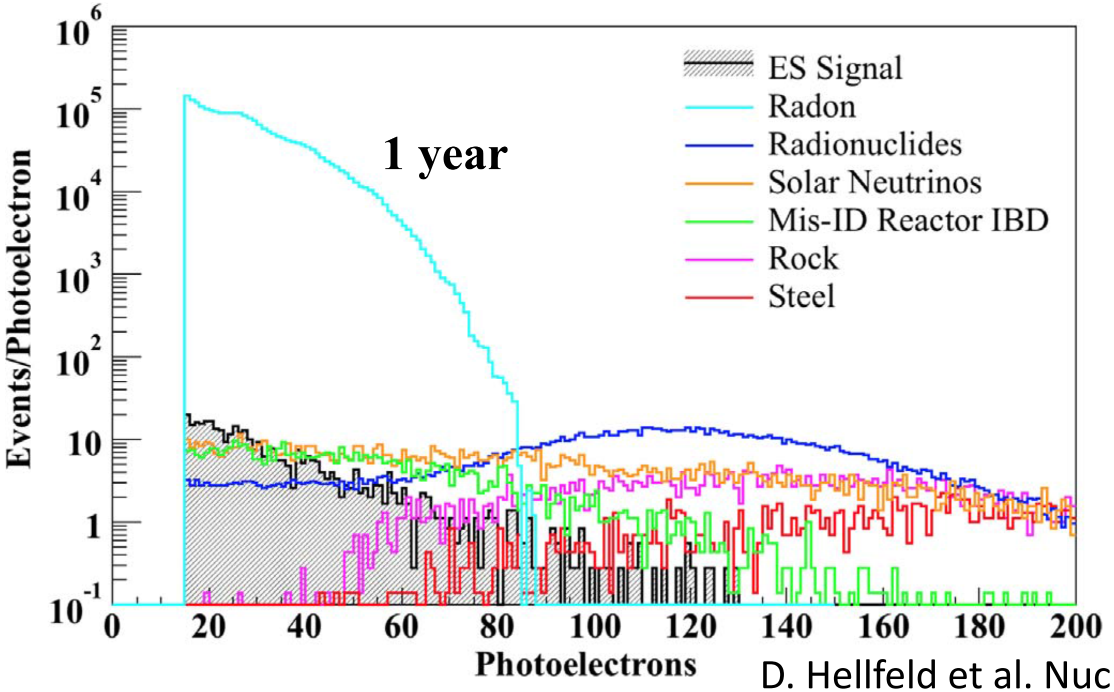
16 PE trigger threshold → 17% detection efficiency

Signal to Background

Assumptions: WATCHMAN at Fairport (13 km from Perry reactor)

- Steel/rock γ's and solar ν scaled from IsoDAR study on KamLAND
  - Take into account larger fiducial volume and different livetime

- Misidentified IBD interactions estimated assuming an event rate of 20 events/day and a 20% missed neutron rate



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Obviously radon dominates at SNO radon levels

Directional signal requirements:

→ Orders of magnitude further radon reduction needed

→ More overburden would also be helpful.

Steven Dazeley – Lawrence Livermore National Laboratory

^{238}U ….. ^{222}Rn ….. ^{214}Bi

Presence of radon gas in the water results in β-decay of ^{214}Bi → electron scatter-like background

Sources:

- Trace amounts of naturally occurring ^{238}U
- Radon gas migrating out of PMT glass
- Radon gas leaking into detector from mine air

- We estimated resulting WATCHMAN signal using the published best ^{238}U contamination of 10^{-14} gU/gD$_2$O (SNO)
  - Results in about 10,000 ^{214}Bi decays somewhere in the kiloton fiducial volume per day
  - Including our 67% livetime and a 20% detection efficiency results in **1350 events/day** (~ 2.5×10^6 events/5 yr)

