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# Status of Development of Anti-neutrino Detector Systems in the UK

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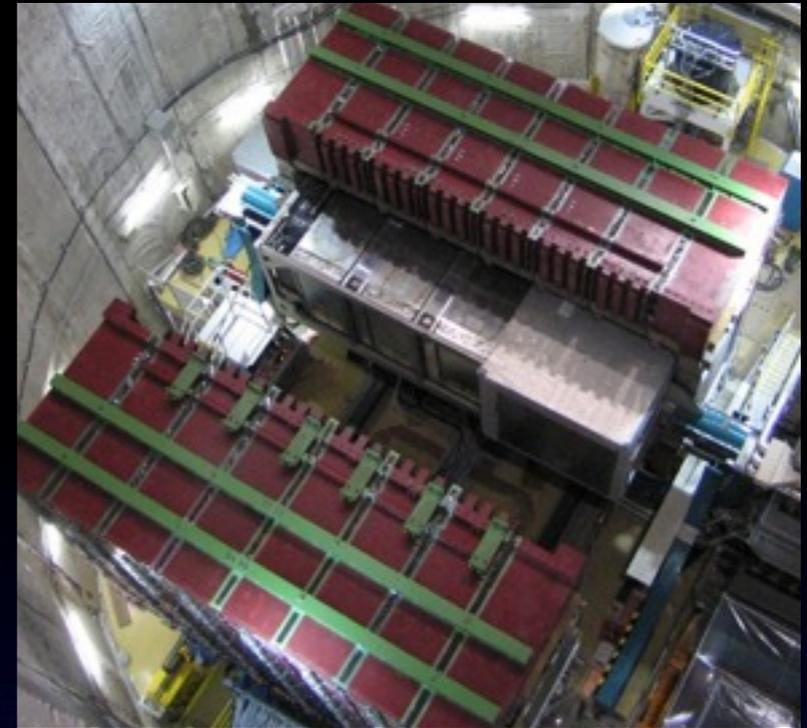
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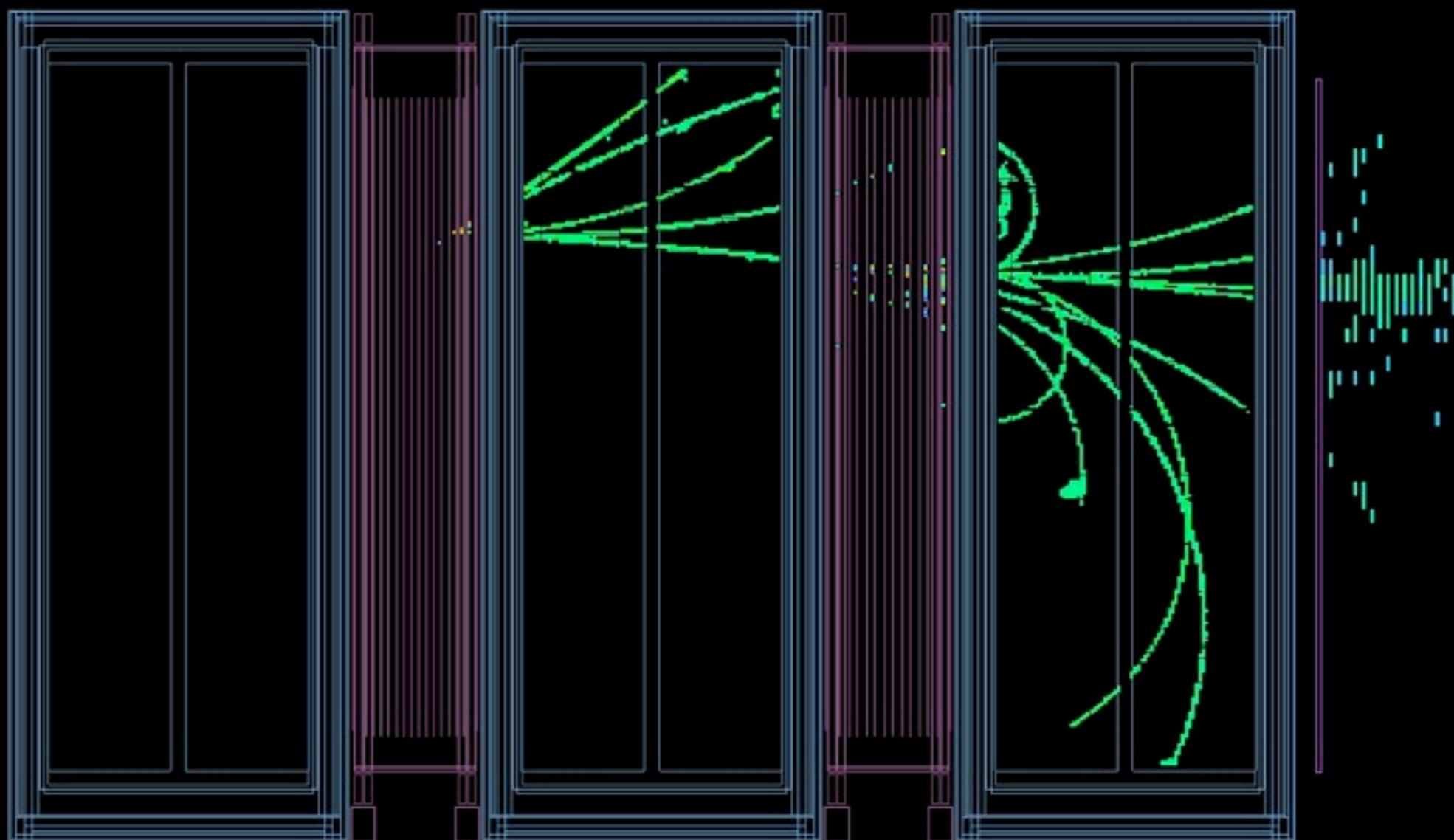
*Applied Anti-neutrino Physics 2013 1-2 Nov 2013, COEX, Seoul, Korea*



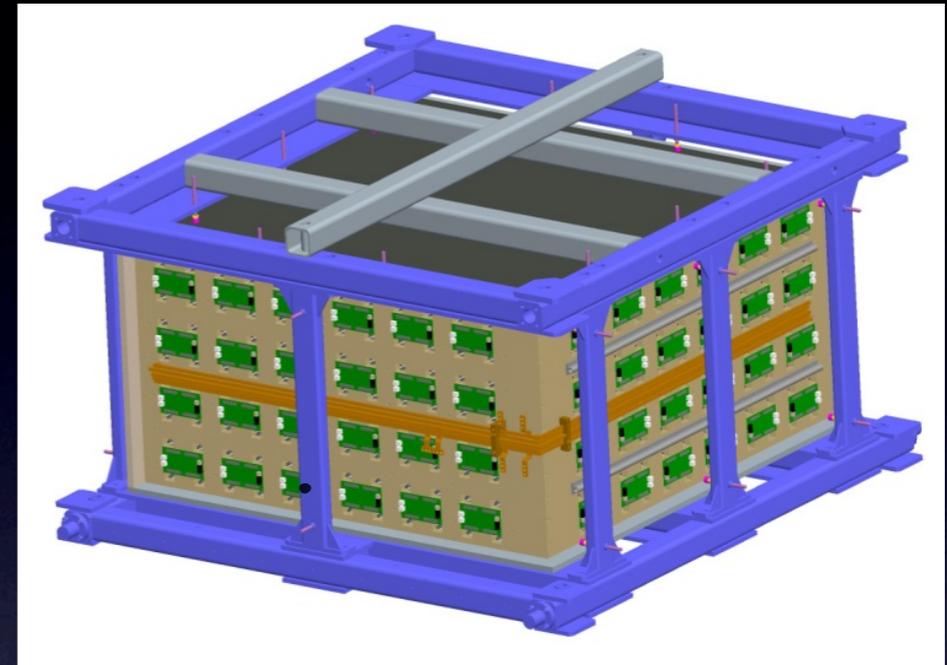
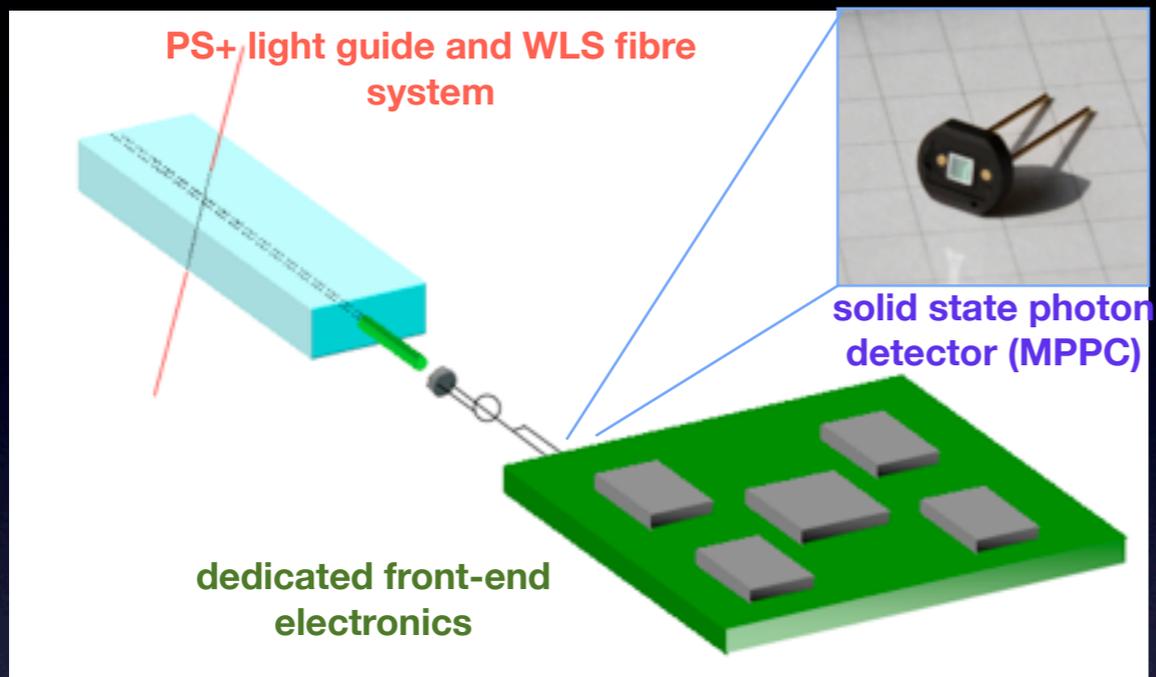
# Groups

- Liverpool University - J. Coleman
  - Gd oxyde sheets, organic scintillator
  - directly translated T2K near detector calorimeter design
- University of Oxford - A. Vacheret
  - ${}^6\text{LiF:ZnS(Ag)}$  organic scintillator (PVT, POLY)
  - Application development part of Sterile Neutrino experiment SoLid
- Both university have been involved in the T2K experiment for many years
  - large expertise in construction of Calorimeter detector systems
    - large mass, highly segmented
  - both systems uses SiPMs photosensors (MPPCs)





