



The
University
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Sheffield.



WATCHMAN Project Overview and New Reconstruction Algorithms

King's College London
15th February 2021

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

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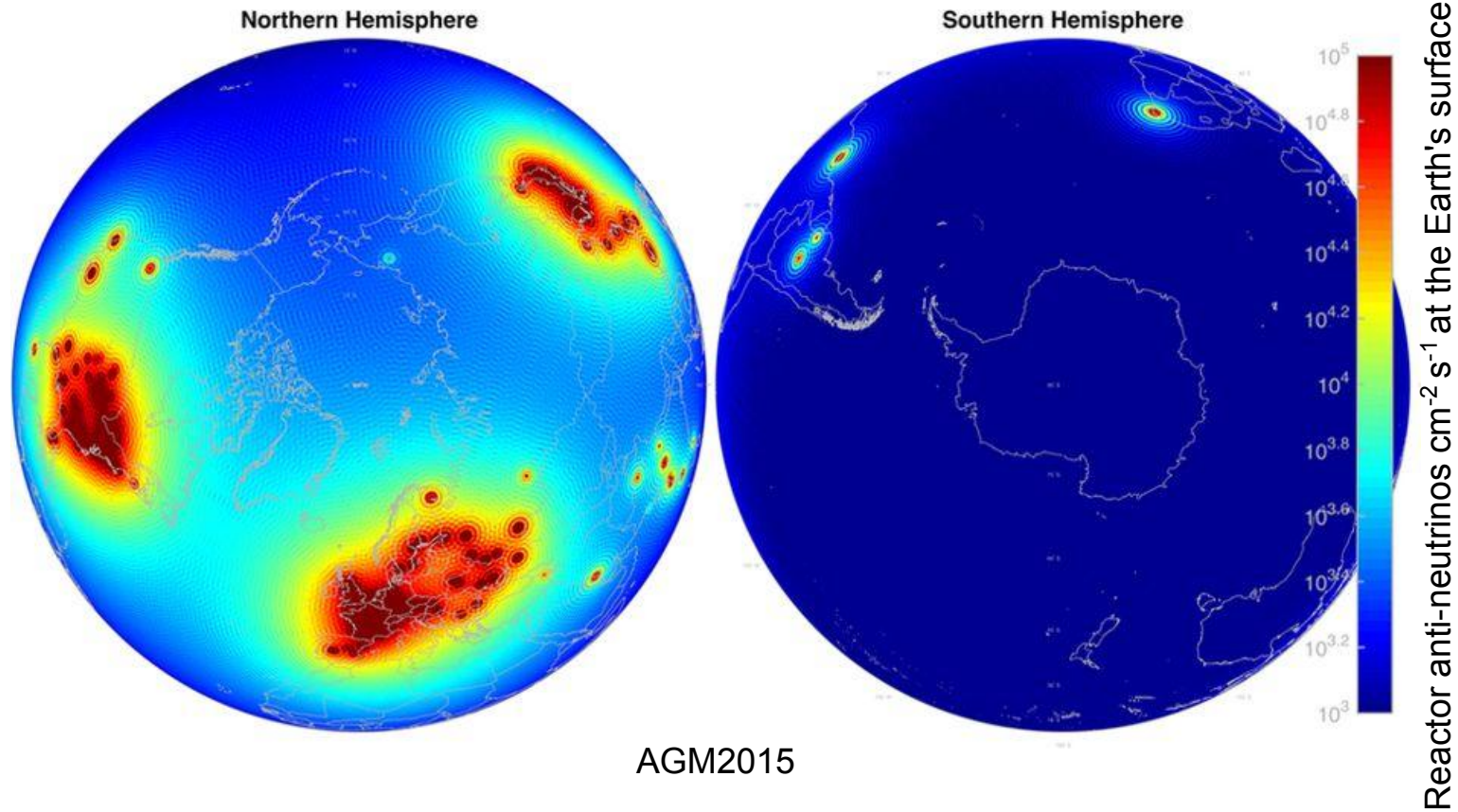
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The Power Paradox

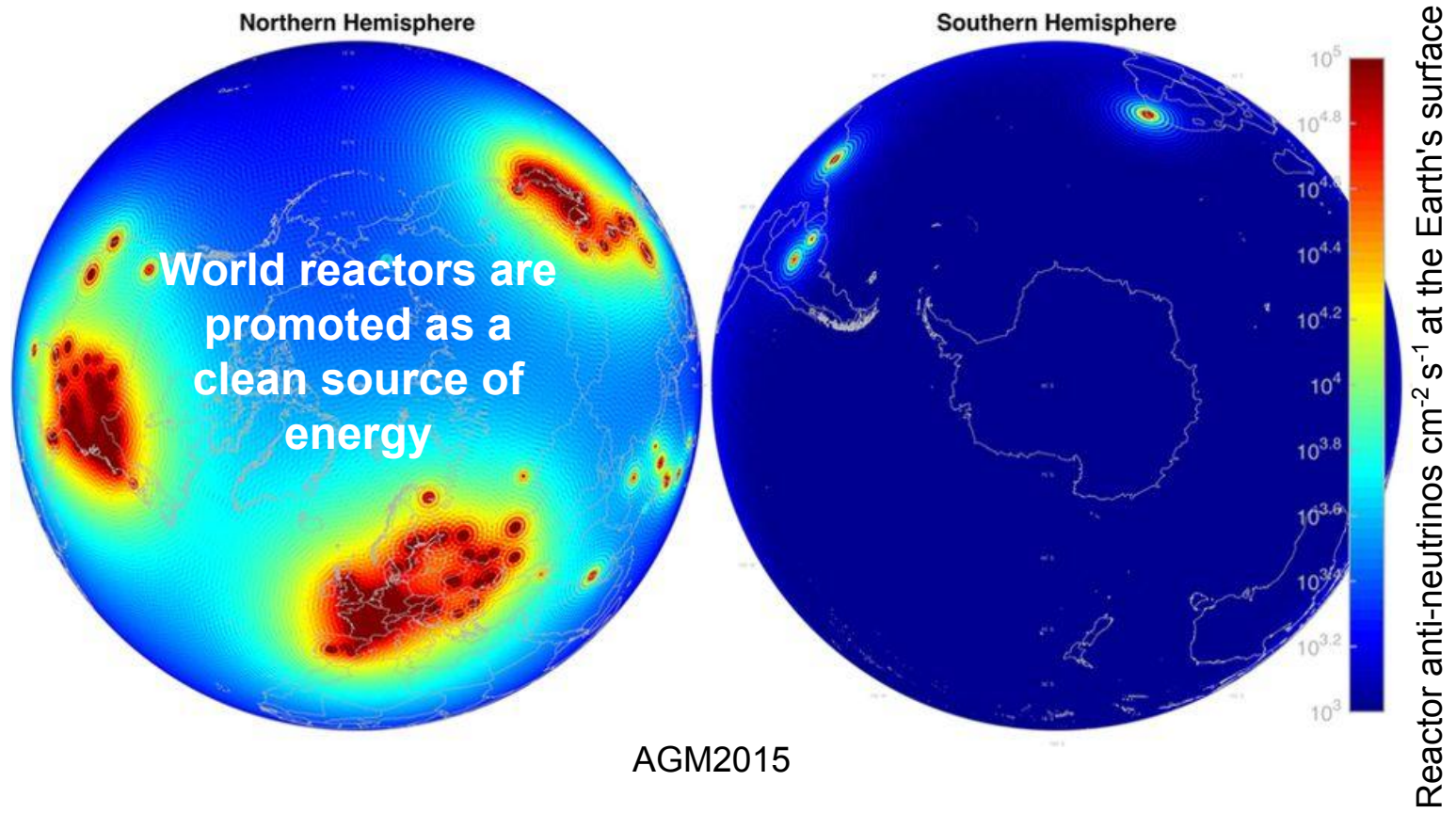
and Neutrinos for Non-Proliferation

Proliferation of nuclear energy



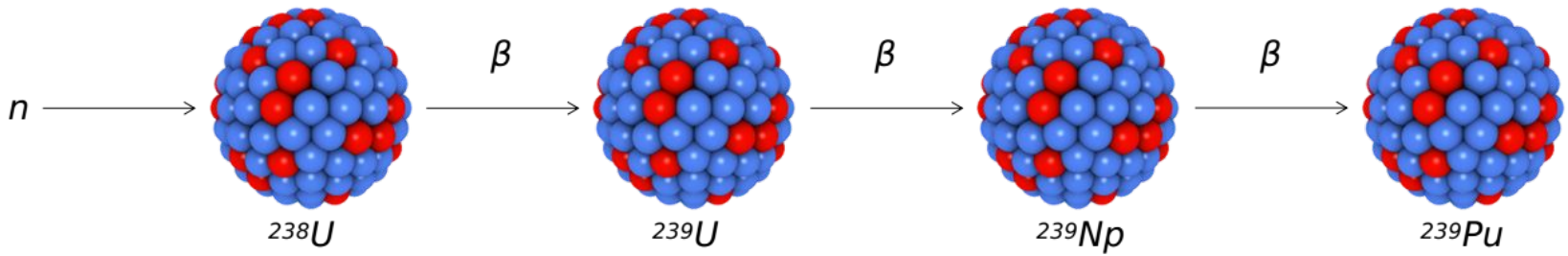
World reactors are promoted as a clean source of energy

Nuclear energy-weapons link

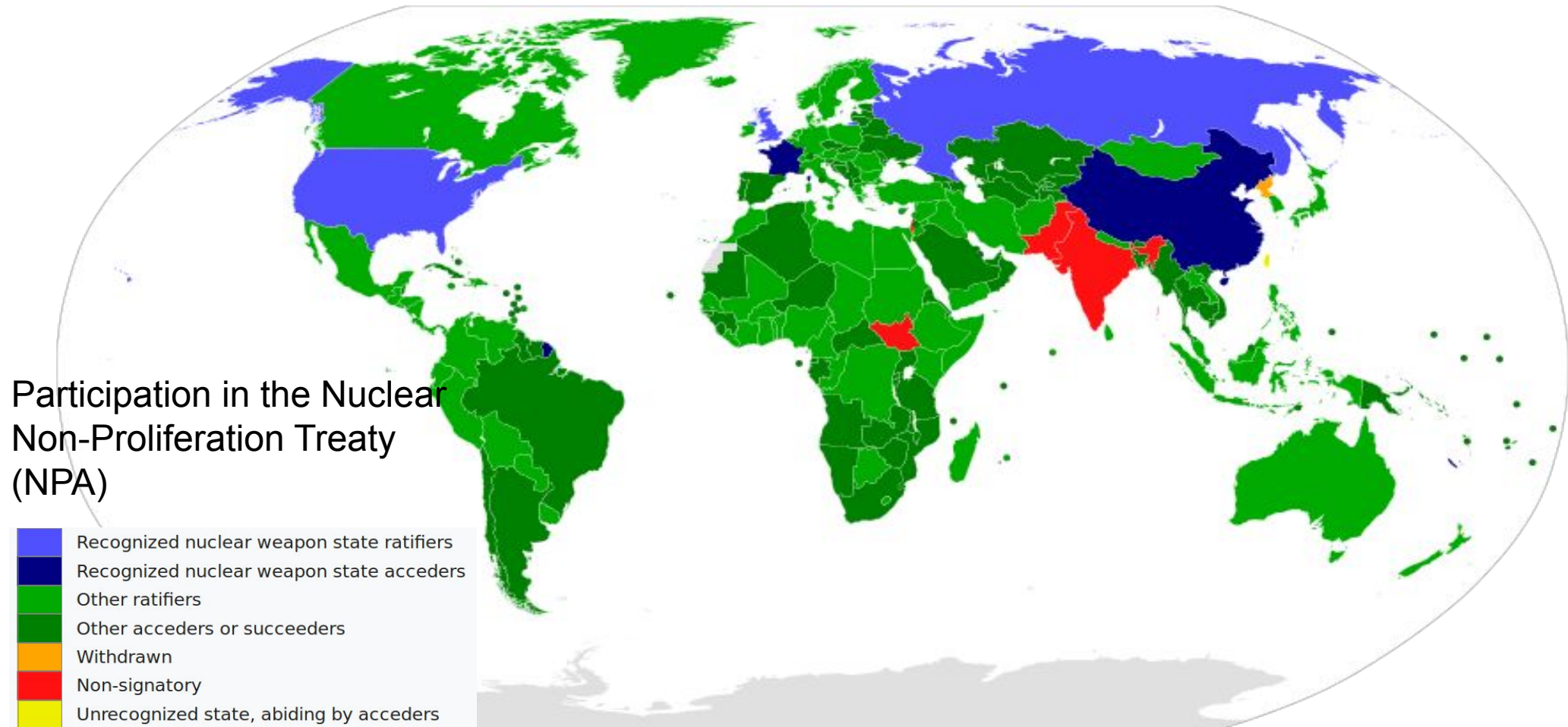


Inextricable link:

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



Remote monitoring supports NPT



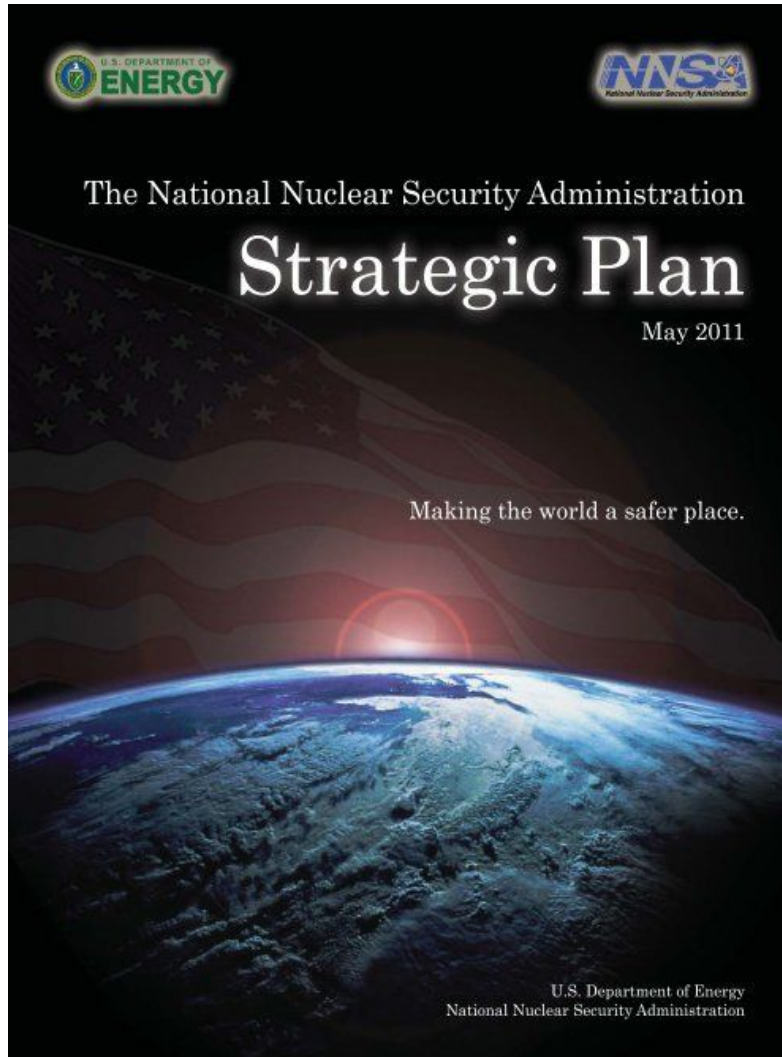
Non-Proliferation Treaty supported by **Comprehensive Safeguard Agreements** provide the framework for monitoring nuclear reactors.

Intrusion and confidence in the balance



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

Call for remote reactor monitoring

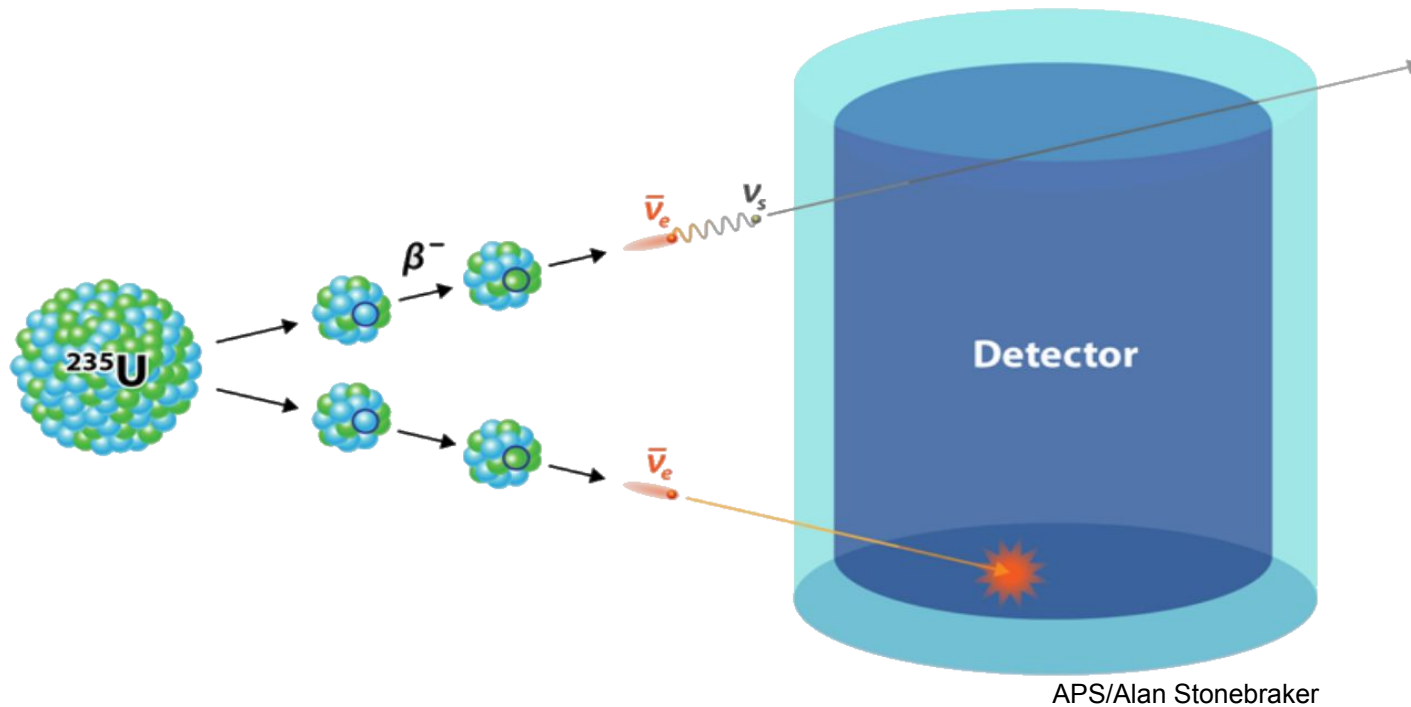


“Demonstrate remote monitoring capabilities for reactor operations”

NNSA Strategic Plan, 2011

Big problem, small solution

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

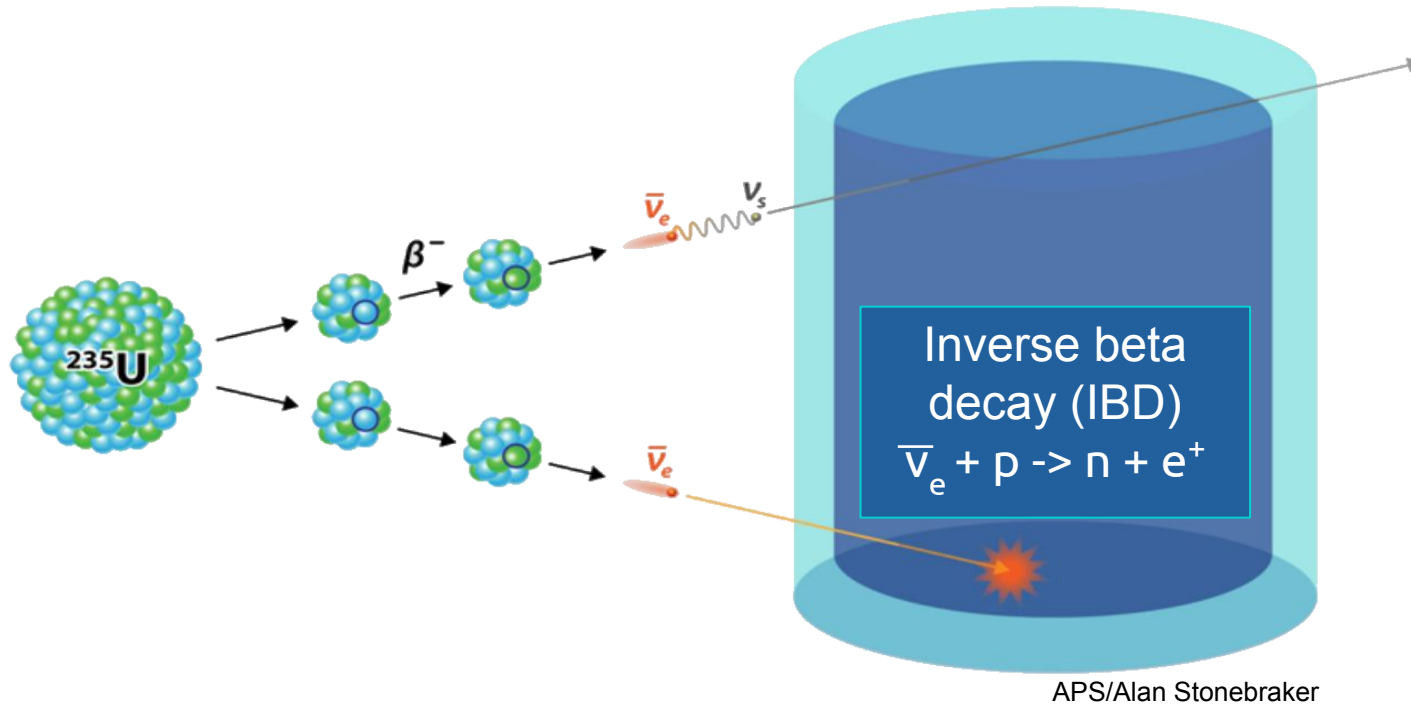


Each fission in a reactor releases on average 6 anti-neutrinos

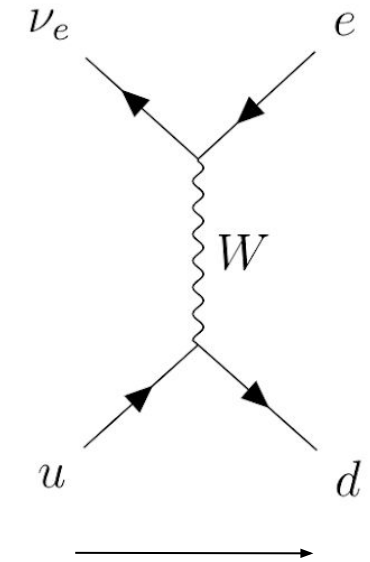
Anti-neutrinos from a 3GW_{th} reactor: 10^{22} per second isotropic emission (10^{21} fissions per second).

