WATCHMAN
Project Overview and New Reconstruction Algorithms

HEP seminar
University of Edinburgh
12th February 2021

Core of Advanced Test Reactor, Idaho National Laboratory
https://commons.wikimedia.org/w/index.php?curid=27024528

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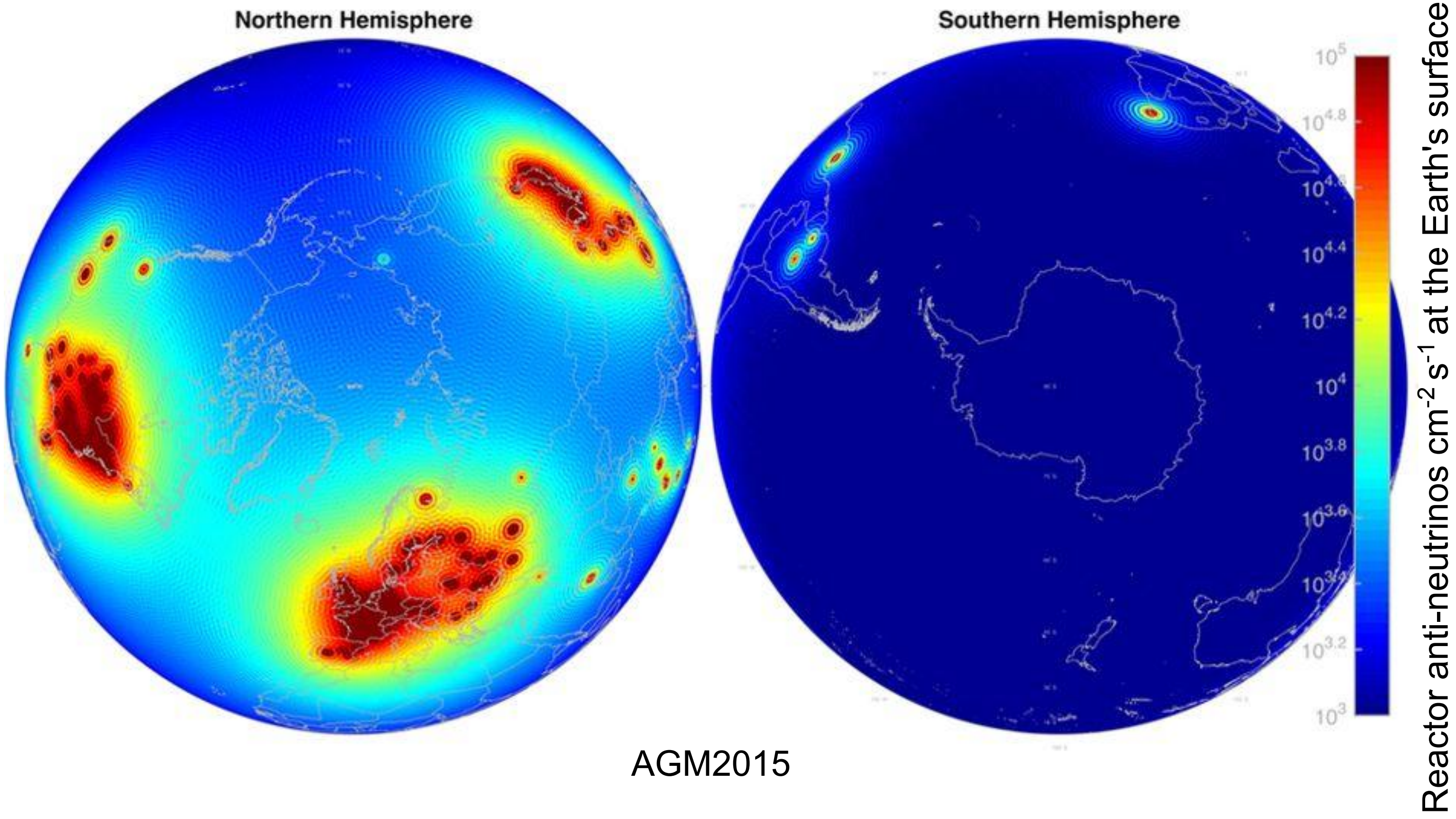
Contents

The Power Paradox

and Neutrinos for Non-Proliferation

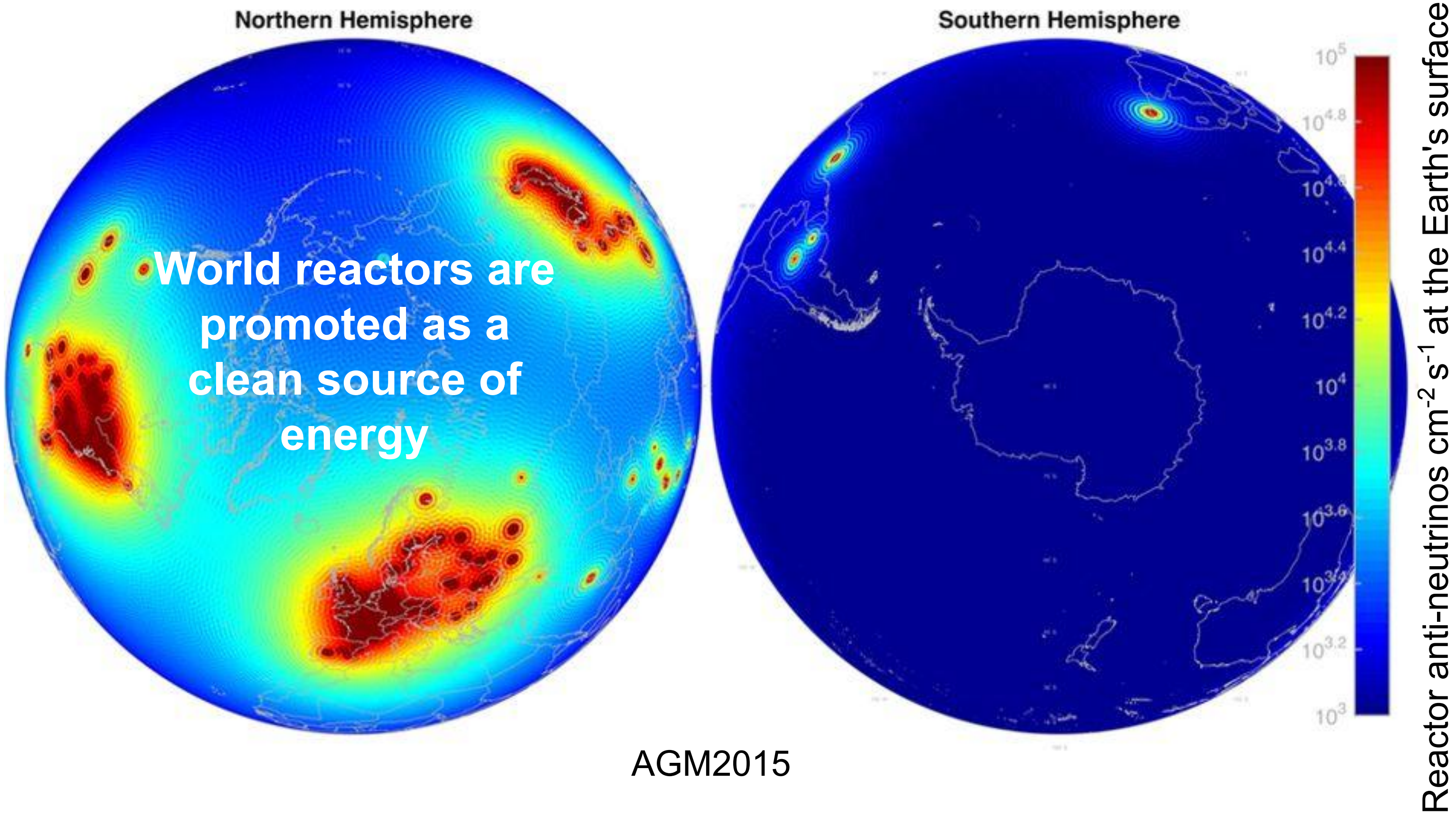
Proliferation of nuclear energy



AGM2015

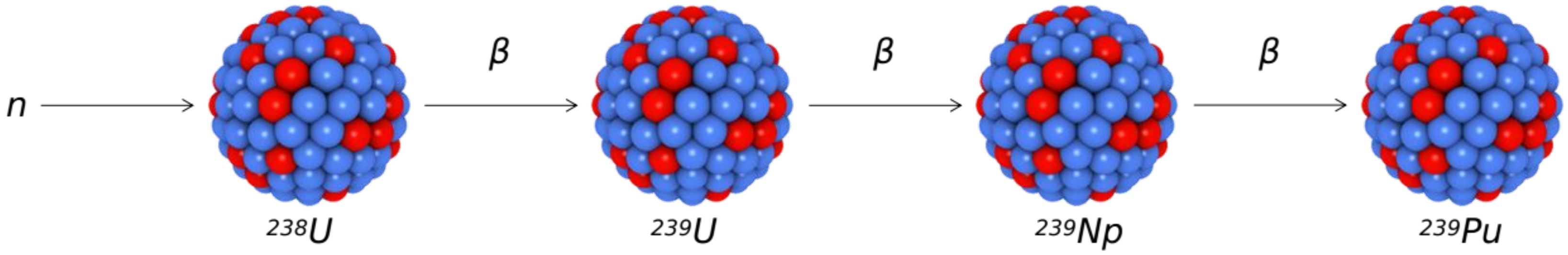
World reactors are promoted as a clean source of energy

Nuclear energy-weapons link



World reactors are promoted as a clean source of energy

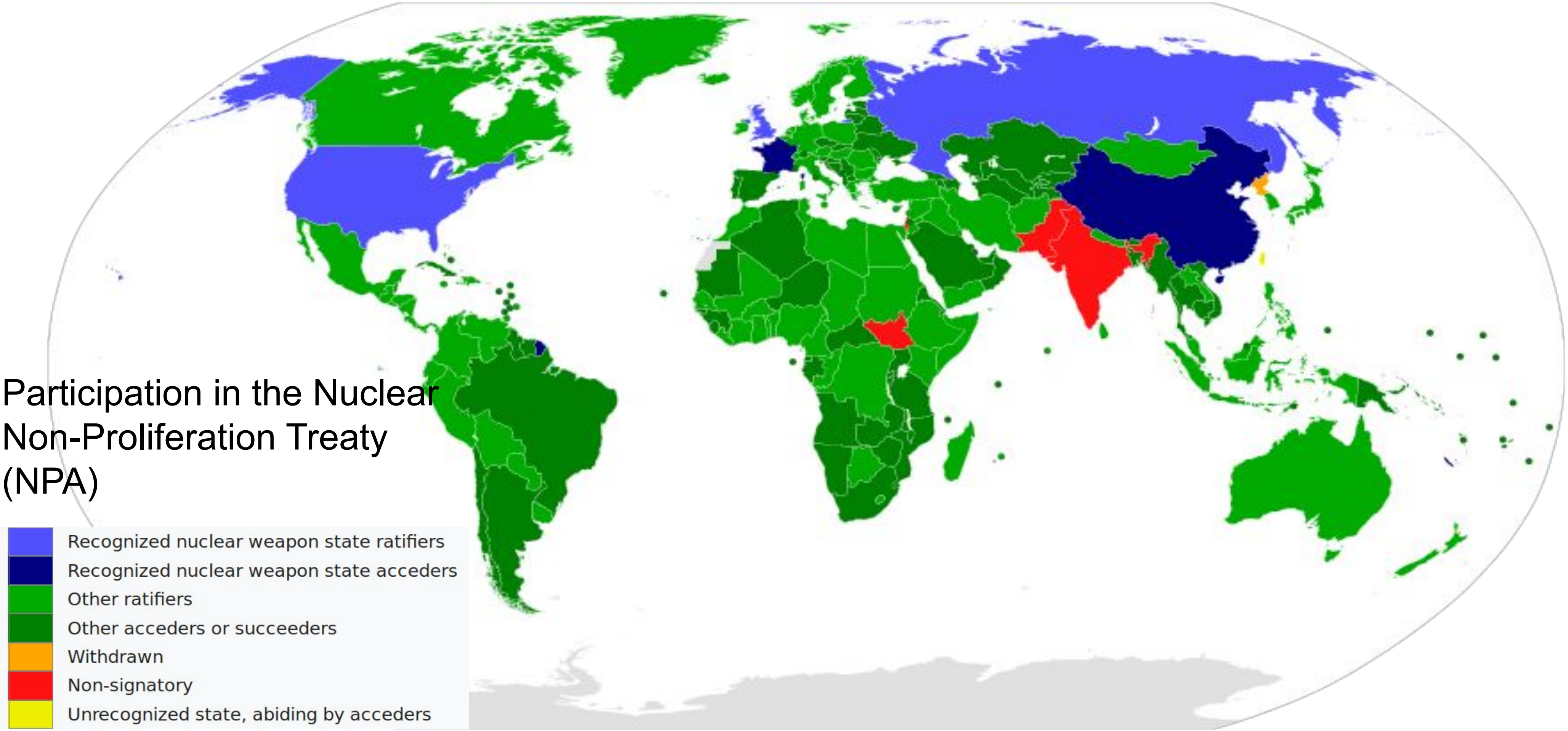
AGM2015



Inextricable link:

^{238}U can be converted to ^{239}Pu in a reactor

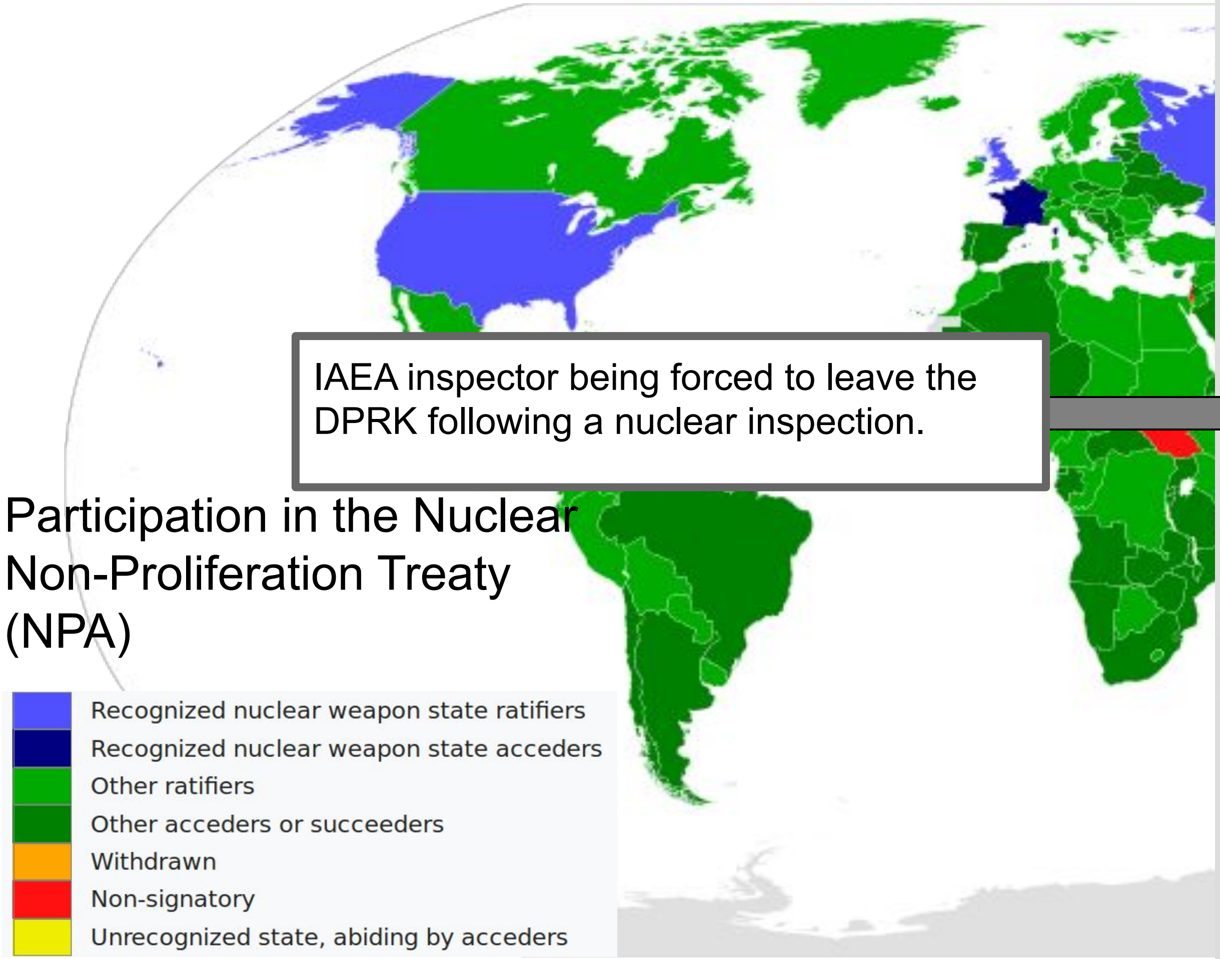
Remote monitoring supports NPT



Participation in the Nuclear Non-Proliferation Treaty (NPA)

Non-Proliferation Treaty supported by **Comprehensive Safeguard Agreements** provide the framework for monitoring nuclear reactors.

Intrusion and confidence in the balance



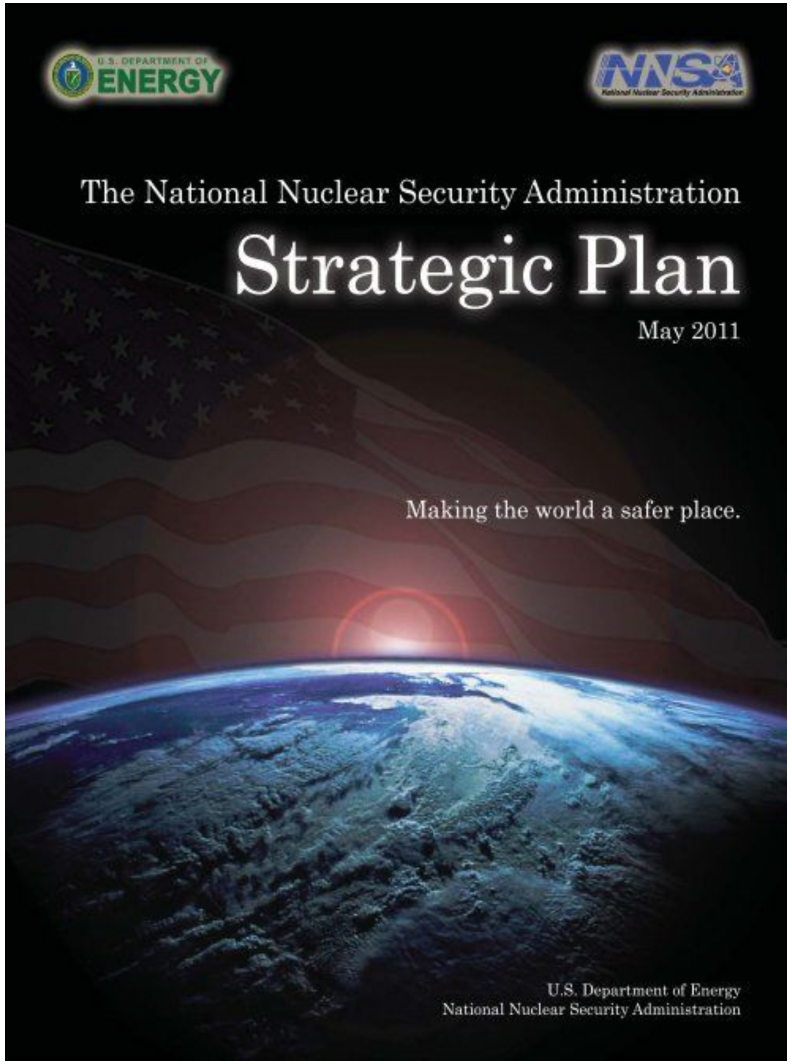
Participation in the Nuclear Non-Proliferation Treaty (NPA)

🟦 Recognized nuclear weapon state ratifiers
🟦 Recognized nuclear weapon state acceders
🟩 Other ratifiers
🟩 Other acceders or succeeders
🟧 Withdrawn
🟥 Non-signatory
🟨 Unrecognized state, abiding by acceders

IAEA inspector being forced to leave the DPRK following a nuclear inspection.

Signatory states may perceive inspections as intrusion and threat to national security.

Call for remote reactor monitoring



The National Nuclear Security Administration

Strategic Plan

May 2011

Making the world a safer place.

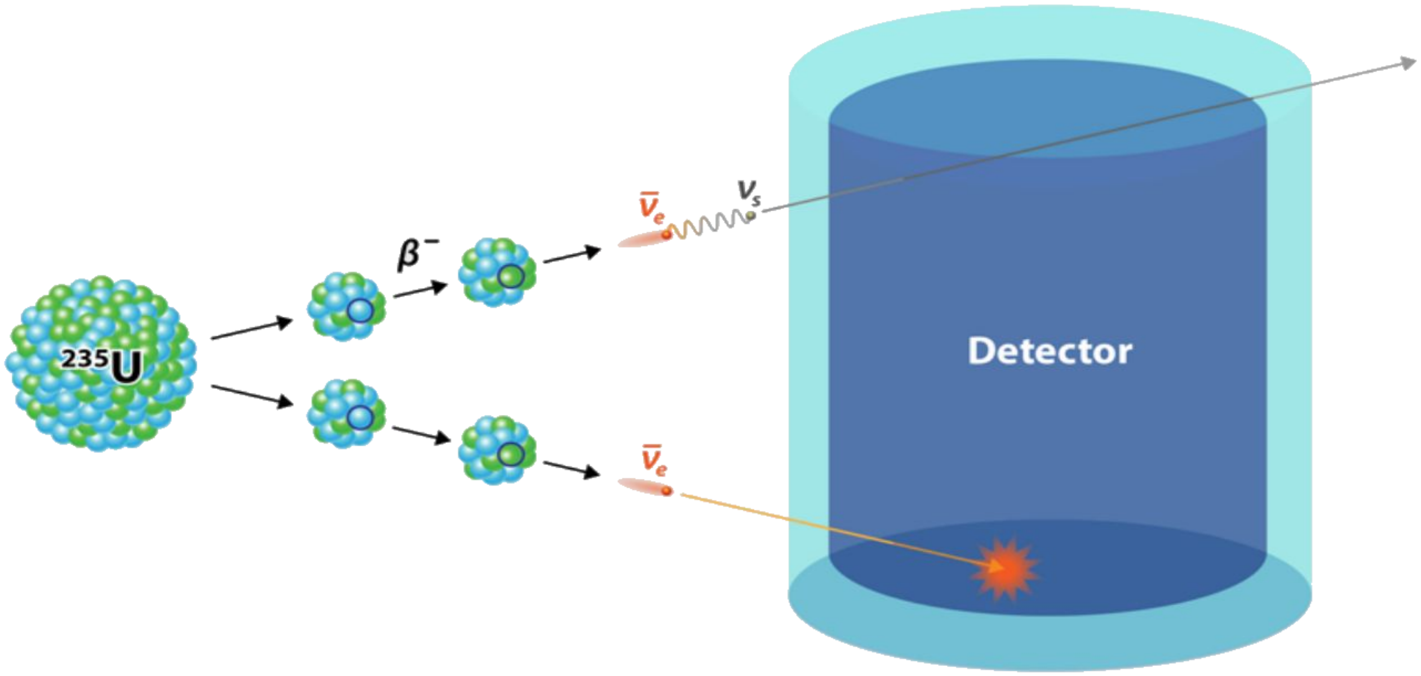
U.S. Department of Energy
National Nuclear Security Administration

“Demonstrate remote monitoring capabilities for reactor operations”

NNSA Strategic Plan, 2011

Big problem, small solution

Reactor anti-neutrino flux carries information about the power, location and composition of a core.