# Liverpool system

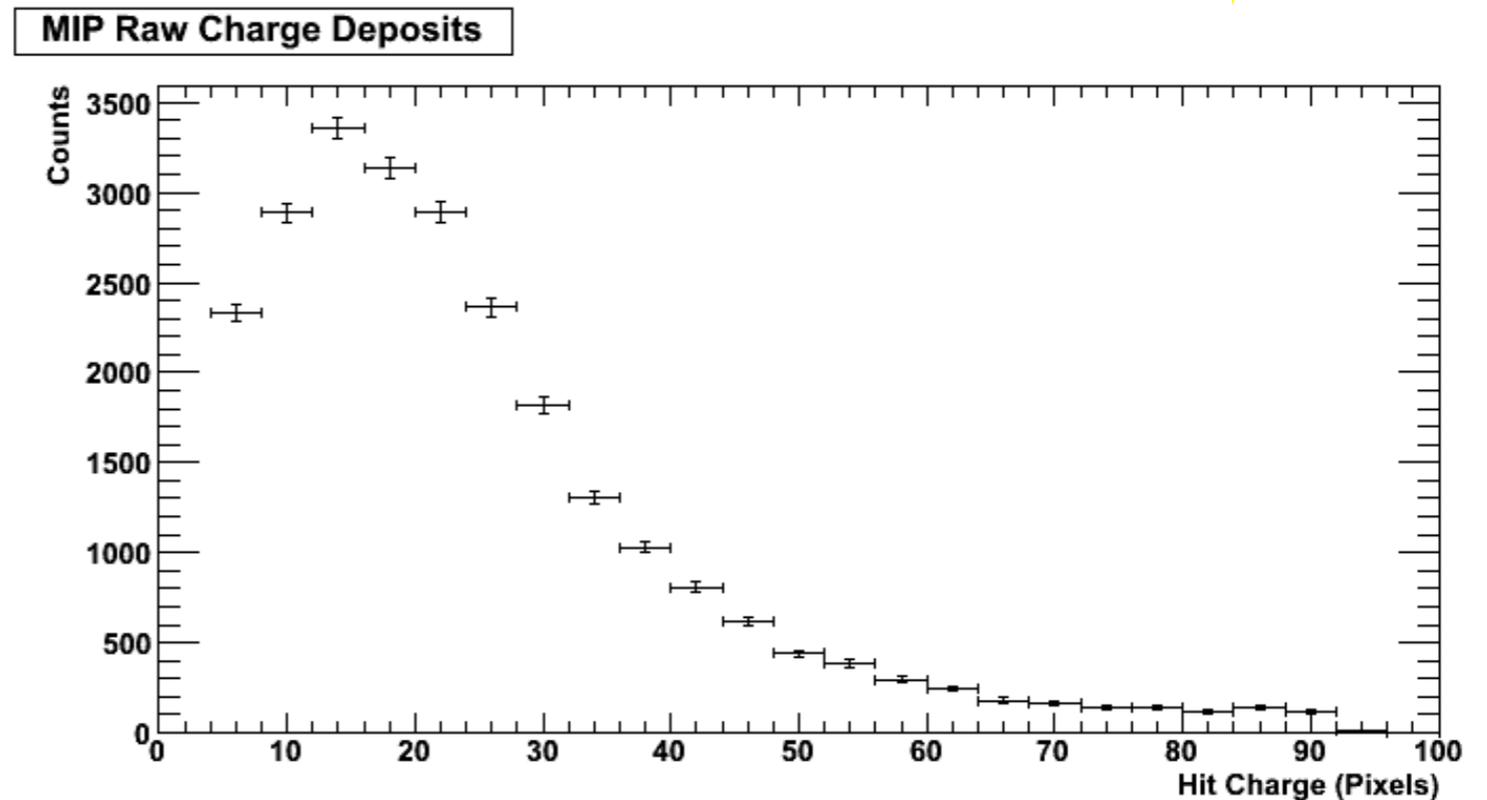


- Highly segmented detector
  - 3000 electronics channels
  - leverage on many man-hours development for T2K
    - FPGA/ASIC based electronics
  - built-in muon veto
  - Detector construction completed

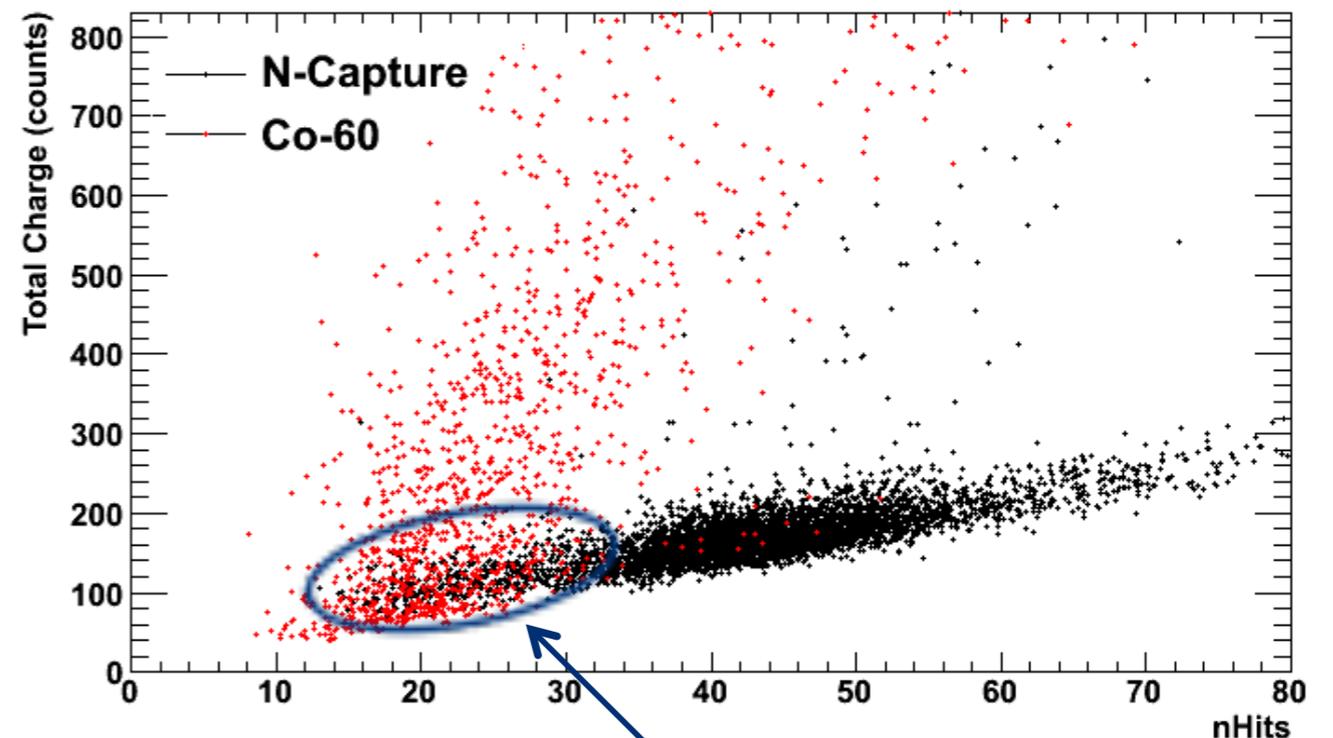
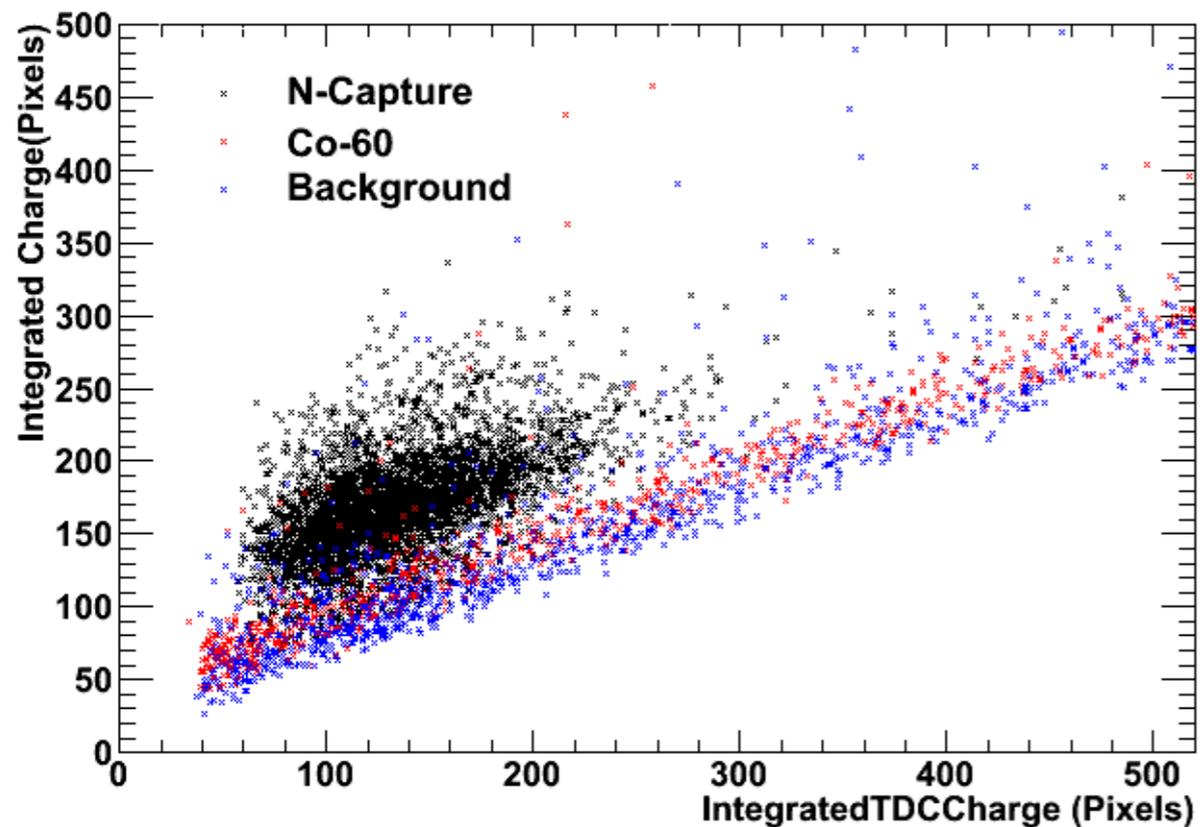


# Light Yield

- Fully configurable trigger and veto
  - Can select or reject cosmics easily
  - Can select penetrating, clipping or stopping cosmics based on veto planes
- Use cosmic muons (MIPs) to calibrate energy scale of detector



# Neutron Detection Using Cf-252



Hydrogen captures give 2.2 MeV gamma (EM) signal

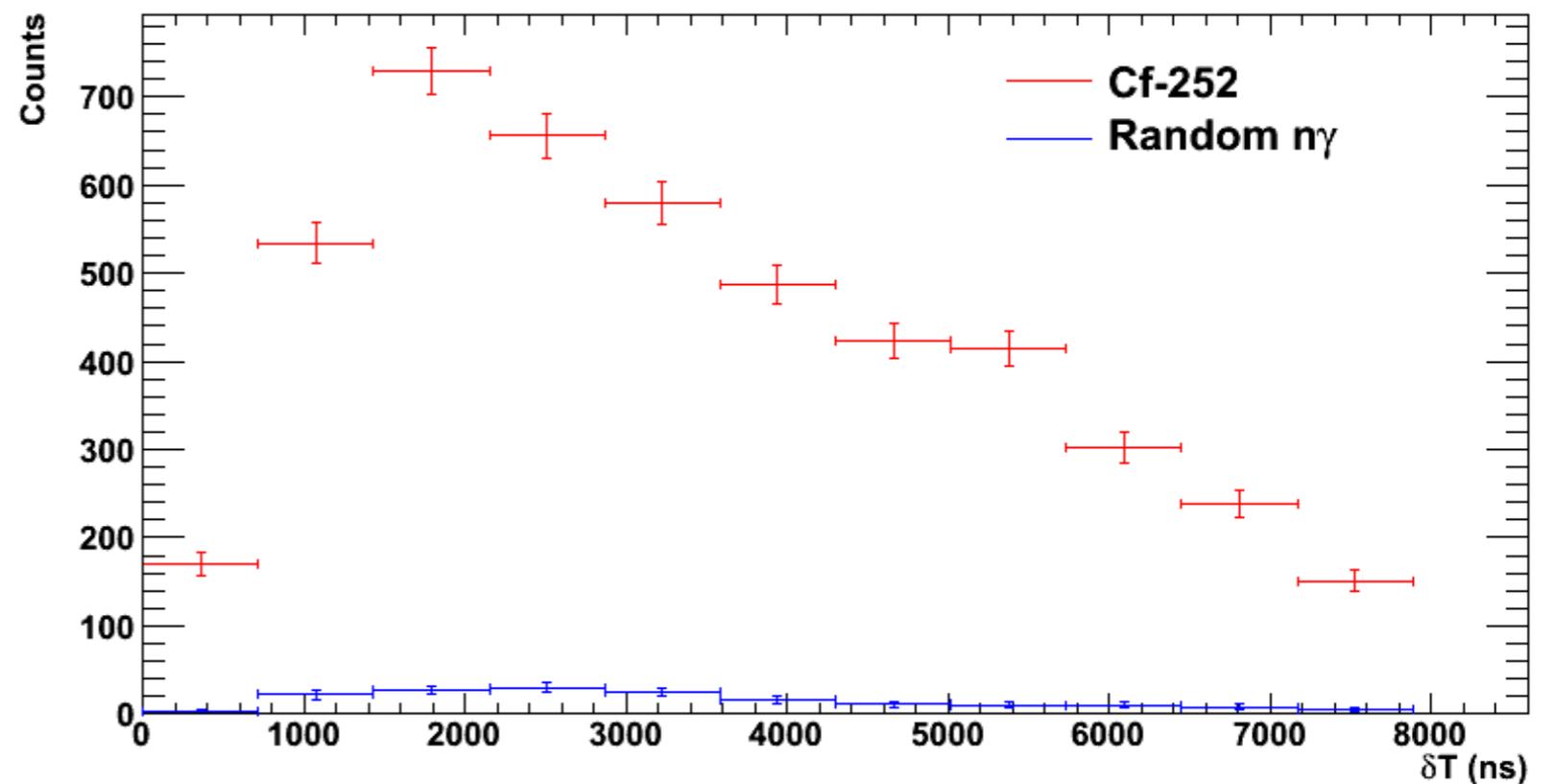
\*IntegratedTDCCharge = sum of all charges above a given threshold