Big problem, small solution

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



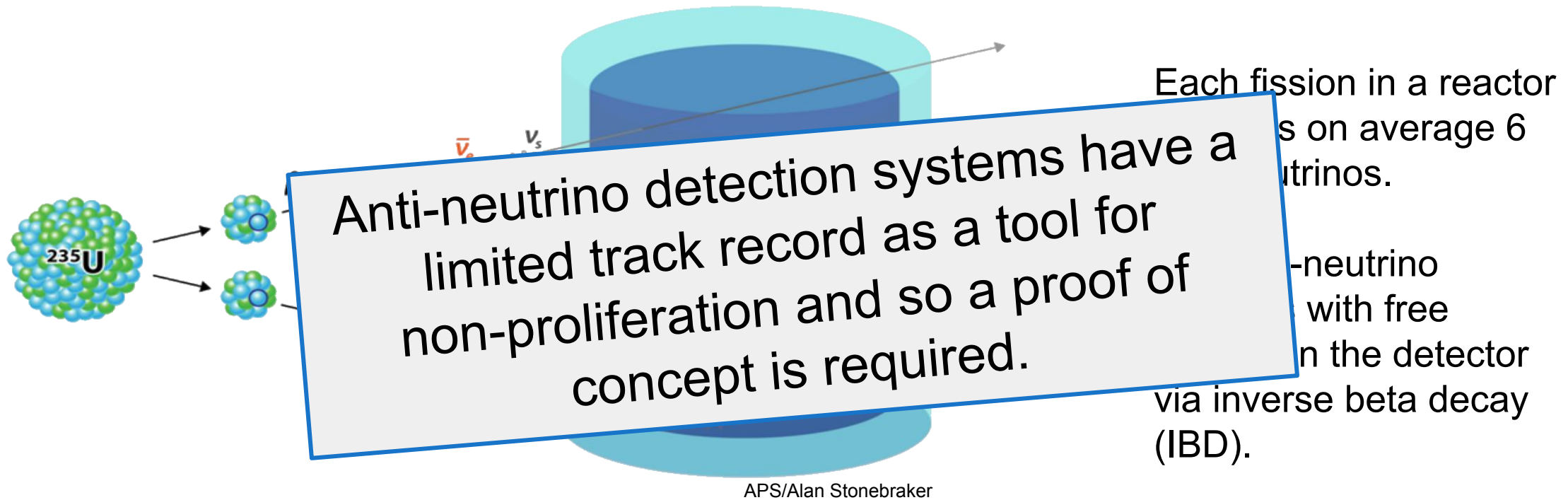
The anti-neutrino interacts with free protons in the detector via inverse beta decay (IBD).



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



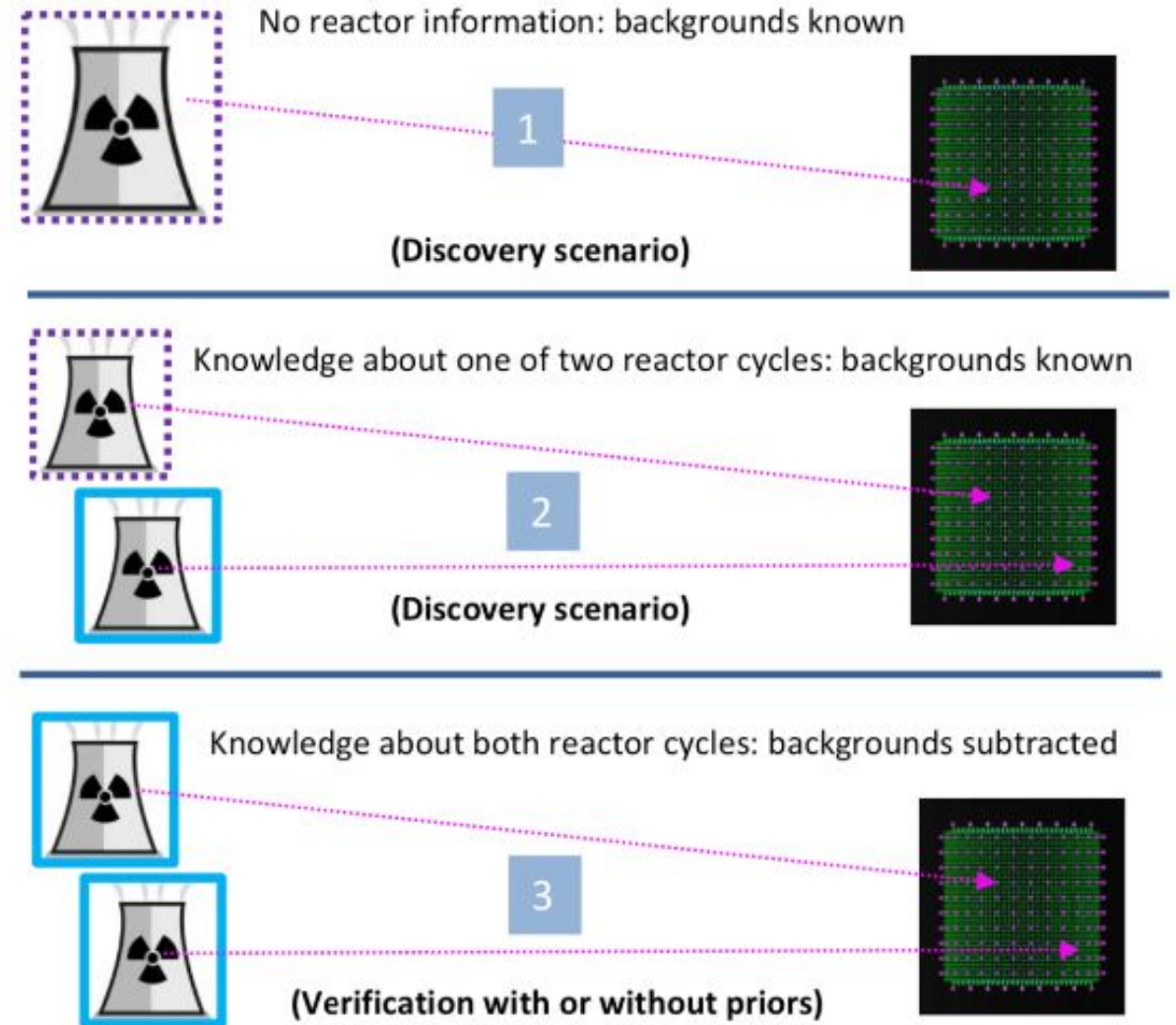
WATCHMAN

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

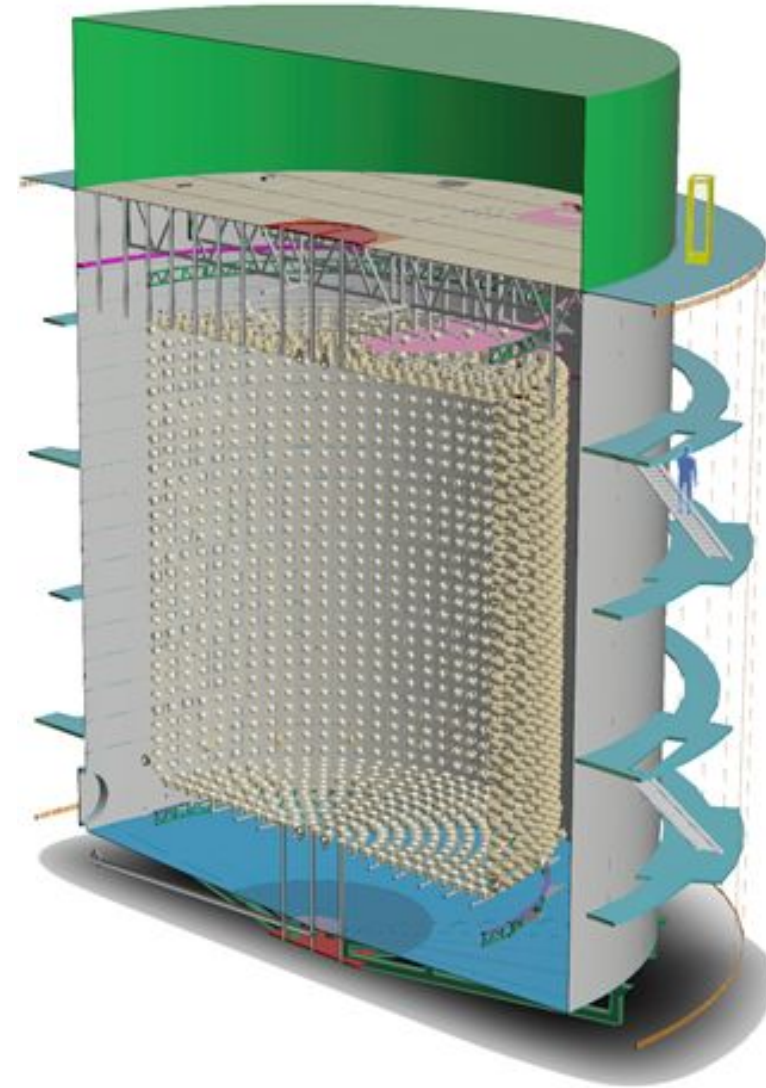
Baseline design:

1 ktonne fiducial mass.

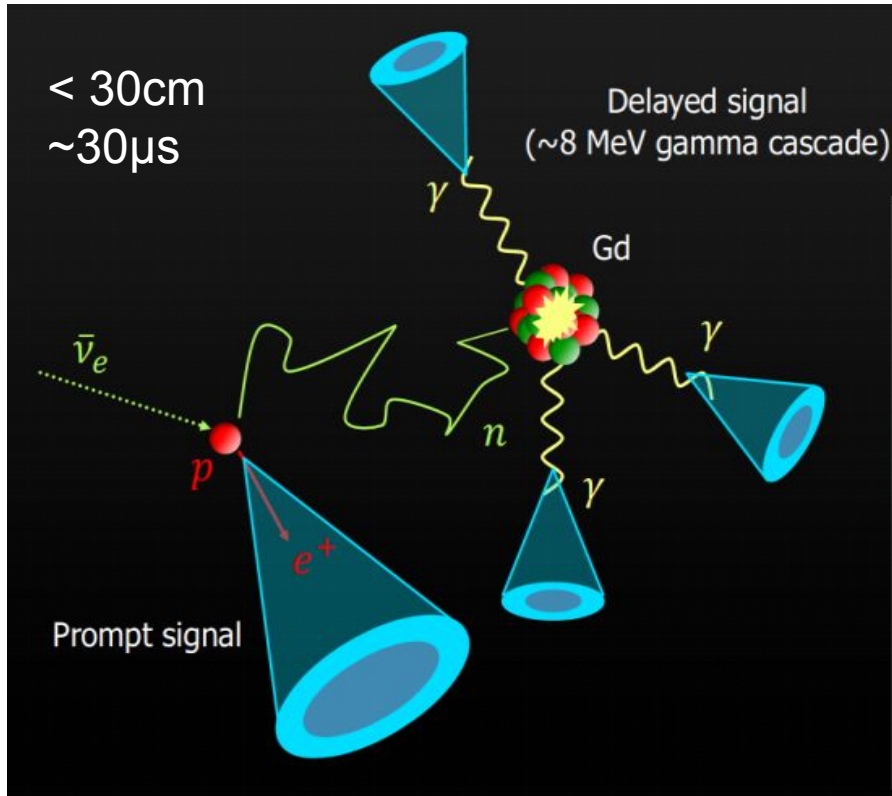
0.1% gadolinium-loaded water.

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 gadoliated 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 **10⁶ muon reduction**).

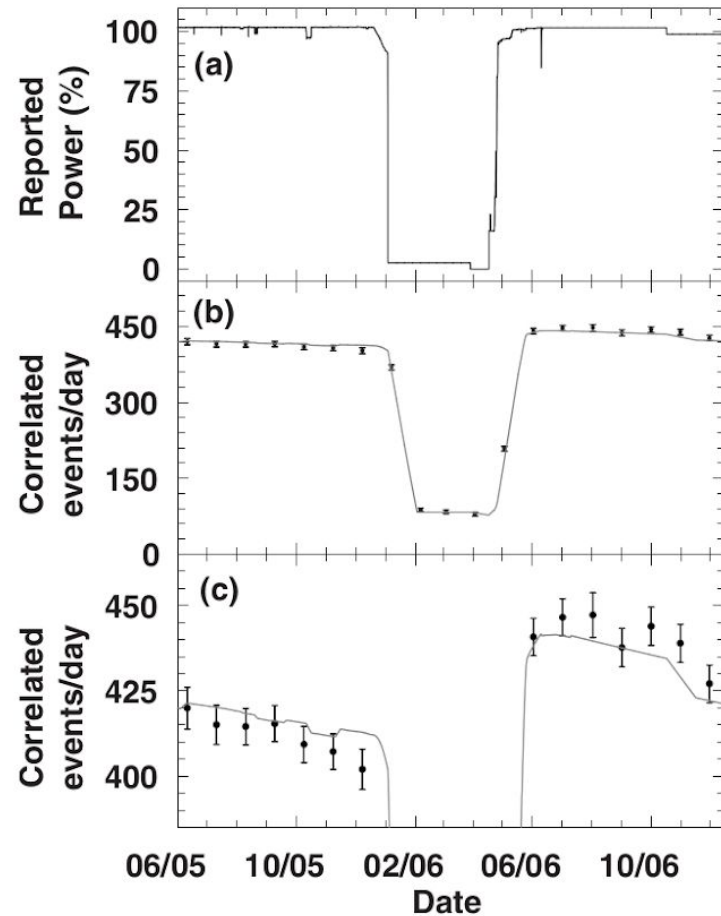
Cavern and laboratory to be built close to existing STFC Boulby Underground Laboratory.

Information encoded in the reactor signal

Information encoded in the

**How can we provide
better information with
limited intrusion?**

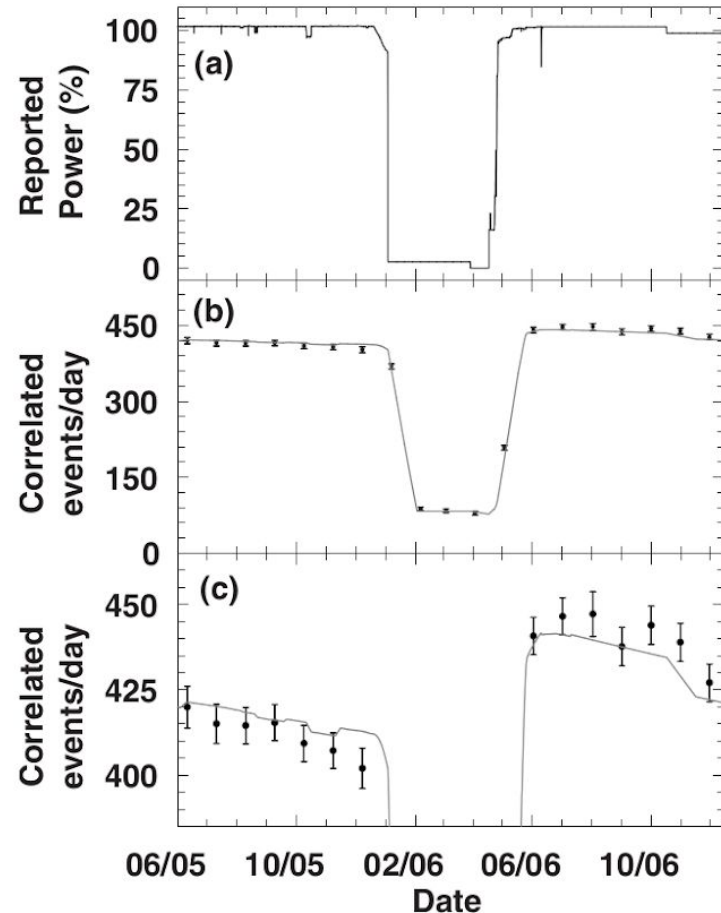
Presence/absence of a reactor



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

Bowden et al, 2009
DOI: 10.1063/1.3080251

Confirmation of reactor/power cycle



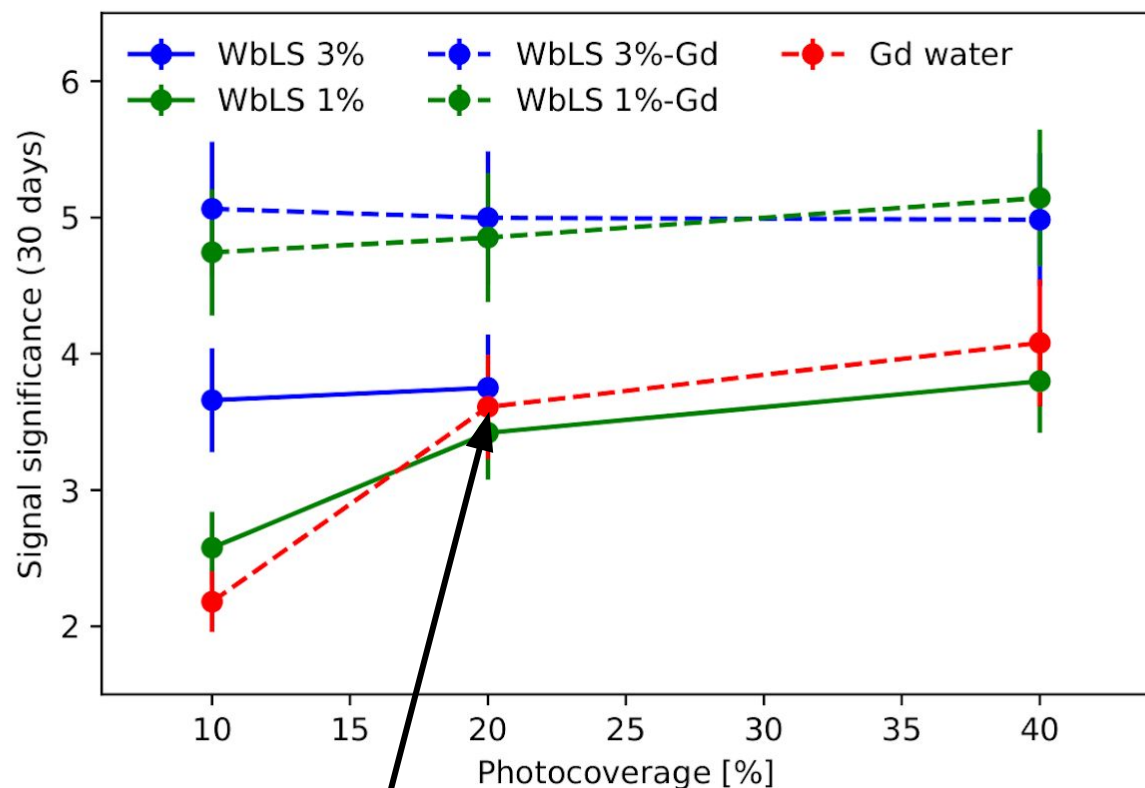
Anti-neutrino detector (gadolinium-doped liquid scintillator) at San Onofre Power Station demonstrated power/anti-neutrino flux connection.