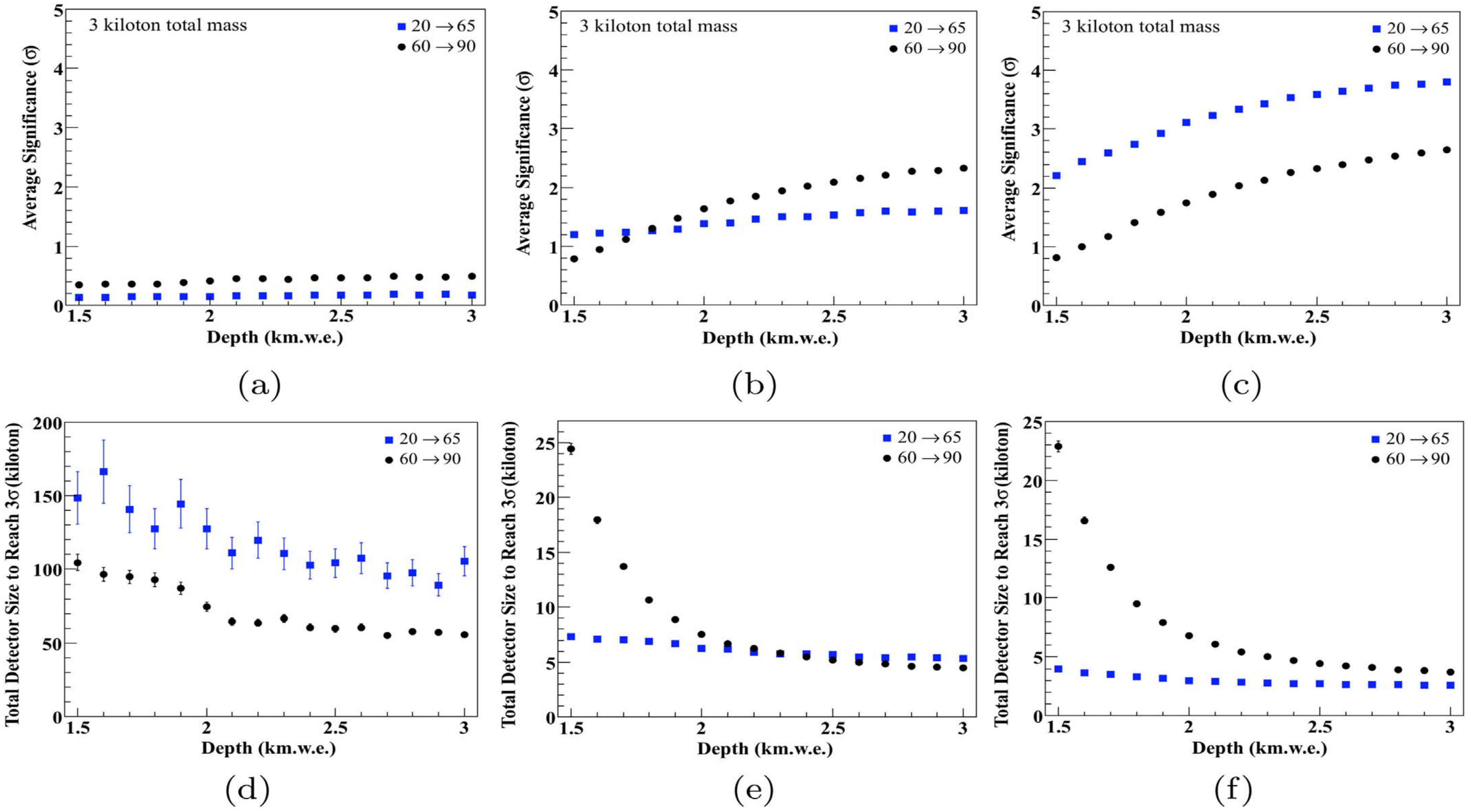
Takeaway – This is the major background
Progress must be made in radon removal