- Already good PID using raw data
  - No calibration
  - Little threshold optimisation
  - No reconstruction

# Coincidence Signal



- Look for coincidence using Cf-252
  - 3 neutrons per fission
  - Average 8 gammas per fission
  - Trigger on delayed neutron capture and look for prompt signal



# Status and future plan

- Finalising commissioning and calibration with radioactive sources
- plan to deploy detector at Ljubljana TRIGA Research Reaktor
  - 14 MW power
- plan to run at UK reactor under UK support program to IAEA and UK office of Nuclear regulation

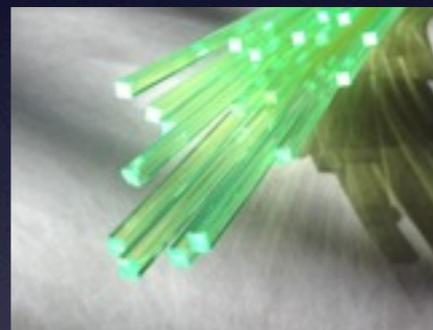
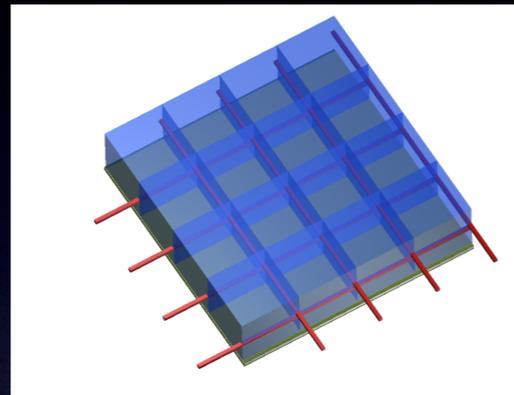
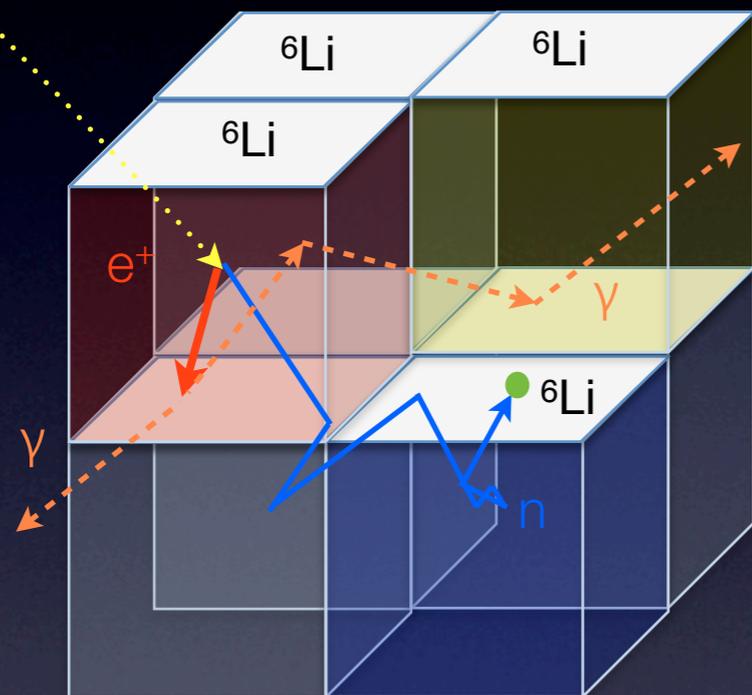
# The MARS project

<http://www2.physics.ox.ac.uk/research/mars-project>

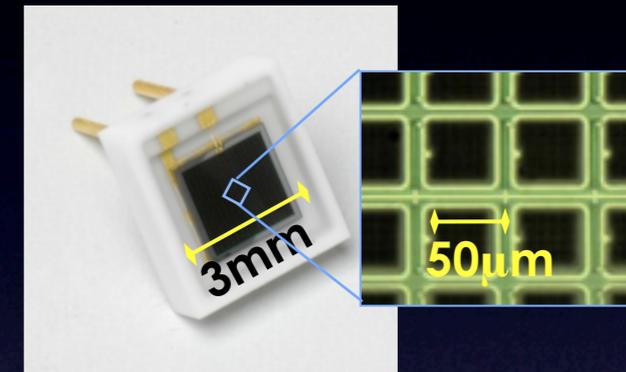
- Aim to develop next generation of neutron detectors around Oxford/Imperial IP
- ${}^6\text{LiF}:\text{ZnS}(\text{Ag})$  combined with light guide and embedded shifting fibre
  - for applications in safeguards, security, dosimetry etc...
  - anti-neutrino detection
- Anti-neutrino applications pursued as part of neutrino oscillation science experiment called SoLid at BR2 MTR reactor
- practical requirements
- reasonable size : compactness but keep high counting rate
- robustness and low maintenance : remote monitoring
- effort to develop new safeguards capabilities convened in ESARDA NA/NT working group

# Detection principle

anti-neutrino



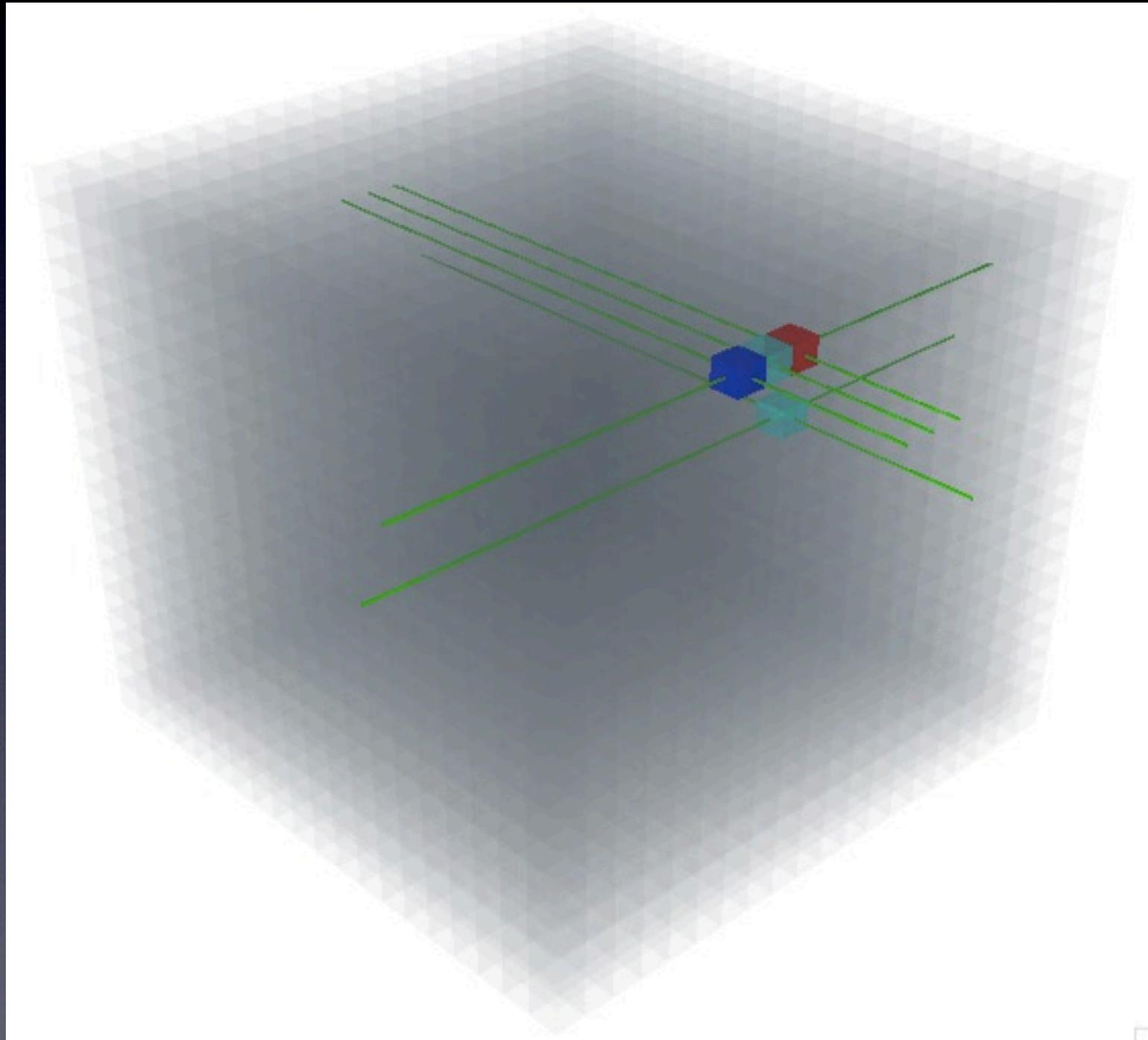
BCF-91A fibre



MPPC  
S10362-33-050C  
3mm x 3mm  
50 um pixel pitch  
60-65% active area  
Pixel RC const~13 ns  
PDE ~ 30-40%

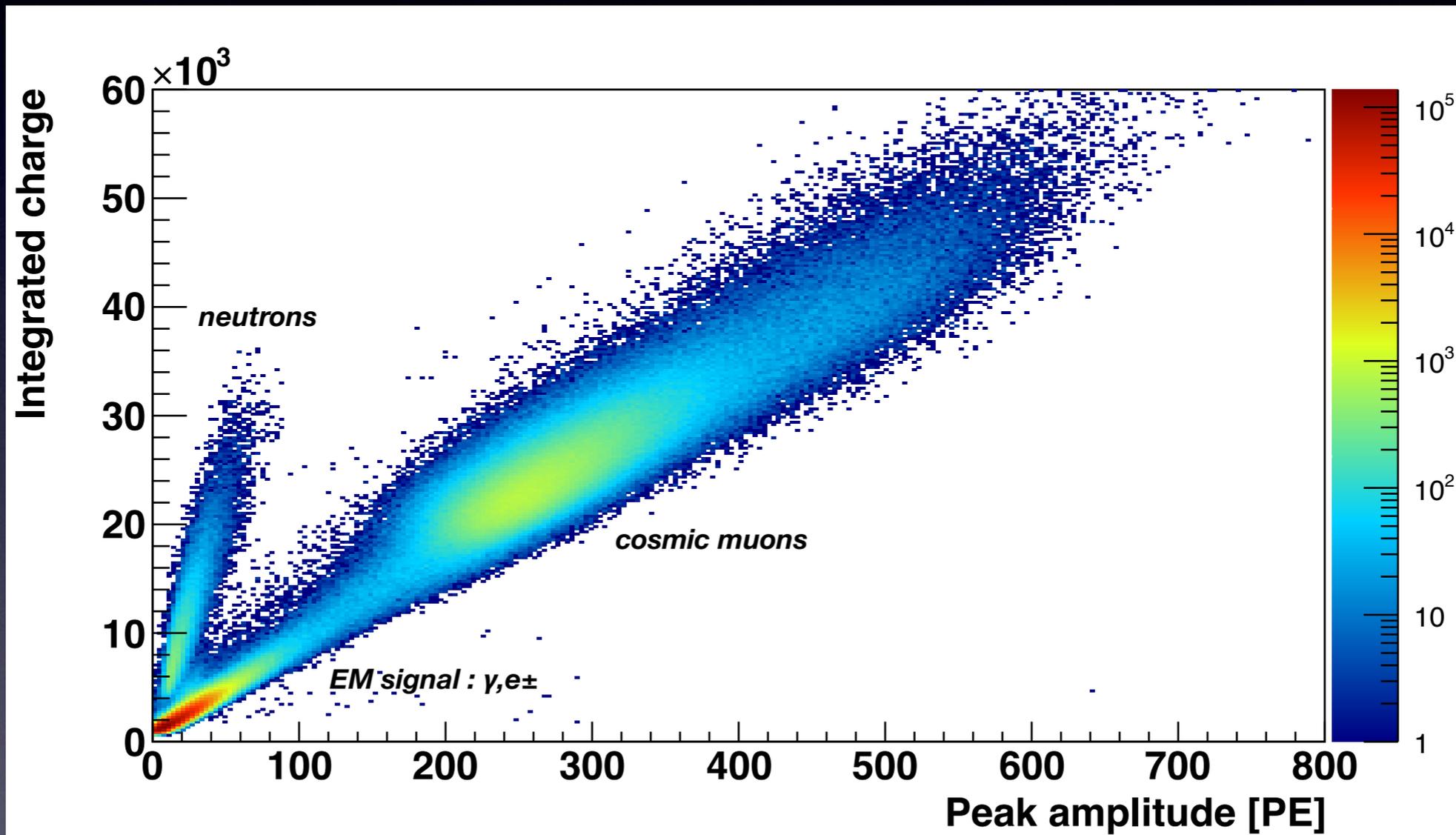
- Plastic scintillator : PVT (EJ-200) or polystyrene based scintillator
- Neutron layer :  ${}^6\text{LiF:ZnS(Ag)}$
- Isolate positron energy in one cube : reconstruct energy not affected by gamma energy leakage
- neutron is captured in neighboring cube increasing **localisation of IBD event**
- Wavelength shifting fibres to read out light from both scintillation signal **Squared BCF-91A fibre**
- MPPC photosensors