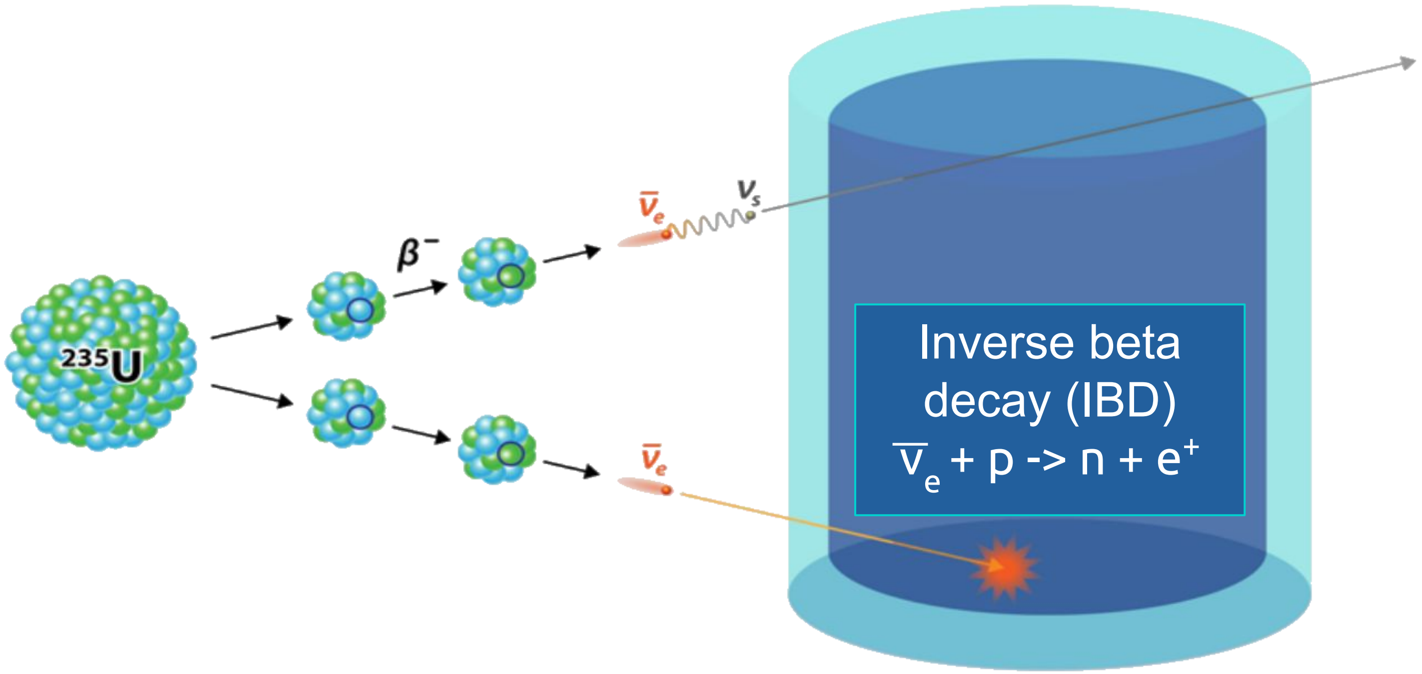
APS/Alan Stonebraker

Each fission in a reactor releases on average 6 anti-neutrinos

Anti-neutrinos from a $3GW_{th}$ reactor: 10^{22} per second isotropic emission (10^{21} fissions per second).

Big problem, small solution

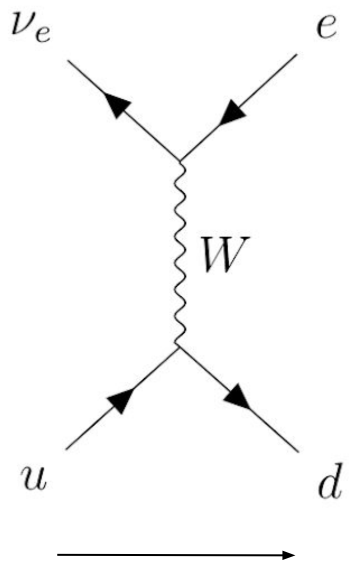
Reactor anti-neutrino flux carries information about the power, location and composition of a core.



Inverse beta decay (IBD)
$\bar{\nu}_e + p \rightarrow n + e^+$

APS/Alan Stonebraker

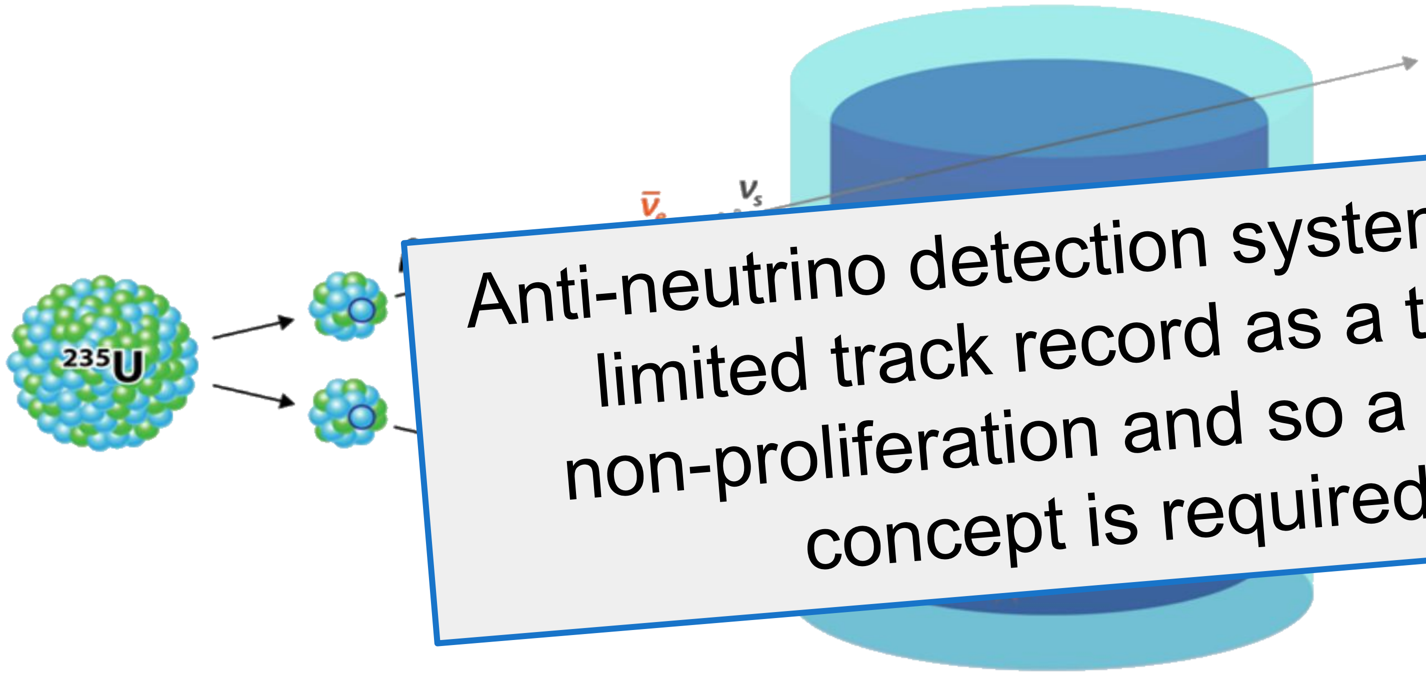
The anti-neutrino interacts with free protons in the detector via inverse beta decay (IBD).



Anti-neutrinos from a 3GW$_{th}$ reactor: 10^{22} per second isotropic emission (10^{21} fissions per second).

Proof of concept is needed

Reactor anti-neutrino flux carries information about the power, location and composition of a core.



Anti-neutrino detection systems have a limited track record as a tool for non-proliferation and so a proof of concept is required.

APS/Alan Stonebraker

Each fission in a reactor
s on average 6
trinos.

-neutrino
with free
n the detector
via inverse beta decay
(IBD).

Anti-neutrinos from a 3GW$_{th}$ reactor: 10^{22} per second isotropic emission (10^{21} fissions per second).

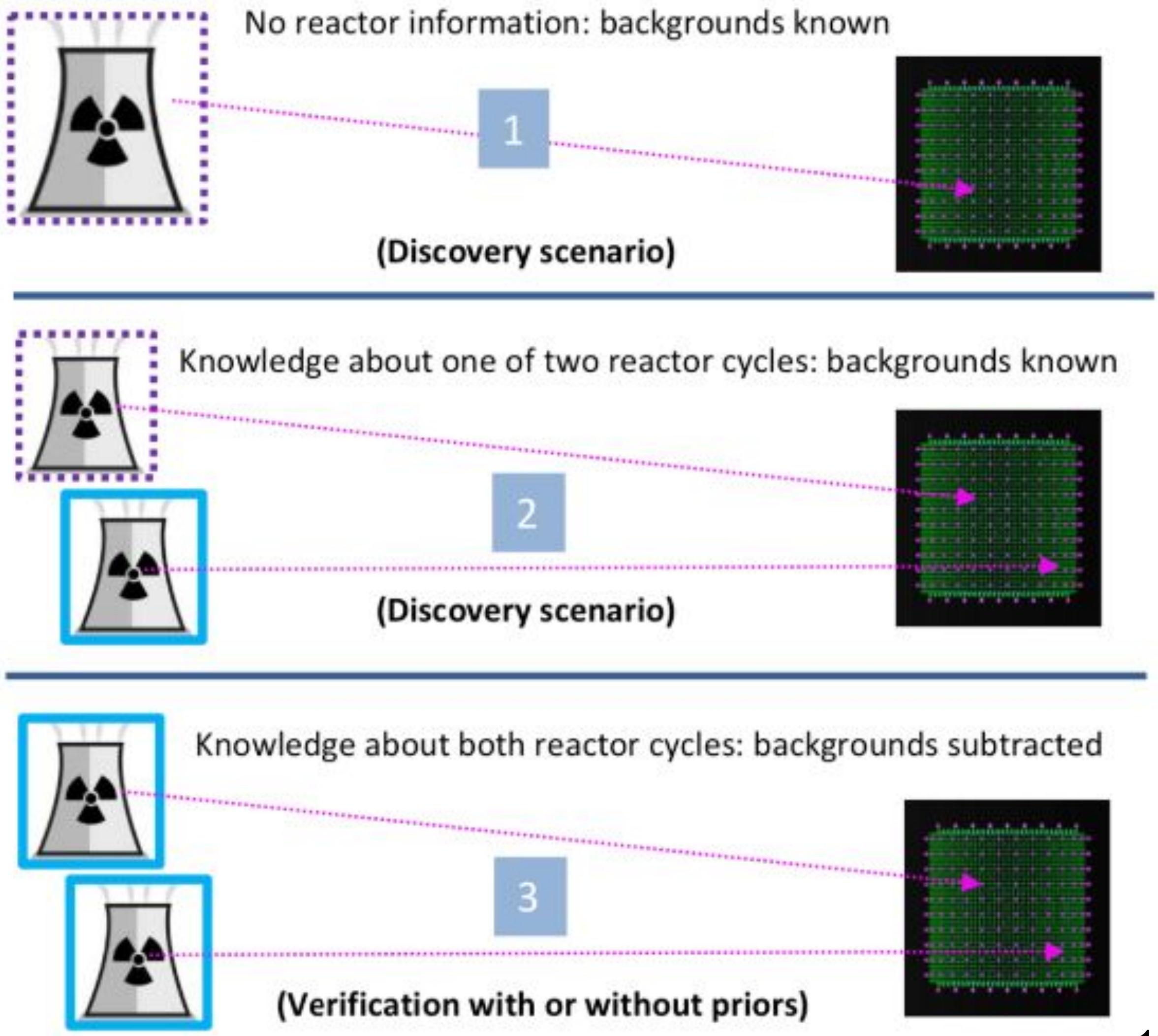
WATCHMAN

technology and proof of concept

Primary goal: ‘discover’ reactor

The primary aim of WATCHMAN in the initial phase is to:

1. Determine existence/power cycle of a reactor with and without prior knowledge.
2. Demonstrate gadolinium-loaded water as a scalable detector medium.
3. Enable future technology upgrades for non-proliferation and other goals.



Ktonne-scale Gd-loaded detector

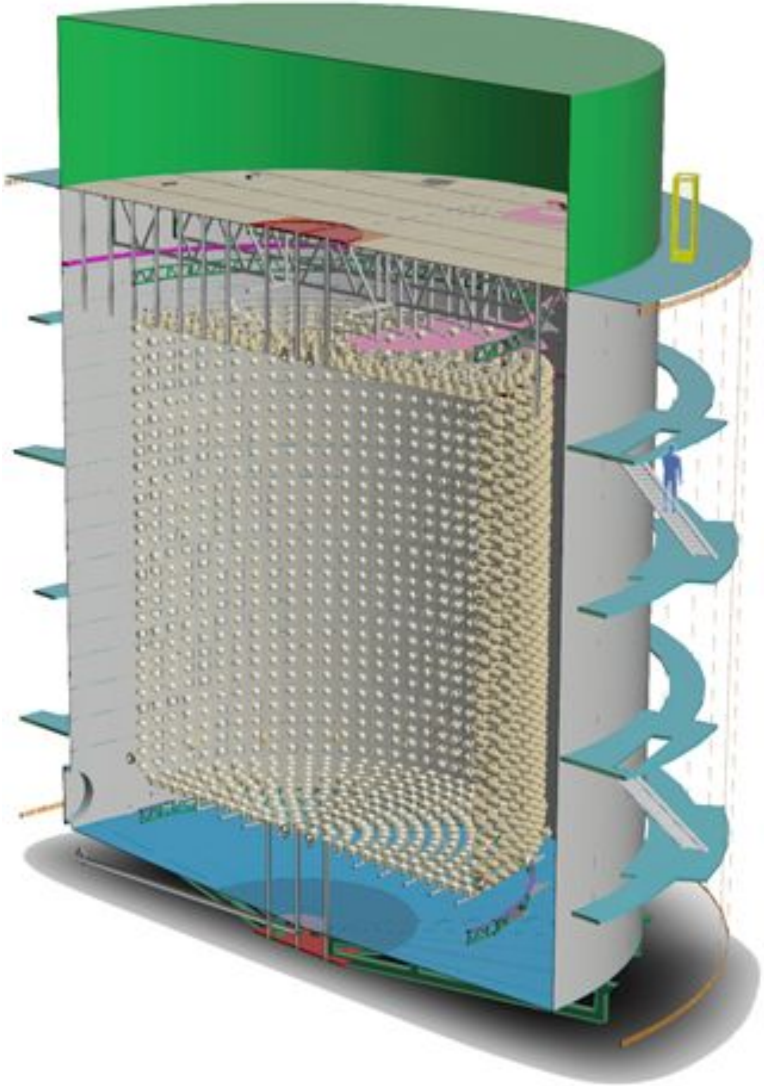
Baseline design:

1 ktonne fiducial mass.

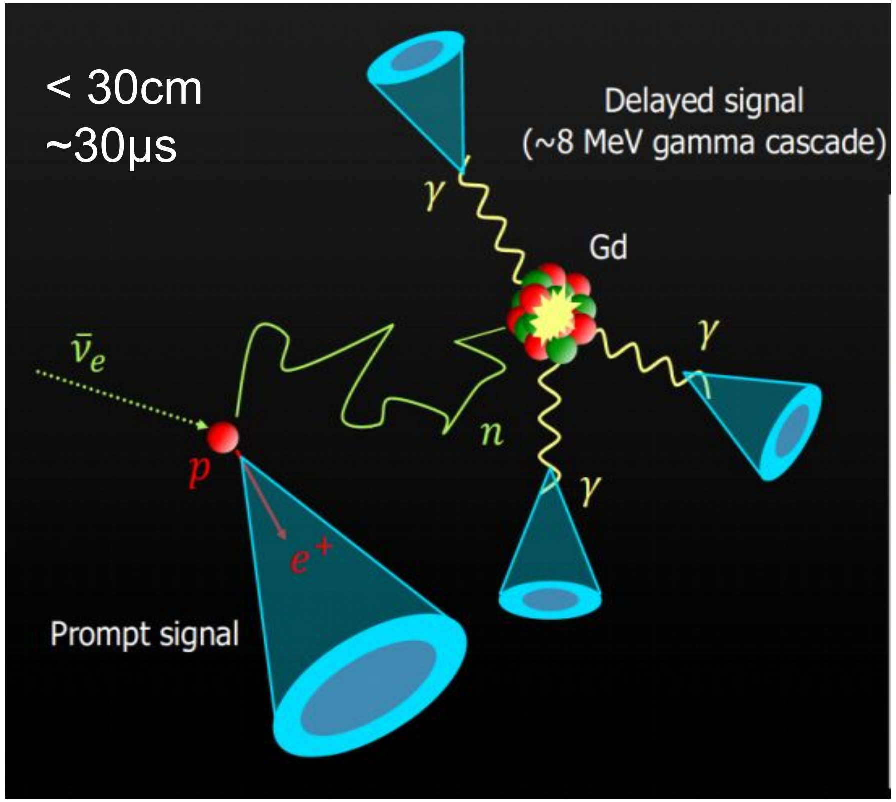
0.1% gadolinium-loaded water.

20% coverage (~3600) Hamamatsu 10” HQE, low radioactivity PMTs.

Active veto (~300 outward-facing PMTs).



Gd-water: proven and scalable



Gadolinium (Gd) loading: IBD heartbeat

- In water:
  Neutron capture on free proton (~0.3 b)
  Capture time ~200 μsec
  2.2 MeV gamma emitted

- In gadiated water:
  Neutron capture on Gd (~ 49 b)
  Capture time ~30 μsec
  ~8 MeV gamma cascade
  4-5 MeV visible energy

> 70% neutron detection efficiency in WATCHMAN

WATCHMAN is also considering a water-based liquid scintillator (WbLS) or Gd-WbLS fill.

Precision neutrino detector in UK

Hartlepool Power Station ***26 km*** *from AIT.*

Twin-core, 2 x **1.5 GW$_{th}$** Advanced Gas-cooled Reactors (AGR).

Dual core mimics complexity of situations we expect in the field.

Boulby Mine: A quiet place in the Universe.

1.1km underground (factor **10^6 muon reduction**).

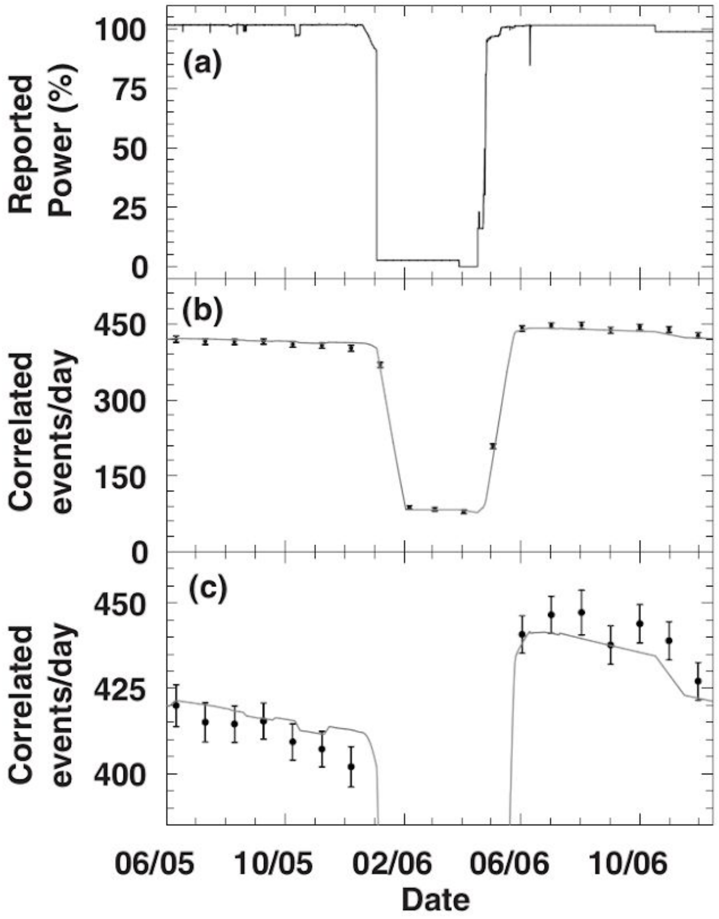
Cavern and laboratory to be built close to existing STFC Boulby Underground Laboratory.

Information encoded in the reactor signal

Information encoded in the

How can we provide better information with limited intrusion?