WATCHMAN Sensitivity as Function of Depth, Detector Response, and Radon Level

(Assumptions: detector located 13 km from Perry reactor)

WATCHMAN size detector

Larger detector sizes



(a) (b) (c)

(d) (e) (f)

1x SNO
Radon levels

10^{-2} x SNO
Radon levels

10^{-4} x SNO
Radon levels

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summary

- We are actively pursuing R&D into reactor antineutrino directionality and other improvements to reactor antineutrino sensitivity, via IBD and electron elastic scattering

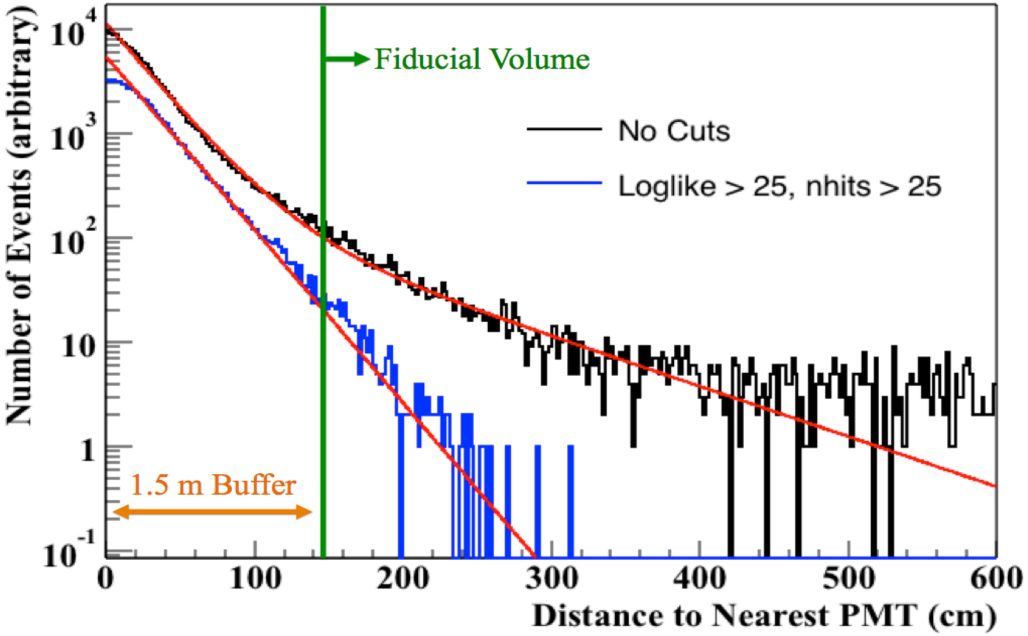
- Short range → primary background from cosmic-ray induced neutron/hadron correlated events.
  - Directionality + particle ID via pulse-shape, track length, etc could produce major improvements to background reduction
  - New PSD sensitive plastic offer the prospect of improved signal/background and above ground detection

- Long range → primary background is other nearby reactors. Directionality is needed.
  - We are exploring electron elastic scattering in gadolinium doped Cherenkov detectors. IBD events are identified via the neutron tag
  - Will require further improvements in water radon reduction
  - Radon R&D will be conducted at WATCHMAN towards this goal.
  - Deep detectors favored

Backups

PMT gamma-ray Backgrounds

- Mostly interact in buffer, however uncertainty in reconstruction can place them in the fiducial volume
- Bad reconstruction depends on detected signal



→ Use exponential behavior to estimate backgrounds

Takeaway – Background is heavily dependent on detector size.
Large detectors should be able to "fiducialize" PMT-based backgrounds to essentially zero

Outline

- Antineutrino detectors near and far
  - reactor antineutrino signal? Backgrounds?
  - What are the factors limiting signal/background for detectors at long and short base-lines?

- Prospects for improving sensitivity
  - Directionality
  - Particle ID via Pulse shape
  - Particle ID via track length
  - Particle ID via contiguousness of energy deposit