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.

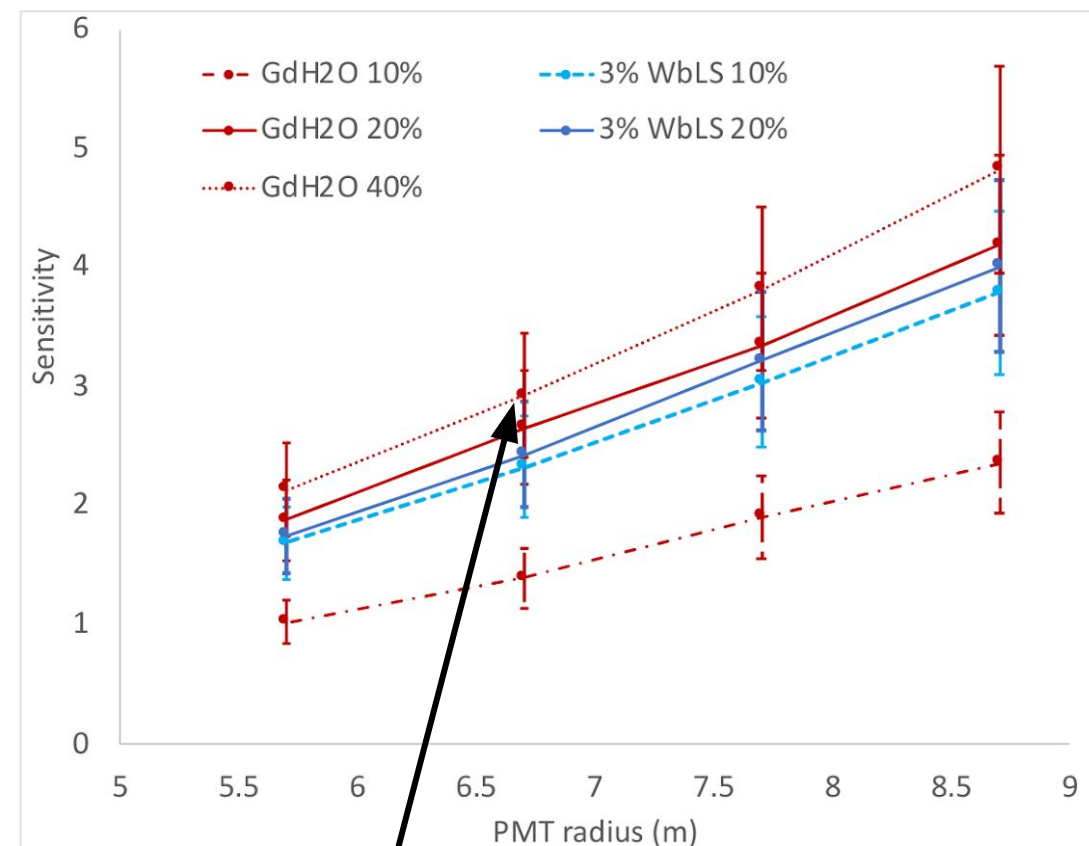
Reactor sensitivity projection

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



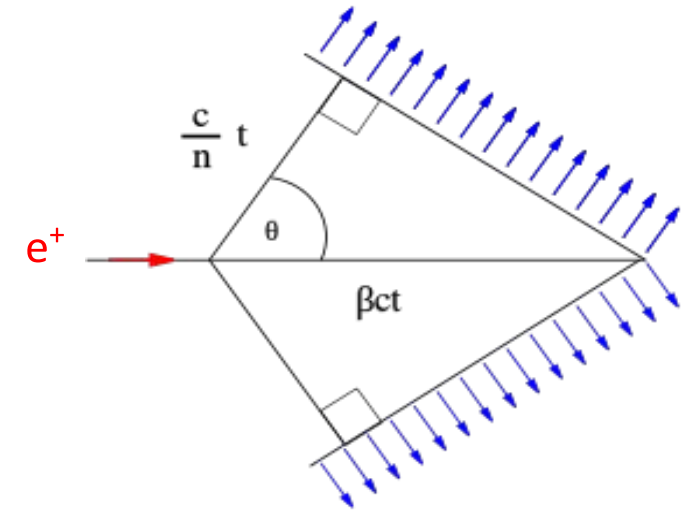
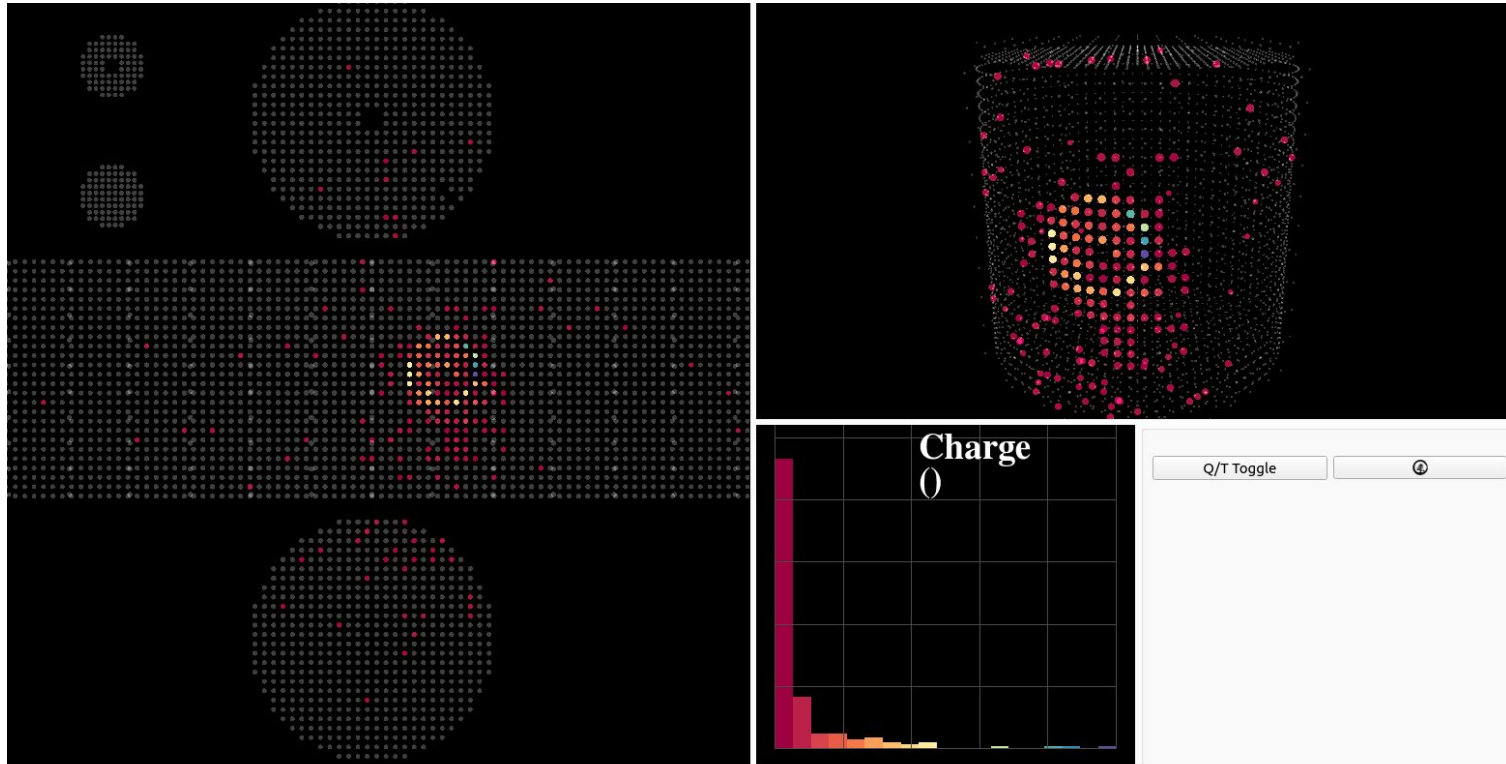
>3 σ significance reached within 30 days with baseline design.

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



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

Let there be (Cherenkov) light!

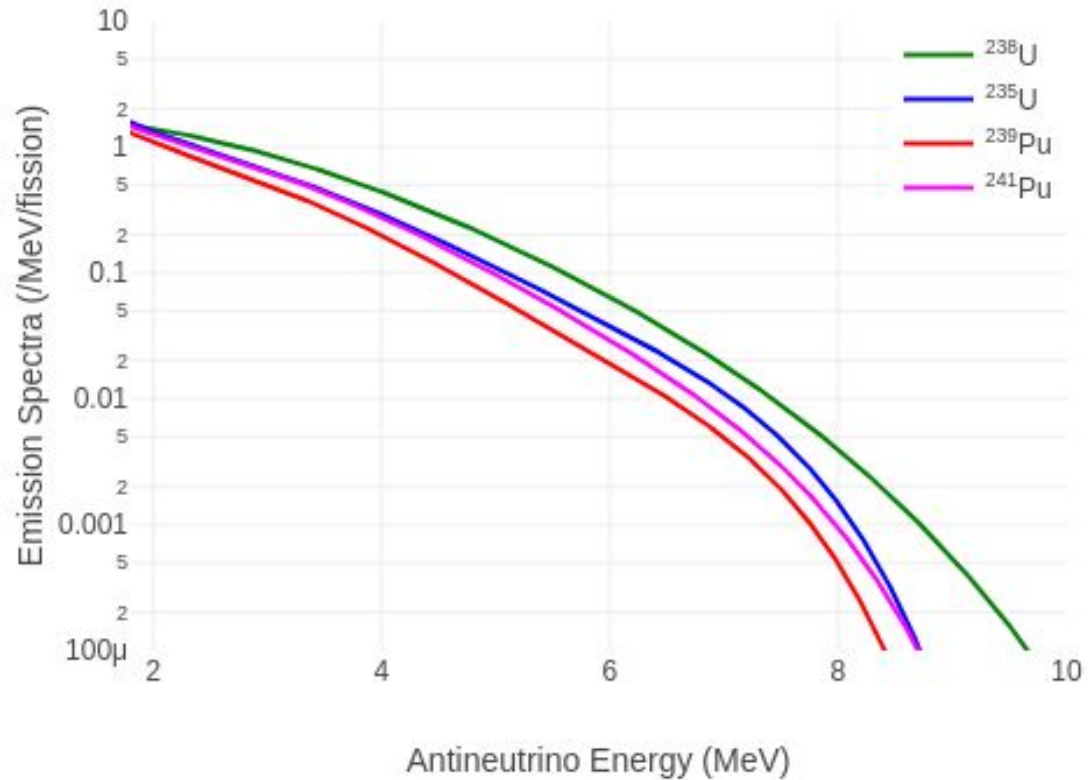


Cherenkov ring can provide information about:

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

Reactor composition

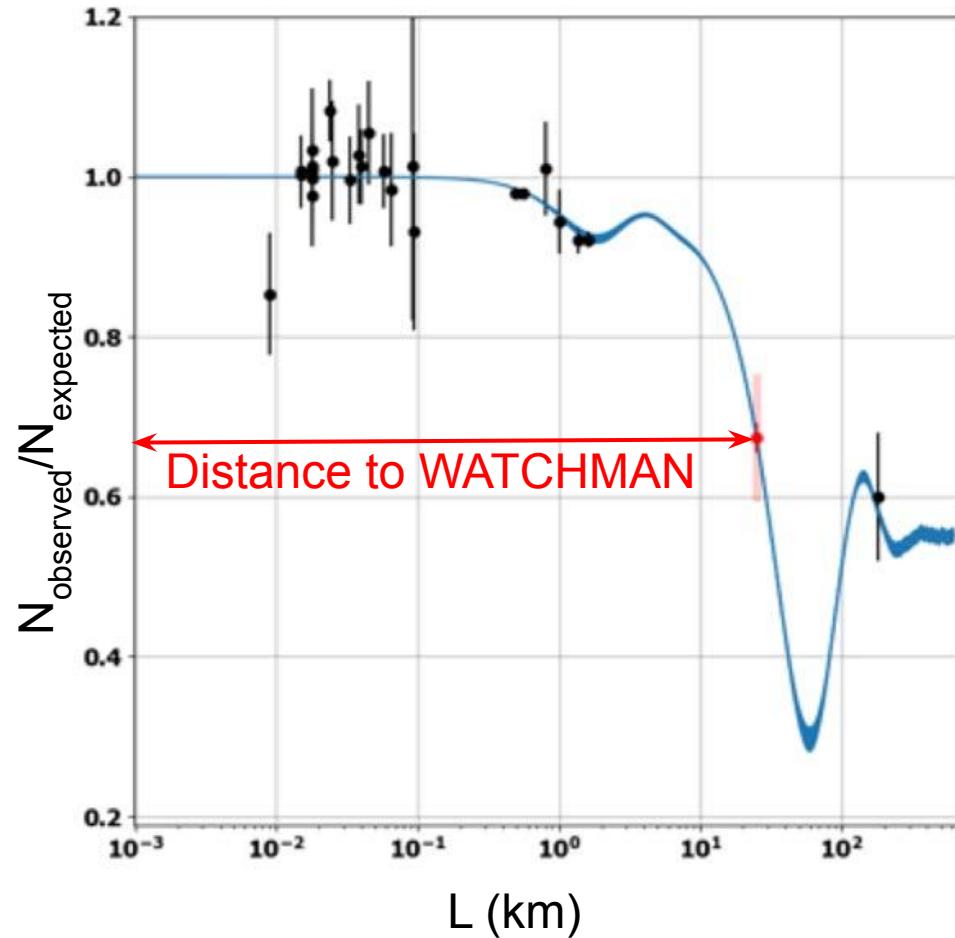
Fission Isotope Emission Spectra



Composition from spectral information.

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

Reactor ranging



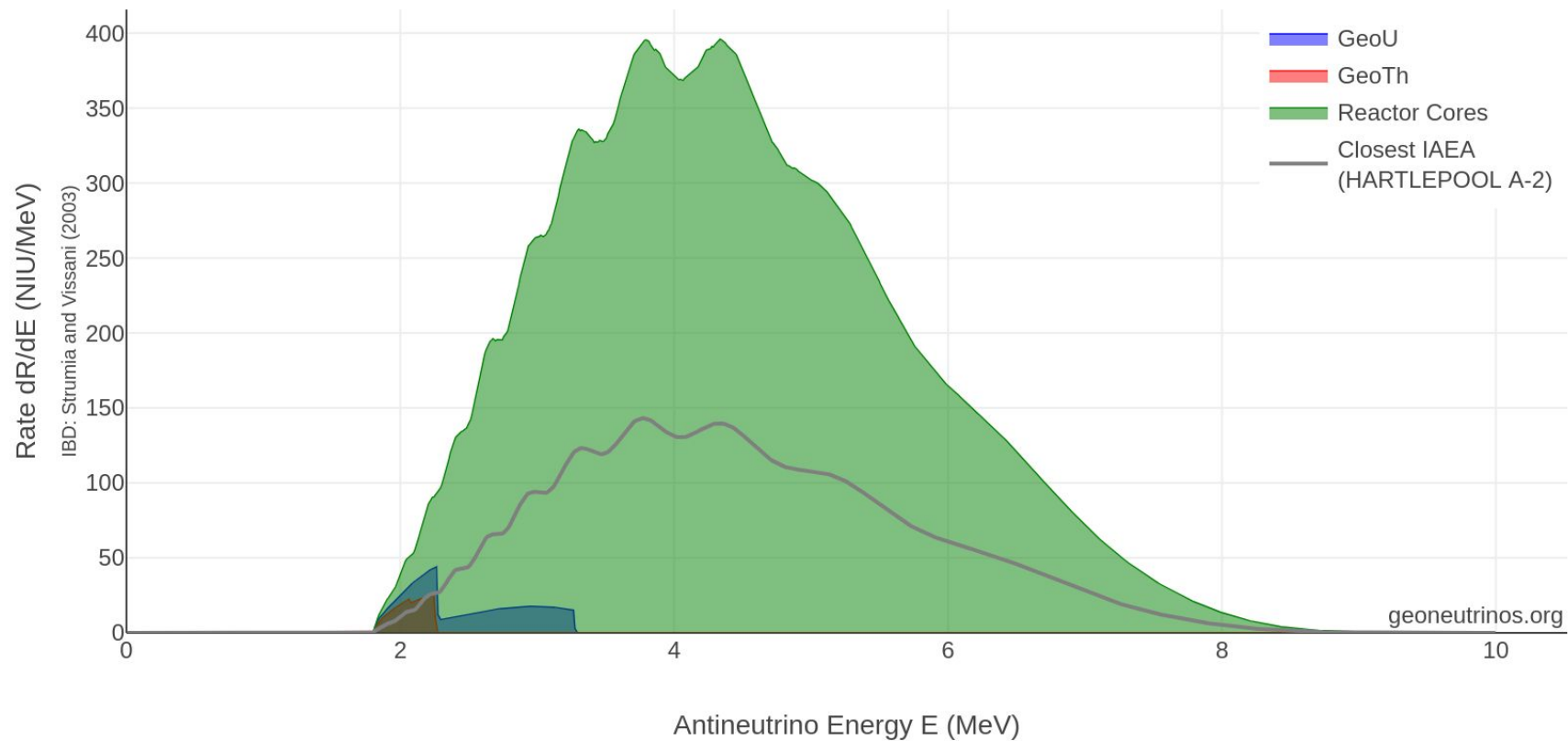
Neutrinos are unique in unambiguously revealing reactor distance.

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

Backgrounds for IBD detection

Anti-neutrino backgrounds

Antineutrino Spectrum: Boulby (54.6N, -0.8E, -1050m)

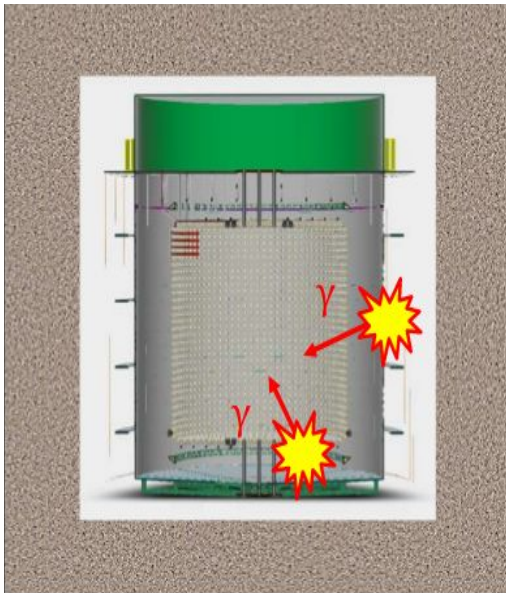


Significant background from other reactors, principally from the other reactor core at the Hartlepool power plant.