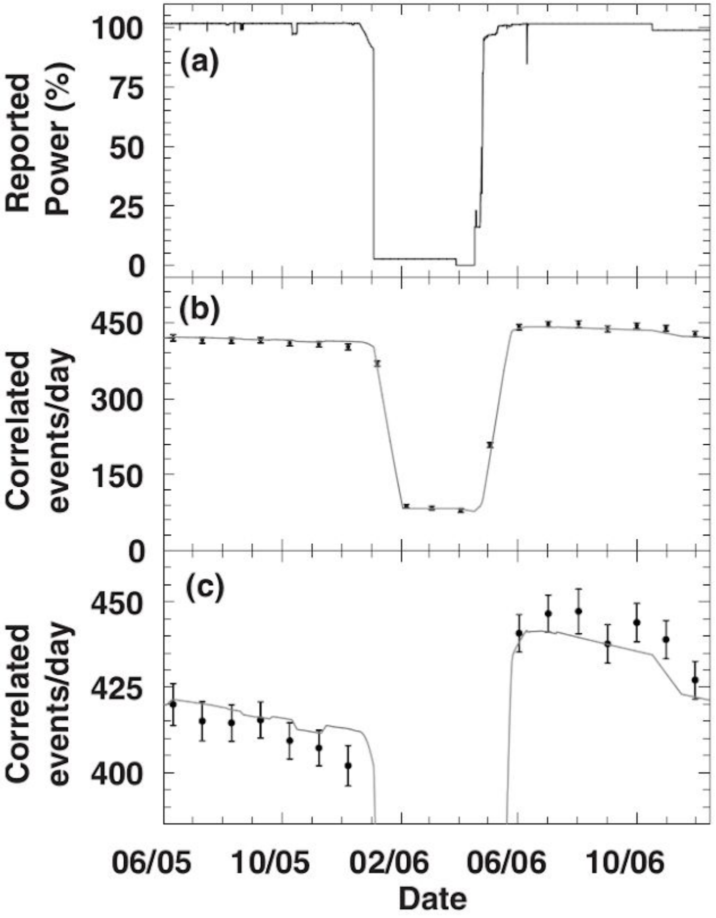
Presence/absence of a reactor



Bowden et al, 2009
DOI: 10.1063/1.3080251

Anti-neutrino detector (gadolinium-doped liquid scintillator) at San Onofre Power Station demonstrated power/anti-neutrino flux connection.

Confirmation of reactor/power cycle



Bowden et al, 2009
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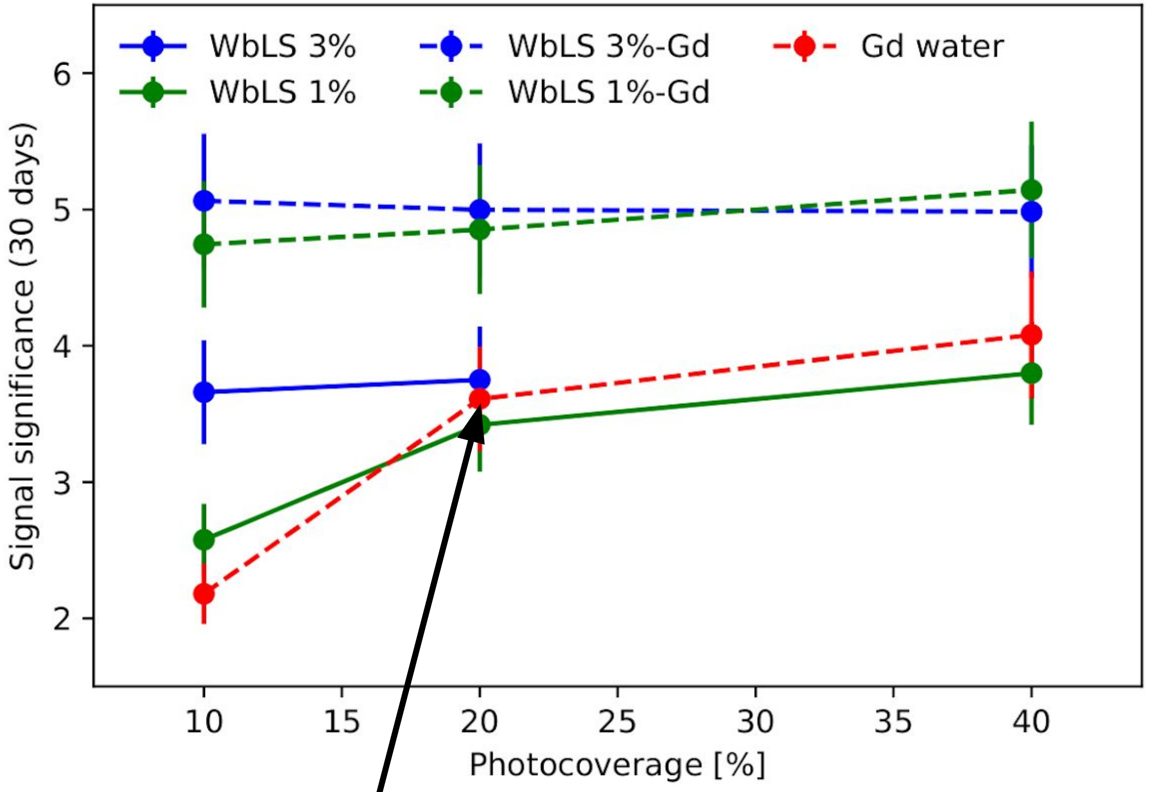
Anti-neutrino detector (gadolinium-doped liquid scintillator) at San Onofre Power Station demonstrated power/anti-neutrino flux connection.

Baseline WATCHMAN capability - mid-field flux measurement for:

Confirmation of presence/power cycle of a reactor with and without prior knowledge of reactor and backgrounds.

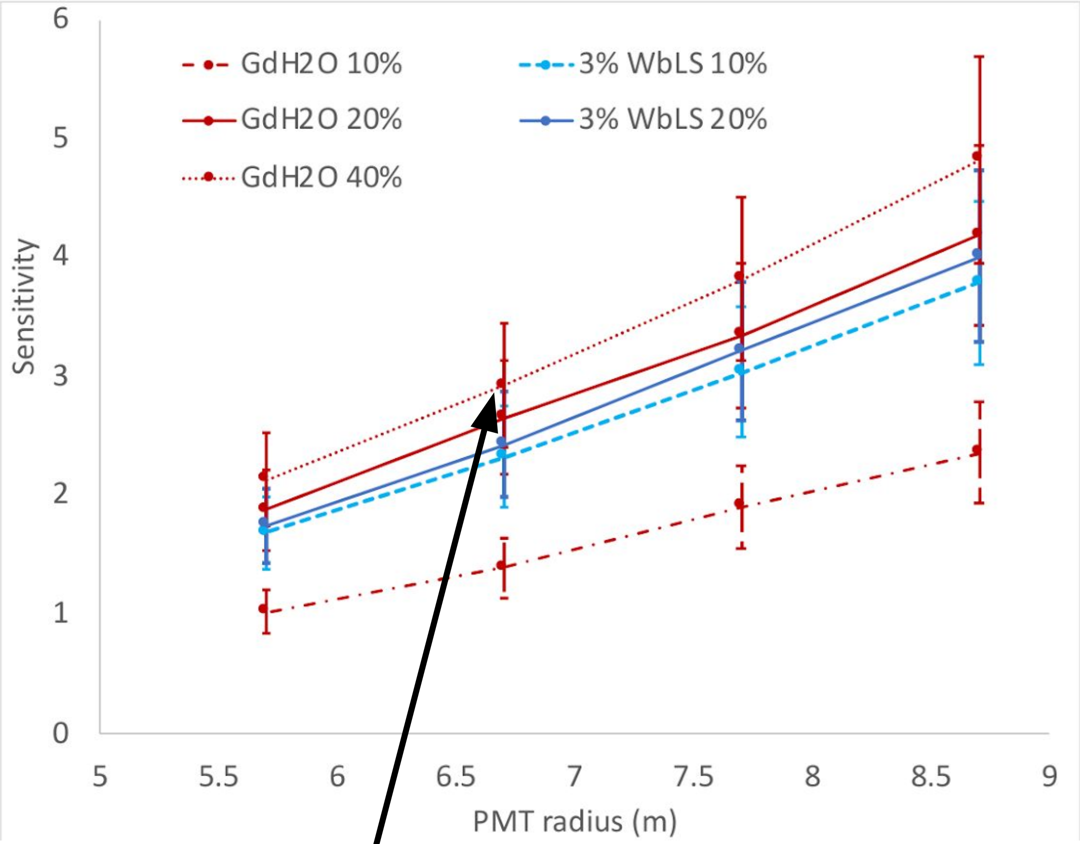
Reactor sensitivity projection

Primary goal: Hartlepool power station
26 km standoff, 2 x 1.5 GW_{th} cores



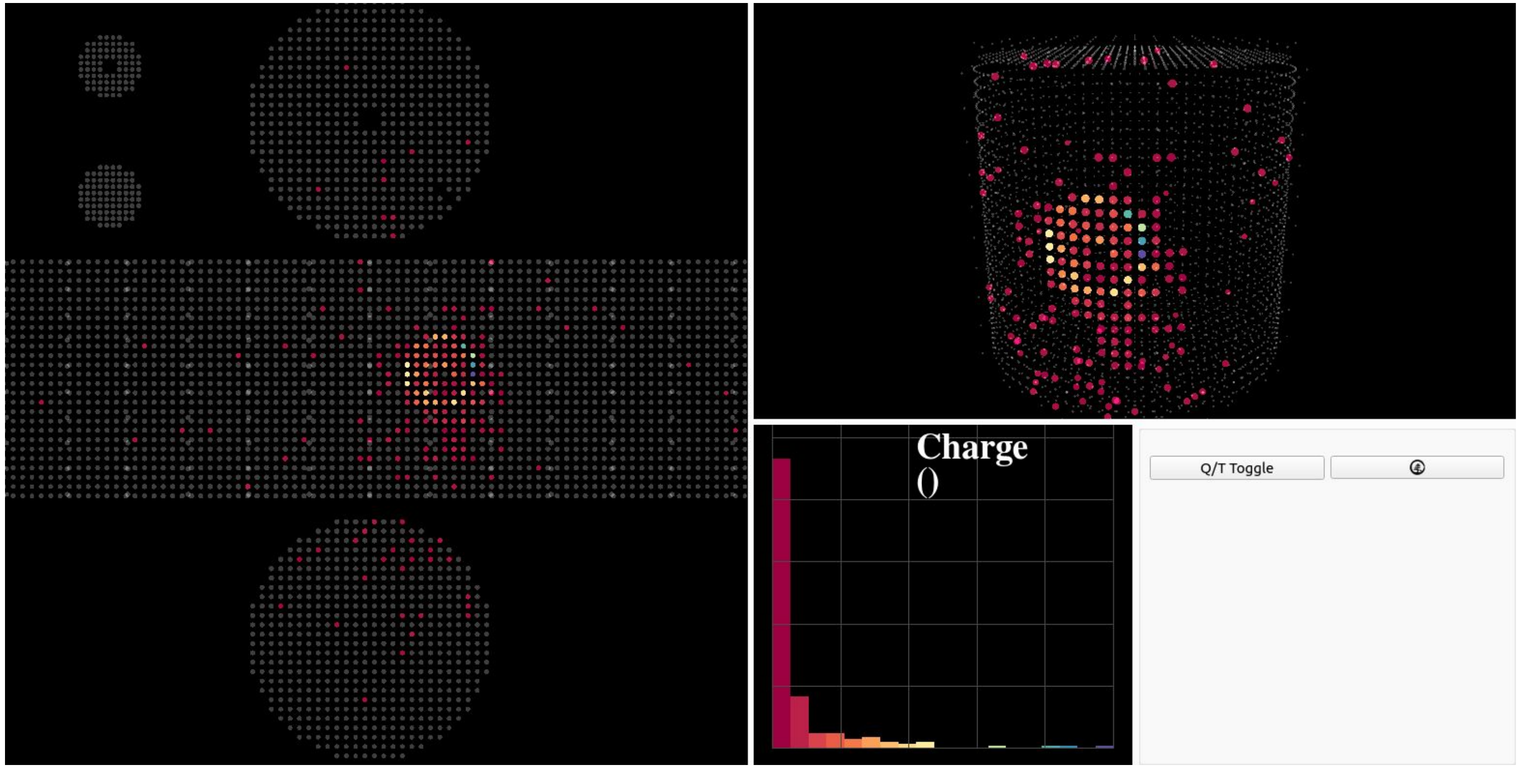
>3σ significance reached within 30 days with baseline design.

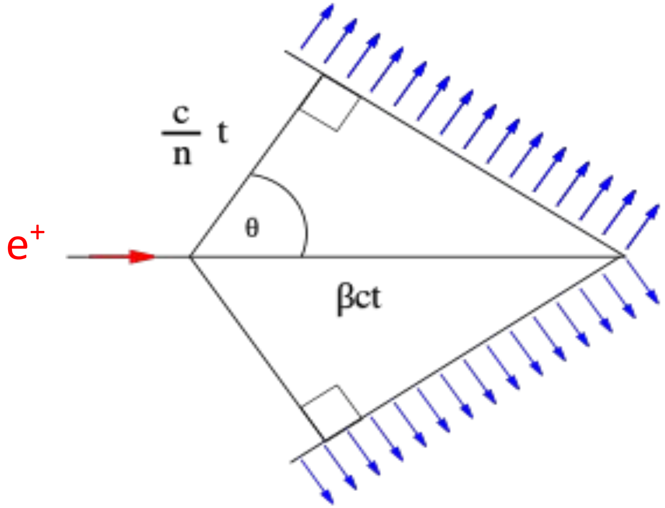
Stretch goal: Heysham power station
148 km standoff, 4 x 1.5 GW_{th} cores



3σ significance reached within 1 year with 40% photocoverage.

Let there be (Cherenkov) light!

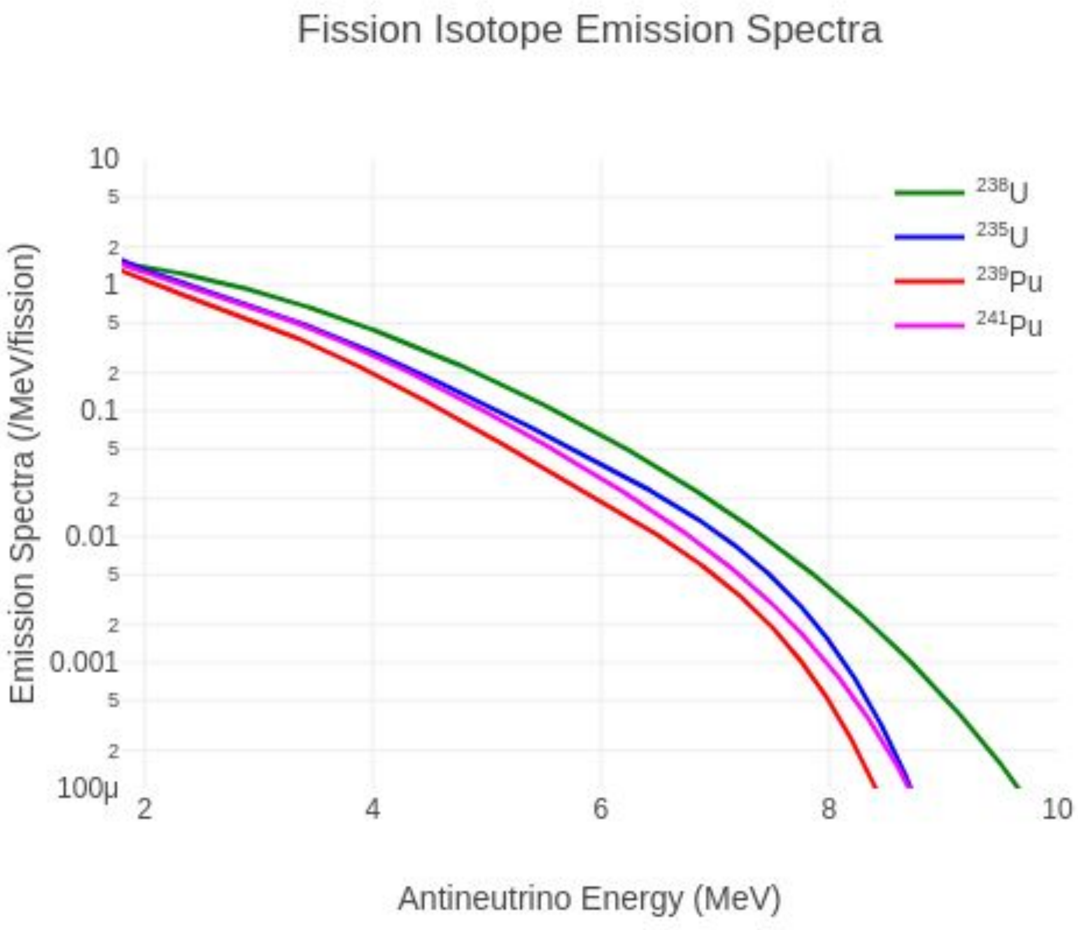




Cherenkov ring can provide information about:

- the vertex - or position of interaction in the detector.
- the energy of the originating particle.
- the direction of the originating particle.

Reactor composition

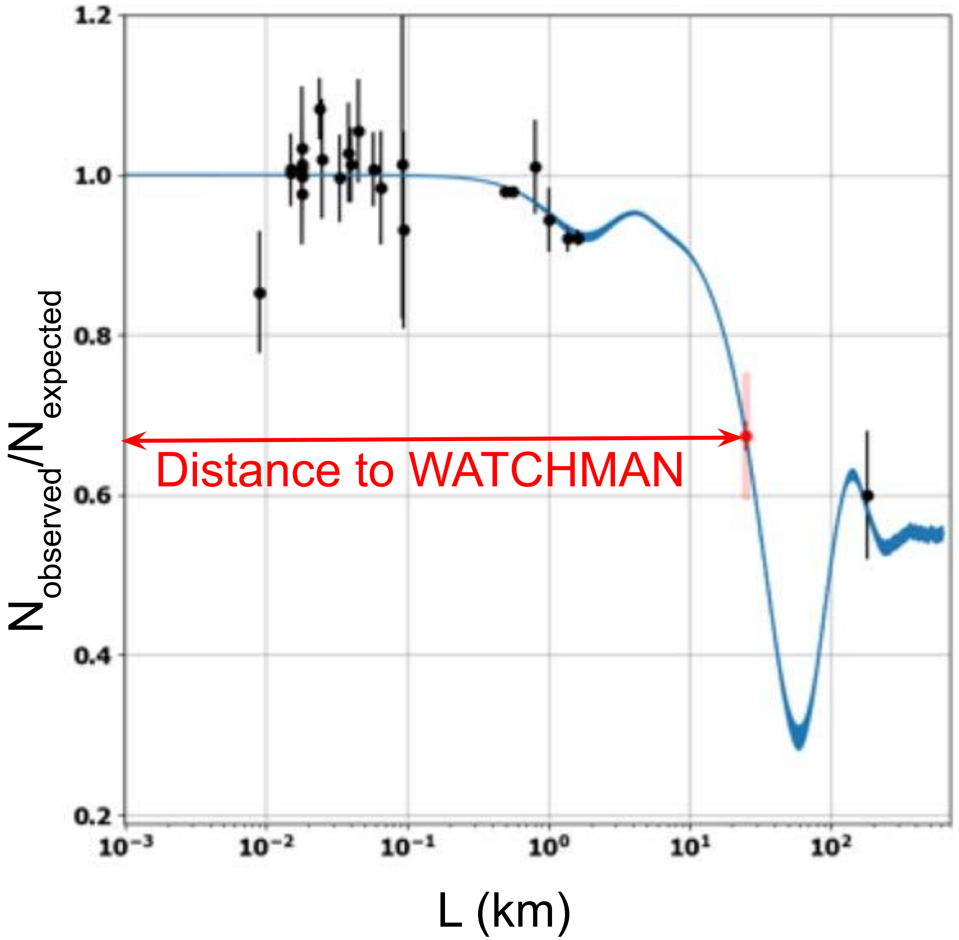


Composition from spectral information.

Challenging: dependent on energy resolution, energy threshold and statistics.

geoneutrinos.org, based on Huber & Mueller spectral calculations

Reactor ranging

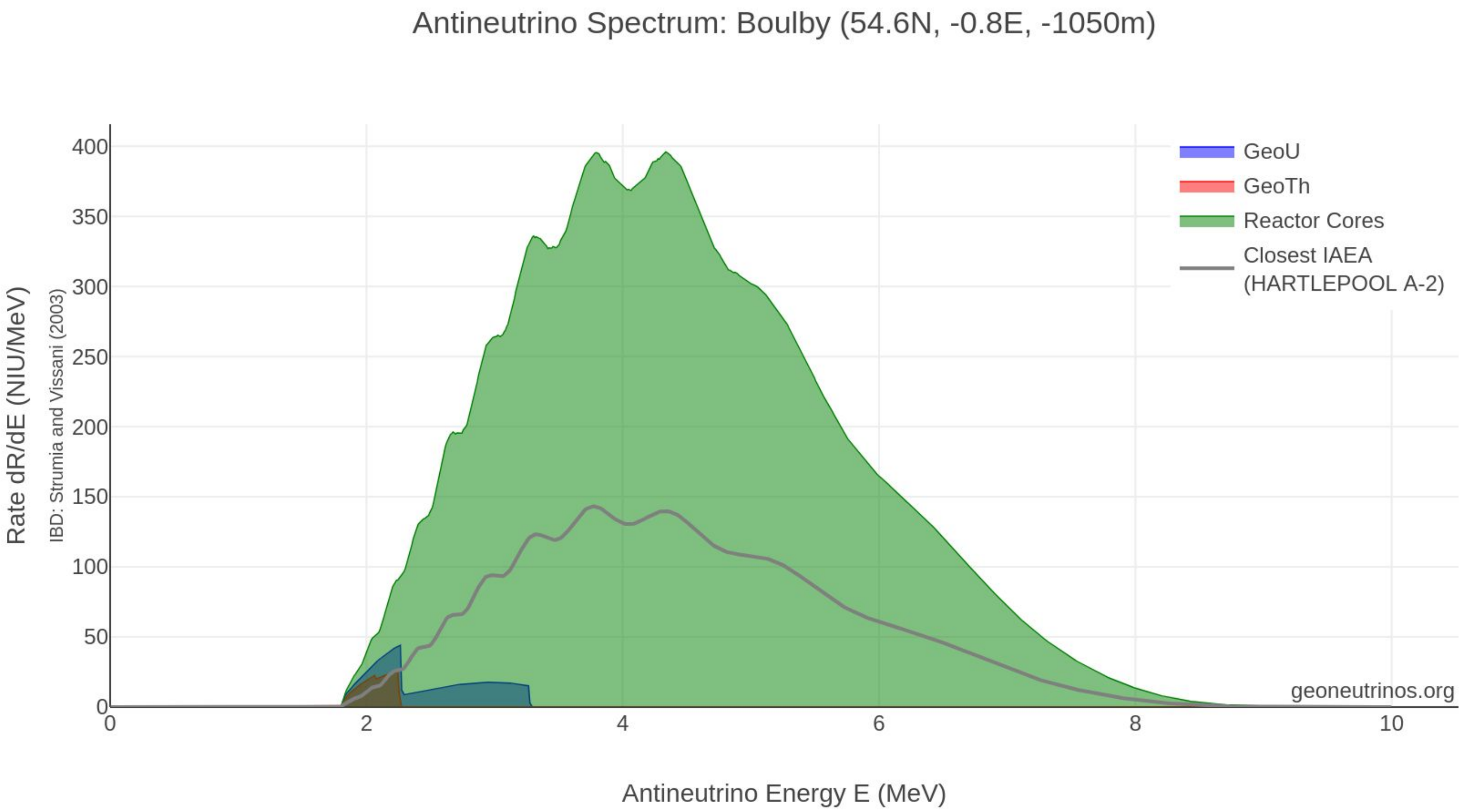


Neutrinos are unique in unambiguously revealing reactor distance.