# Anti-neutrino event



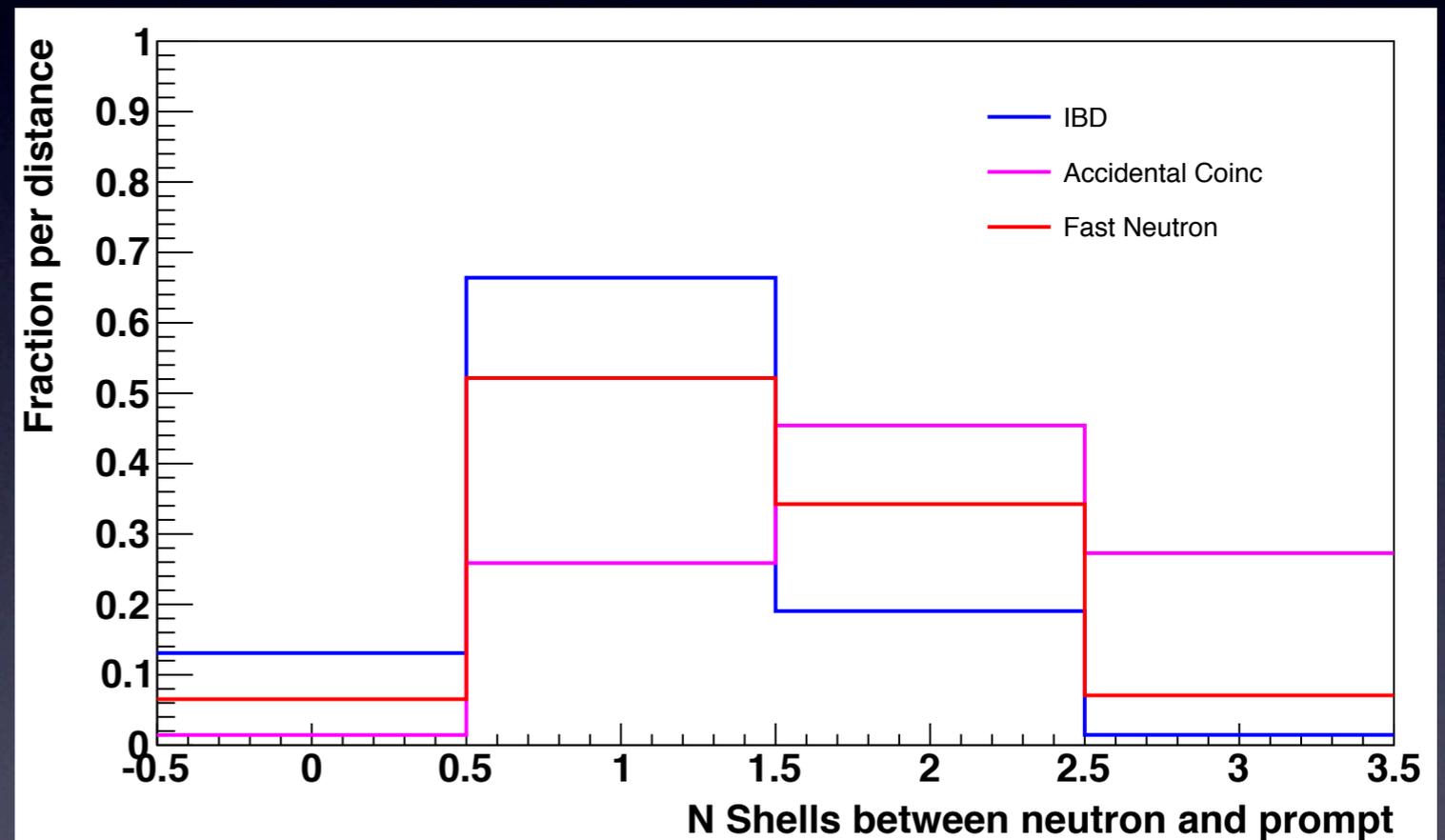
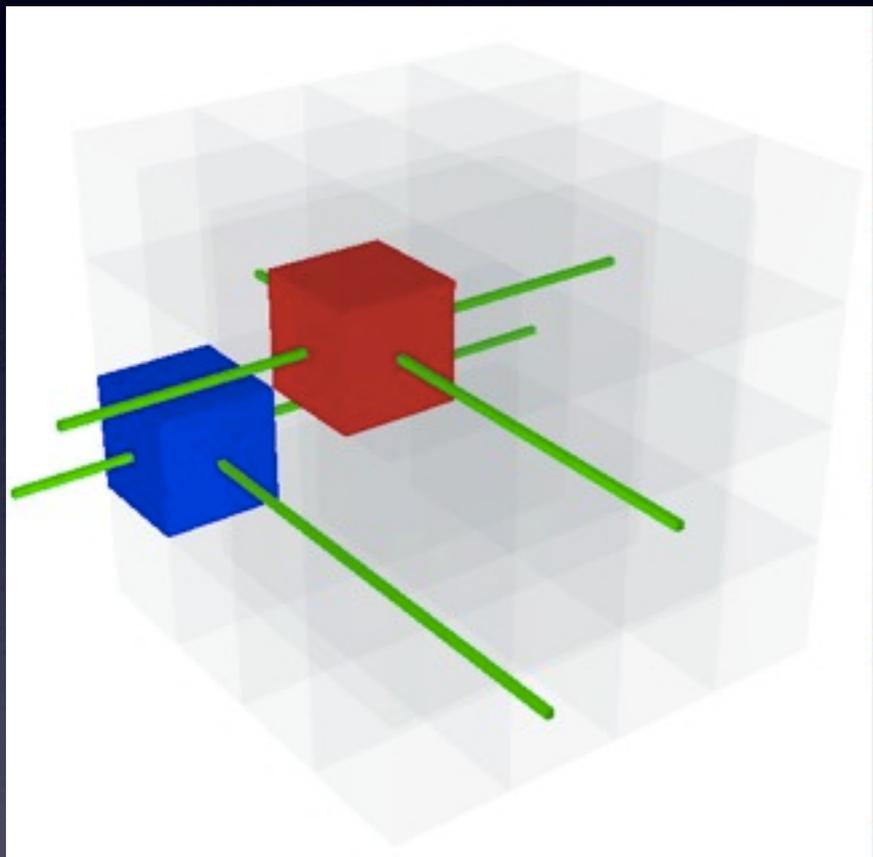
$e^+$   
 $n$   
 $\gamma$

# Detector response



- Calibrated energy response

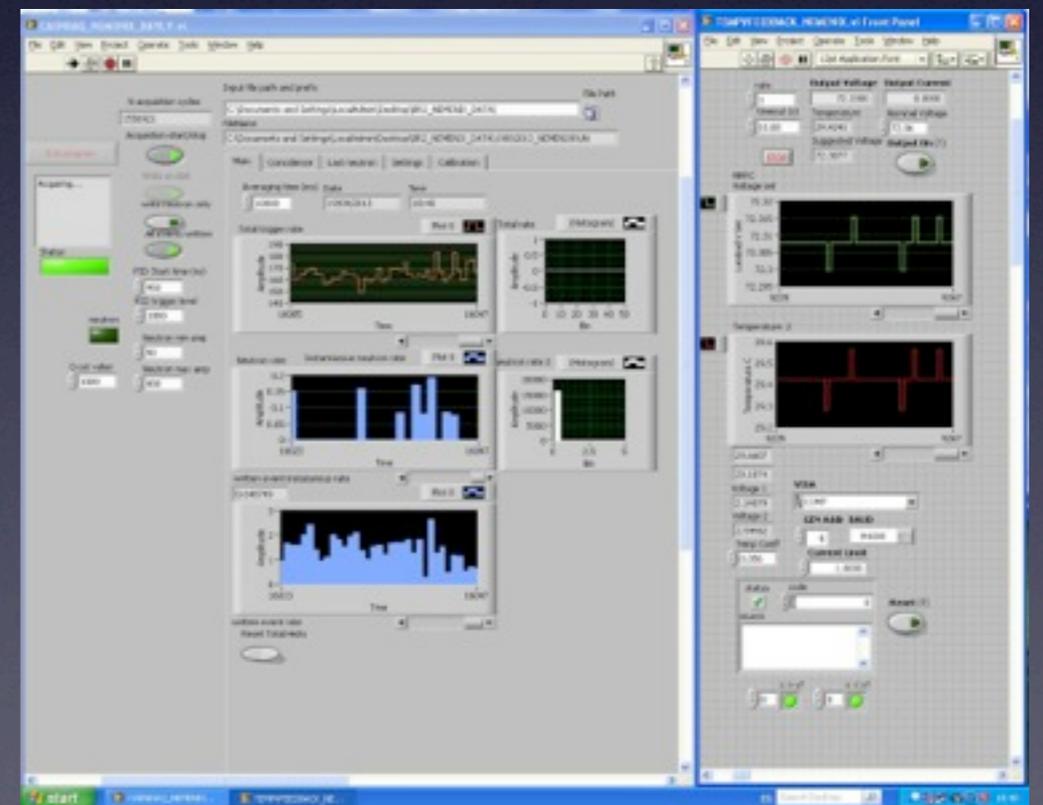
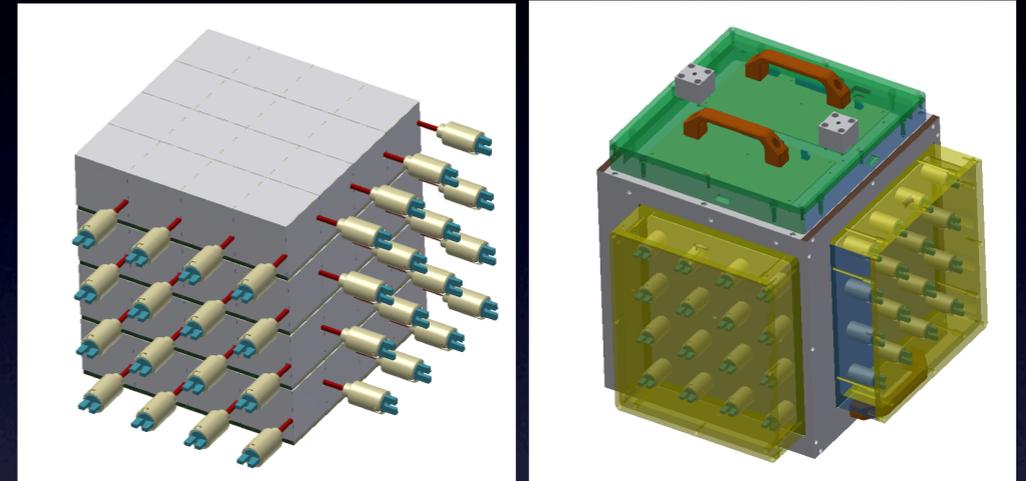
# Unique handle : spatial topology