Reflects the complexity of the challenge in the field.

Uncorrelated backgrounds

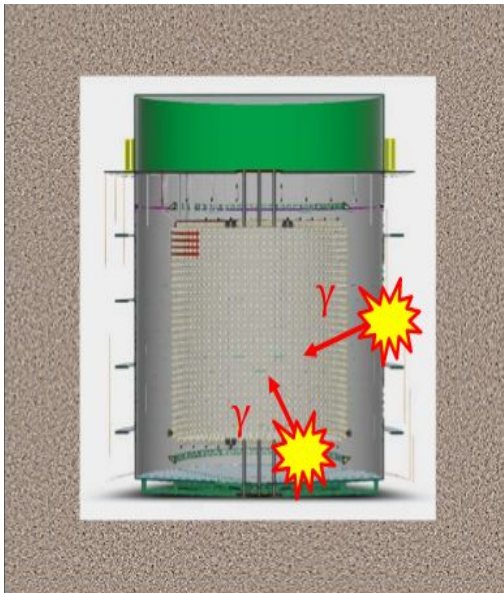
Accidental coincidences of uncorrelated events



Gammas from radioactivity in the detector components and environs.

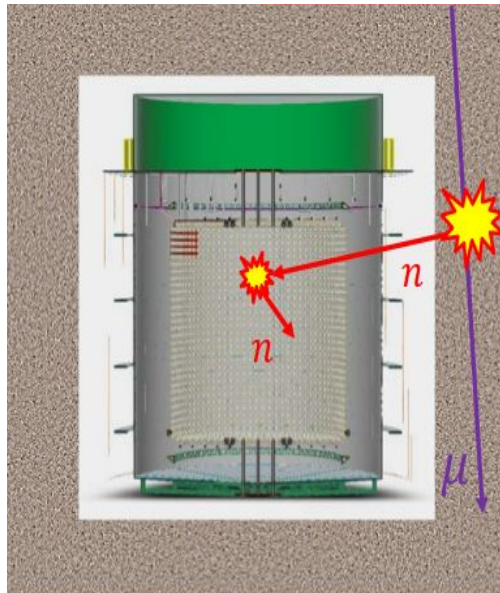
Correlated backgrounds

Accidental coincidences of uncorrelated events

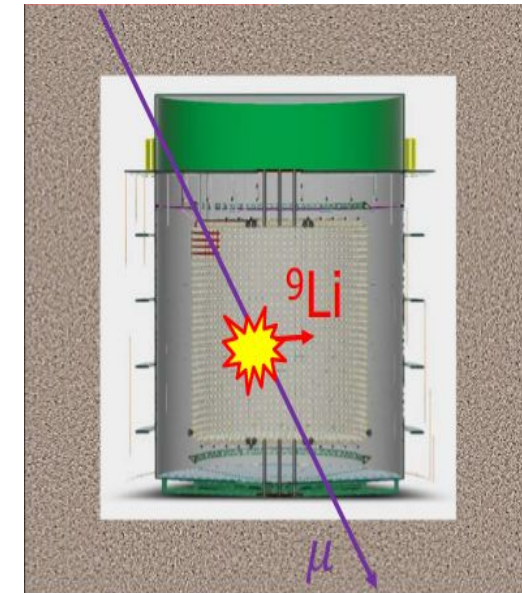


Gammas from radioactivity in the detector components and environs.

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



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

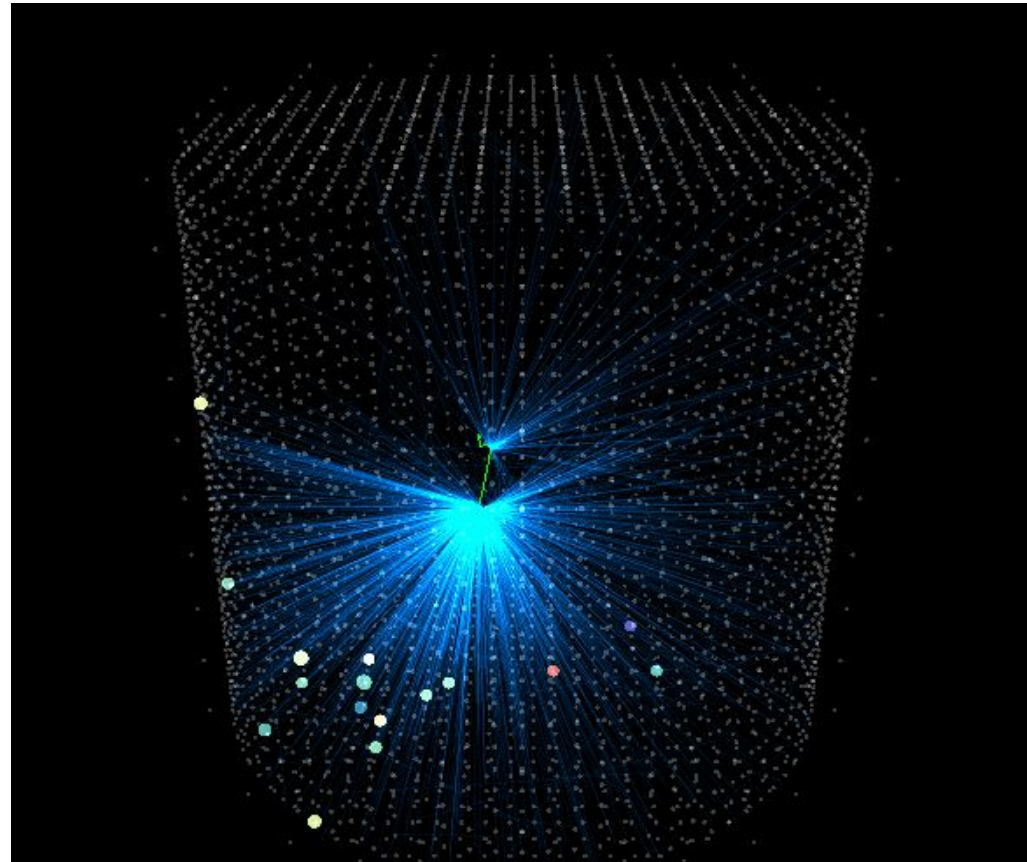


Reconstructing the IBD heartbeat

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.

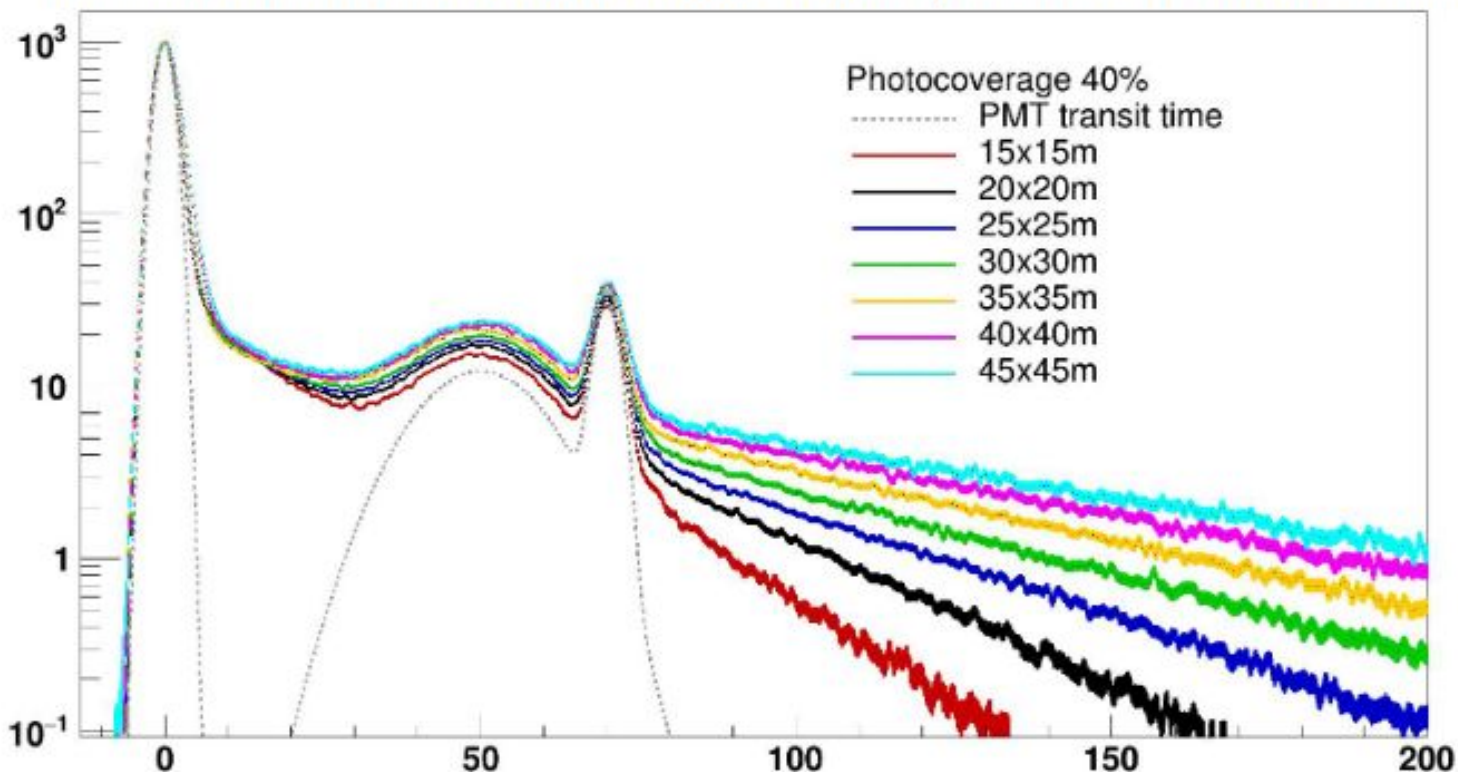
The time residual is the hit time - time of flight - time of emission:

$$\Delta t_i(\mathbf{x}) = t_i - \text{tof}_i(\mathbf{x}) - t_0$$

Time residuals form the basis of the fit

$$\Delta t_i(\mathbf{x}) = t_i - \text{tof}_i(\mathbf{x}) - t_0$$

Based on 5 MeV electrons, simulated uniformly inside the detector volume



Courtesy of Kat Frankiewicz, BU

time - time-of-flight - emission time(ns)

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:

$$\Delta t_i(\mathbf{x}) = t_i - \text{tof}_i(\mathbf{x}) - t_0$$

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

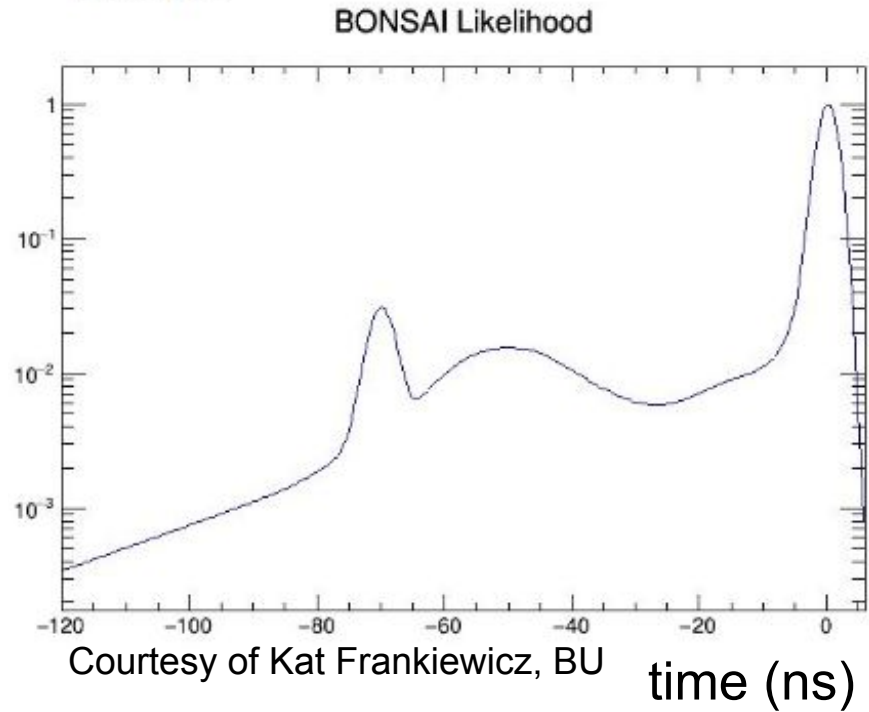
$$\mathcal{L}(\mathbf{x}, t_0) = \log(\Pi \text{ pdf}(\Delta t_i(\mathbf{x})))$$

Likelihood constructed from time residuals

$$\mathcal{L}(\mathbf{x}, t_0) = \log(\prod \text{pdf}(\Delta t_i(\mathbf{x})))$$

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.



The BONSAI search tree

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

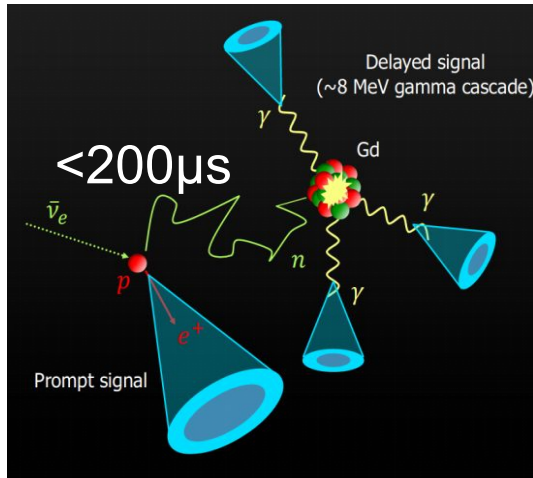
Test vertices from direct hits

Test vertices in top range of likelihoods

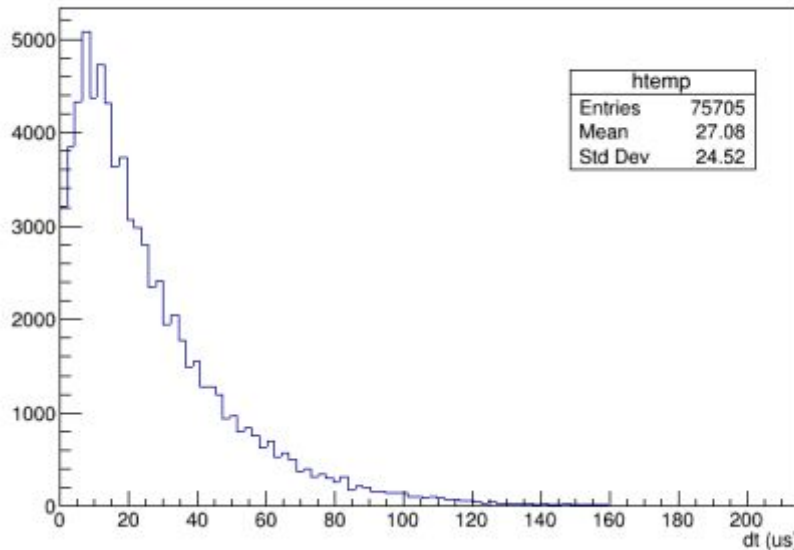
Search sets of 12 daughter branches with each test vertex at the centre.



The PairBONSAI process



Time between positron and neutron



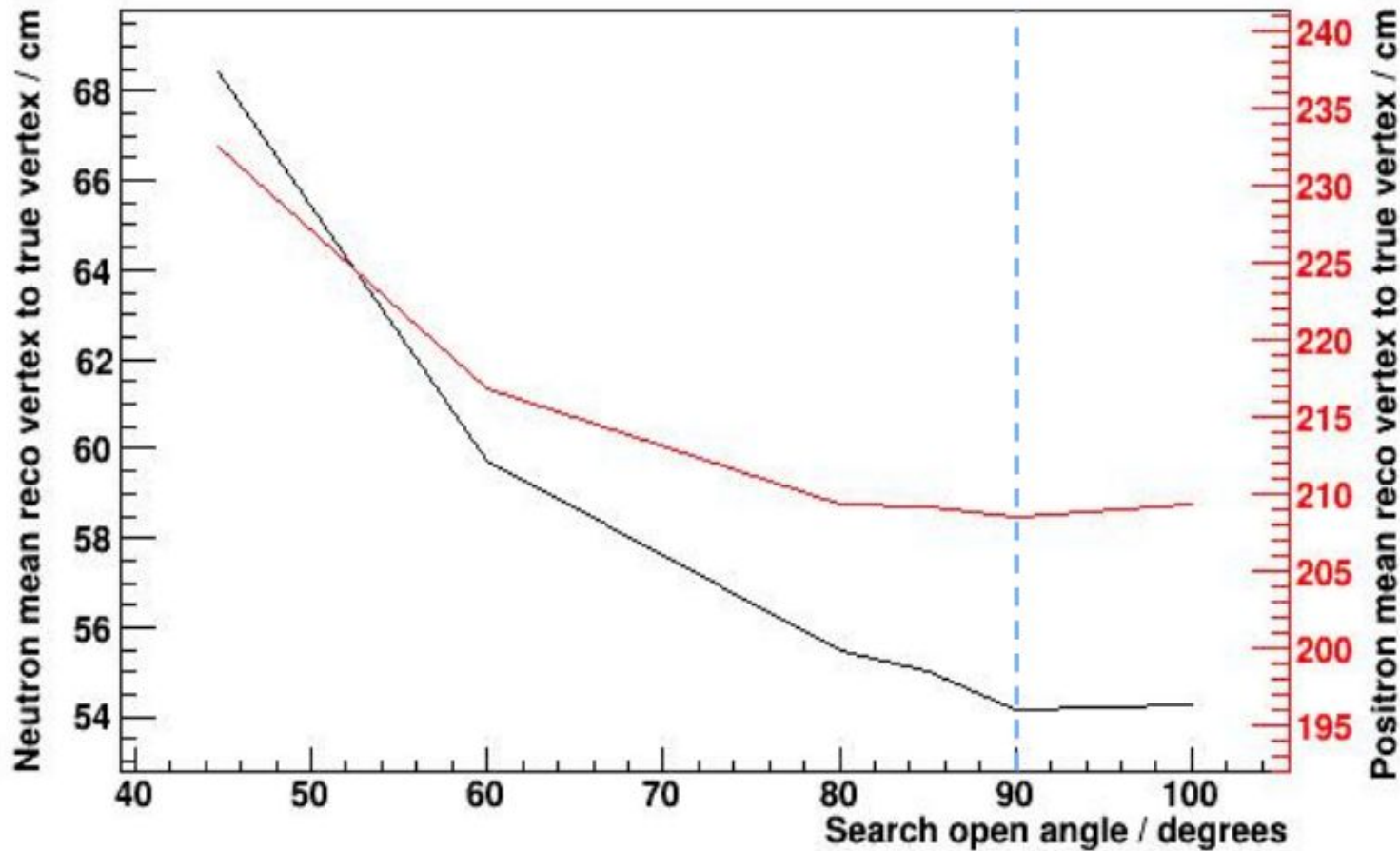
- Select interactions that trigger in the detector within e.g. $200 \mu\text{s}$.
- Create combined search grid: more starting solutions means better rejection of local maxima.

- Call the likelihood maximisation of

$$\mathcal{L}(\mathbf{x}, t_0) = \mathcal{L}_p(\mathbf{x}, t_0) + \mathcal{L}_d(\mathbf{x}, t_0)$$

- Output a common vertex.

BONSAI pair reconstruction



BONSAI searches assume the Cherenkov angle for e^+/e^- of $\sim 45^\circ$ but light from neutron capture is more isotropic.