Ranging from neutrino oscillations depends heavily on energy resolution and threshold, statistics and backgrounds.

Backgrounds for IBD detection

Anti-neutrino backgrounds

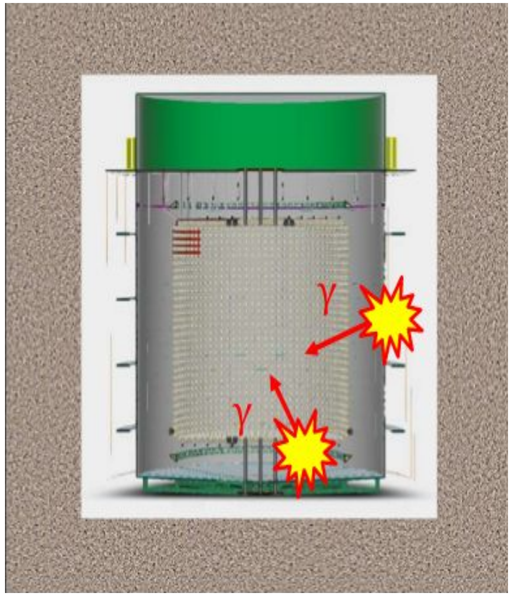


Significant background from other reactors, principally from the other reactor core at the Hartlepool power plant.

Reflects the complexity of the challenge in the field.

Uncorrelated backgrounds

Accidental coincidences of uncorrelated events

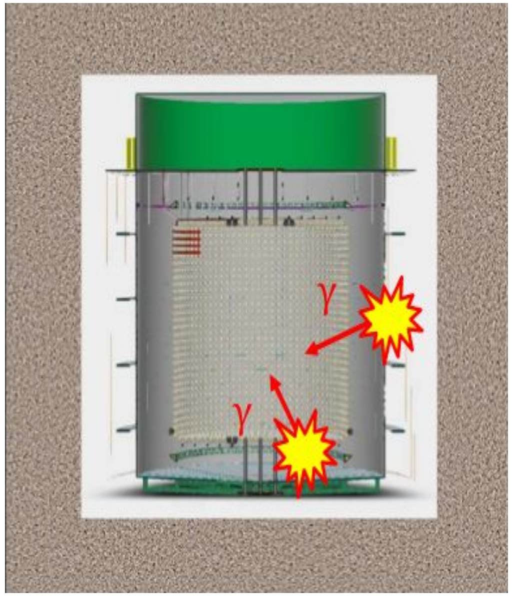


Gammas from radioactivity in the detector components and environs.

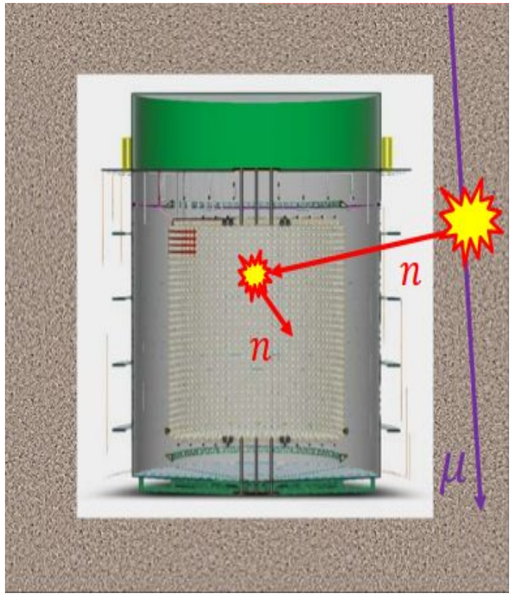
Correlated backgrounds

Accidental coincidences of uncorrelated events

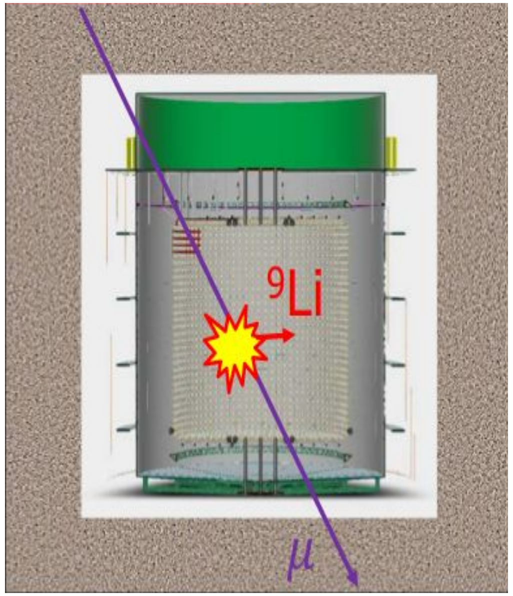
Correlated interactions due to cosmogenic muons in the rock and detector.



Gammas from radioactivity in the detector components and environs.



Fast neutron pairs from cosmic muons interacting in the rock surrounding the detector.



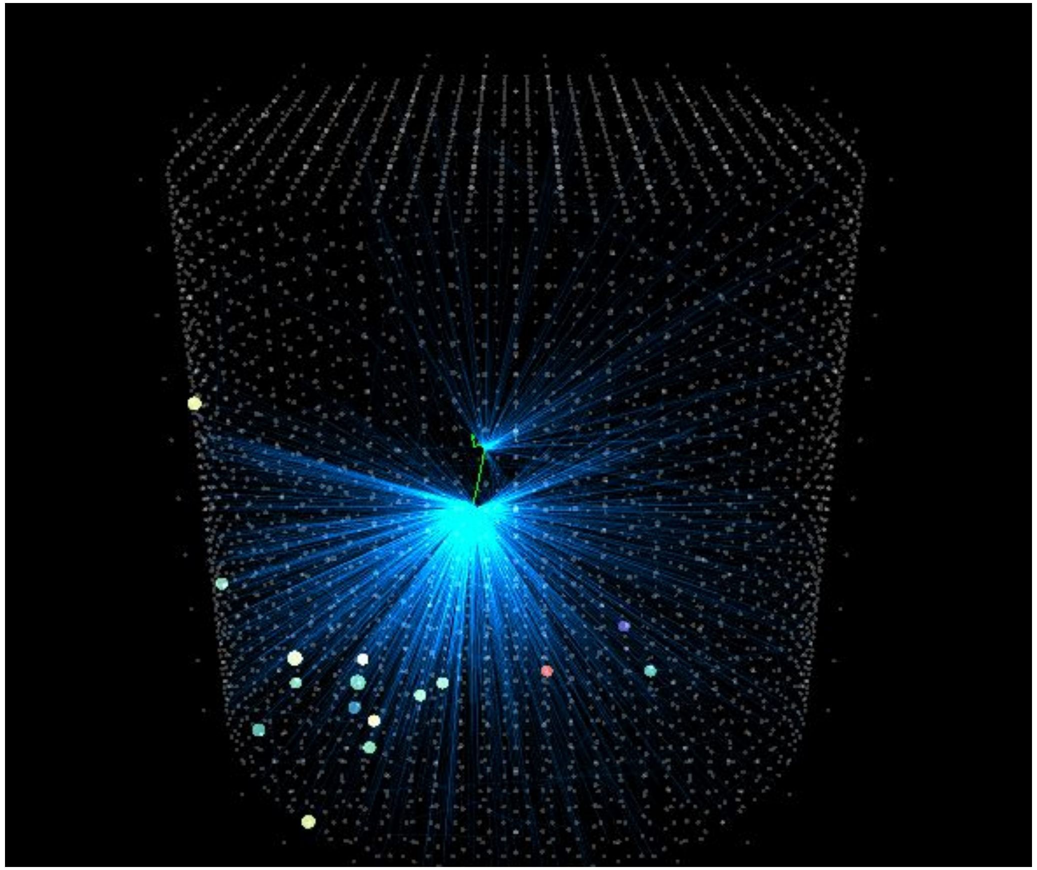
Long-lived radionuclides from cosmic muons interacting in the detector medium (spallation).

New Reconstruction Method 1

PairBONSAI

Reconstructing the IBD heartbeat

The aim of a combined vertex reconstruction is to use the additional light from the neutron to improve reconstruction, particularly at the low energies of reactor antineutrinos.



The result?

1. Better vertex resolution.
2. Better background rejection.
3. Sensitivity down to lower energies.

BONSAI - essentially a time fitter

Performs maximum likelihood fit based on the hit time residuals of the Cherenkov signal.

Time residuals form the basis of the fit

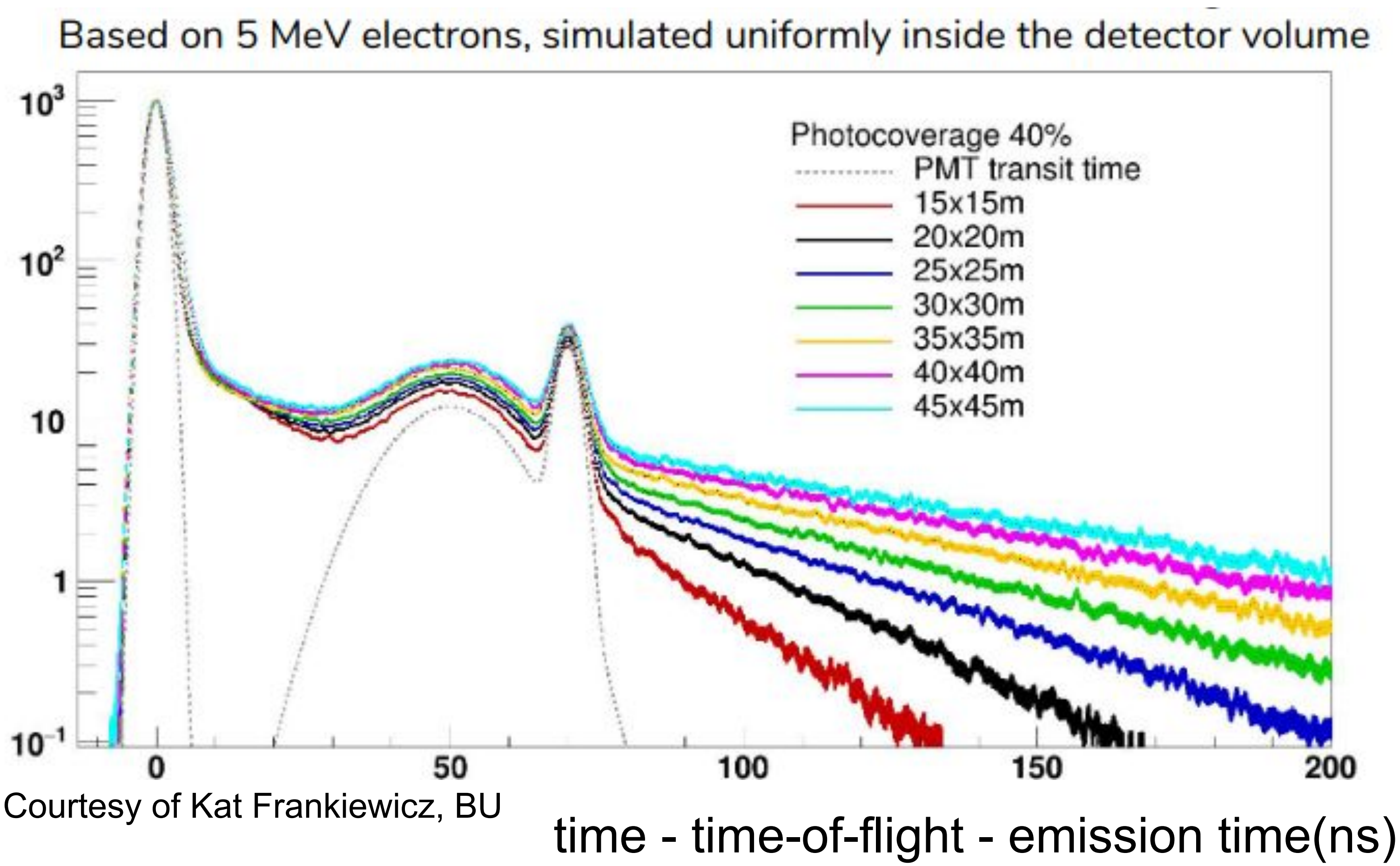
Performs maximum likelihood fit based on the hit time residuals of the Cherenkov signal.

The time residual is the hit time - time of flight - time of emission:

$$\Delta \mathrm{t_i}(\boldsymbol{x}) = \mathrm{t_i} - \mathrm{tof_i}(\boldsymbol{x}) - \mathrm{t_0}$$

Time residuals form the basis of the fit

$$\Delta \mathrm{t_i}(\boldsymbol{x}) = \mathrm{t_i} - \mathrm{tof_i}(\boldsymbol{x}) - \mathrm{t_0}$$



Courtesy of Kat Frankiewicz, BU

The shape of the time residuals is dominated by the PMT transit time and folds in the effects of the detector medium and the size of the detector.

Larger detector > longer tails due to increased scattering.

Likelihood constructed from time residuals

Performs maximum likelihood fit to the hit time residuals of the Cherenkov signal.

The time residual is the hit time - time of flight - time of emission:

$$\Delta \mathrm{t_i}(\boldsymbol{x}) = \mathrm{t_i} - \mathrm{tof_i}(\boldsymbol{x}) - \mathrm{t_0}$$

And the likelihood to be maximised is based on the time residuals:

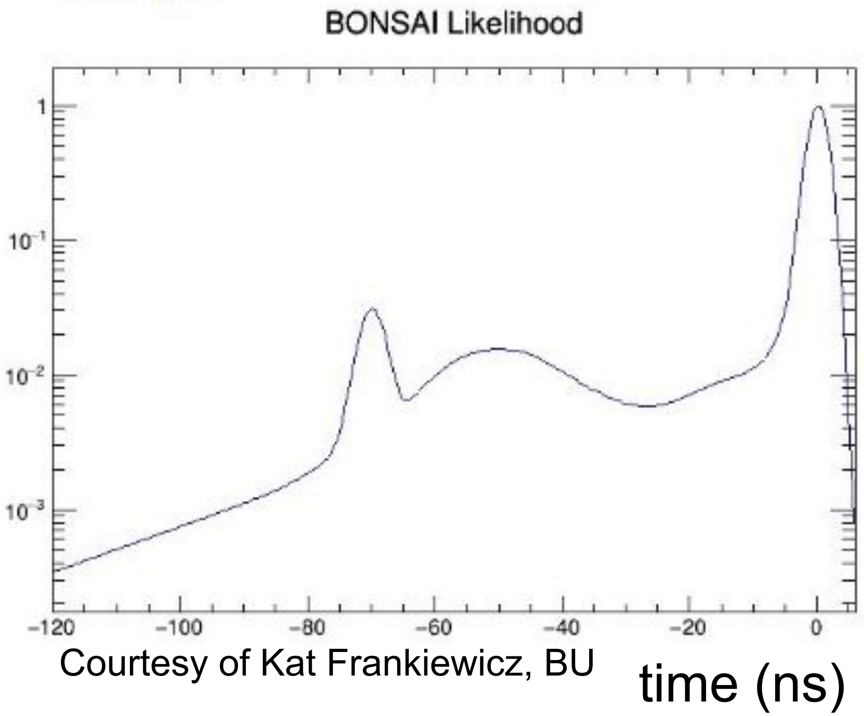
$$\mathcal{L}(\boldsymbol{x}, \mathrm{t_0}) = \log(\Pi \, \mathrm{pdf}(\Delta \mathrm{t_i}(\boldsymbol{x})))$$

Likelihood constructed from time residuals

$$\mathcal{L}(\boldsymbol{x}, \mathrm{t}_0) = \log(\Pi\, \mathrm{pdf}(\Delta \mathrm{t}_\mathrm{i}(\boldsymbol{x})))$$

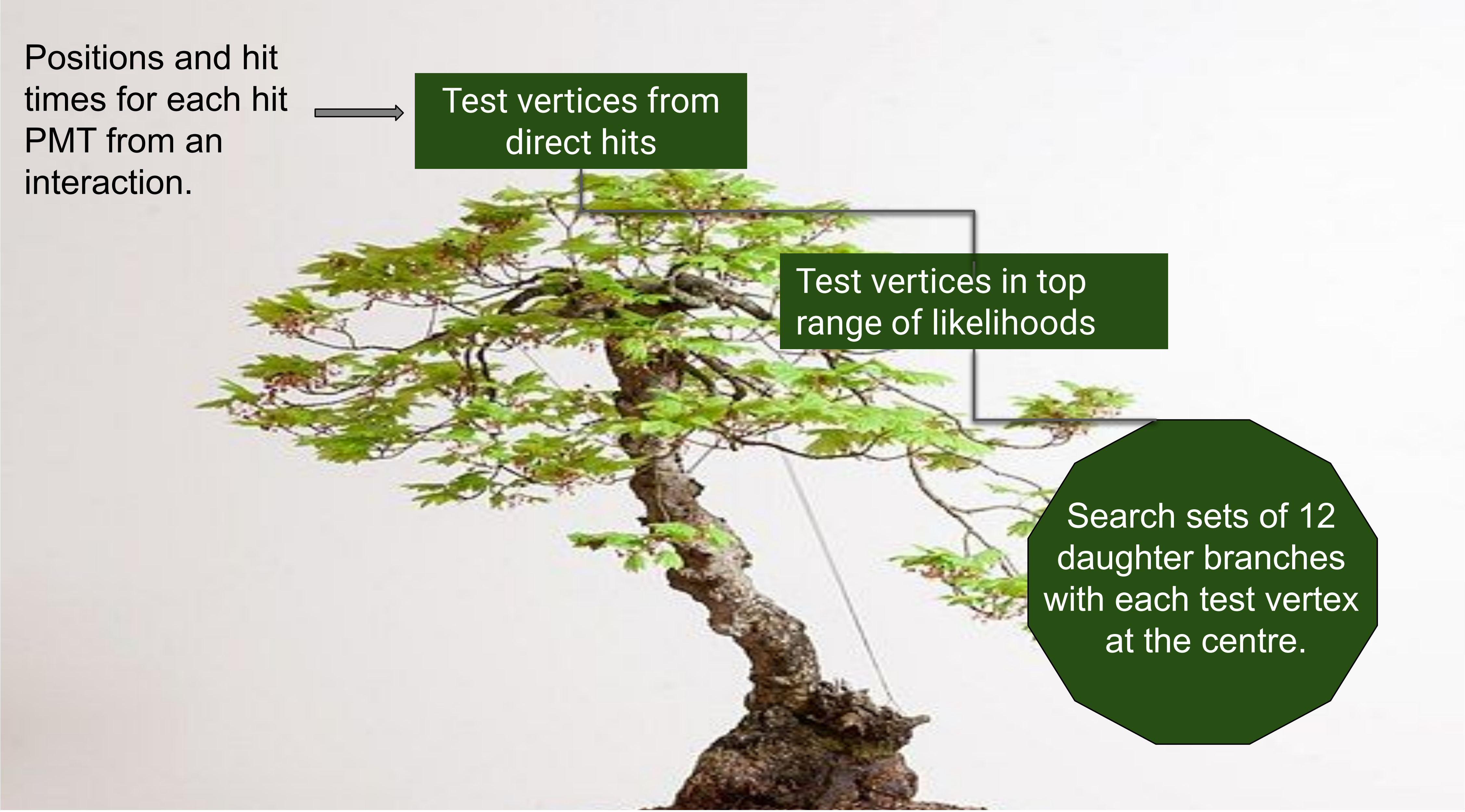
The pdf is built from the time residuals plot for a given detector design.

The maximum likelihood estimate of the vertex is the value of the vertex for which the likelihood has its maximum, given the location and timing of the observed hits.



Courtesy of Kat Frankiewicz, BU

The BONSAI search tree



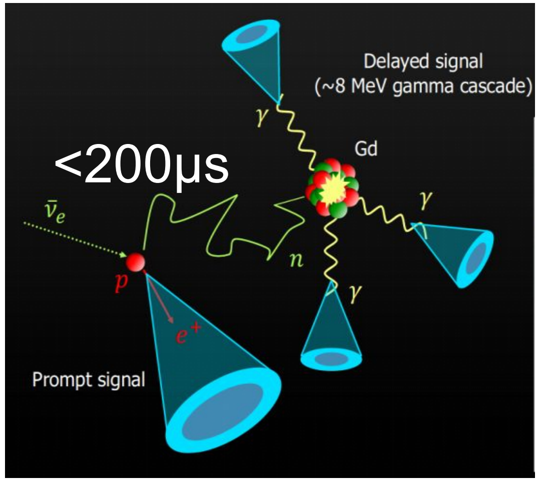
Positions and hit times for each hit PMT from an interaction.

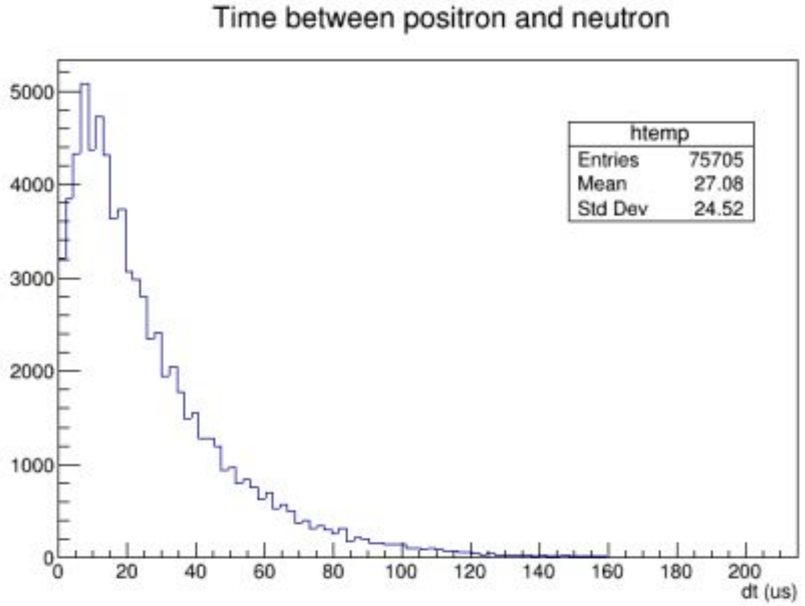
Test vertices from direct hits

Test vertices in top range of likelihoods

Search sets of 12 daughter branches with each test vertex at the centre.