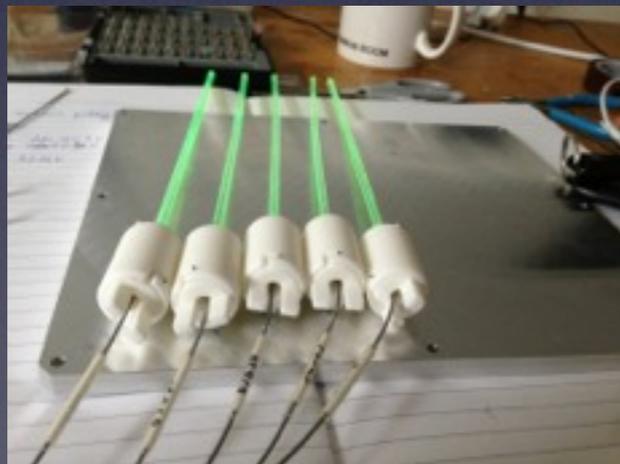
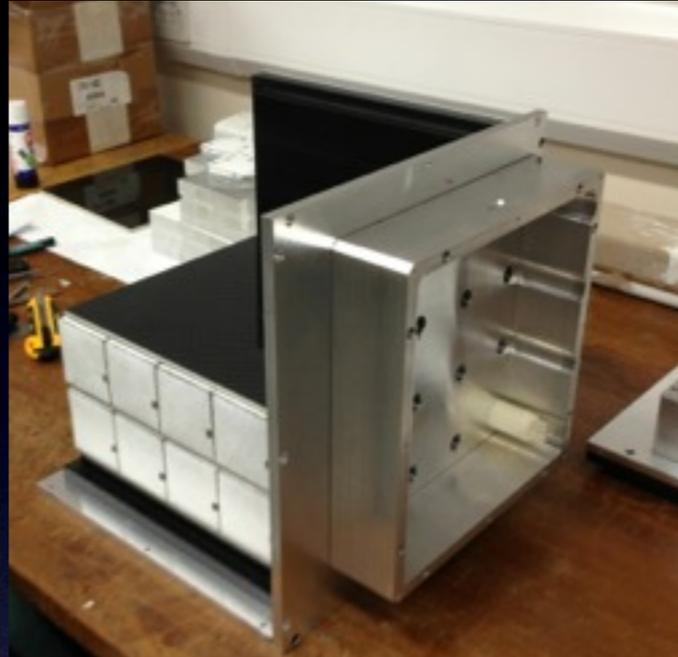
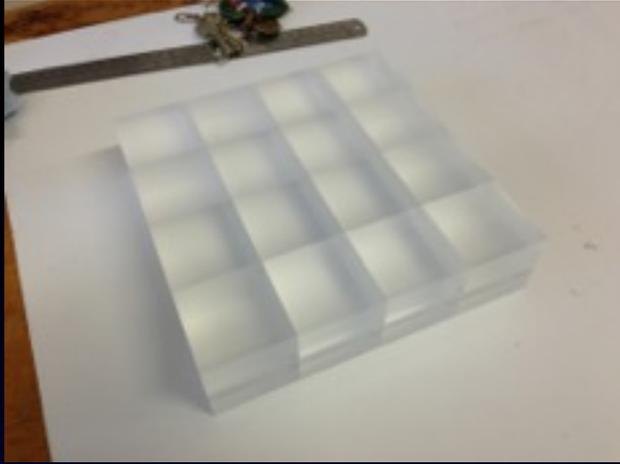
- Detector robust to background by design
- limiting external shielding (20cm HPDE but Pb front wall only, no muon veto)
- Can handle high rate of accidentals

# NEMENIX : 8 mtons prototype

- 4 x 4 x 4 cubes (8kg target mass) detector system
- smallest anti-neutrino detector ?
- 32 read out channels
- Oxford PHOBOS amplifier cards
- Caen DT5740 desktop digitiser 62.5MS/s
- custom Labview front-end
- Temperature-voltage drift feedback loop
- Expected IBD efficiency  $\sim 0.3$  (no threshold)

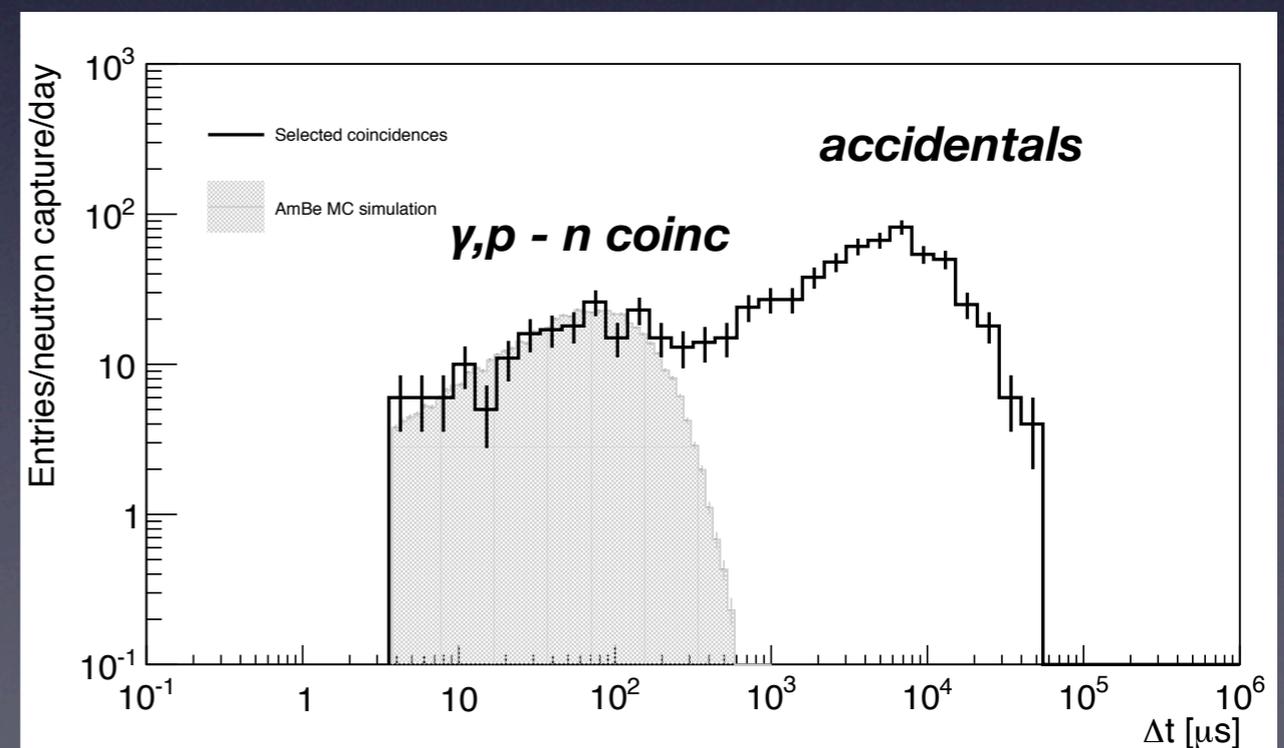
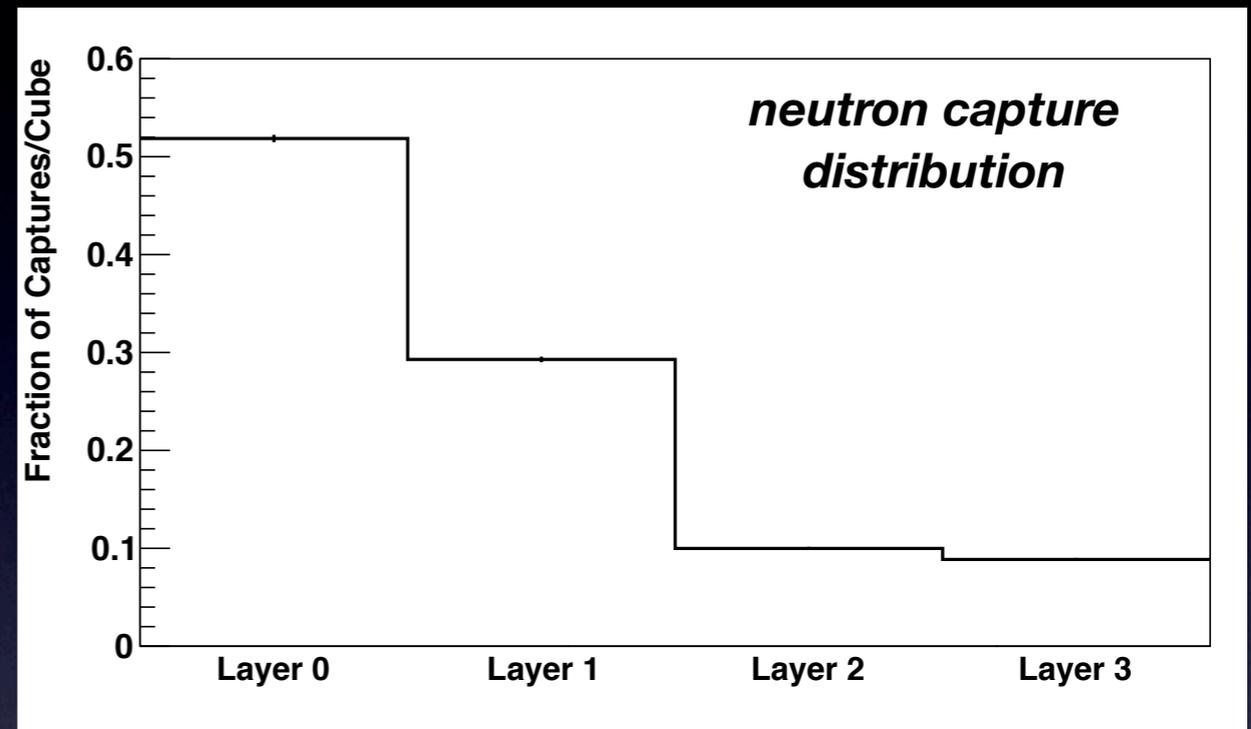


# NEMENIX Construction



# Correlation signal with neutron : AmBe source test

- AmBe emits gamma-rays in coincidence with neutrons
- coincidence also possible from proton recoil
- Prompt-delay time coincidence verified