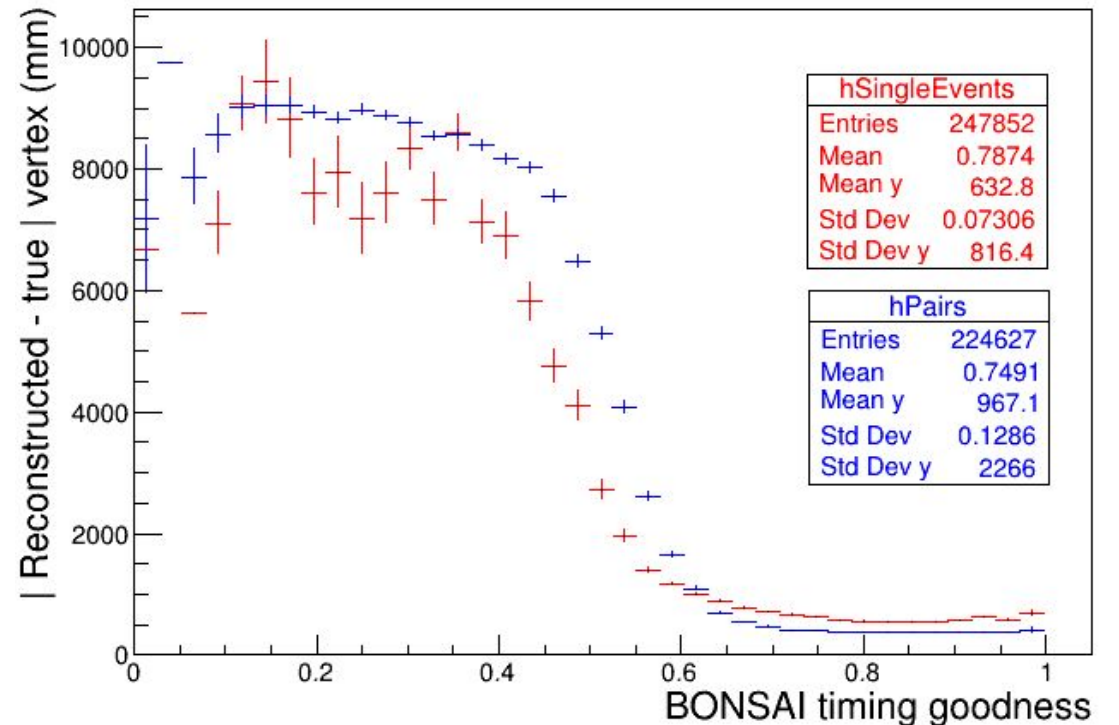
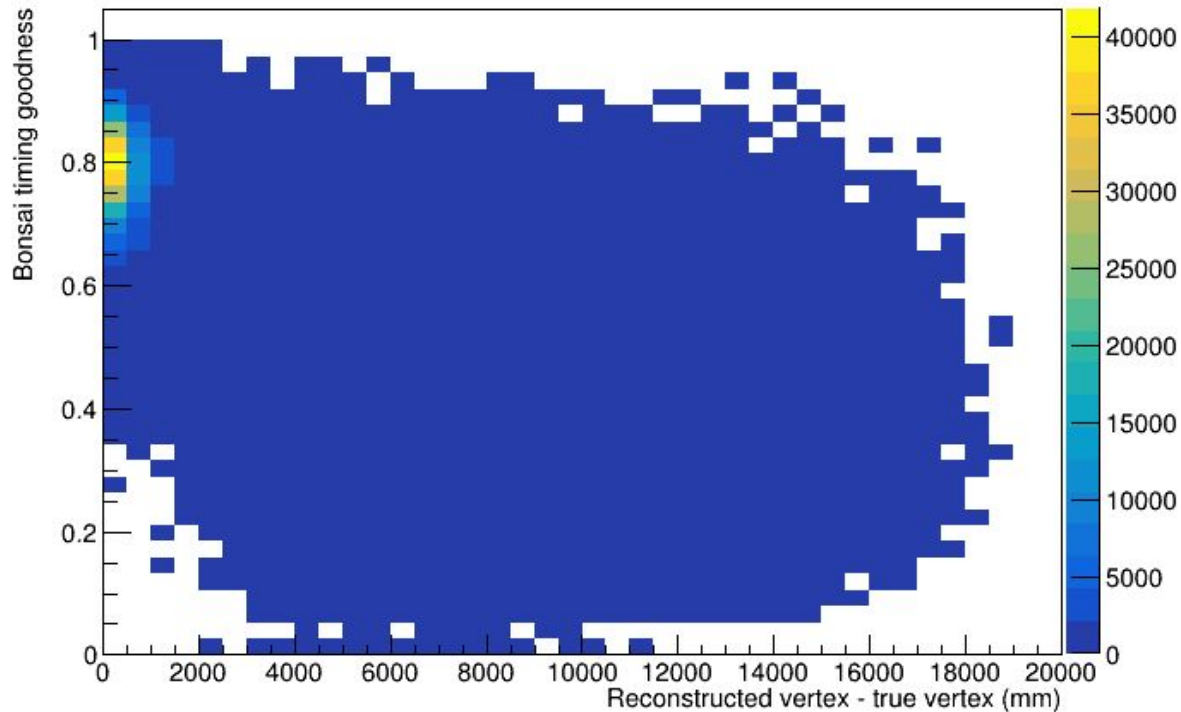
Widening the search angle to 90° improves the fit for both interactions in the IBD event.

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

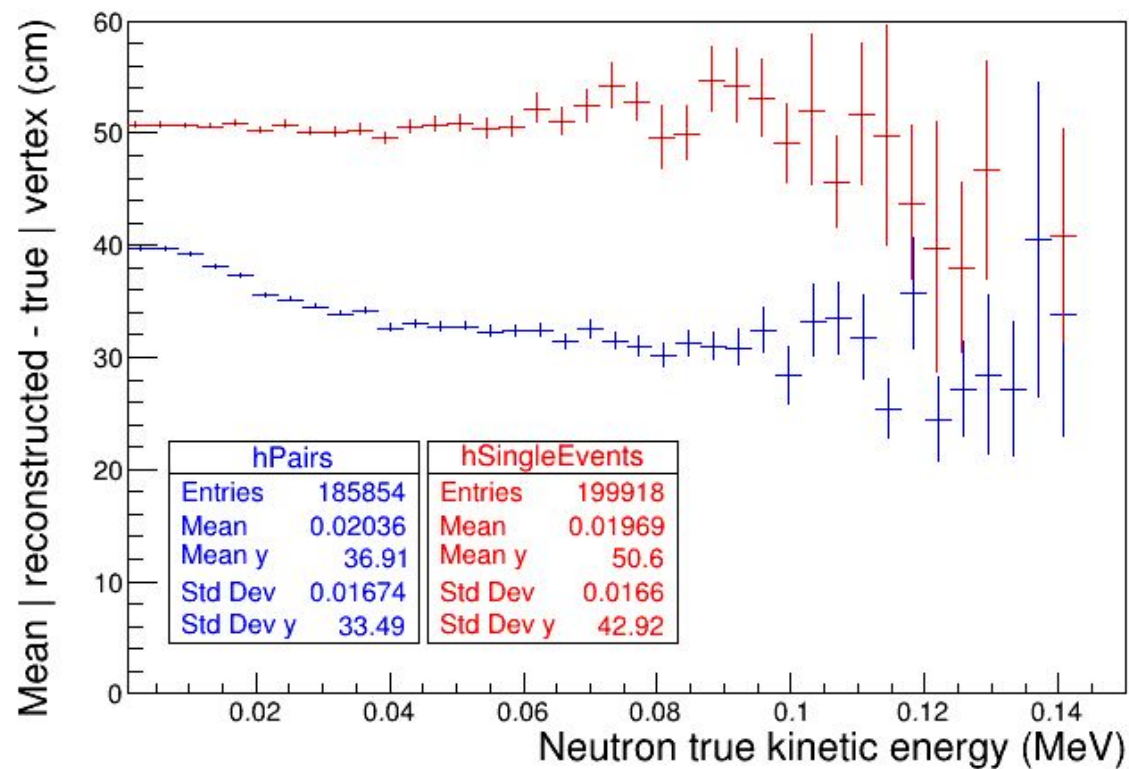
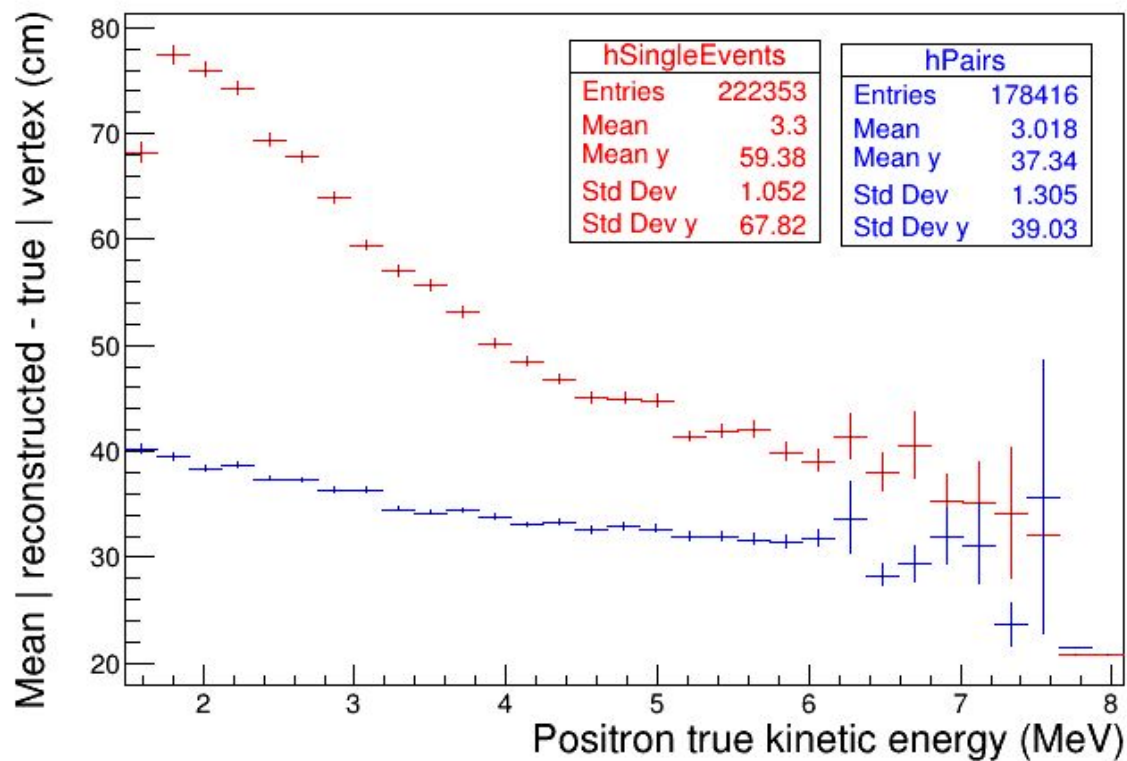
Fit quality - BONSAI timing goodness

$$g(\mathbf{x}) = \frac{\sum_{\text{hits}} w_i e^{-0.5 \left(\frac{\Delta t_i(\mathbf{x})}{\sigma} \right)^2}}{\sum_{\text{hits}} w_i}$$

IBD fit quality



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.

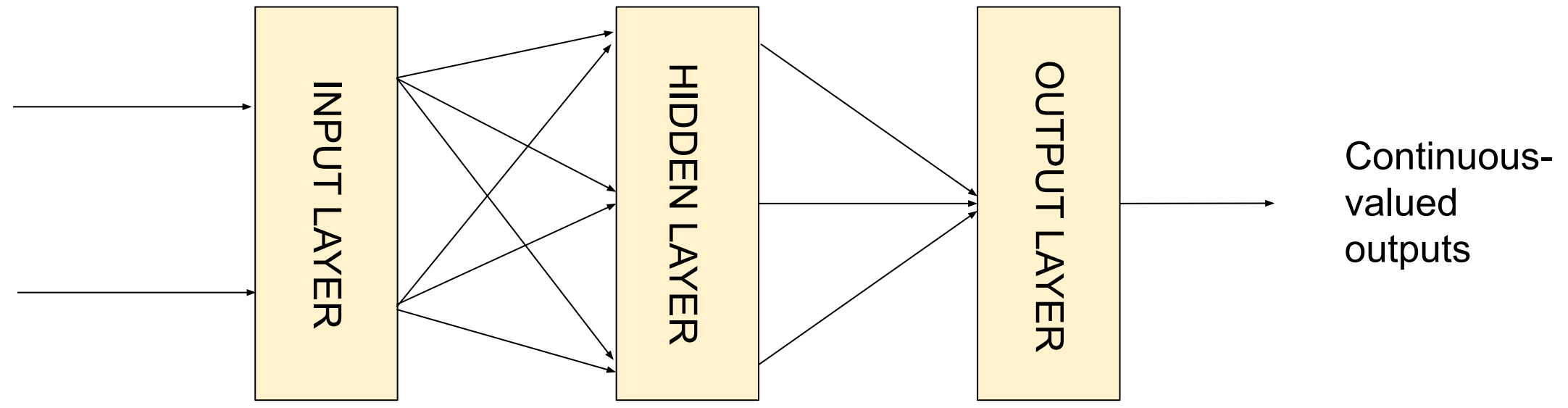


New Reconstruction Method 2

Vertex reconstruction with machine learning

Deep learning for regression problems

Simple artificial neural network.



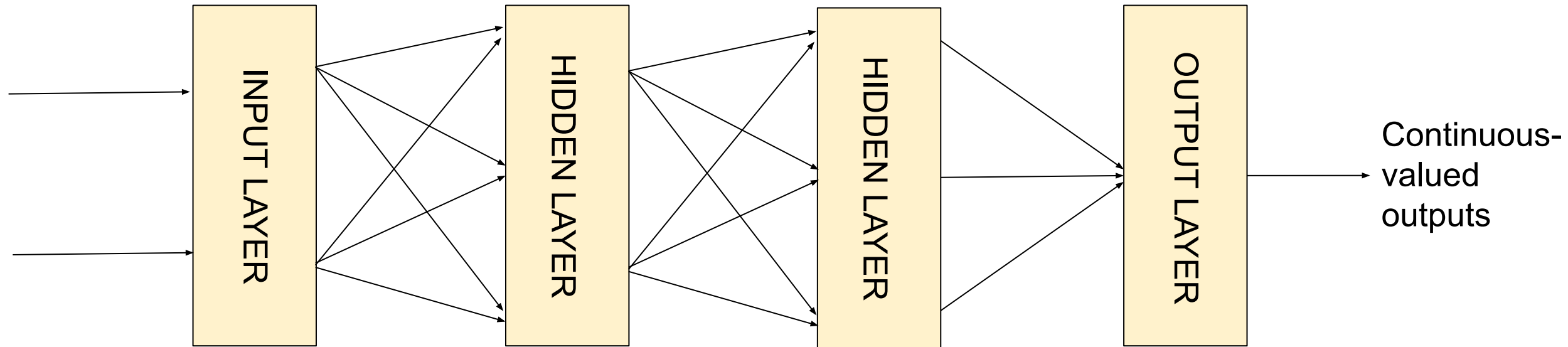
Input layer with 2 input 'features' for each 'sample'

Hidden layer with 3 'neurons'

Output layer with 1 'target' output

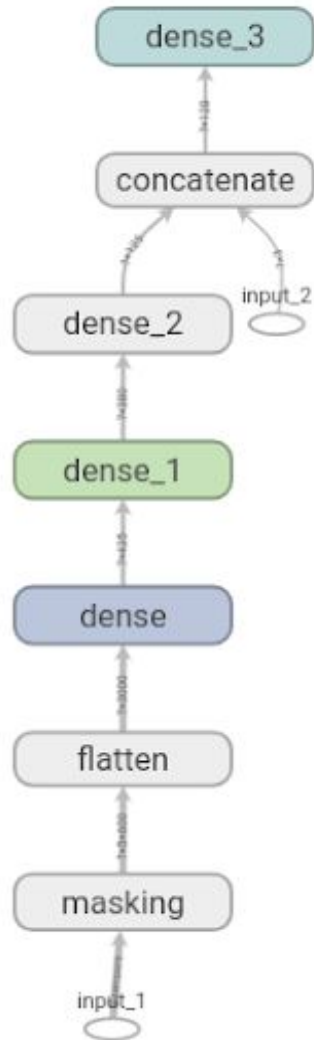
Deep learning for regression problems

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



The computer trains itself to process data and make predictions.

BONSAI + Multi-Layer Perceptron (MLP)



Outputs: x, y and z for each interaction.

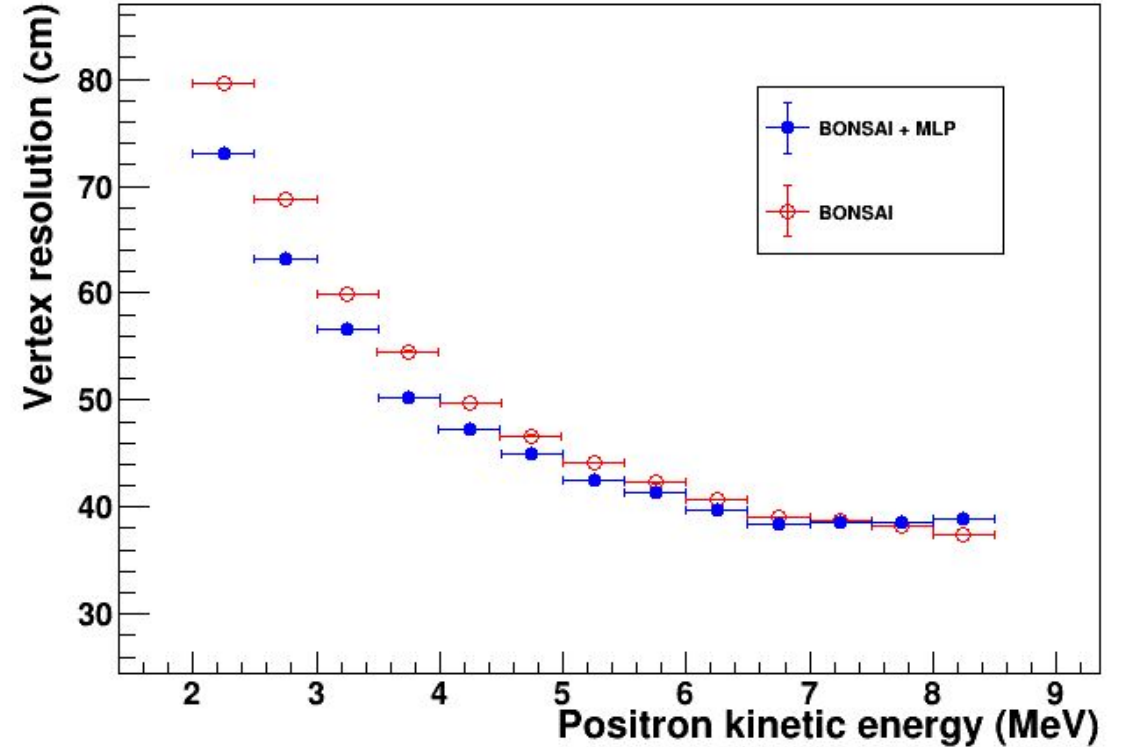
Input 2: reconstructed vertex from BONSAI reconstruction.

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.)