The PairBONSAI process





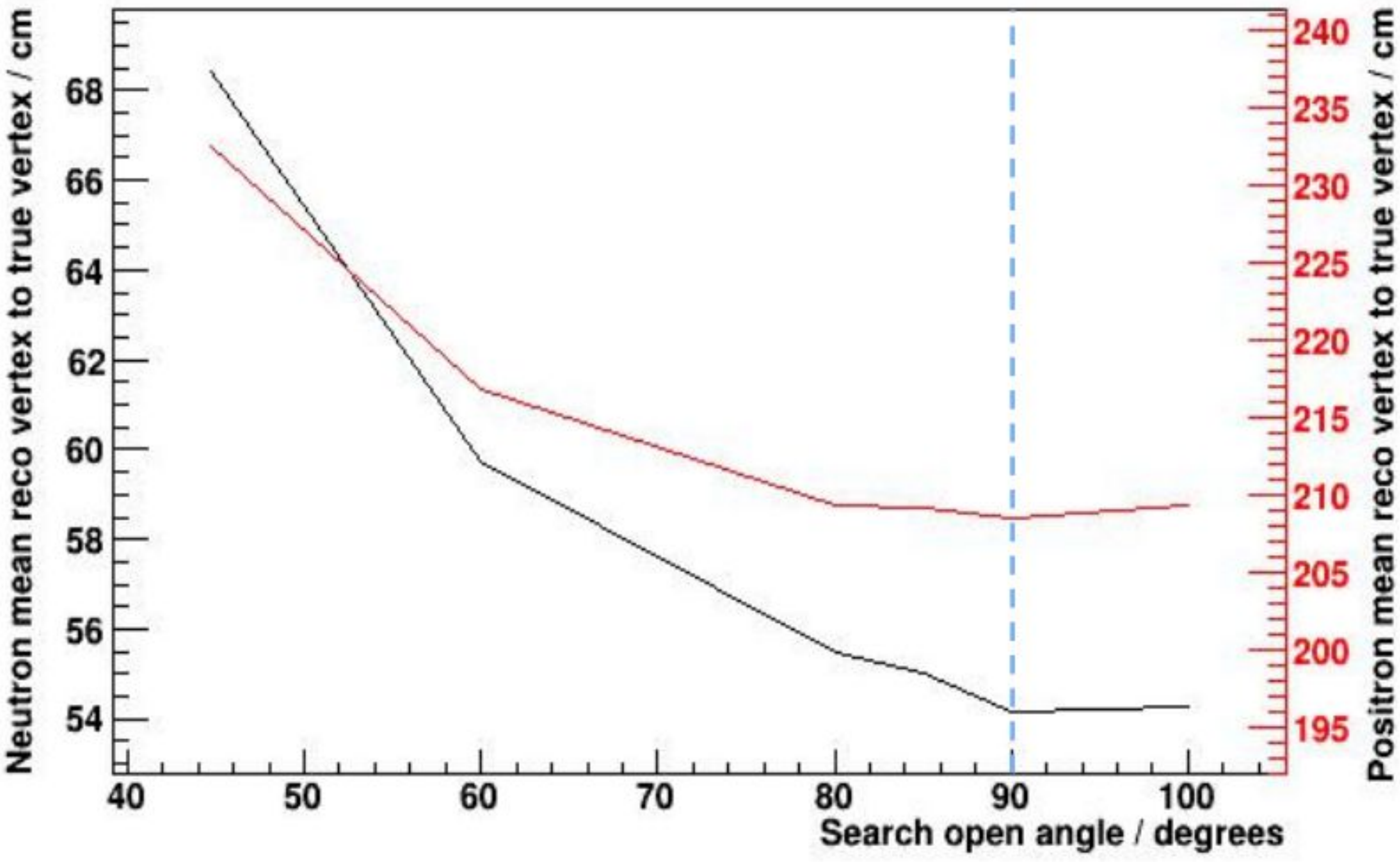
- Select interactions that trigger in the detector within e.g. 200μs.
- Create combined search grid: more starting solutions means better rejection of local maxima.

- Call the likelihood maximisation of

$$\mathcal{L}(\boldsymbol{x}, \mathrm{t}_0) = \mathcal{L}_\mathrm{p}(\boldsymbol{x}, \mathrm{t}_0) + \mathcal{L}_\mathrm{d}(\boldsymbol{x}, \mathrm{t}_0)$$

- Output a common vertex.

BONSAI pair reconstruction



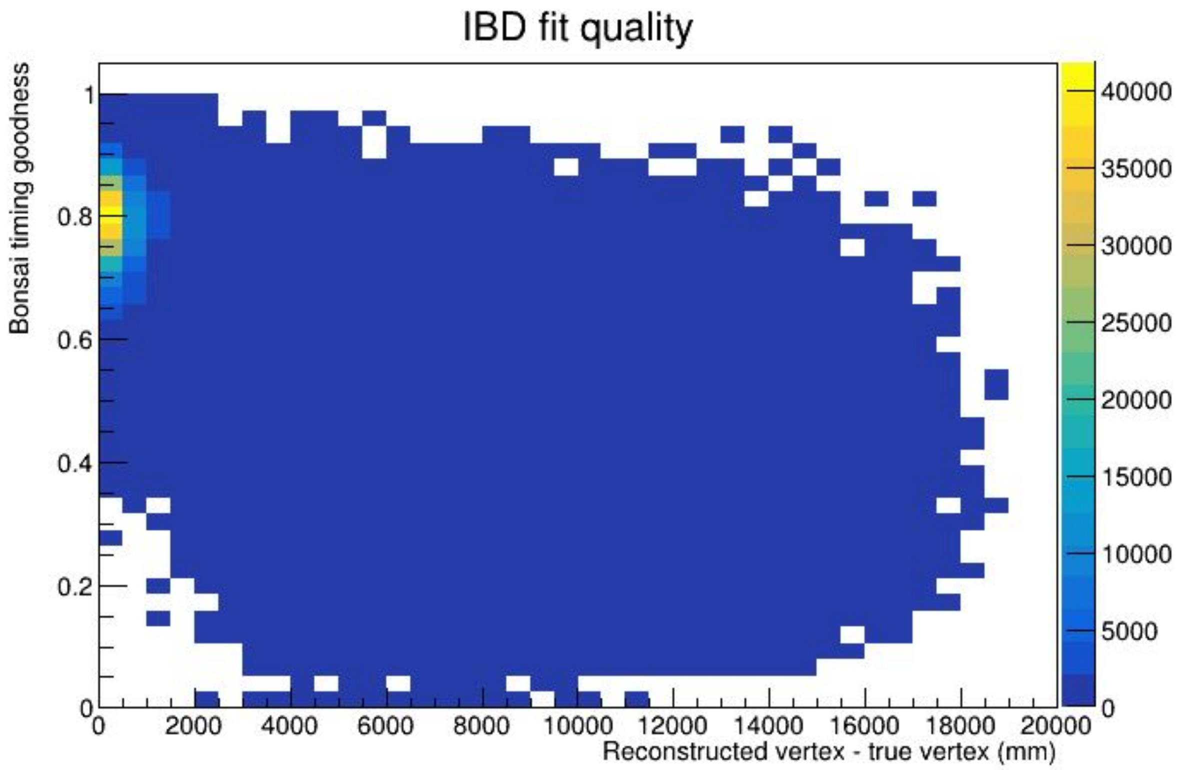
Optimal open angle for hit search found to be 90° for neutrons *and* positrons.

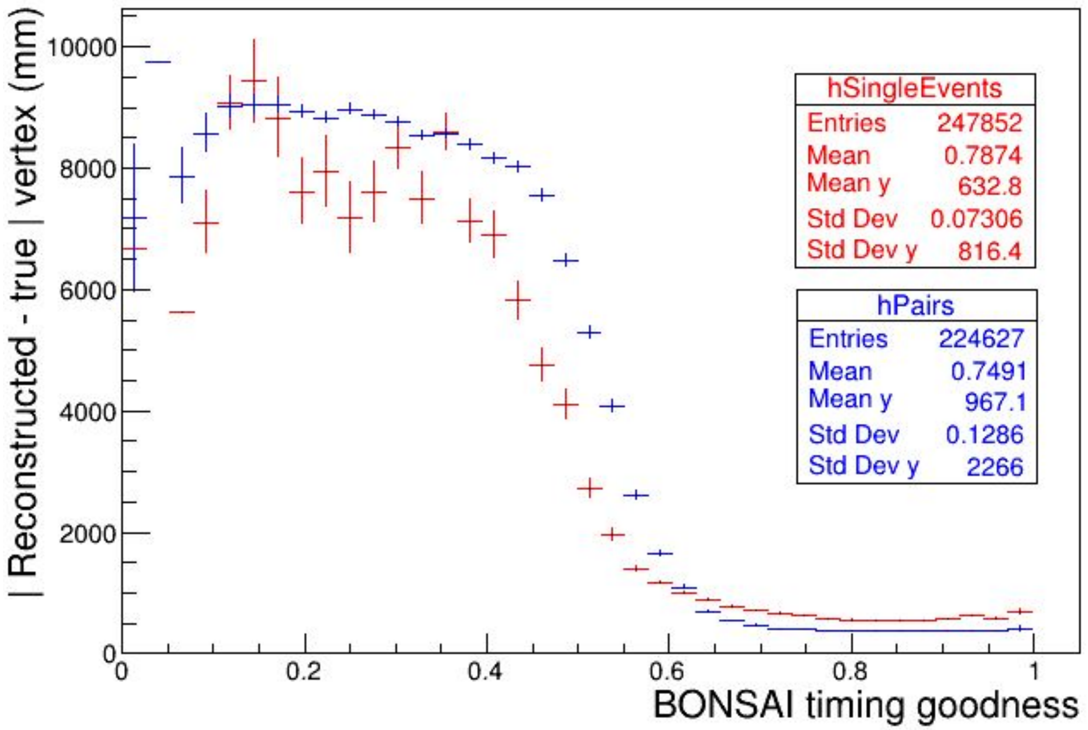
BONSAI searches assume the Cherenkov angle for e+/e- of ~45° but light from neutron capture is more isotropic.

Widening the search angle to 90º improves the fit for both interactions in the IBD event.

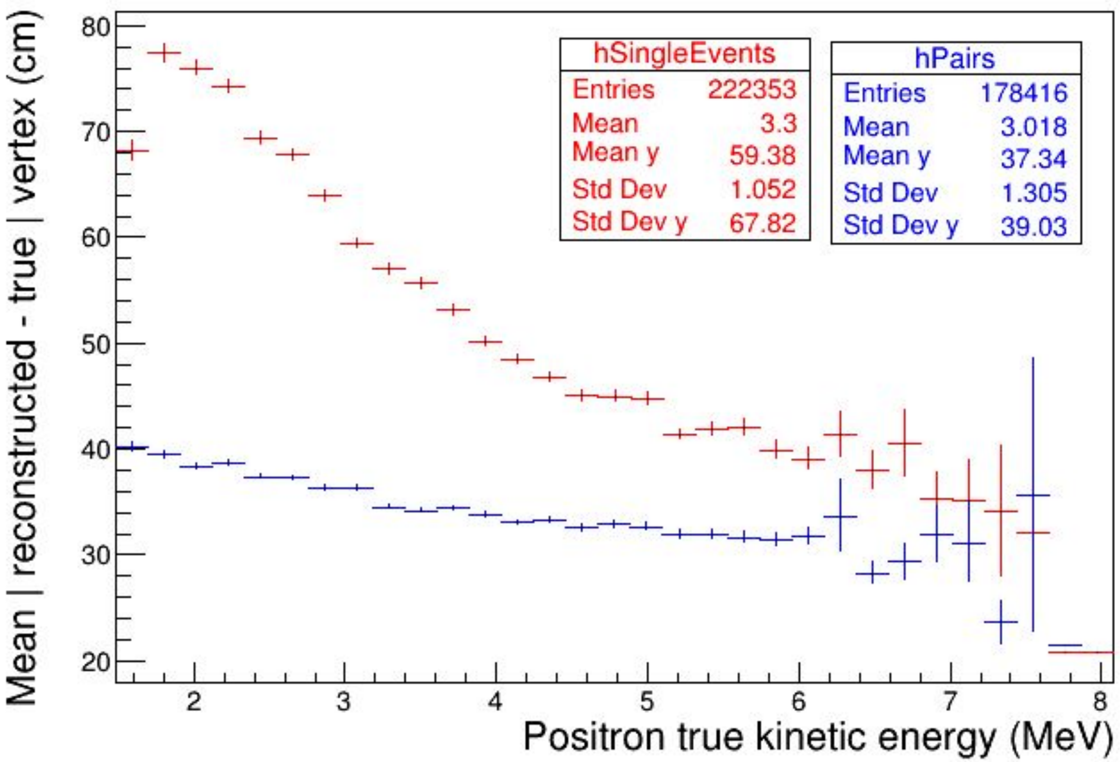
Fit quality - Bonsai timing goodness

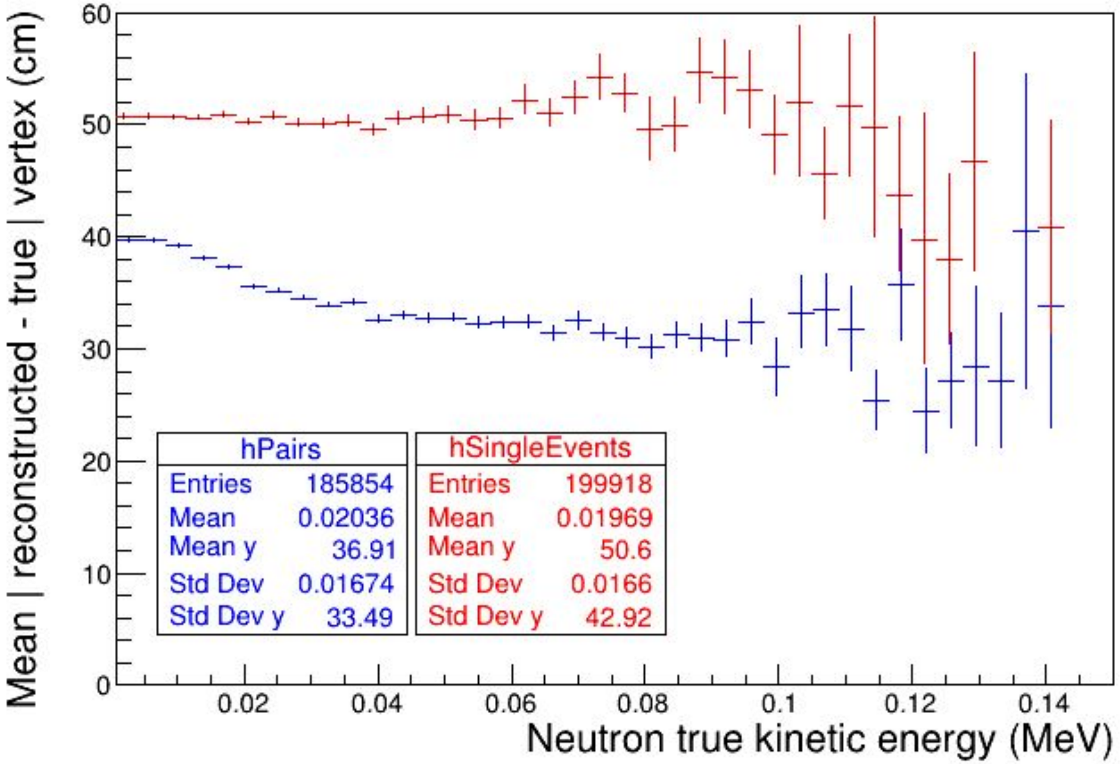
$$g(\boldsymbol{x}) = \frac{\sum_{\mathrm{hits}} \mathrm{w_i} e^{-0.5\left(\frac{\mathrm{t_i} - |\boldsymbol{x_i} - \boldsymbol{x}|/\mathrm{c}}{\sigma}\right)^2}}{\sum_{\mathrm{hits}} \mathrm{w_i}}$$





Improved vertex resolution





Positron resolution ~halved for 2.5 MeV positrons using pairbonsai on IBD pairs.

Preliminary results for Pairbonsai

	Single-event reconstruction	Pair reconstruction
3 MeV positron vertex resolution (cm)	64.1 (±0.54)	33.5 (±0.33)
5 MeV positron vertex resolution (cm)	50.3 (±0.73)	24.5 (±0.41)
Signal rate day^{-1} (efficiency)	0.501 ±0.0019	0.841 +/-0.00442
Accidentals day^{-1}	0.050	5.85 x 10^{-5}
Radionuclides day^{-1}	0.017	0.029
Other reactors day^{-1}	0.368	0.583
Total background rate day^{-1}	0.435 ±0.0026	0.612 +/-0.00307
30-day significance	2.8	3.8

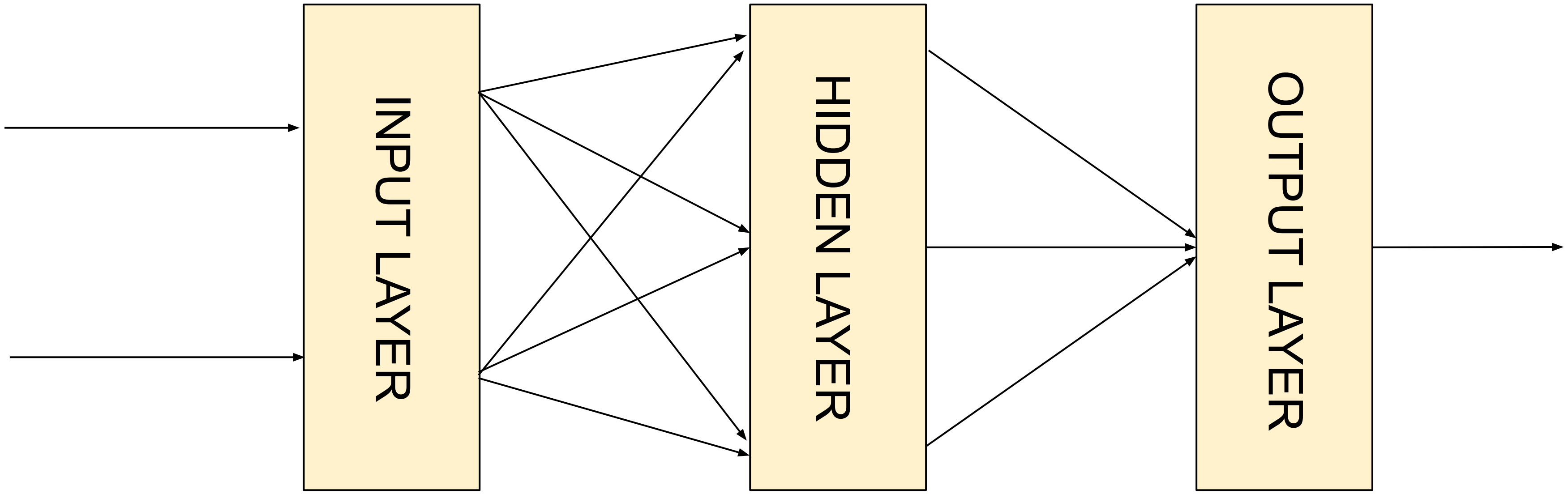
Preliminary results: we can get closer to the PMTs and down to lower energies.

New Reconstruction Method 2

Vertex reconstruction with machine learning

Deep learning for regression problems

Simple artificial neural network.



Continuous-valued outputs

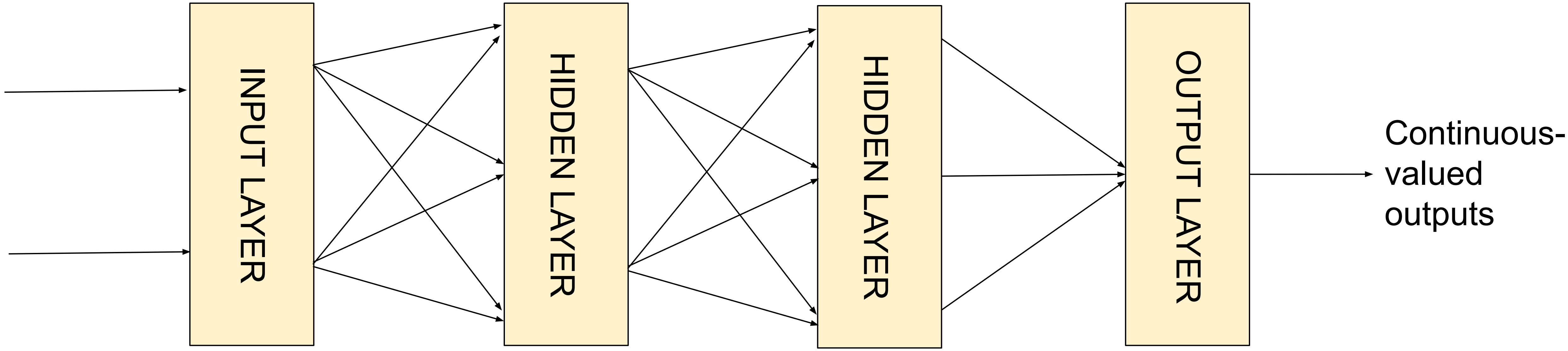
Input layer with 2 input ‘features’ for each ‘sample’

Hidden layer with 3 ‘neurons’

Output layer with 1 ‘target’ output

Deep learning for regression problems

Deep learning algorithms are artificial neural networks with multiple hidden layers.



INPUT LAYER

HIDDEN LAYER

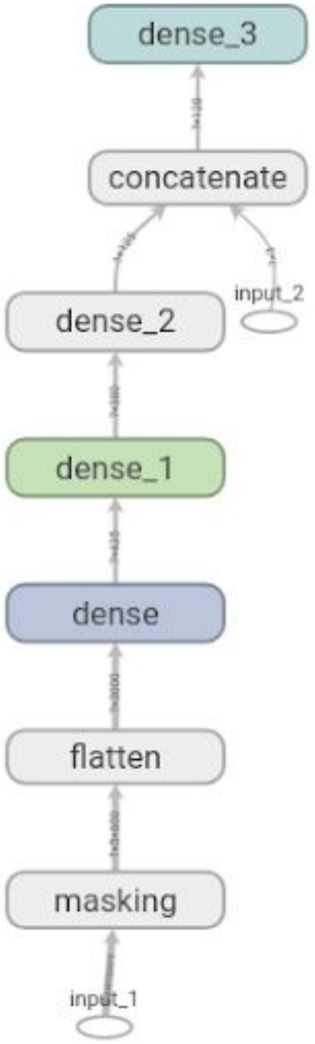
HIDDEN LAYER

OUTPUT LAYER

Continuous-valued outputs

The computer trains itself to process data and make predictions.

BONSAI + Multi-Layer Perceptron (MLP)



Outputs: x, y and z for each interaction.

↑

Input 2: reconstructed vertex from BONSAI reconstruction.