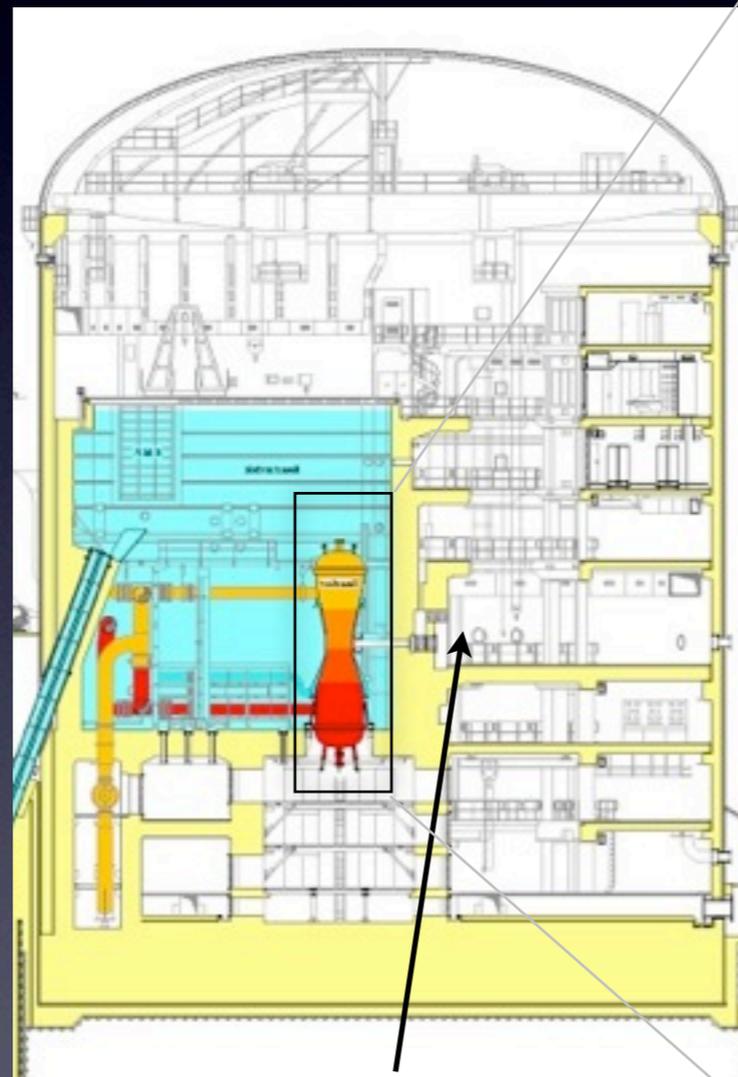


# SCK•CEN BR2

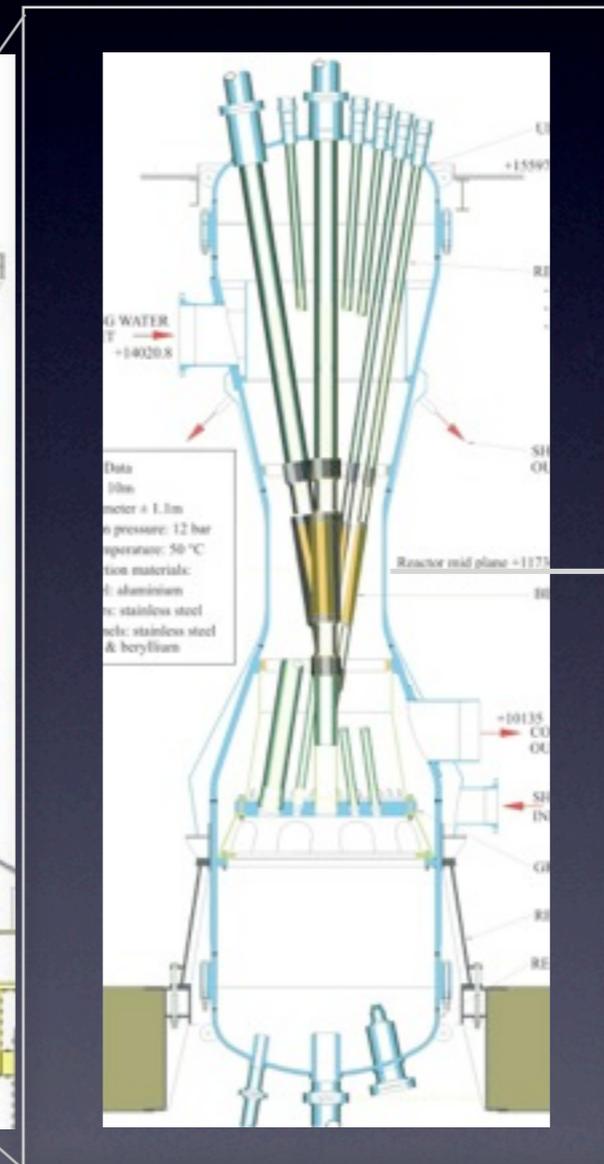


- Tank in Pool research reactor
- Licensed to run at power up to 100 MW
  - variable operating power
- 5/6 cycles per year

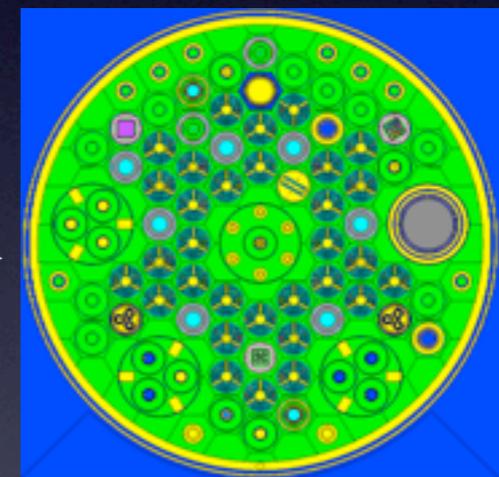
Confinement building



Level 10m67  
on axis with reactor



Aluminum pressure Vessel  
Twisted core



1.0 m

Beryllium matrix  
and assemblies

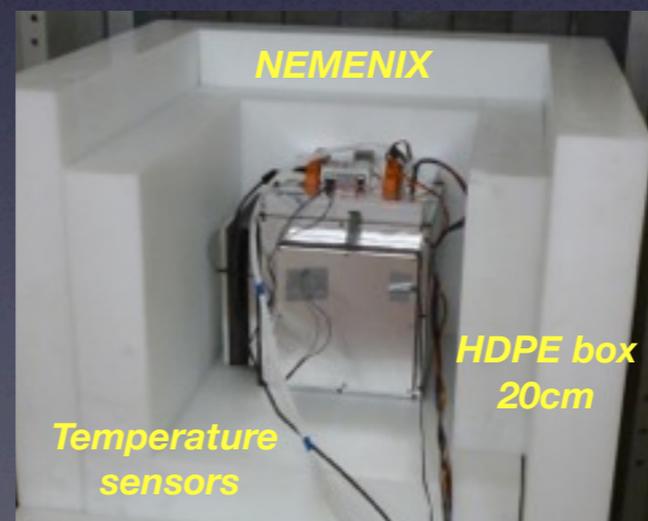
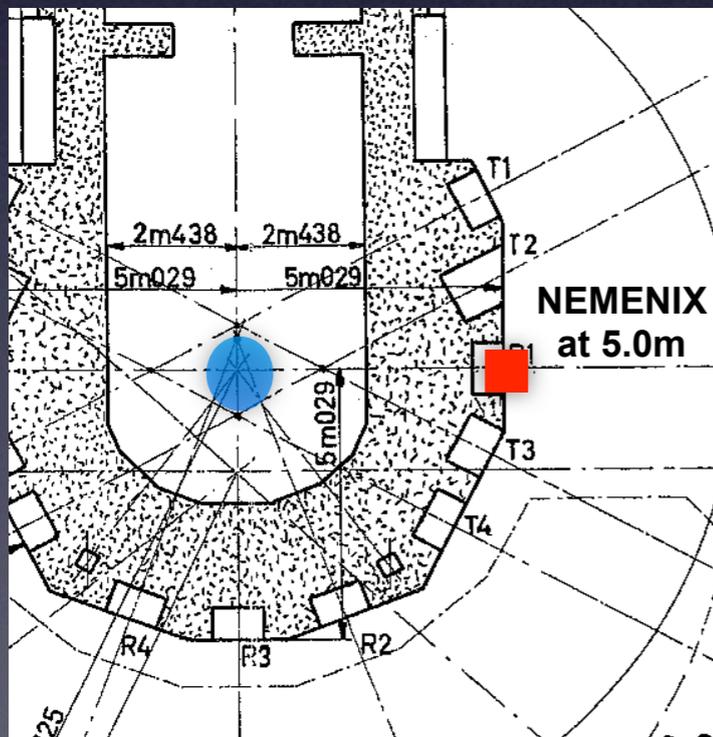
# Deployment at BR2