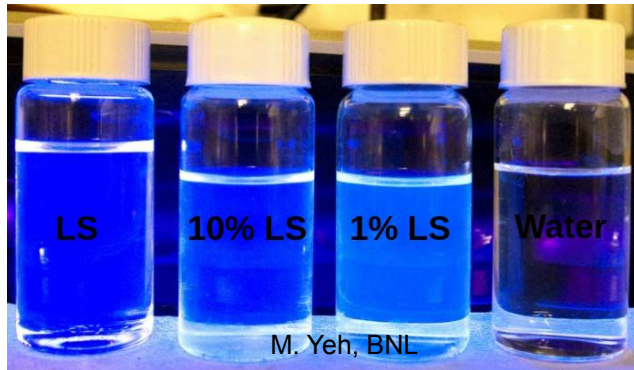
£1M funding from Ministry of Defence

BACKUP SLIDES

Physics and technology goals

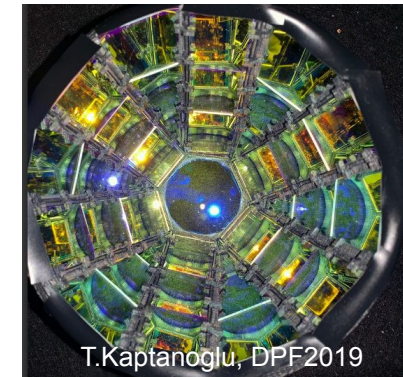
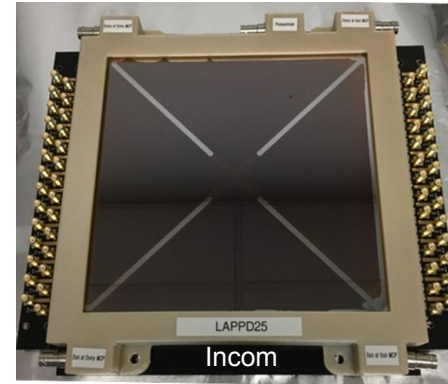
Technology upgrades

First or future phase



+

Augmented solutions



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

Picosecond photosensors: fast timing

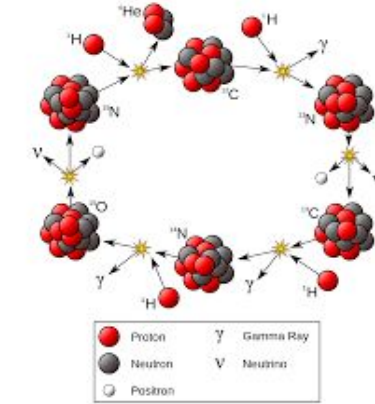
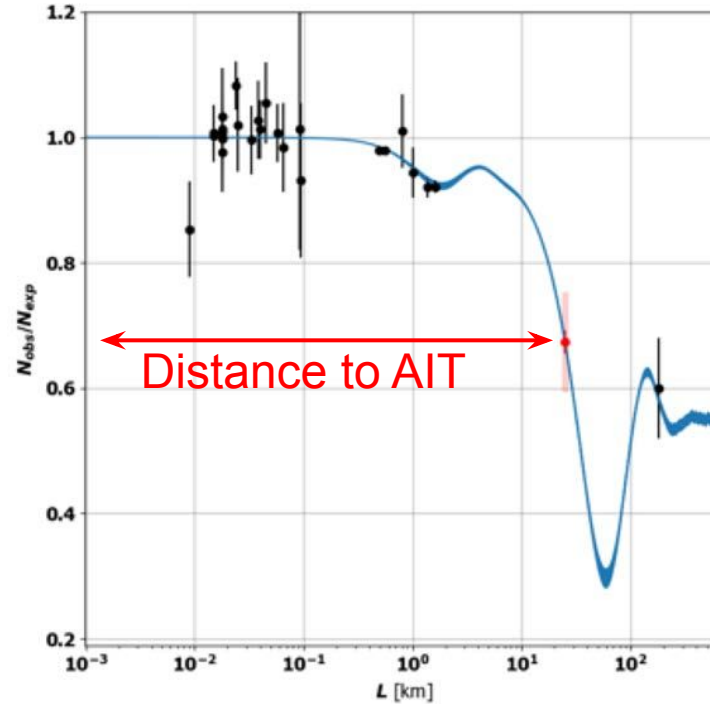
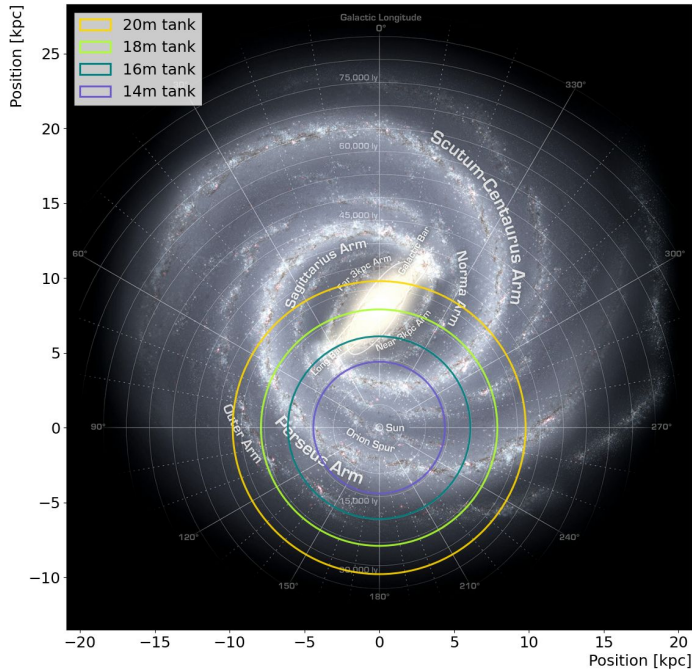
Dichroicons: light concentration and separation by wavelength

= the 'Holy Grail' of Cherenkov and scintillation separation

Remote monitoring... and beyond

First phase

Future

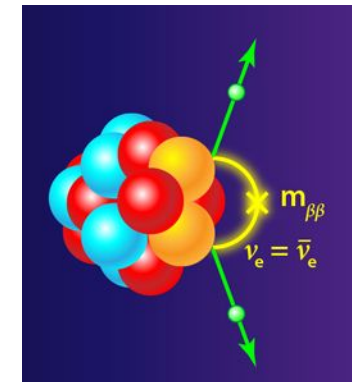


©Borb

CNO solar neutrinos

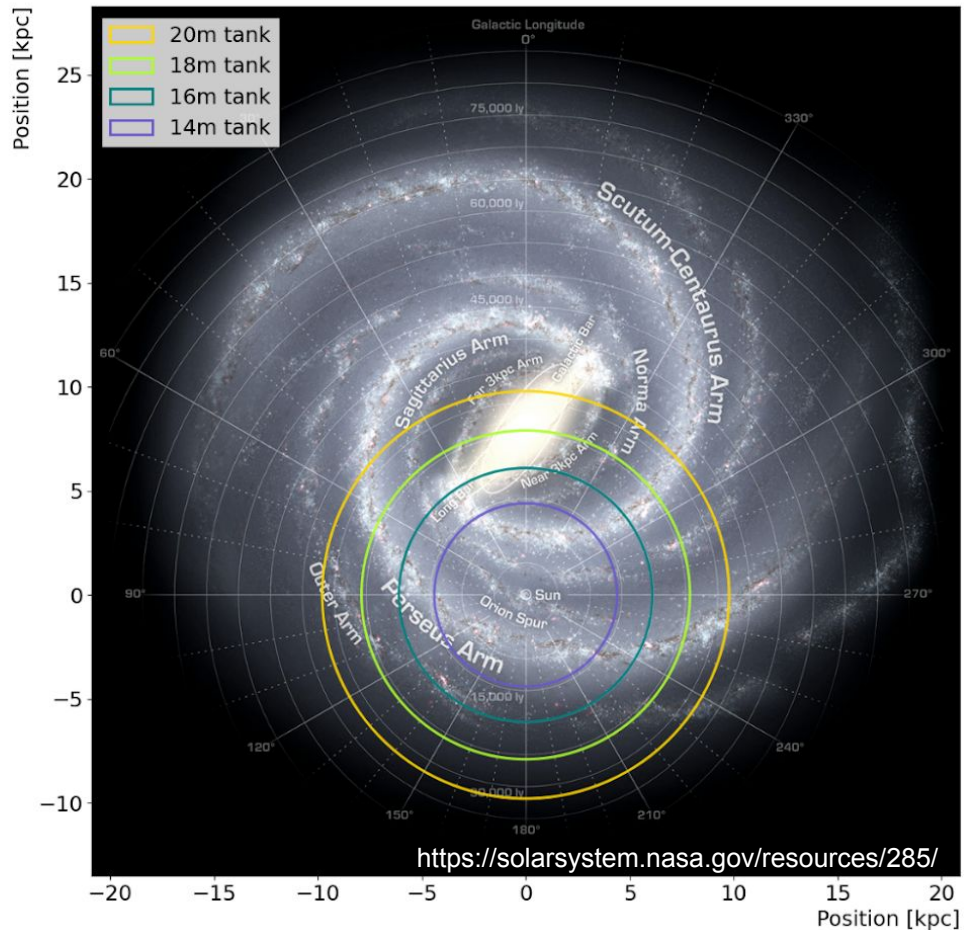
Supernova neutrino detection and input into Supernova NEutrino Warning System (SNEWS)

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

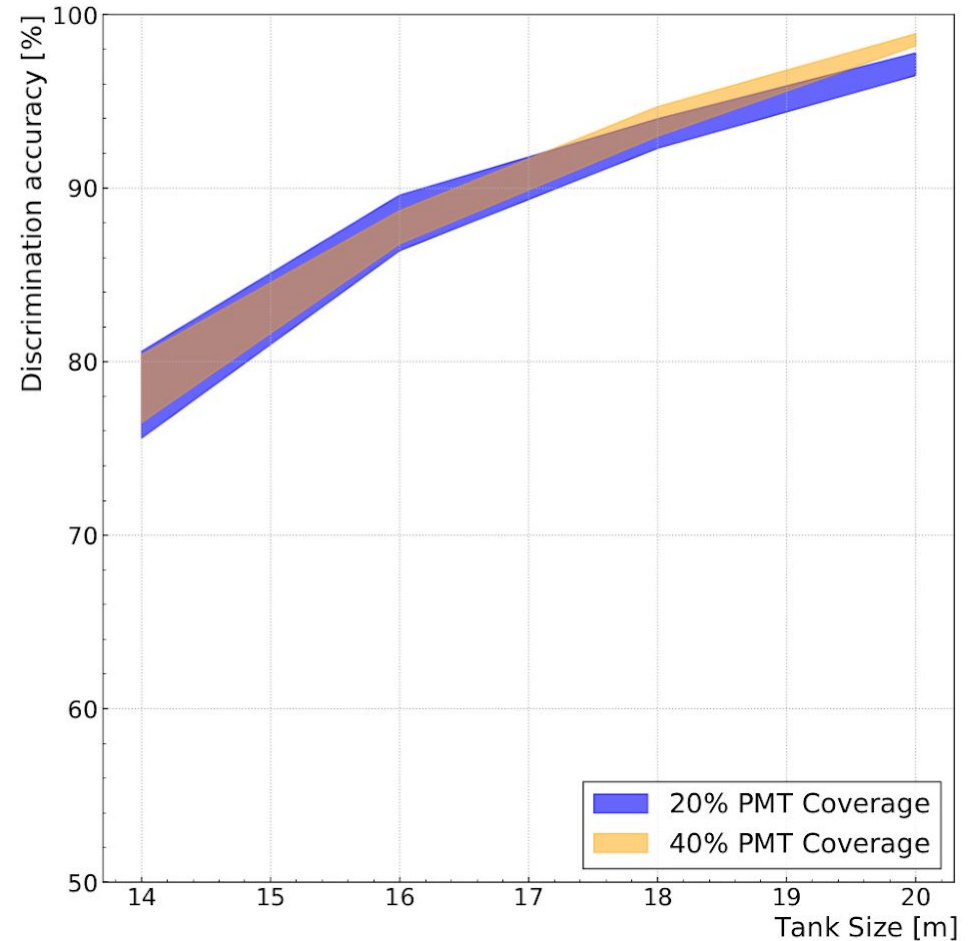


Neutrinoless- $\beta\beta$ decay

Supernova model discrimination

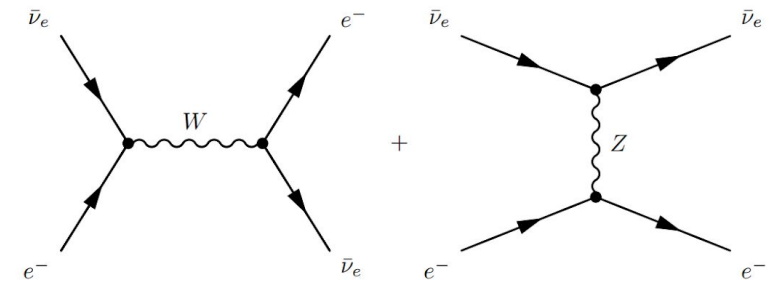
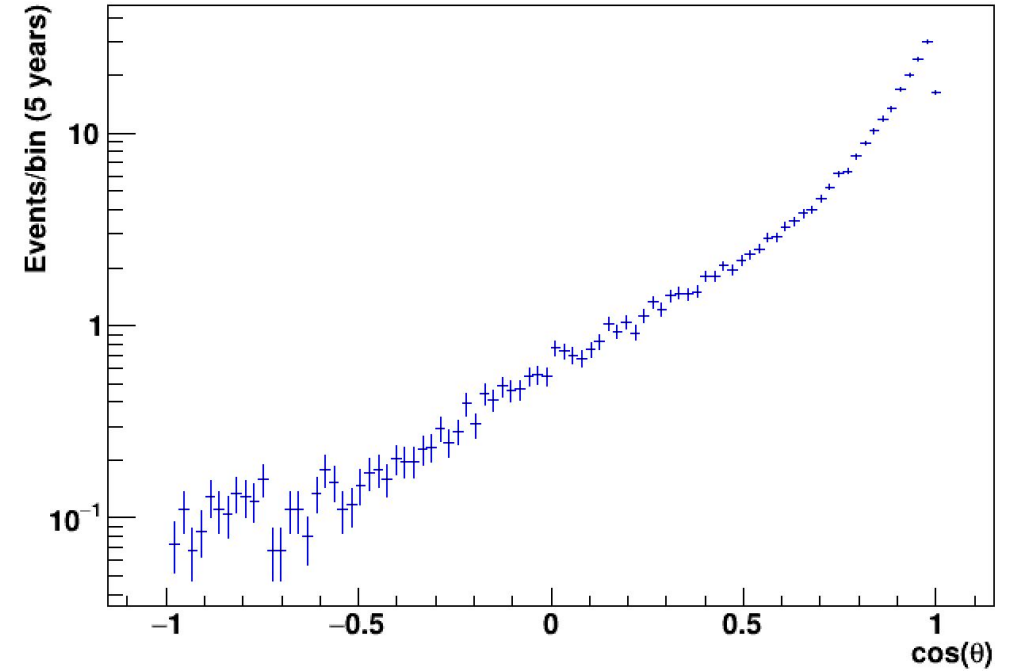
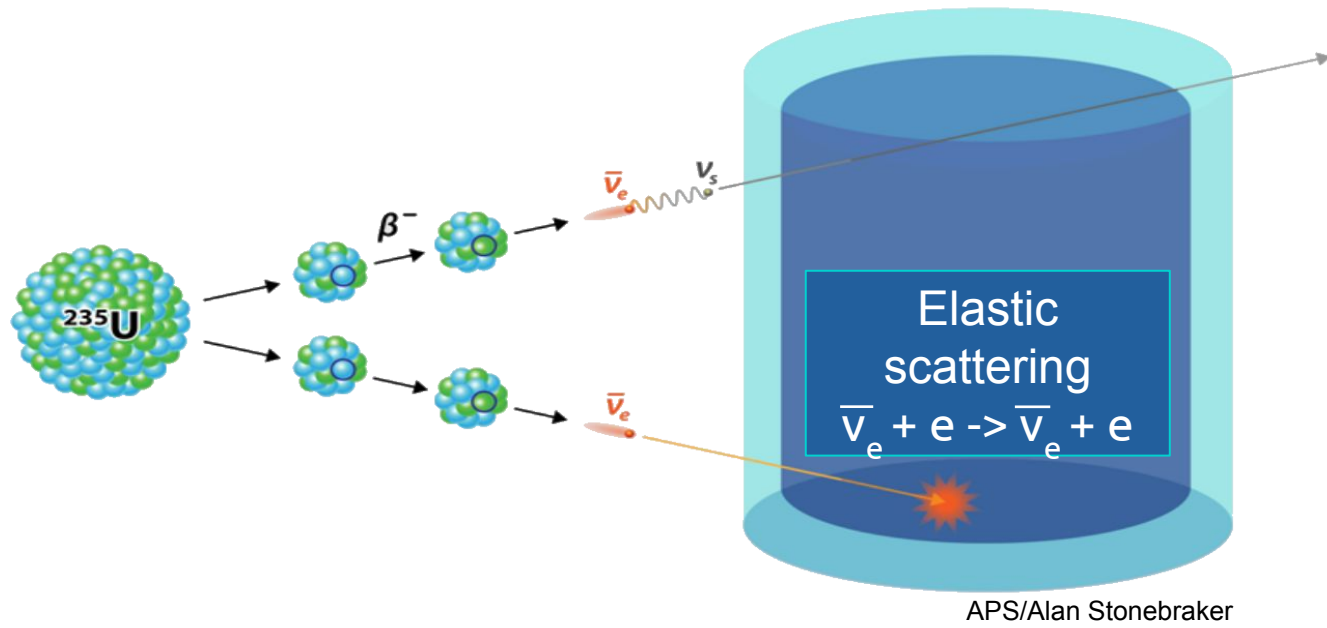


Maximum distance for different tank sizes with 20% PMT coverage to observe ≥ 100 events, assuming the Nakazato supernova model.



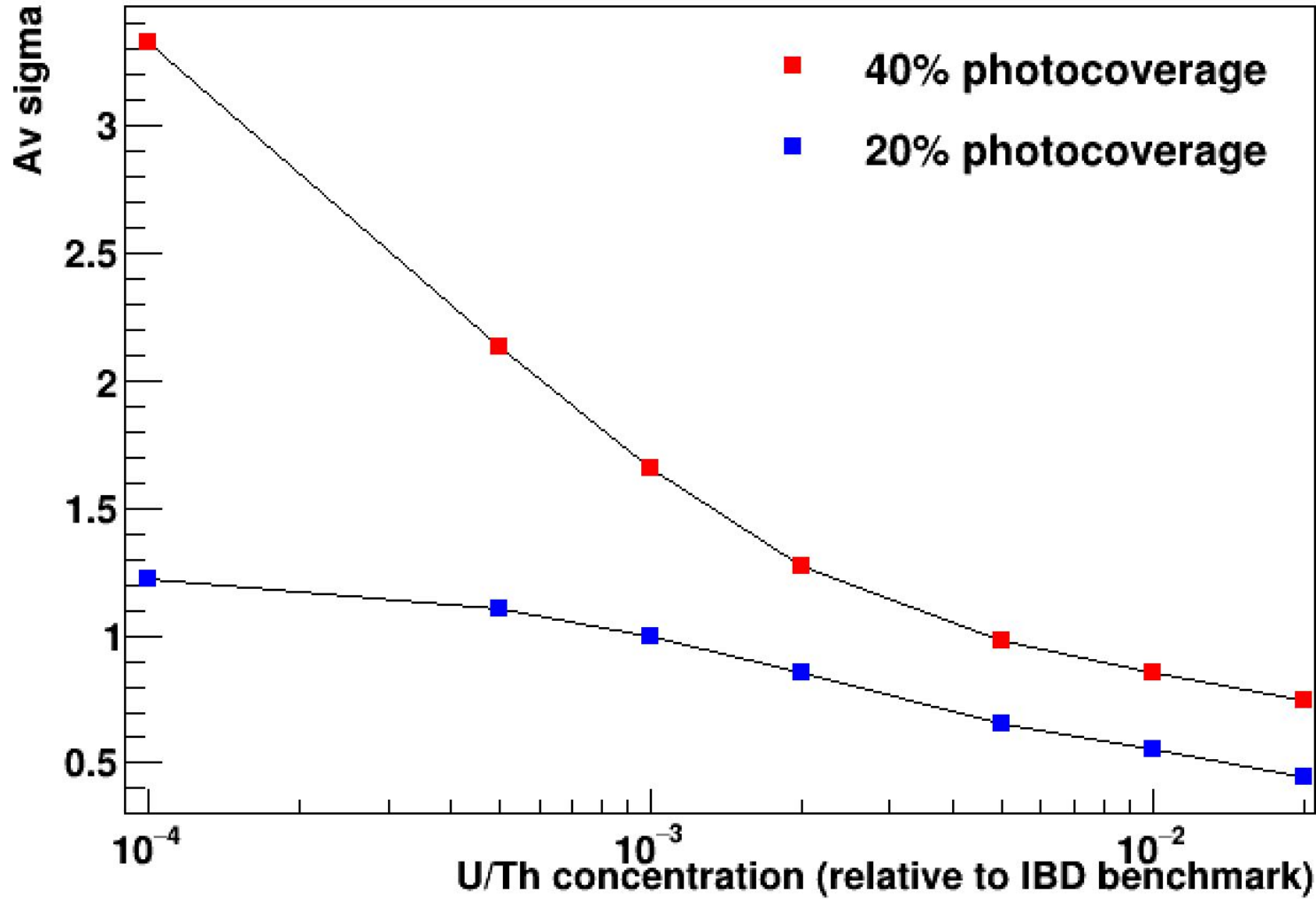
Discrimination accuracy for a supernova at a fixed distance with respect to detector tank size and PMT coverage.