↑

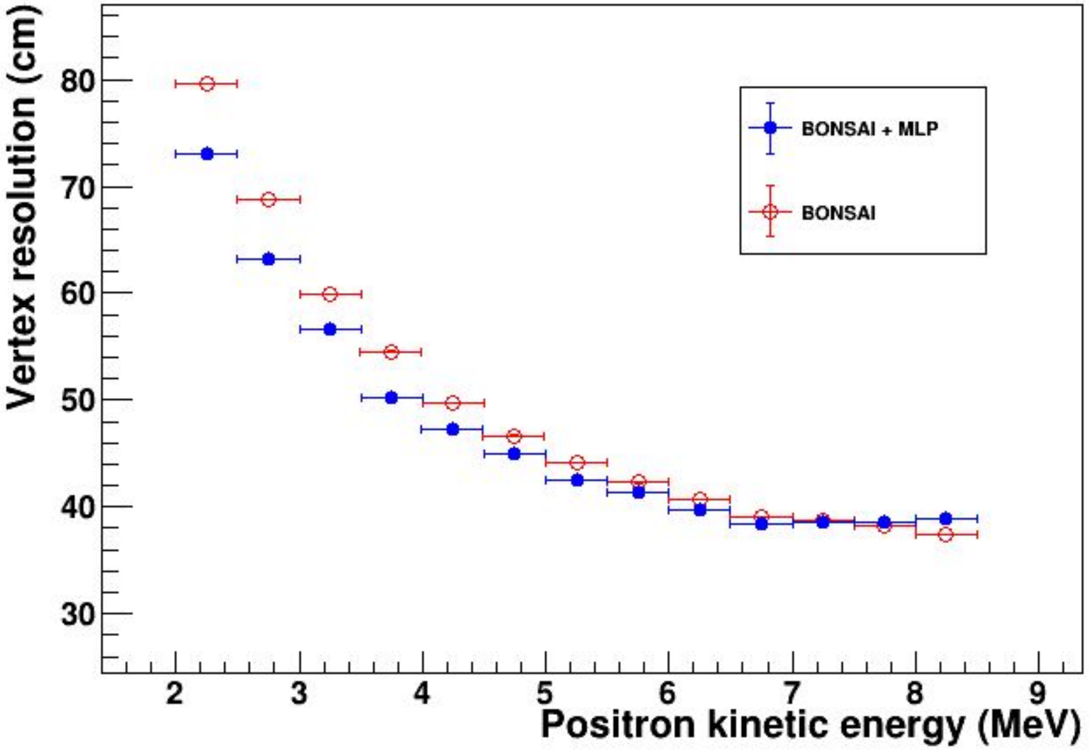
3 hidden layers

↑

Input 1: pmt x, y and z position, time and charge for each PMT hit by a photon due to each interaction.

Using MLP to improve BONSAI vertex

	BONSAI	BONSAI+MLP
RMS	77cm	71cm
2.5 MeV positrons	80cm	71cm
3 MeV positrons	69cm	62cm
5MeV positrons	47cm	45cm



This is for single-event reconstruction, adding the bonsai vertex information just before the output layer.

In summary...

- ★ Antineutrino detection can be a powerful addition to a remote monitoring toolkit to balance confidence and intrusion in reactor monitoring.
- ★ WATCHMAN will be built close to the Boulby Underground Laboratory to demonstrate Gd-water Cherenkov and other technologies for non-proliferation and science.
- ★ Identifying and reconstructing the *IBD heartbeat* increases background rejection and improves vertex reconstruction for the signal, improving reactor sensitivity and opening up the possibility of seeing down to lower energies.
- ★ Machine learning techniques for vertex reconstruction are now being explored.
- ★ WATCHMAN will be a precision neutrino detector and future upgrades offer the potential to explore other goals for non-proliferation and beyond.

WATCHMAN: UK-US collaboration

22 institutions in the US and UK.

Primary funding from US Defense Nuclear Non-Proliferation (part of NNSA).

WATCHMAN UK:

5 universities - Sheffield, Edinburgh, Glasgow, Liverpool and Warwick.

STFC-Boulby Underground Lab

Atomic Weapons Establishment

£9.7M funding from STFC (via UKRI Fund for International Collab.)
£1M funding from Ministry of Defence

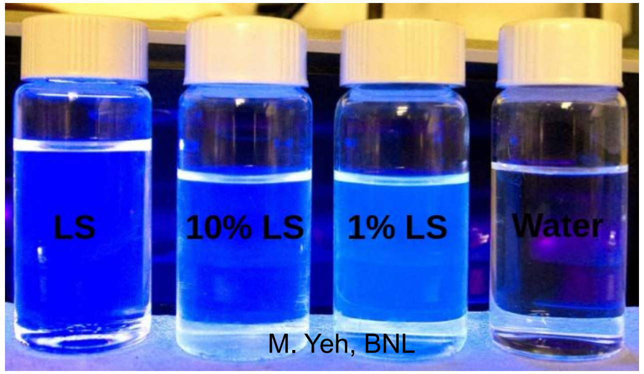
BACKUP SLIDES

Physics and technology goals

Technology upgrades

First or future phase

Augmented solutions



M. Yeh, BNL

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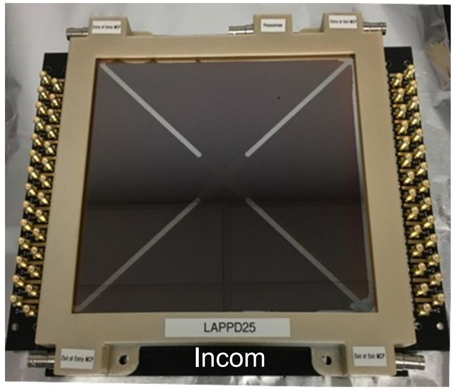
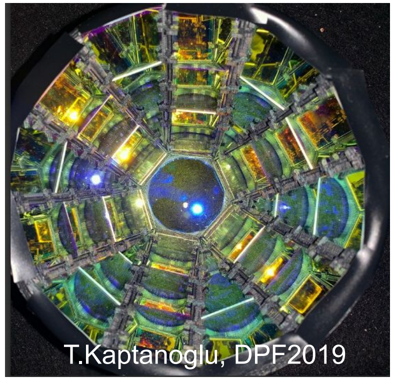


Incom



T.Kaptanoglu, DPF2019

Water-based liquid scintillator (WbLS): added bonus of scintillation light

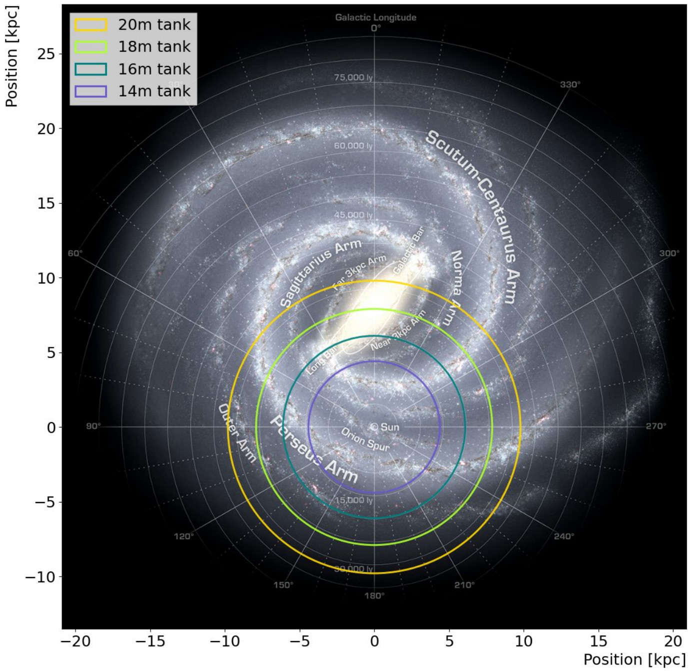
Picosecond photosensors: fast timing

Dichroicons: light concentration and separation by wavelength

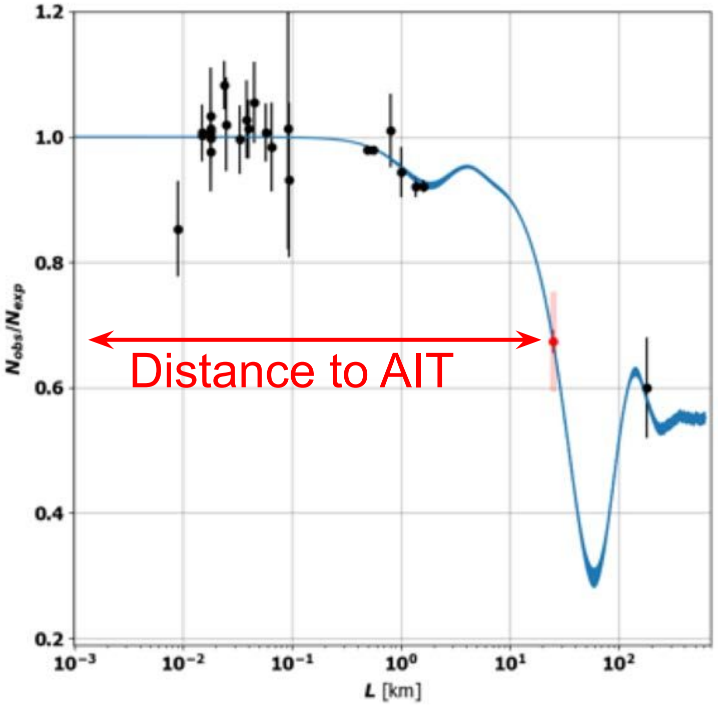
= the 'Holy Grail' of Cherenkov and scintillation separation

Remote monitoring… and beyond

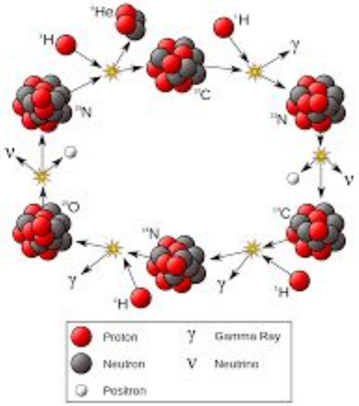
First phase → Future



Supernova neutrino detection and input into Supernova NEutrino Warning System (SNEWS)

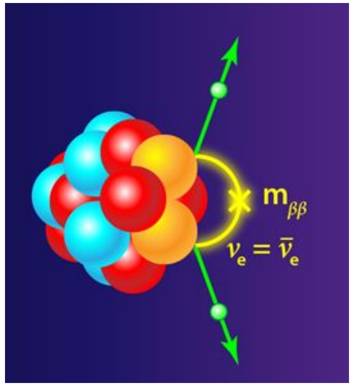


Neutrino oscillations (Δm^2_{12} and reactor ranging)



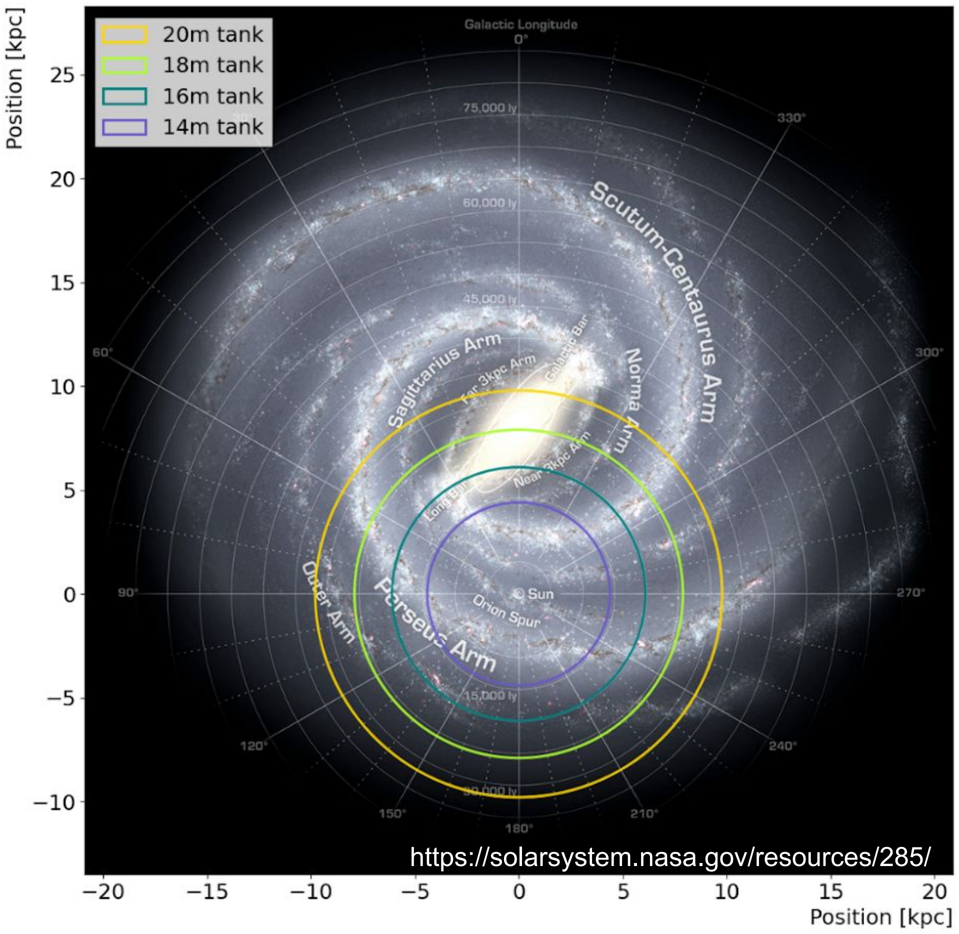
©Borb

CNO solar neutrinos



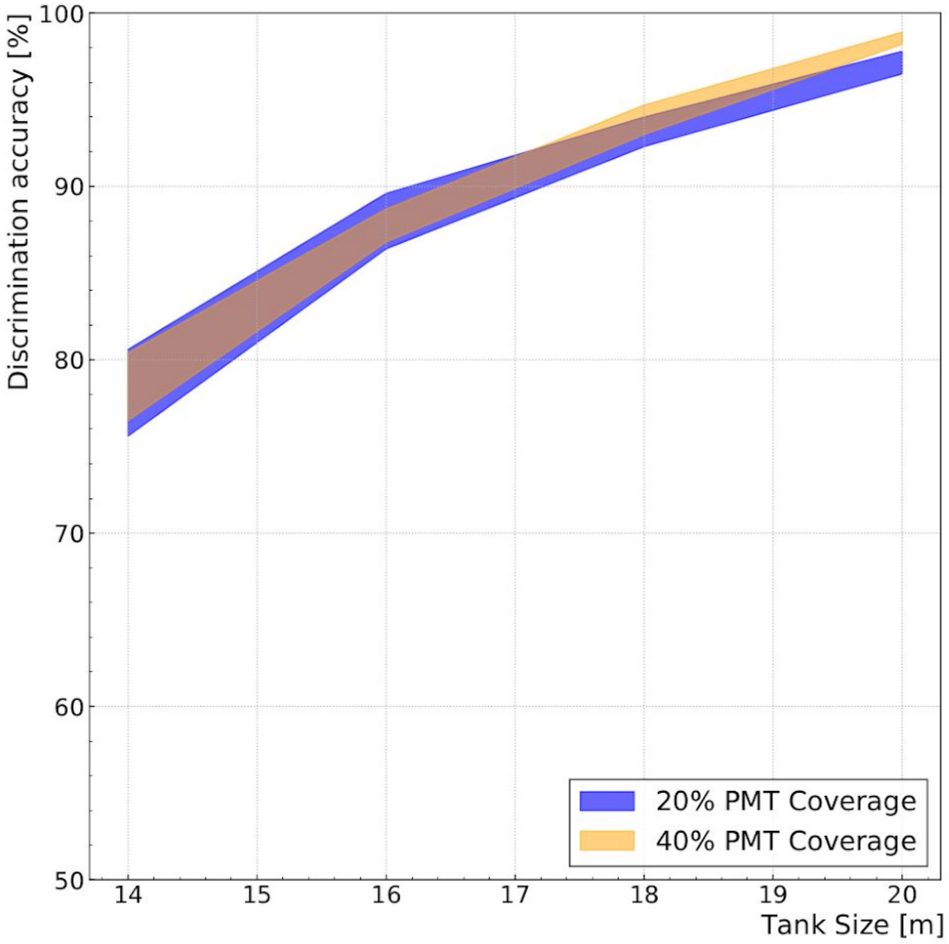
Neutrinoless-ββ decay

Supernova model discrimination



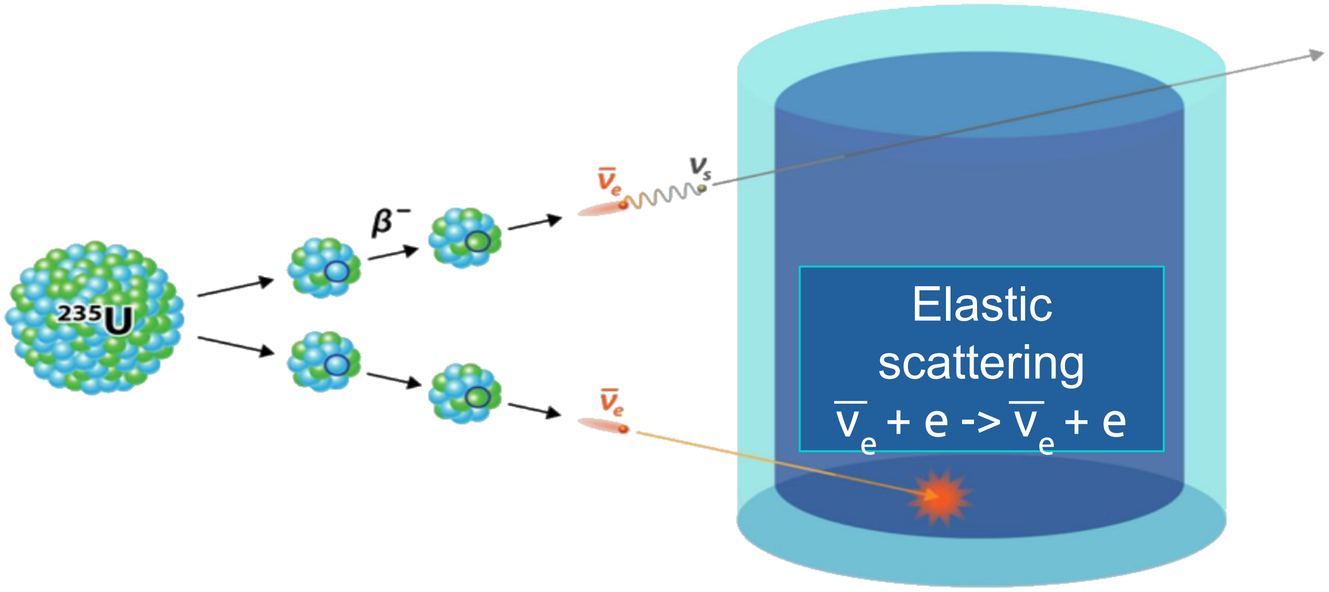
https://solarsystem.nasa.gov/resources/285/

Maximum distance for different tank sizes with 20% PMT coverage to observe ≥ 100 events , assuming the Nakazato supernova model.



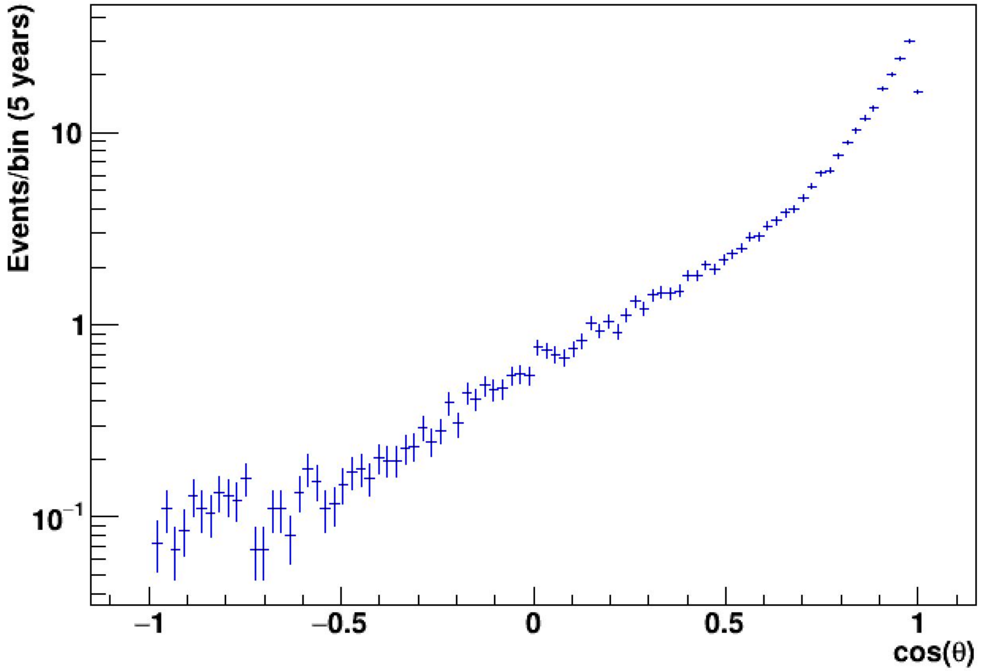
Discrimination accuracy for a supernova at a fixed distance with respect to detector tank size and PMT coverage.