NEMENIX prototype moved to BR2 level 10 at R1 position at end of July 2013

- very short commissioning period

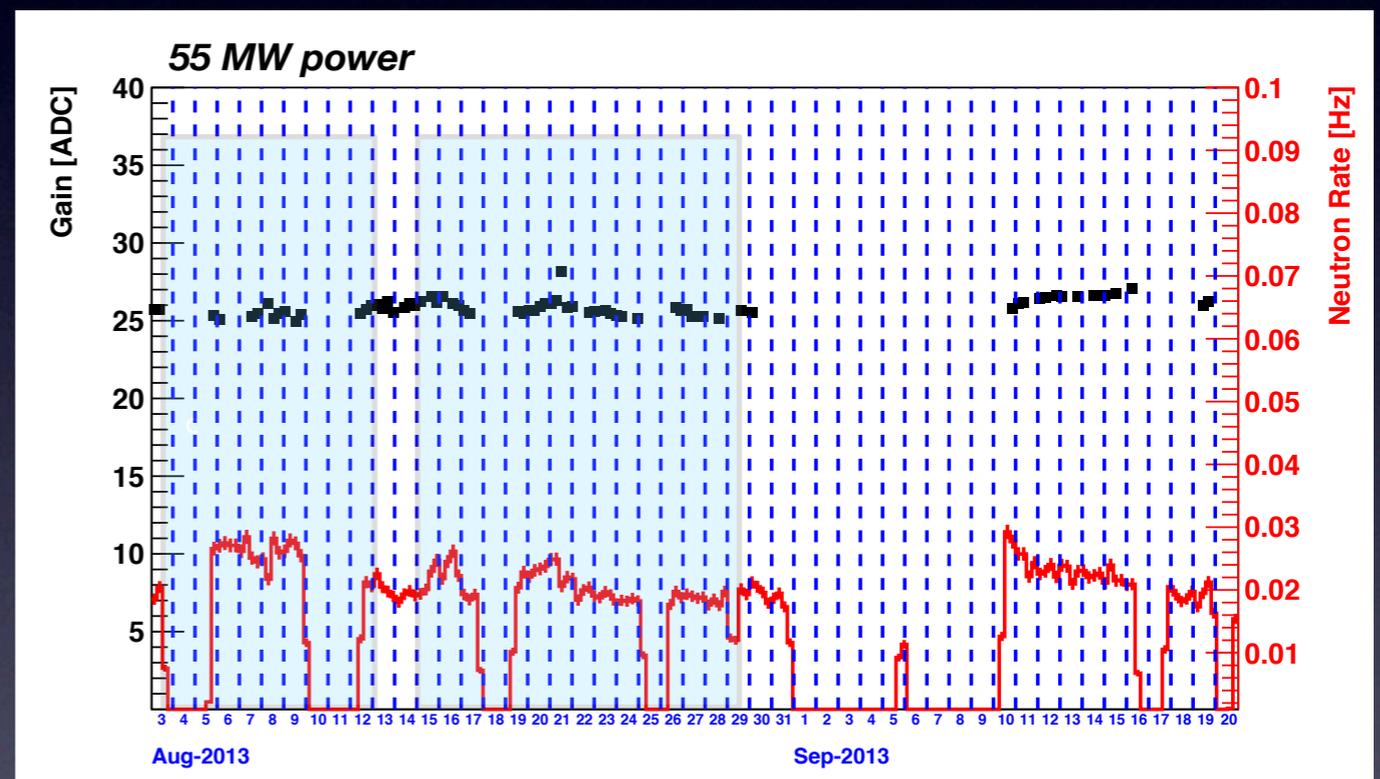
SCK-CEN R&D project

- Detector shielding provided and installed by BR2 staff



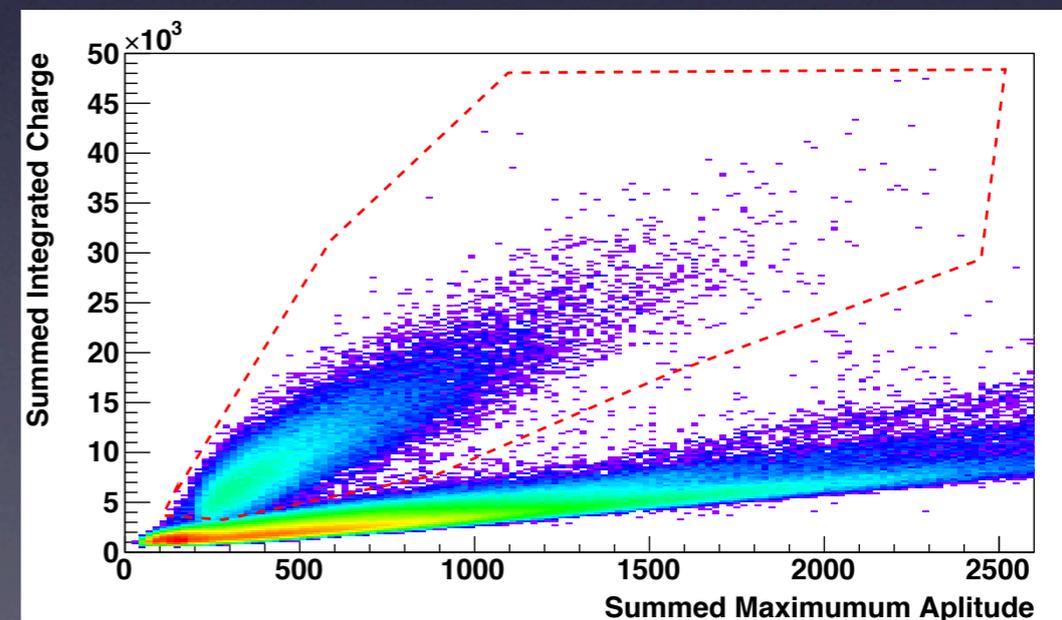
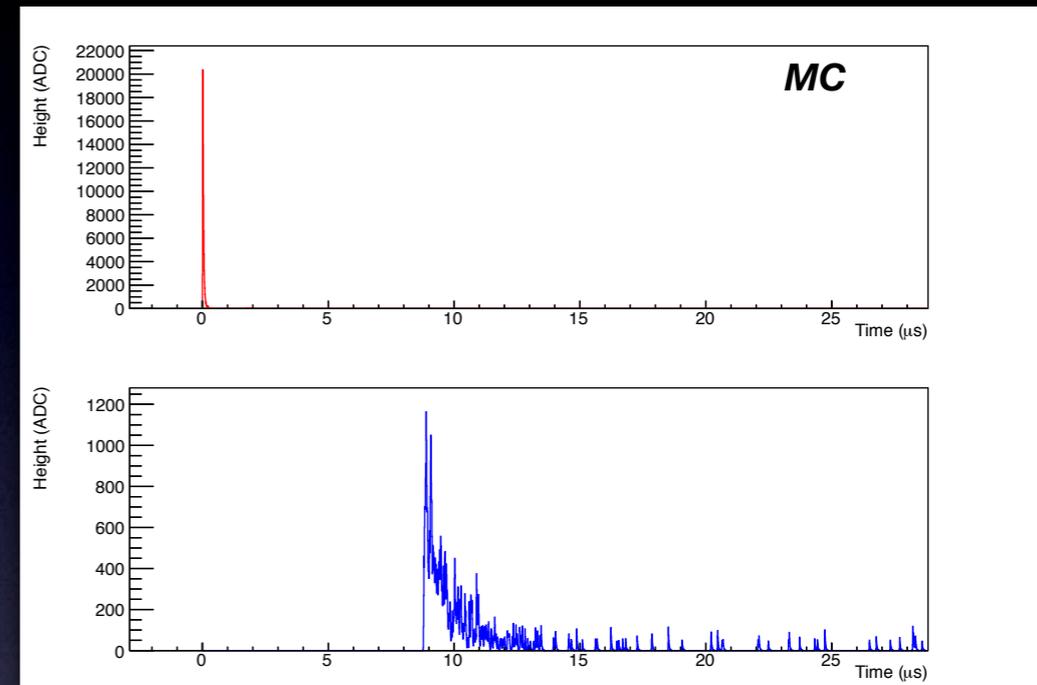
# Summer run data

- 55 MW August cycle
- Reactor ON
  - 22.79 days / 17.67 recorded
- Reactor OFF
  - 13.46 days
- good gain stability with manual temperature correction
- average temperature 30° C
- < 5% variation
- can be improved with automated feedback loop

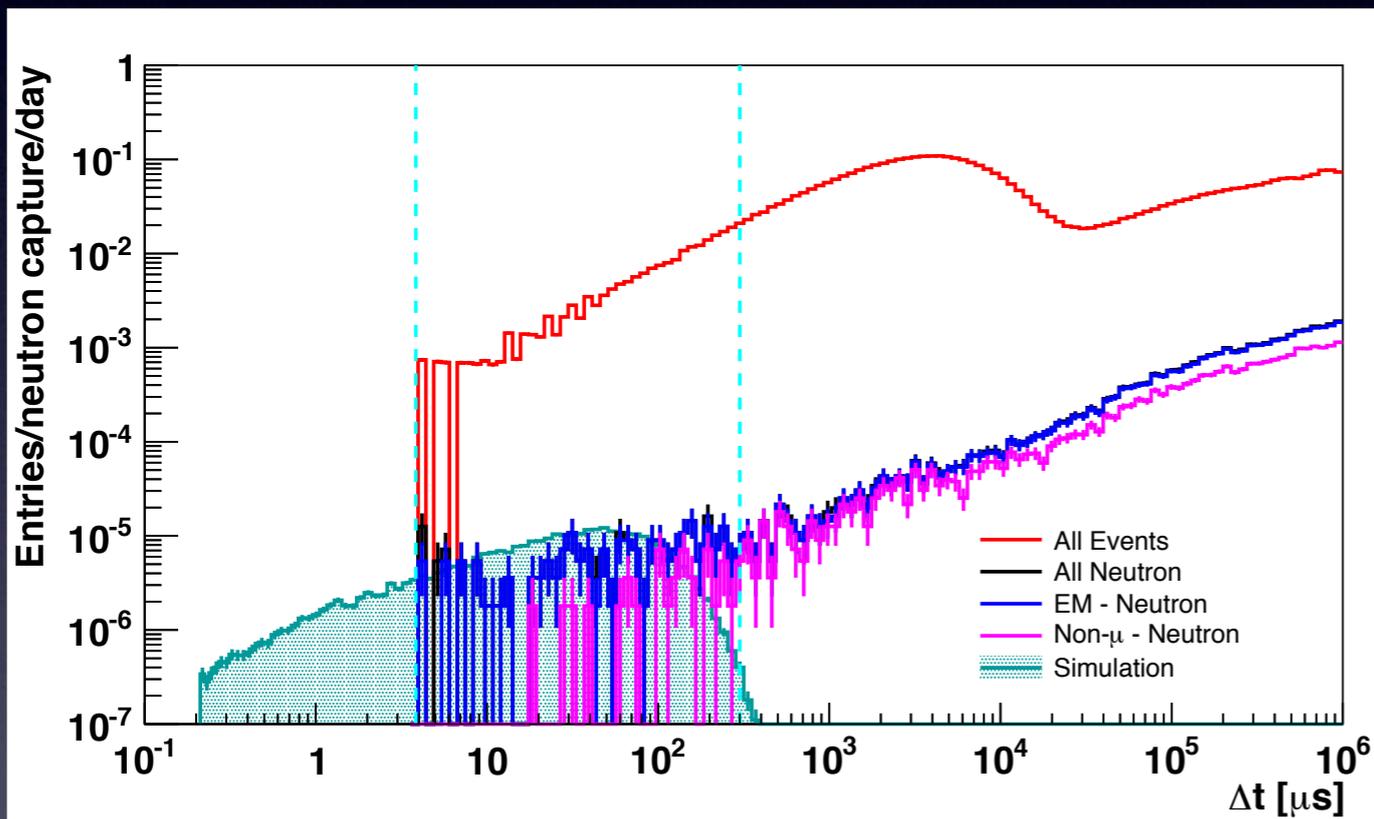


# Anti-neutrino analysis

- neutron selection using 2D cuts
- positron : X & Y cube highest prompt signal
- four way analysis:
  - Reactor ON / OFF
  - side-band analysis

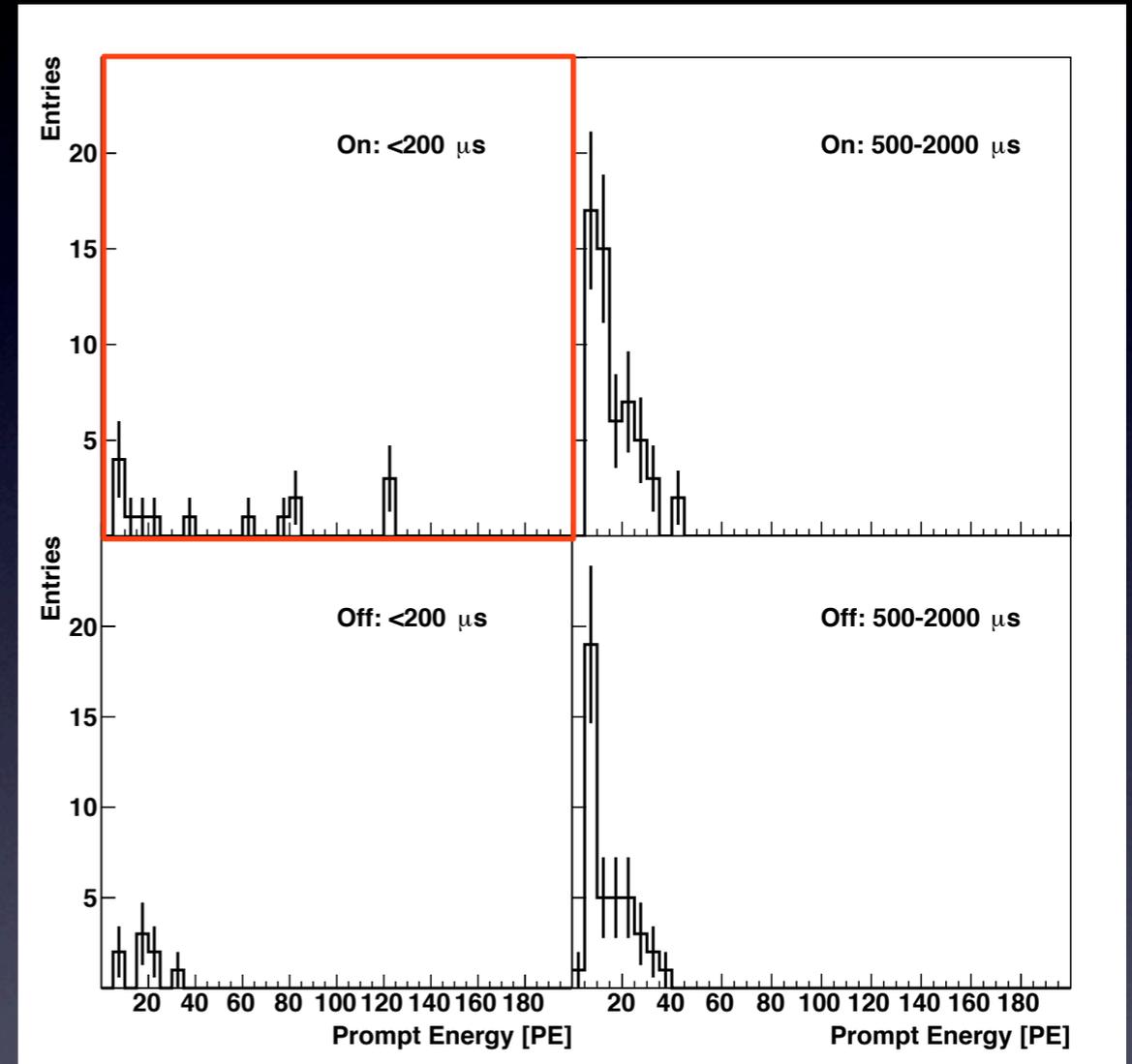
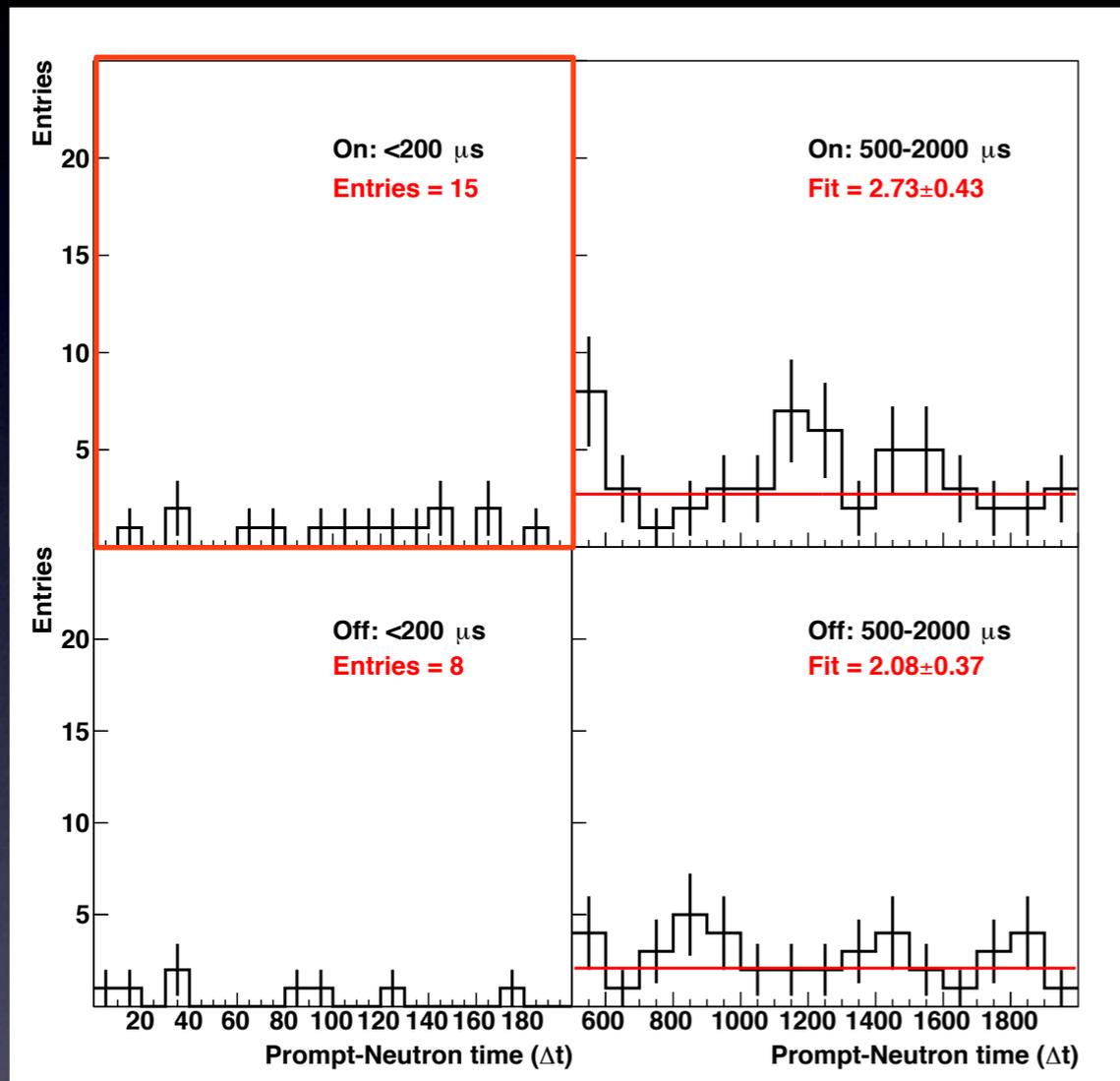