Reactor directionality



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

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



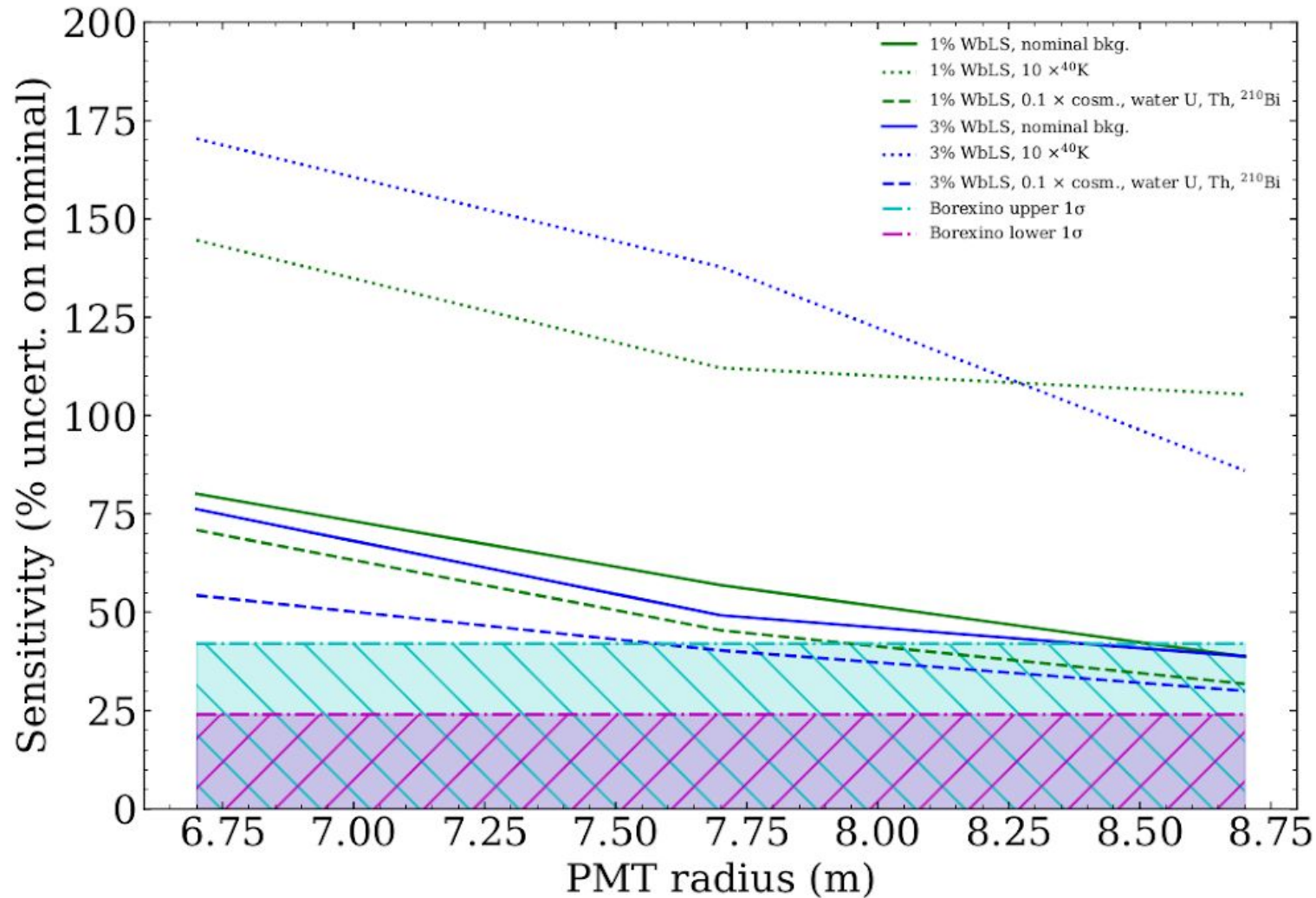
Event with 40% photocoverage and an inner detector radius of 8.7 m (increased from 6.7 m):

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

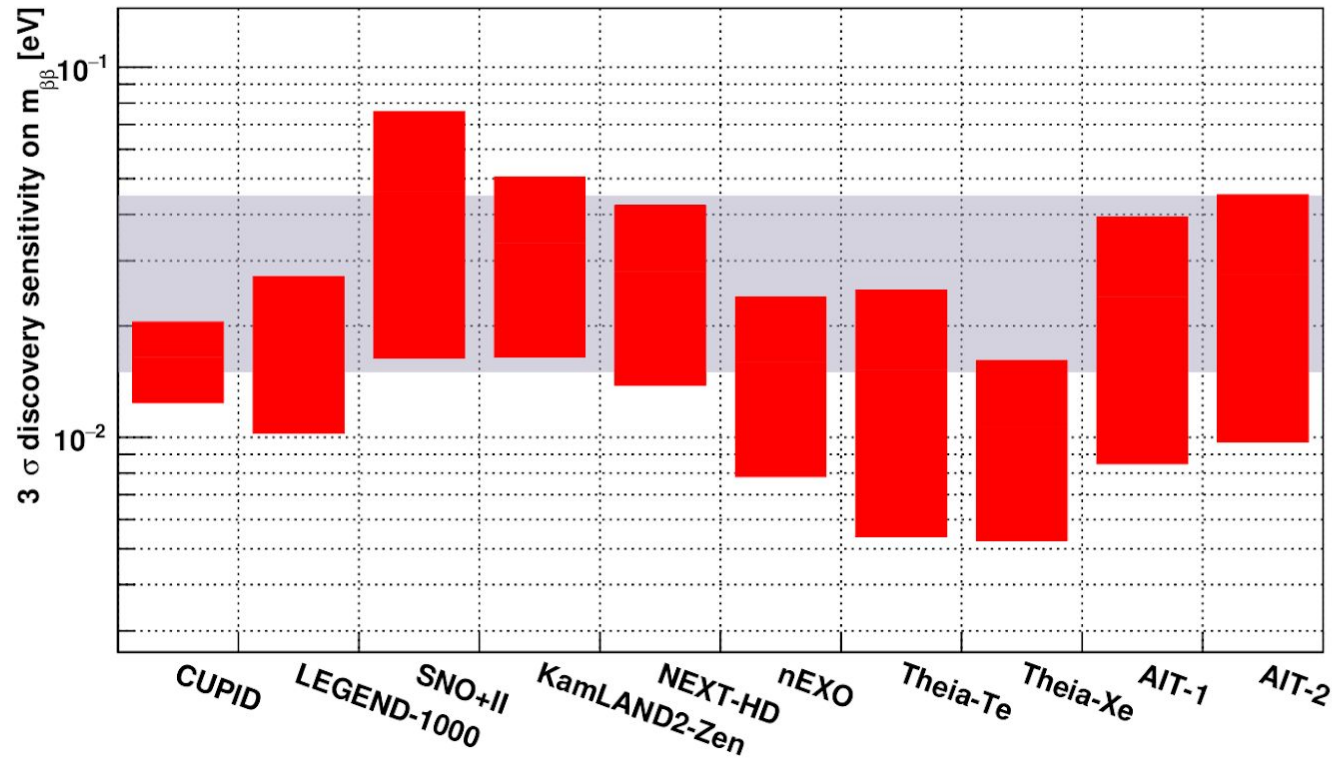
CNO solar



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

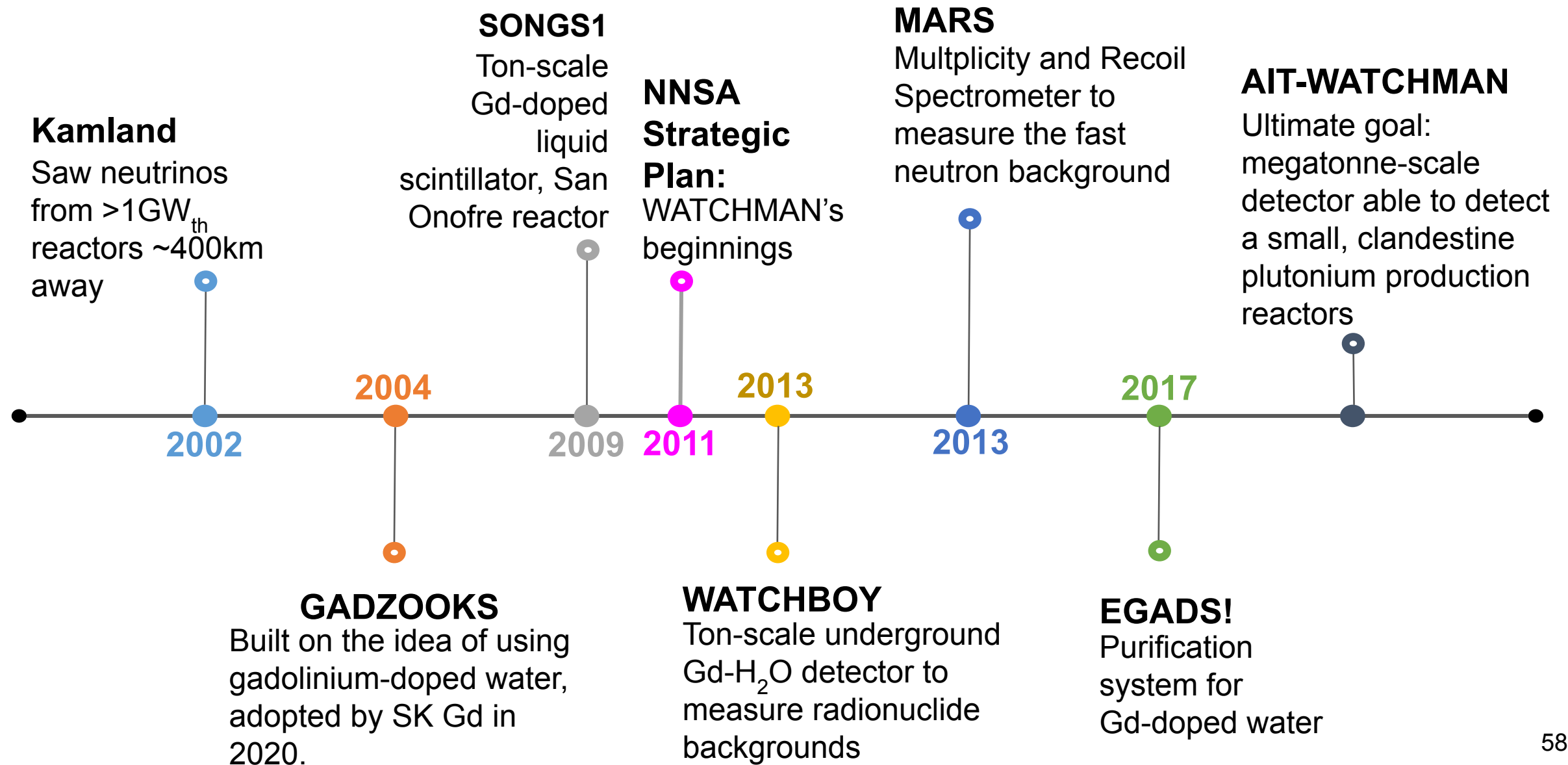


Yu. G. Kolomensky

WATCHMAN with a liquid scintillator fill.

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

Towards a remote reactor monitor



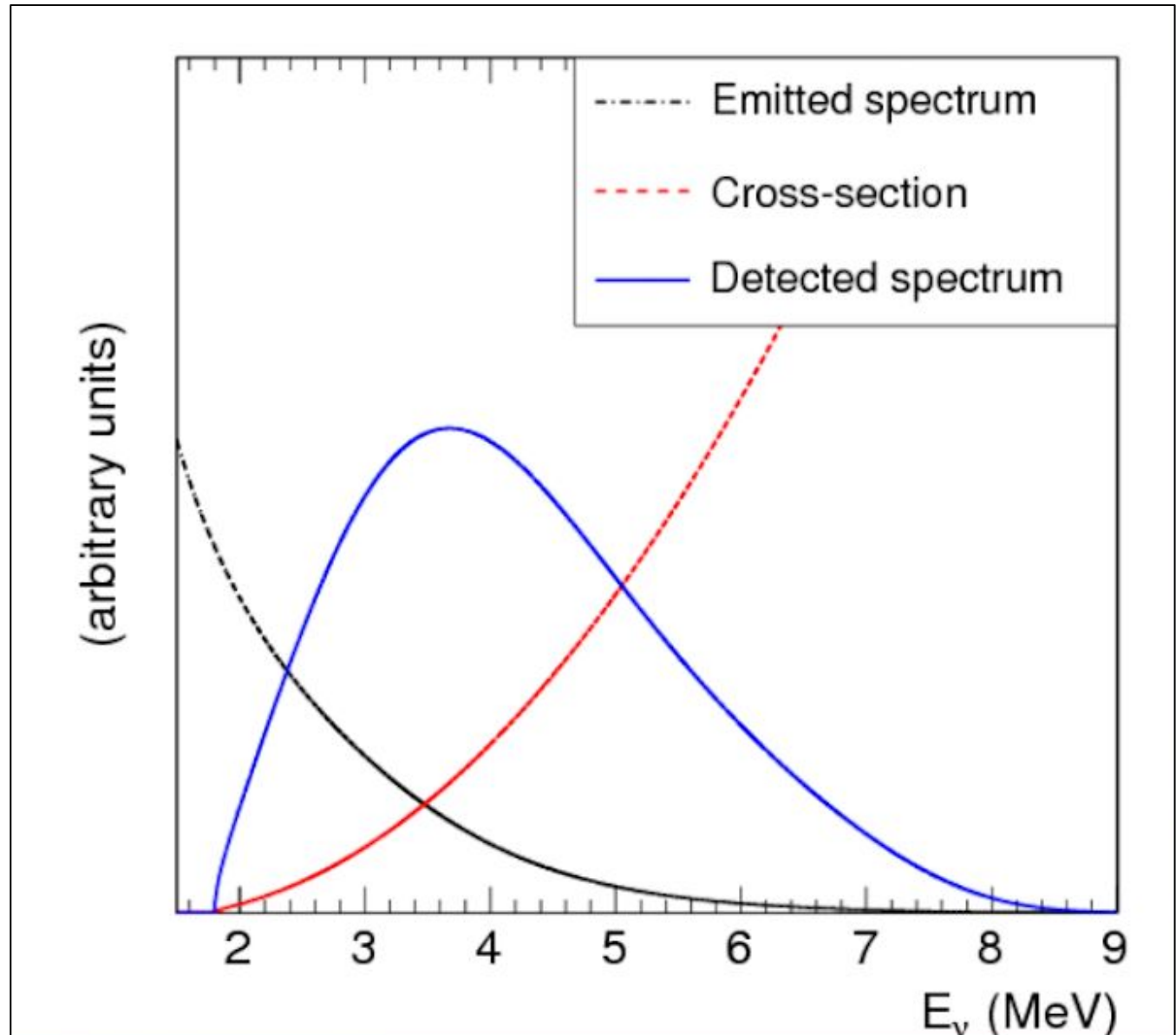
What information is useful?

'Simple' counting analyses:

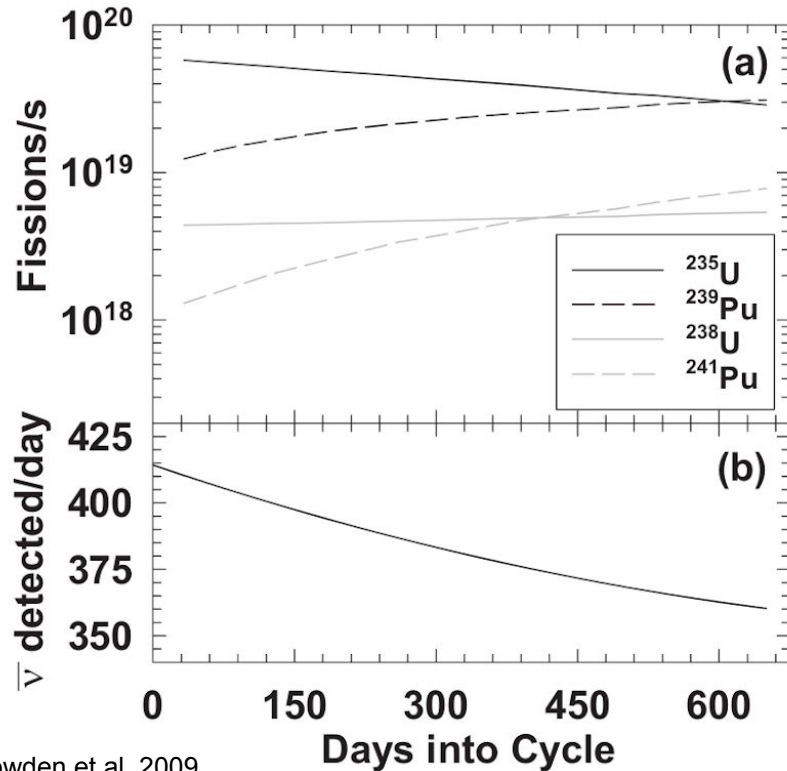
1. Presence/absence of a reactor
2. Fuel burnup in the core

More complex, spectral analyses:

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



Reactor composition



Burnup-dependent flux.

Relatively straightforward where refueling is infrequent: useful for verification.

Bowden et al, 2009
DOI: 10.1063/1.3080251

BONSAI* reconstruction *Michael Smy, UCL

B_{ranch}

Demonstrated in Super-Kamiokande to work well in the reactor antineutrino energy range (down to $\sim 3\text{eV}$).

O_{ptimisation}

Optimisation by the maximum-likelihood method.

N_{avigating}

S_{uccessive}

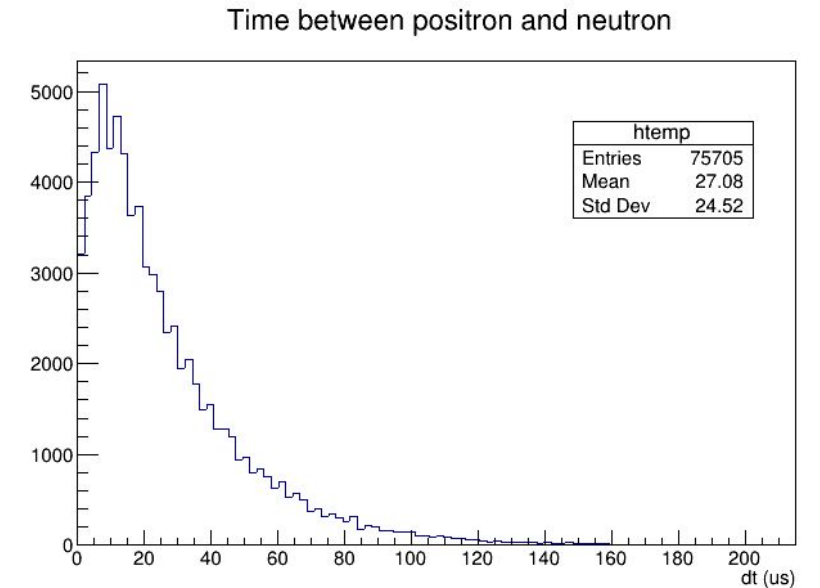
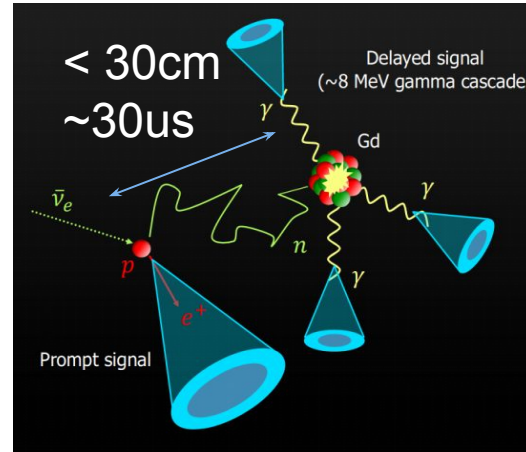
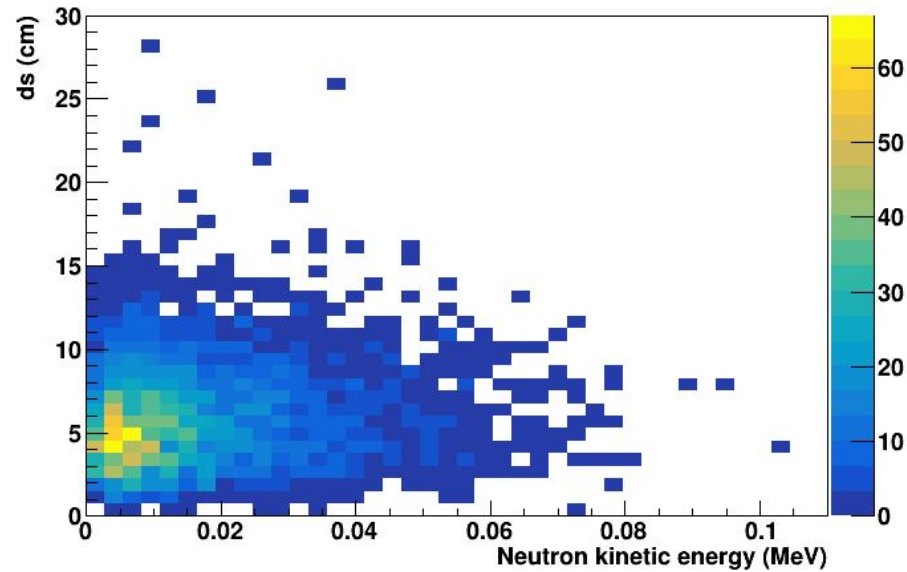
Successively more localised searches converge on the point in the detector at which the likelihood is maximised.