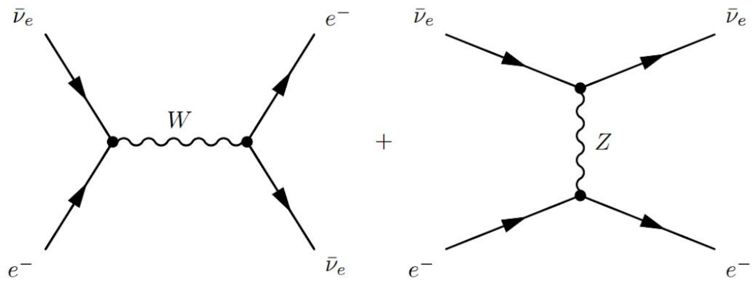
Reactor directionality



Elastic scattering
$\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e$

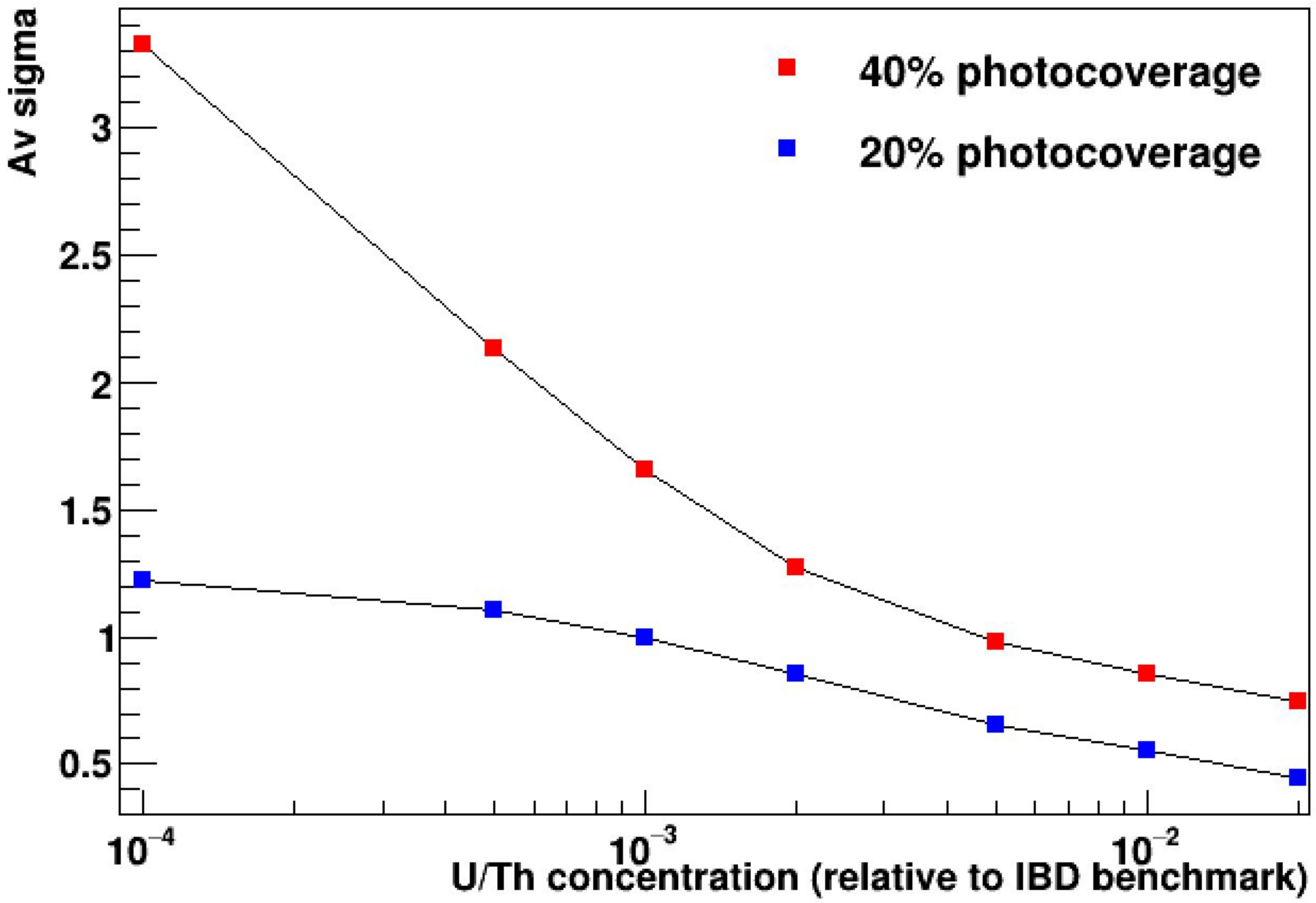
APS/Alan Stonebraker





Anti-neutrino elastic scattering on electrons points back towards the reactor.

Requires U/Th in water O(10^3)x lower



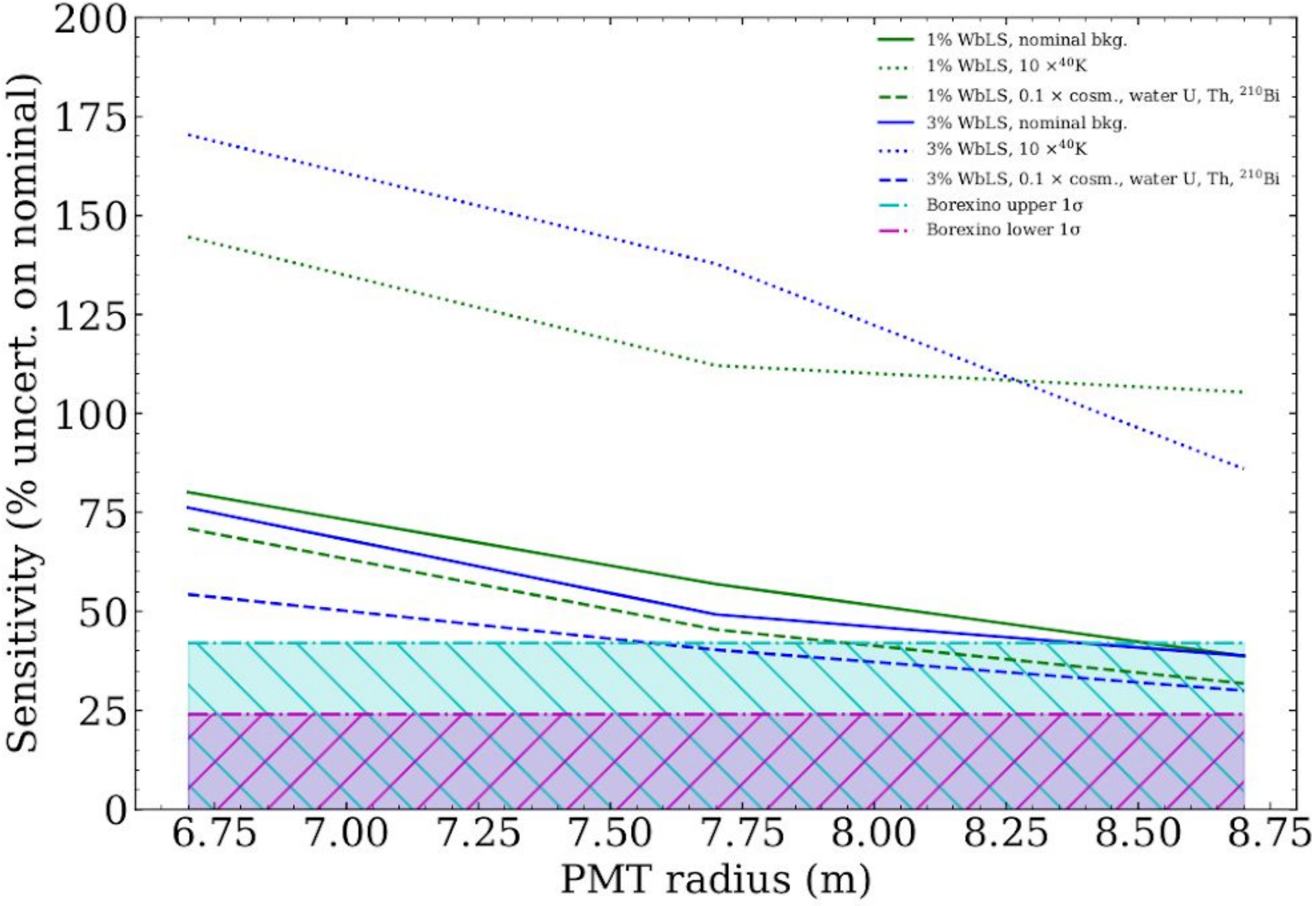
Event with 40% photocoverage and an inner detector radius of 8.7 m (increased from 6.7 m):

2σ directional detection would require 1150 times lower U/Th concentration in the water than the IBD benchmark for WATCHMAN:

U: 8.1×10^{-14} g/g
Th: 2.5×10^{-14} g/g

SNO background levels:
U: 6.6×10^{-15} g/g
Th: 8.6×10^{-16} g/g

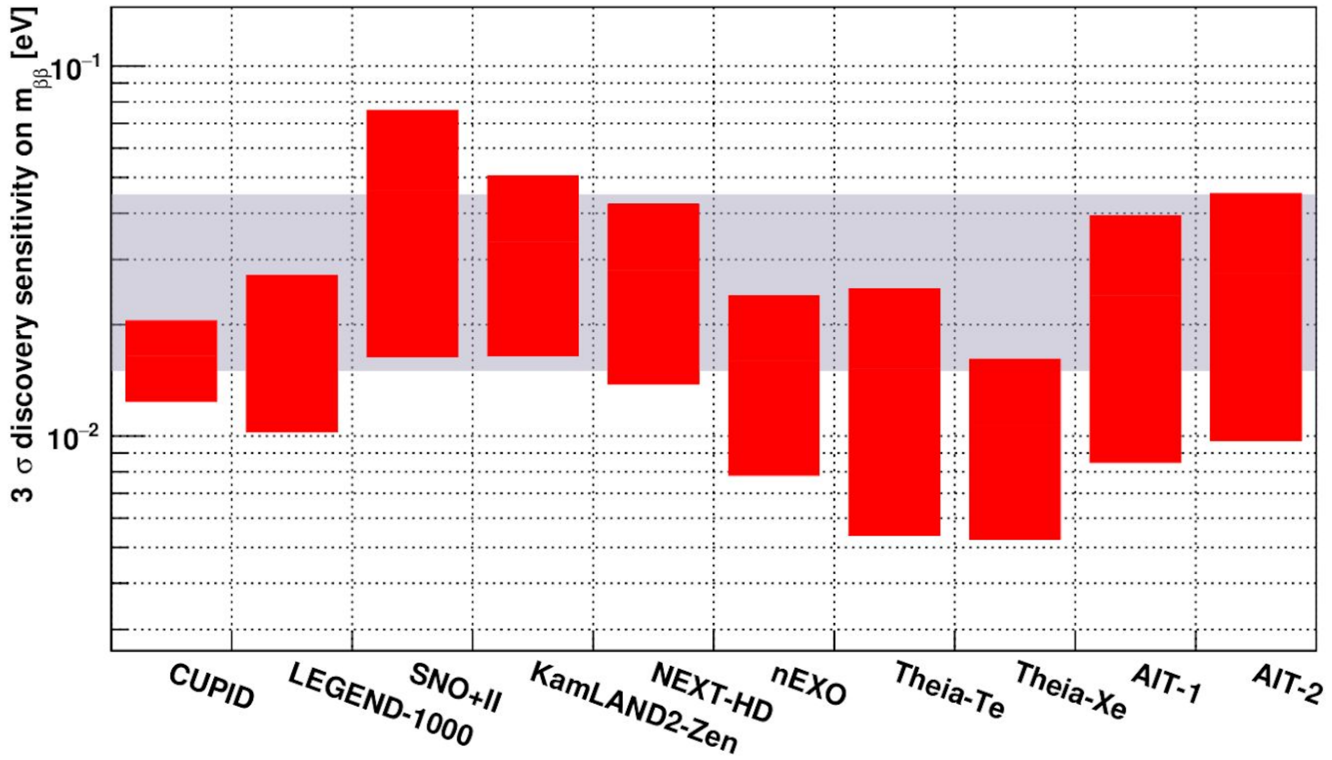
CNO solar



Sensitivity to CNO solar with different WbLS cocktails for conservative and aggressive background rejection scenarios.

CNO solar sensitivity is critically dependent on low ^{40}K levels.

Neutrinoless double-beta decay

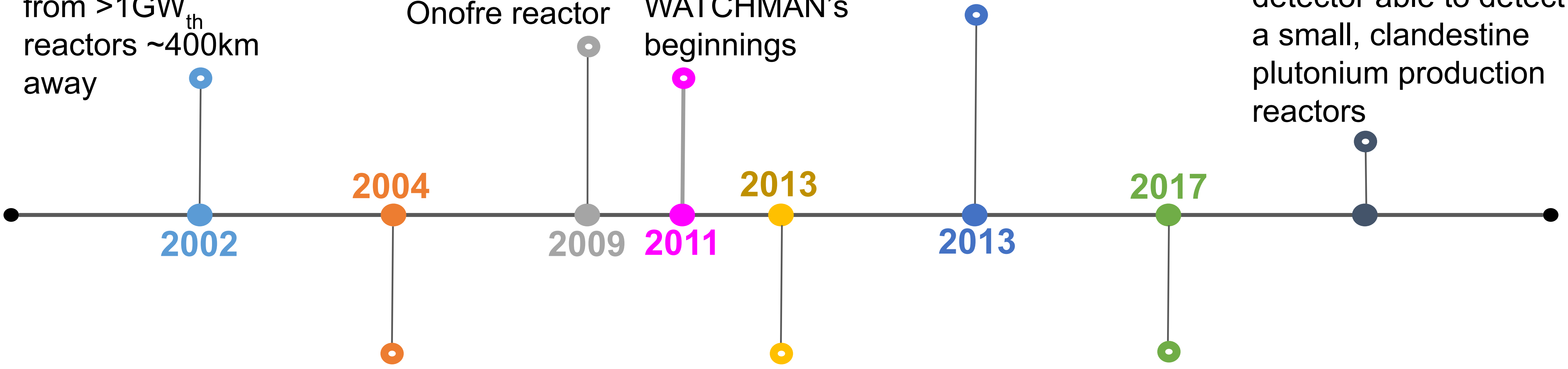


Yu. G. Kolomensky

WATCHMAN with a liquid scintillator fill.

Sensitivity of next-generation experiments to neutrinoless-ββ decay for 10 years of data (Askins et al., 2020)

Towards a remote reactor monitor



Kamland
Saw neutrinos from >1GW$_{th}$ reactors ~400km away

GADZOOKS
Built on the idea of using gadolinium-doped water, adopted by SK Gd in 2020.

SONGS1
Ton-scale Gd-doped liquid scintillator, San Onofre reactor

NNSA Strategic Plan:
WATCHMAN’s beginnings

WATCHBOY
Ton-scale underground Gd-H_2O detector to measure radionuclide backgrounds

MARS
Multplicity and Recoil Spectrometer to measure the fast neutron background

EGADS!
Purification system for Gd-doped water

AIT-WATCHMAN
Ultimate goal: megatonne-scale detector able to detect a small, clandestine plutonium production reactors

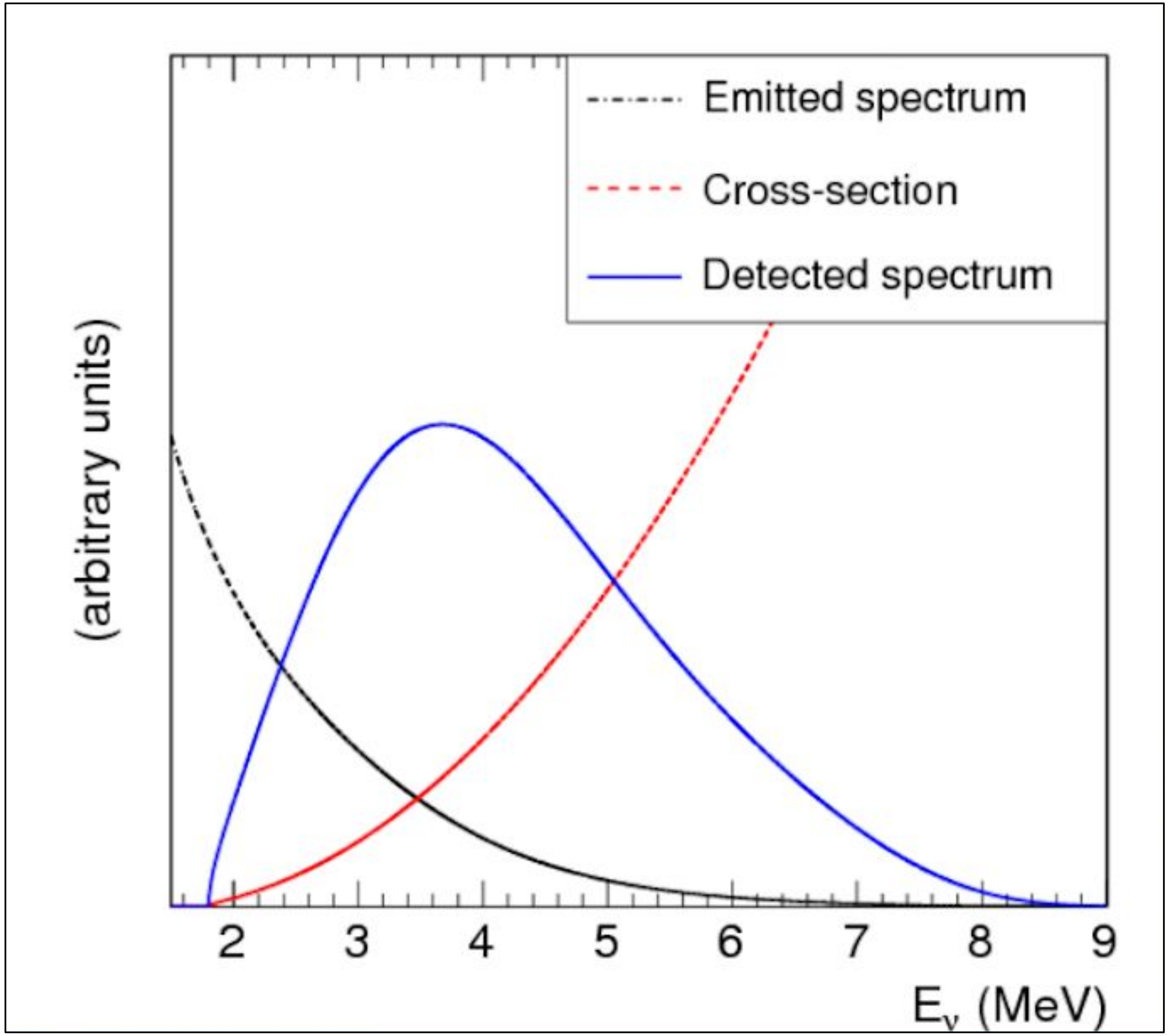
What information is useful?

‘Simple’ counting analyses:

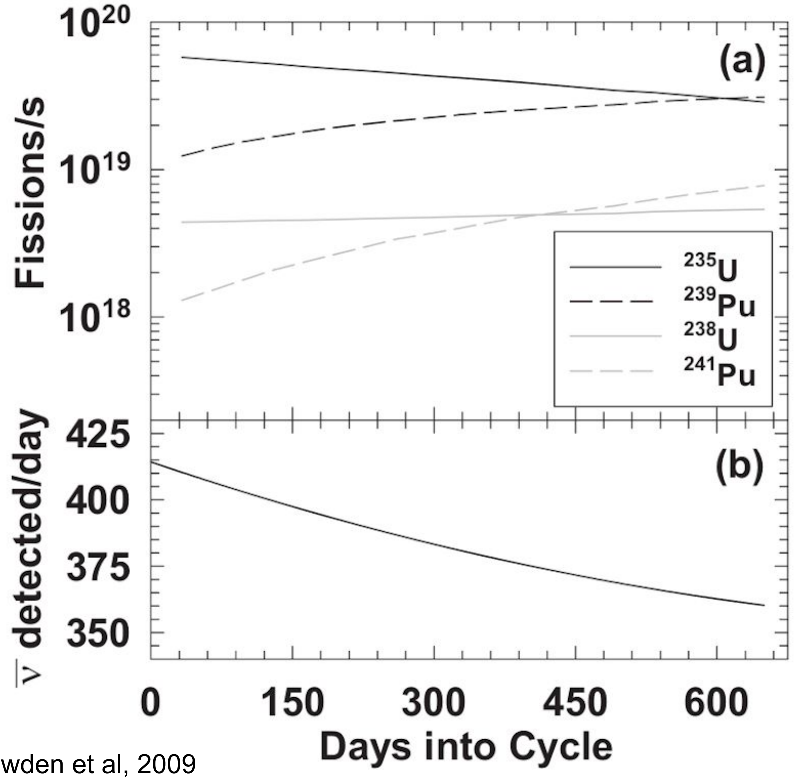
1. Presence/absence of a reactor
2. Fuel burnup in the core

More complex, spectral analyses:

1. Reactor composition
2. Reactor ranging
3. Reactor location



Reactor composition



Bowden et al, 2009
DOI: 10.1063/1.3080251

Burnup-dependent flux.

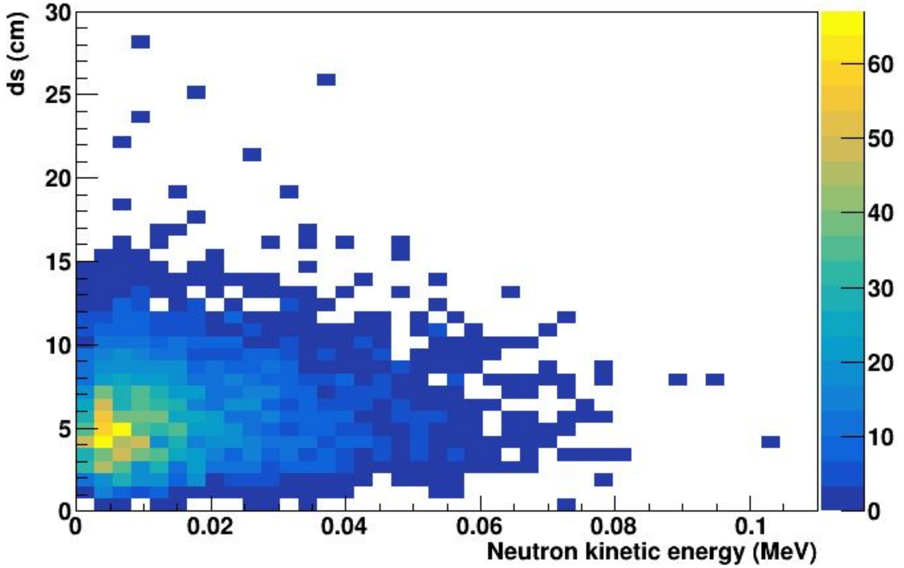
Relatively straightforward where refueling is infrequent: useful for verification.

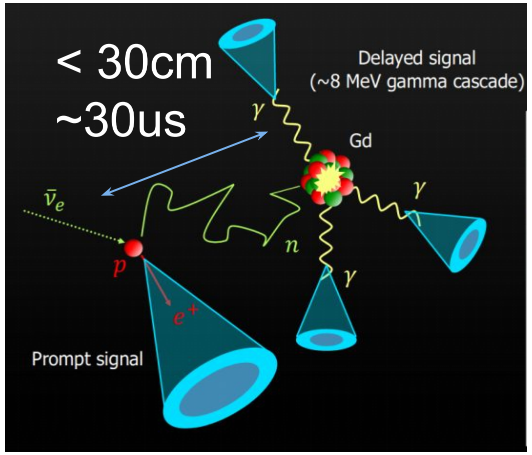
BONSAI* reconstruction

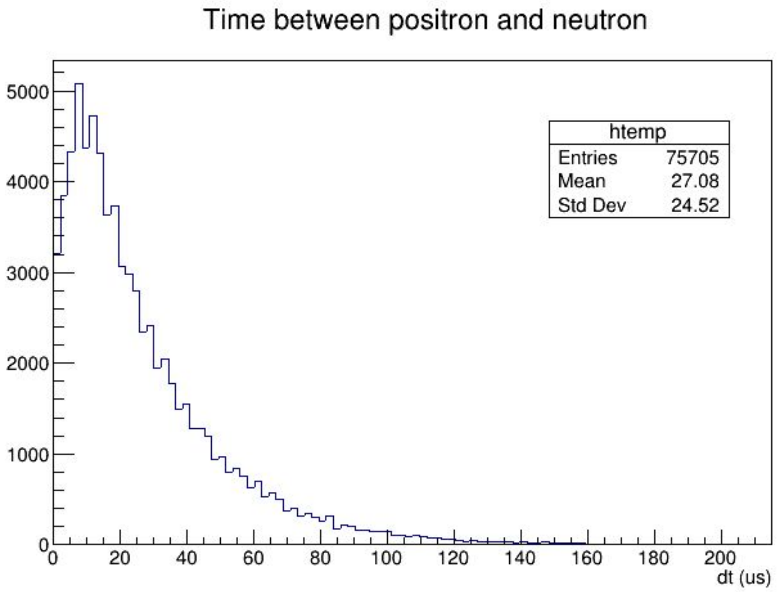
*Michael Smy, UCL

Branch	Demonstrated in Super-Kamiokande to work well in the reactor antineutrino energy range (down to ~3eV).
Optimisation	Optimisation by the maximum-likelihood method.
Navigating	
Successive	Successively more localised searches converge on the point in the detector at which the likelihood is maximised.
Annealing	Simulated annealing is a probabilistic search-and-test method by which the probability of selecting worse solutions decreases slowly as the search progresses. Good for finding the global maximum where there are many local maxima.
Iterations	

The IBD heartbeat





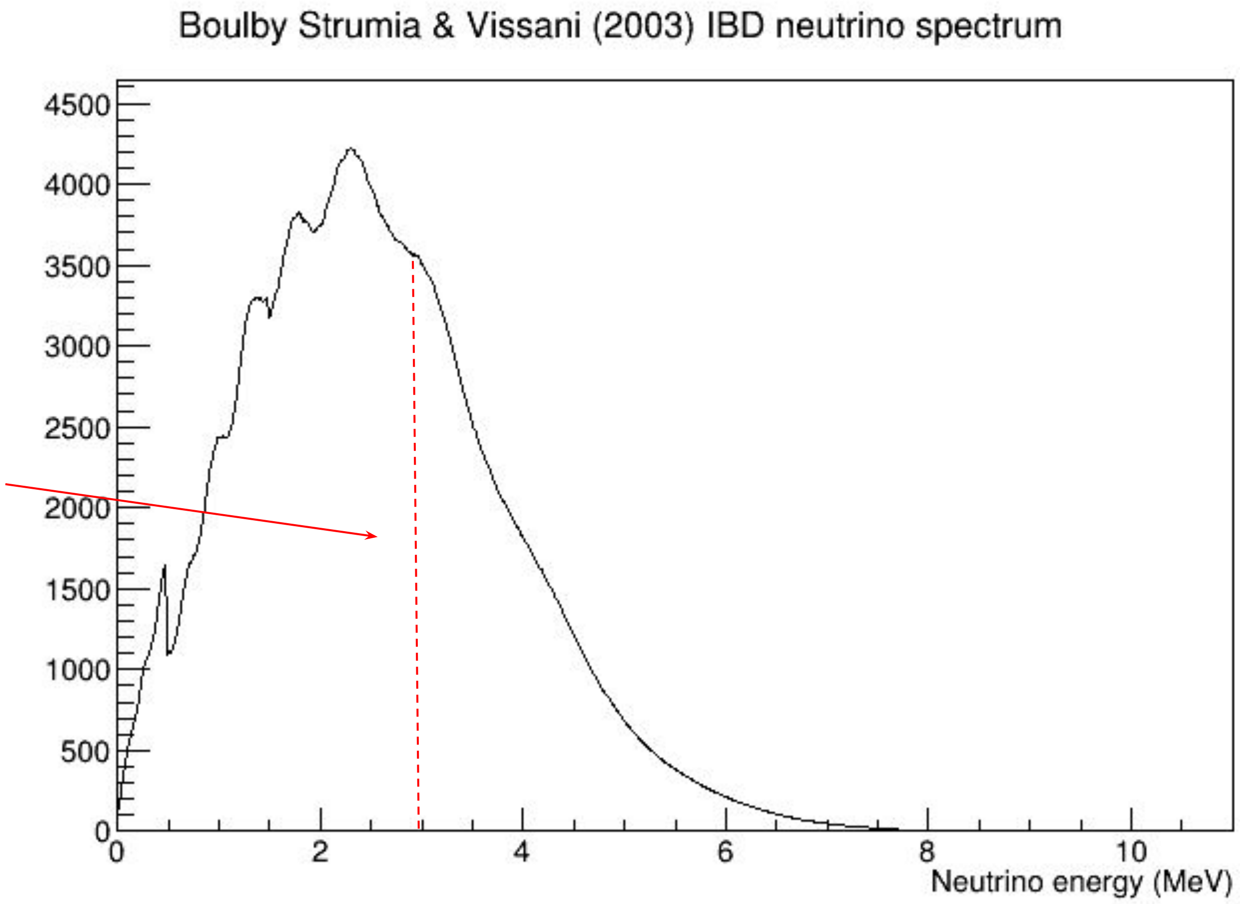


The IBD-pair positron and neutron are generally within ~30cm and ~150μs for reactor neutrinos.
The mean time between events is ~30μs. The mean distance between events is ~5cm.

Reconstructing the IBD heartbeat

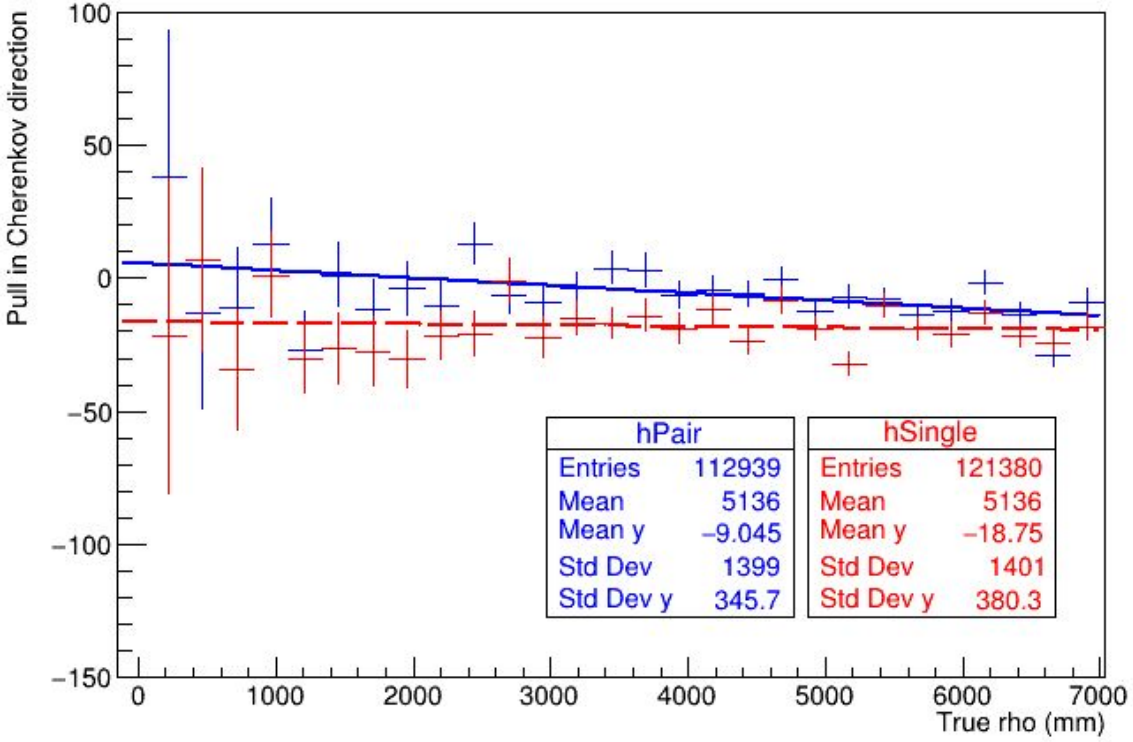
The aim of a combined reconstruction is to use the additional light from the neutron to improve reconstruction, particularly at the low energies of reactor antineutrinos.

We are looking for ways to get this detectable threshold as low as possible



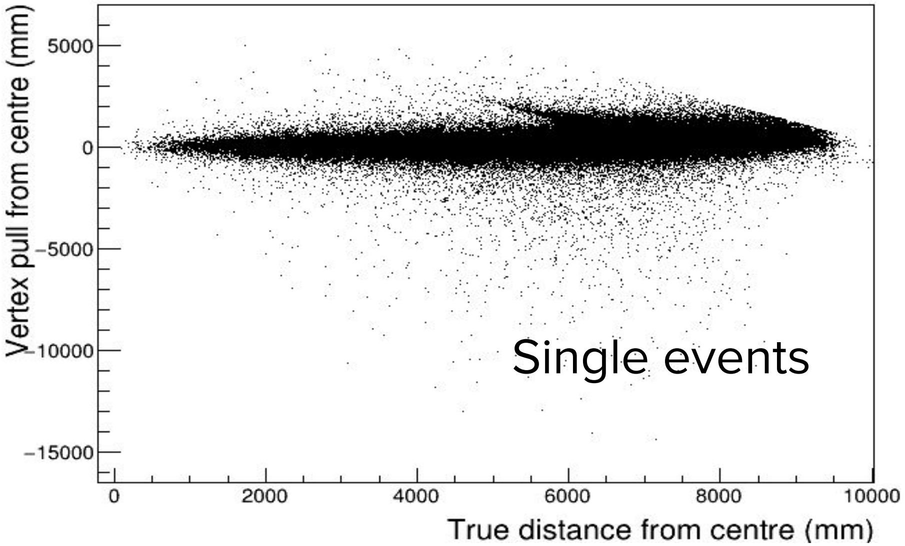
Improved vertex pull

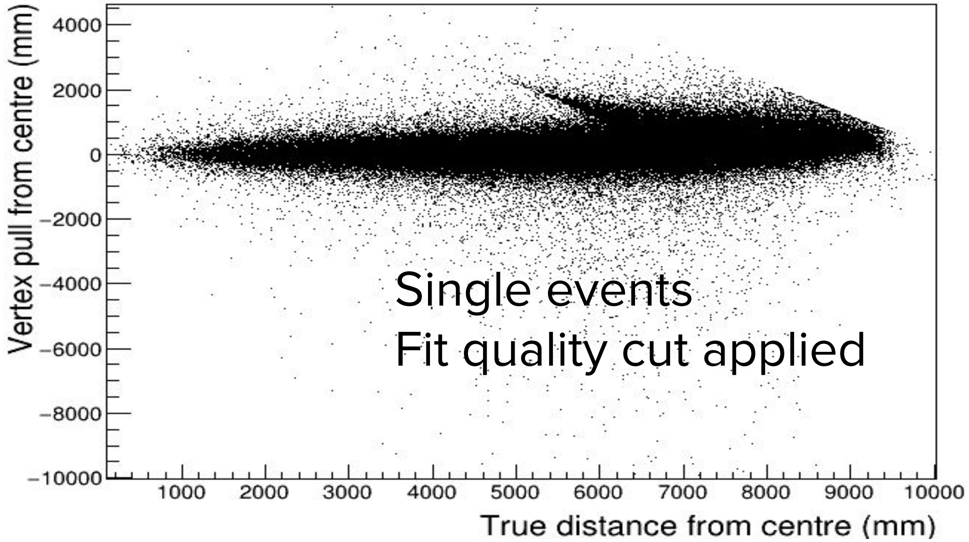
Taking the mean of the vertex pull in the Cherenkov direction also shows an overall improvement in the reconstruction in the direction of the light (with a cut on goodness of fit - see later slide).

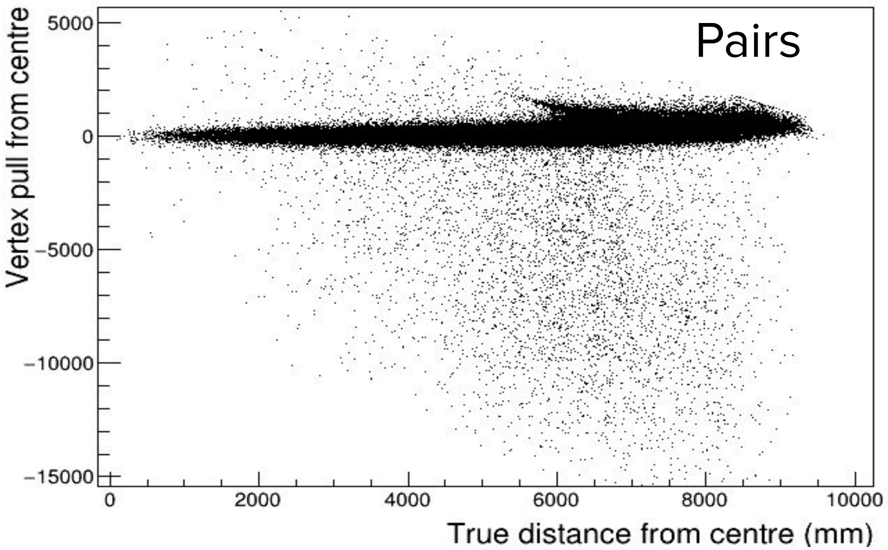


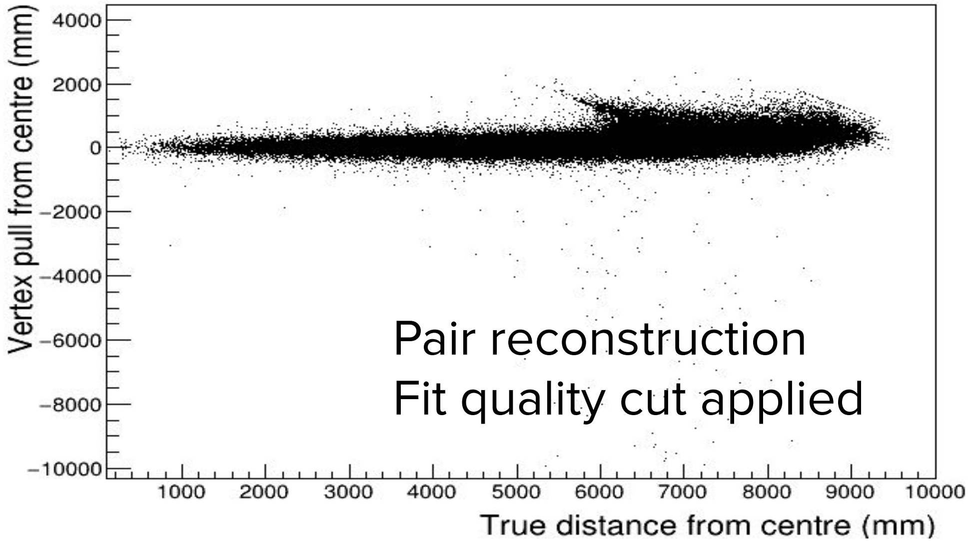
Information from additional hits gives better reconstruction in the Cherenkov direction.

Pairbonsai fit quality cut more effective

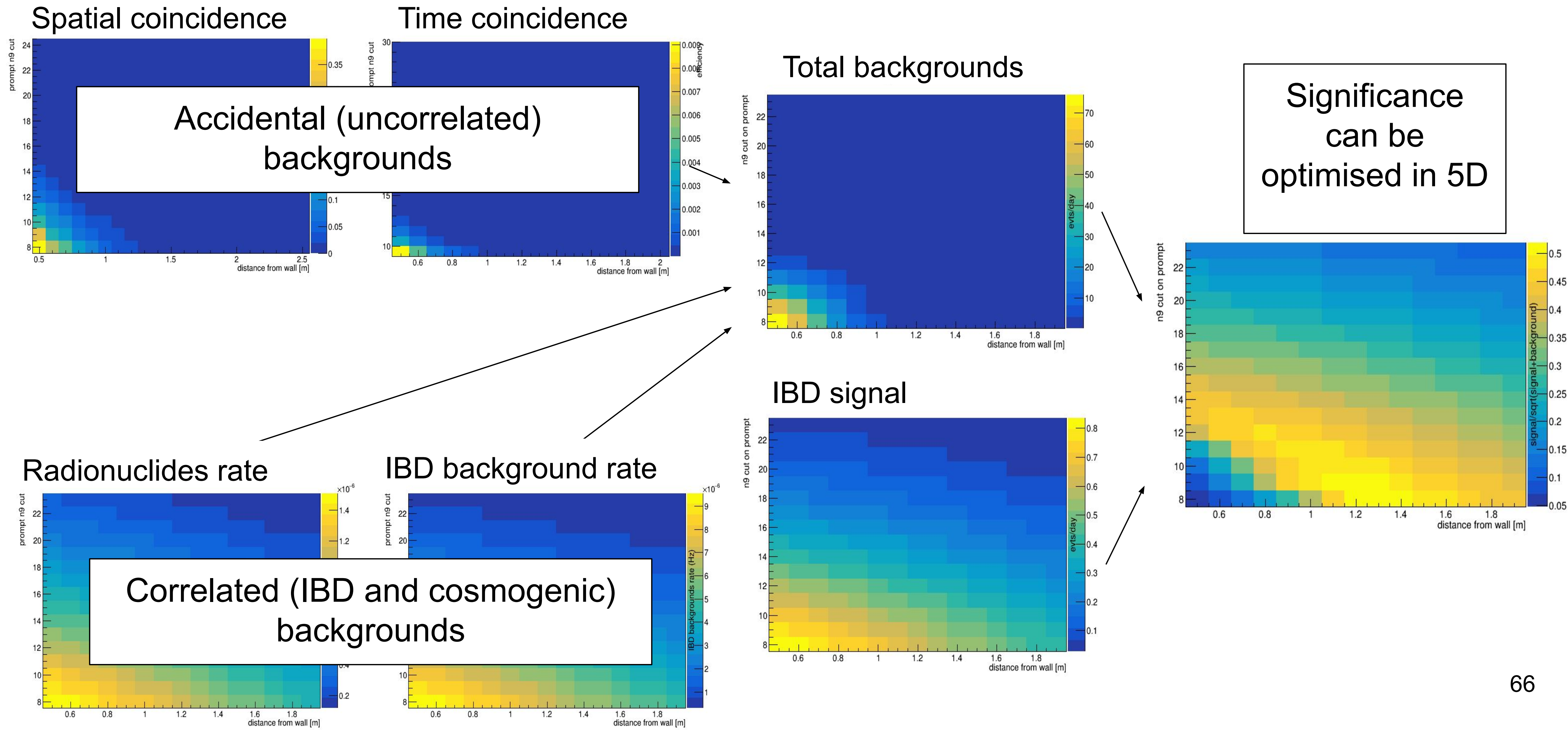

Single events


Single events
Fit quality cut applied


Pairs


Pair reconstruction
Fit quality cut applied

Sensitivity analysis for WATCHMAN



Spatial coincidence

Time coincidence

Accidental (uncorrelated) backgrounds

Total backgrounds

IBD signal

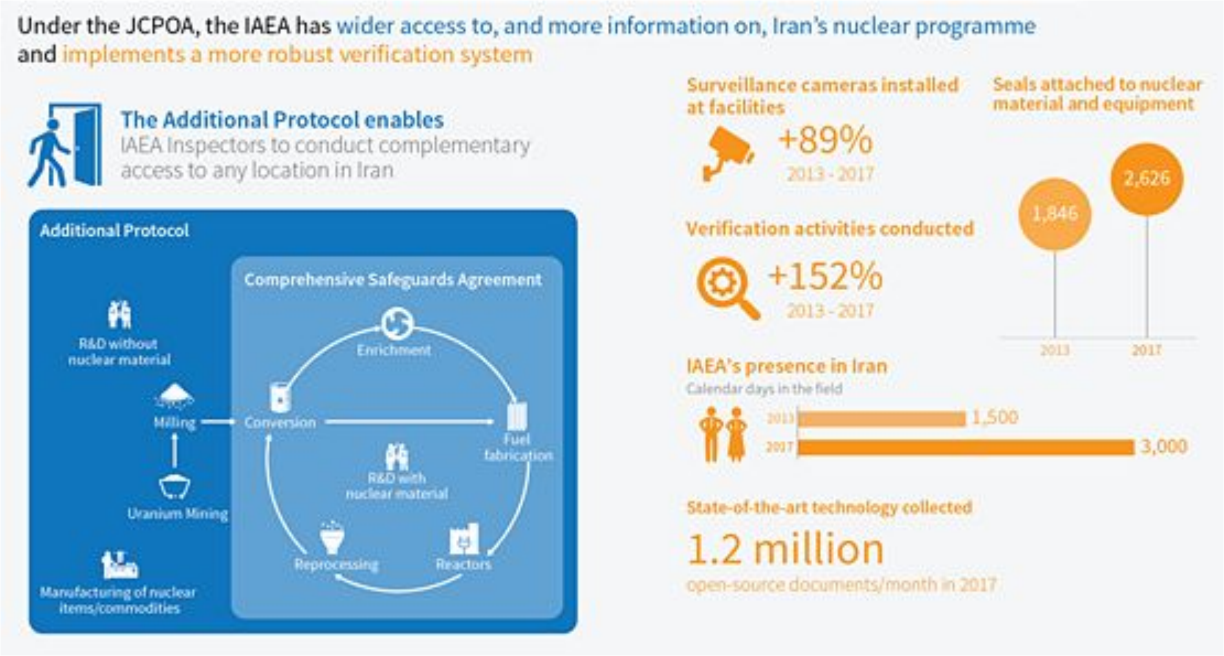
Significance can be optimised in 5D

Radionuclides rate

IBD background rate

Correlated (IBD and cosmogenic) backgrounds

Part of a remote monitoring toolkit



Cooperative for verification of declared reactor activity: local/wide area absence or power cycle verification.

Main switchboard of Krasnoyarsk-26 (Mining Chemical Combine) underground nuclear complex
RIA Novosti archive, image #804630 / A. Solomonov / CC-BY-SA 3.0

Non-cooperative for detection of a hidden reactor: far field (nearby State) detection of undeclared activity.

Balancing intrusion and confidence: **non-intrusive monitoring with remote detection.** Supplements standard monitoring and could form part of a remote monitoring system for both declared and undeclared nuclear facilities.