A_{nnealing}

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.

I_{terations}

The IBD heartbeat

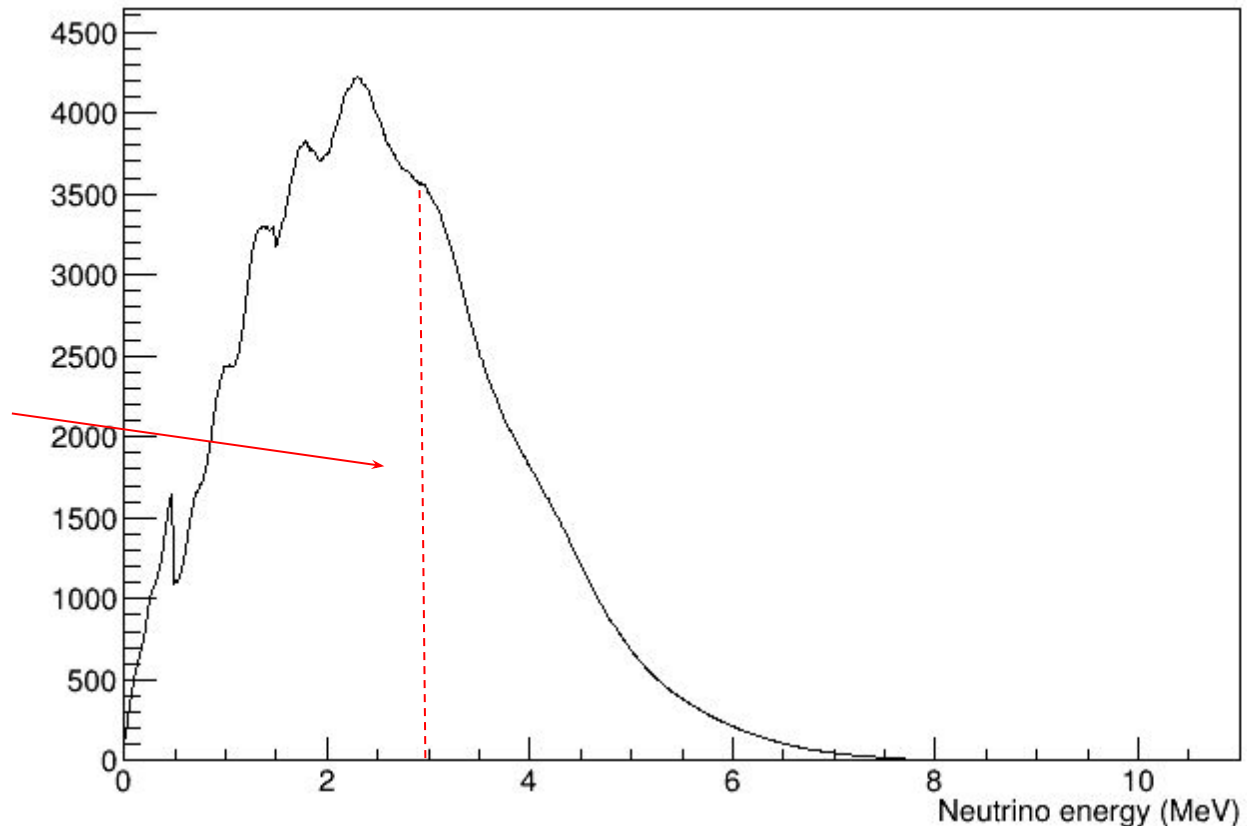


The IBD-pair positron and neutron are generally within $\sim 30\text{cm}$ and $\sim 150\mu\text{s}$ for reactor neutrinos. The mean time between events is $\sim 30\mu\text{s}$. The mean distance between events is $\sim 5\text{cm}$.

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.

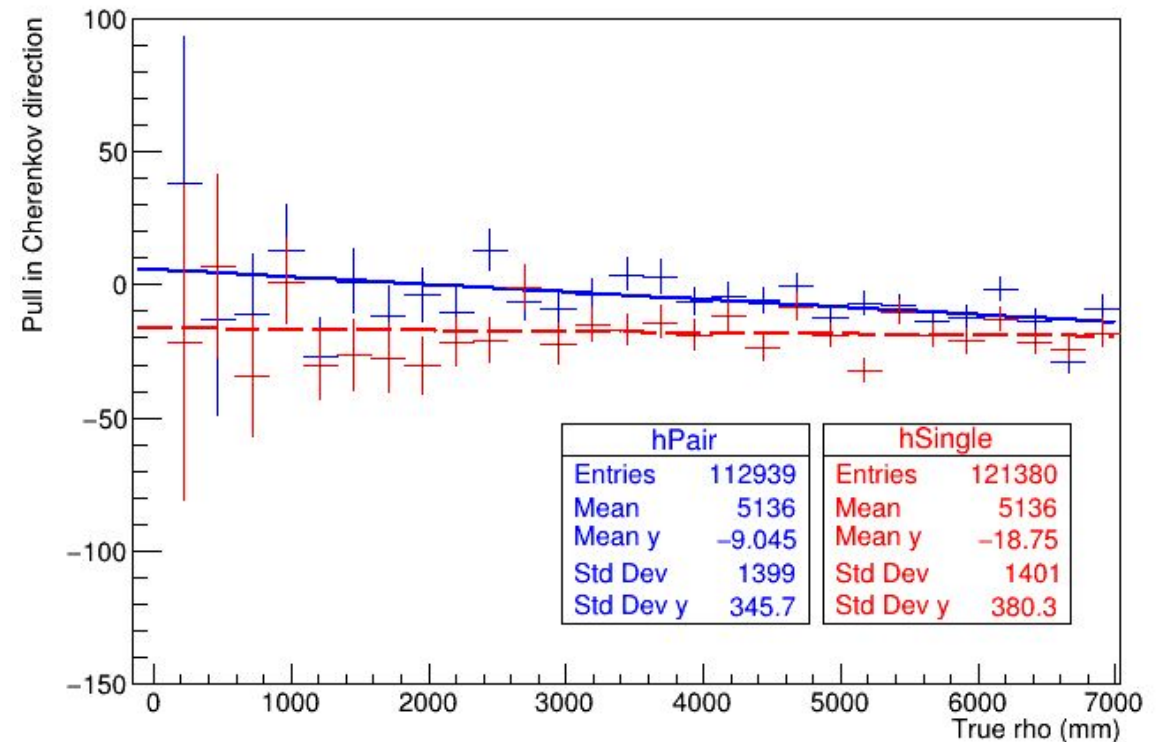
Boulby Strumia & Vissani (2003) IBD neutrino spectrum



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

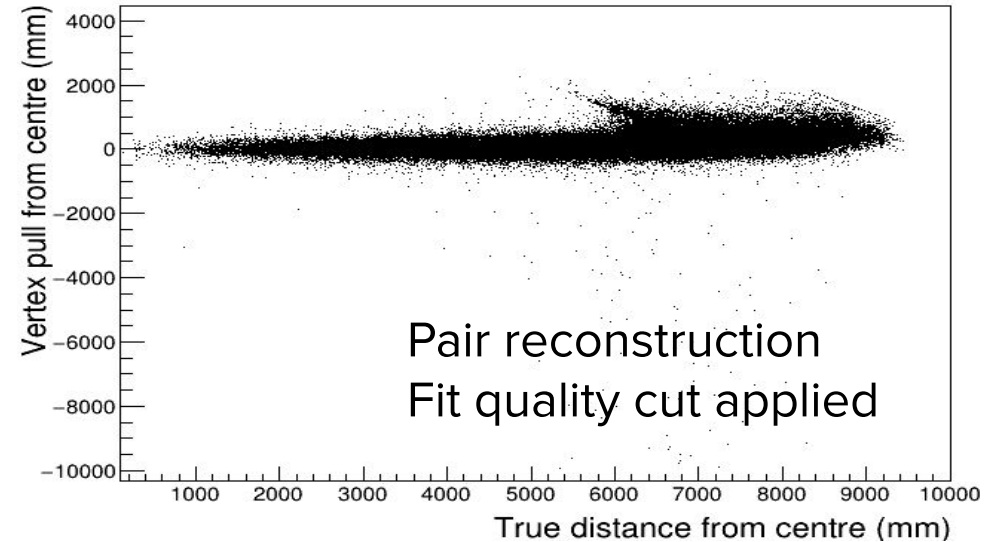
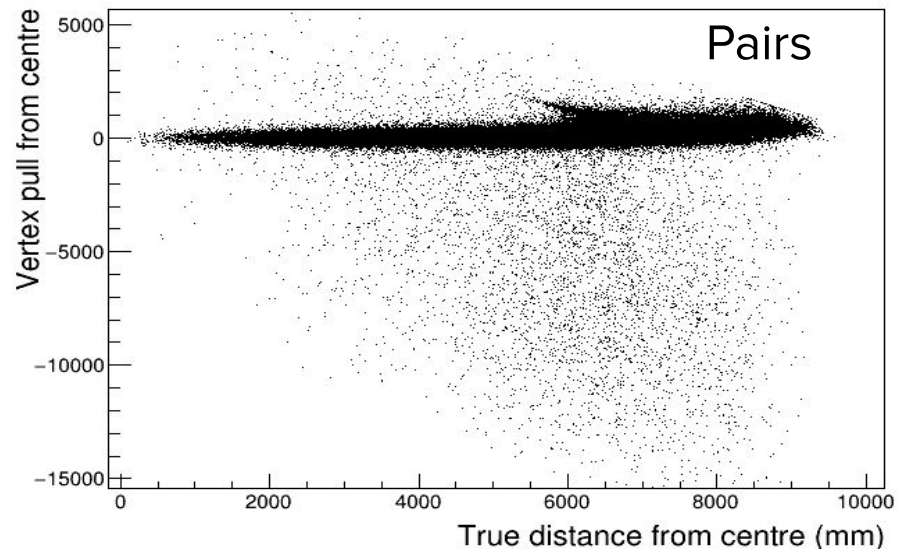
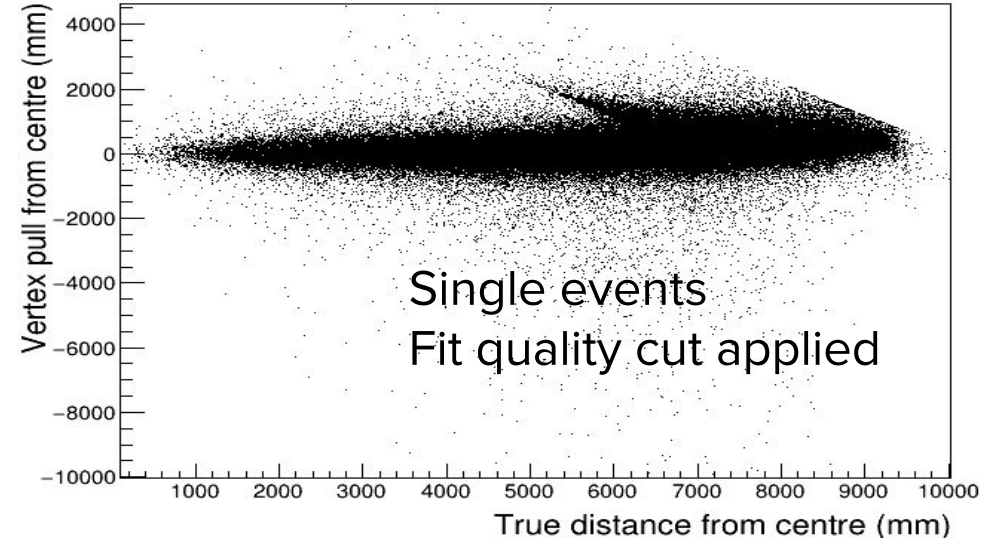
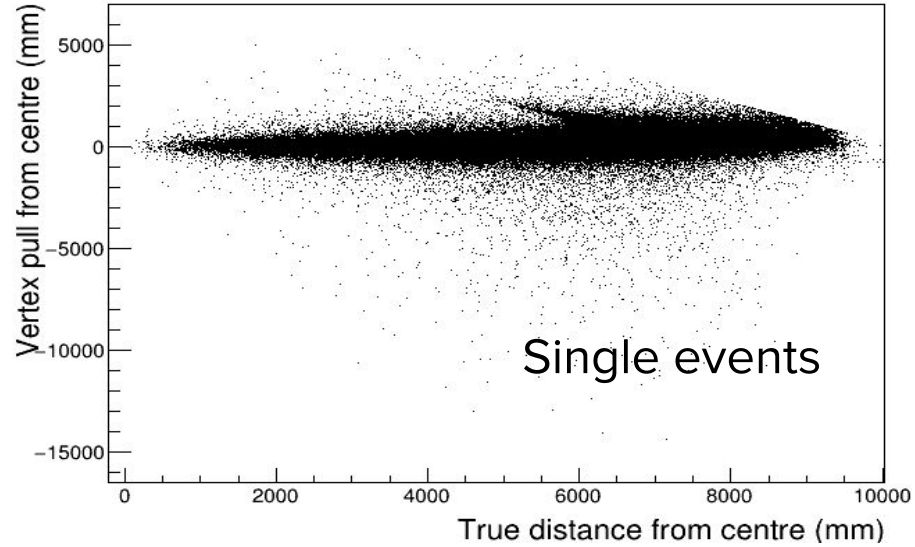
Improved vertex pull

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).

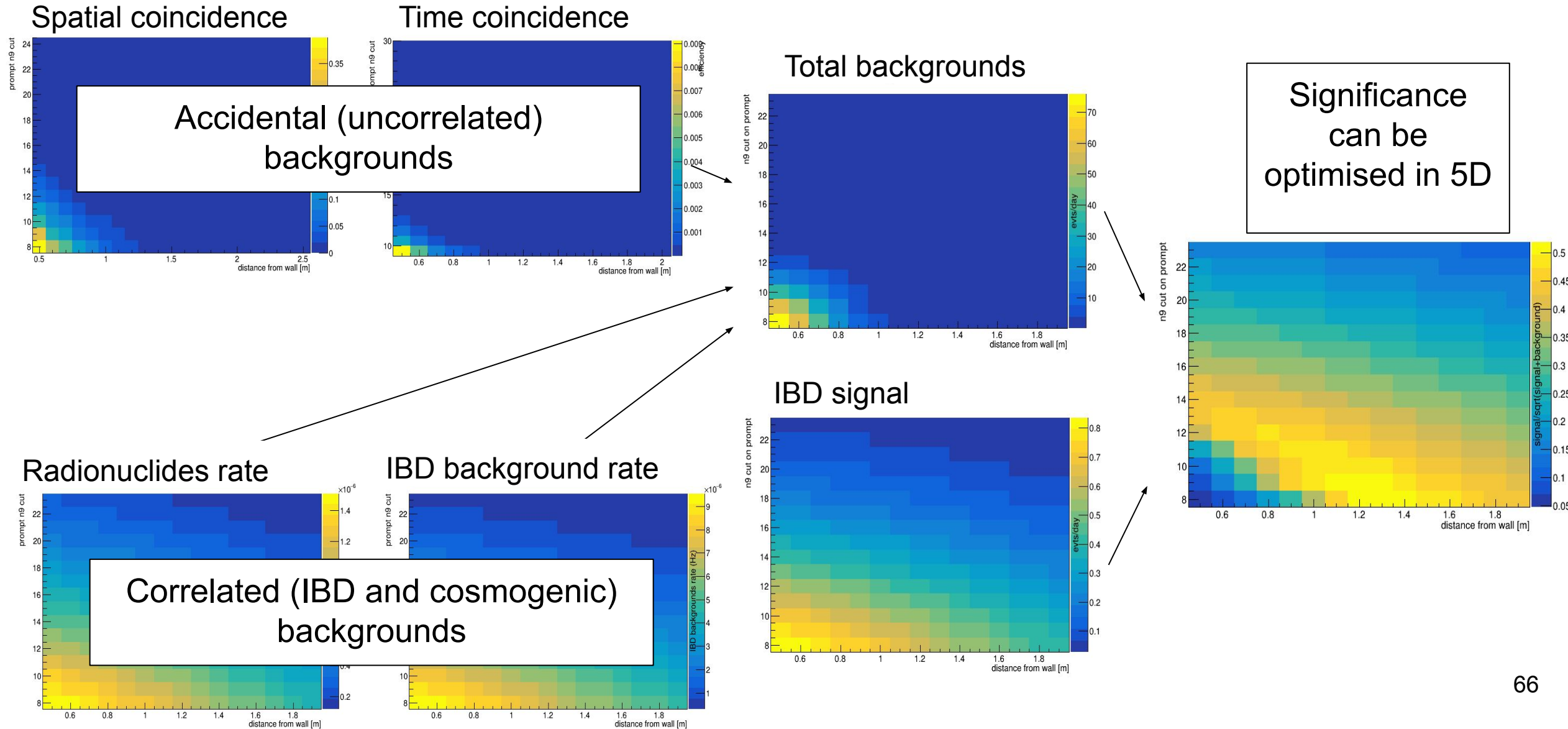


Information from additional hits gives better reconstruction in the Cherenkov direction.

Pairbonsai fit quality cut more effective




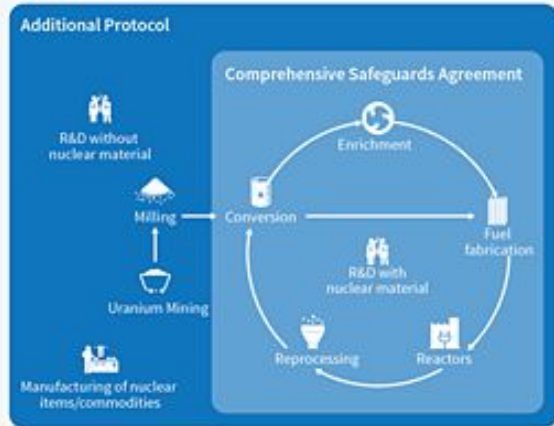
Sensitivity analysis for WATCHMAN



Part of a remote monitoring toolkit

Under the JCPOA, the IAEA has wider access to, and more information on, Iran's nuclear programme and implements a more robust verification system

 The Additional Protocol enables IAEA inspectors to conduct complementary access to any location in Iran



Surveillance cameras installed at facilities

 +89%
2013 - 2017

Seals attached to nuclear material and equipment



Verification activities conducted

 +152%
2013 - 2017

IAEA's presence in Iran

Calendar days in the field



State-of-the-art technology collected

1.2 million
open-source documents/month in 2017



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

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.