# Power of rejection



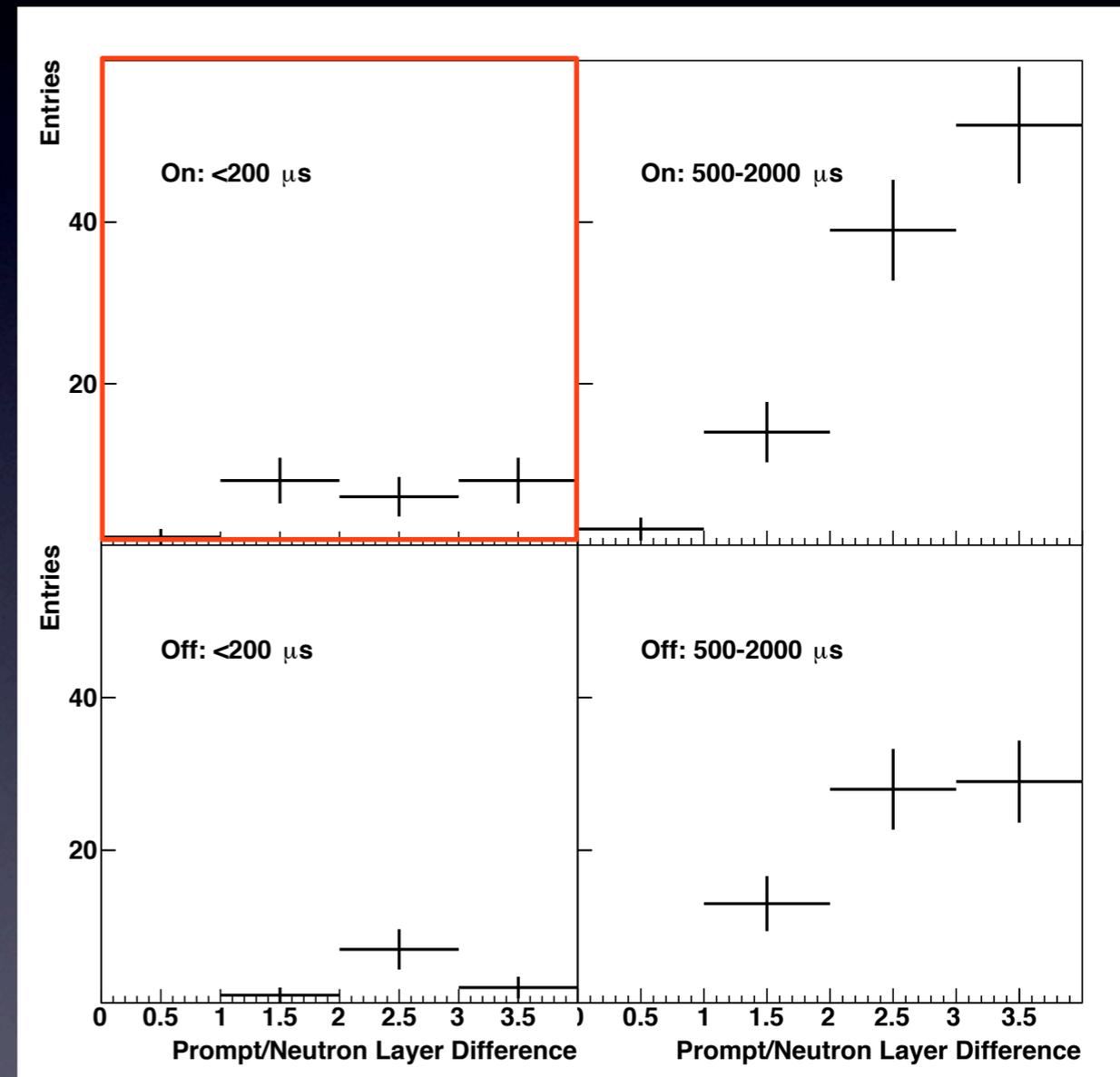
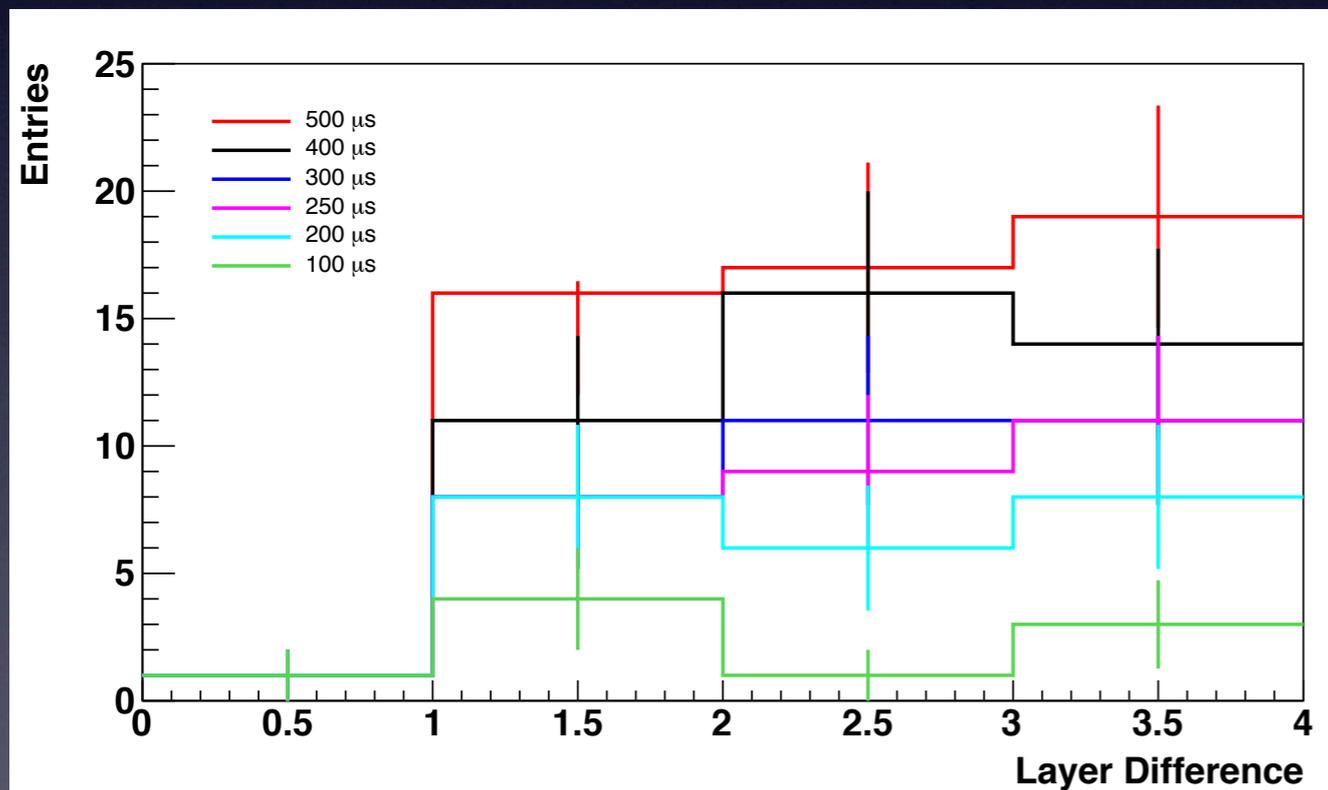
selection cut	coincidences
no cut	$2883919 \pm 1698$
delay n	$31751 \pm 178$
em - n	$30749 \pm 175$
em - n & no $\mu$	$18940 \pm 138$
em - n & no $\mu$ - 200us	$23 \pm 5$

# Time & Energy



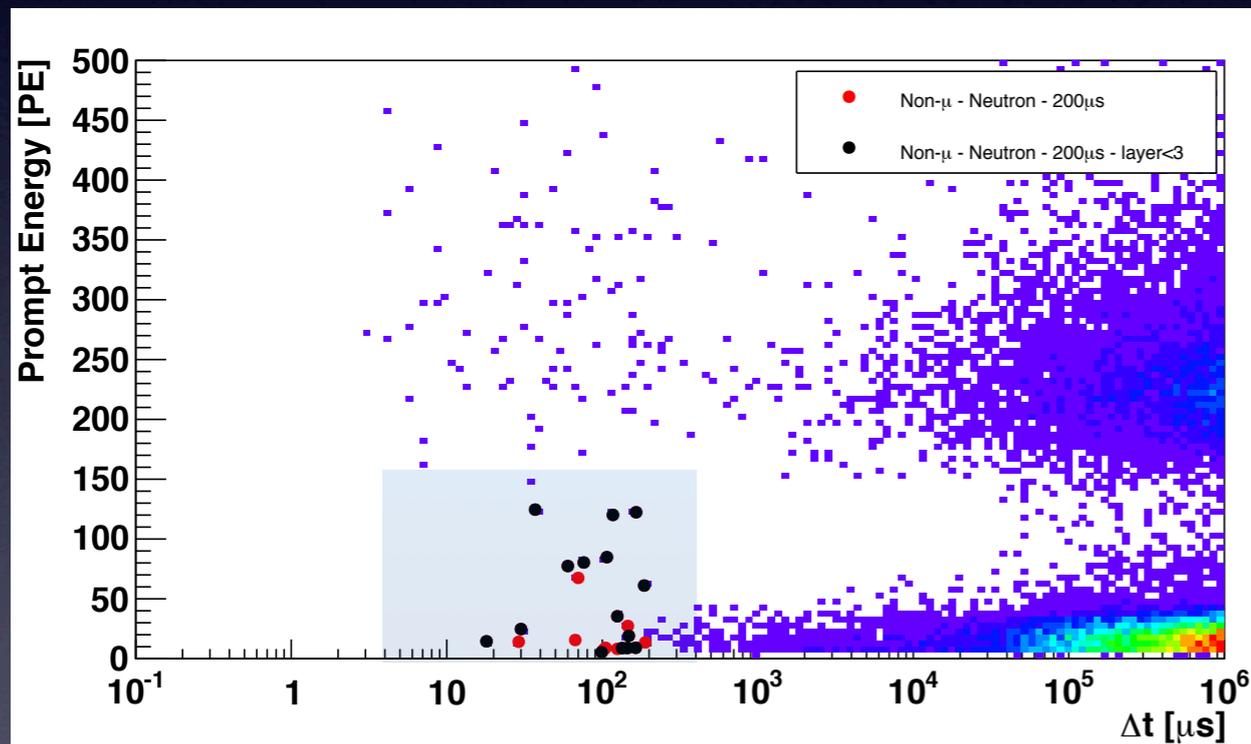
# Adding topological cut

- cut  $> 2$  layers
- evidence for reduction of accidentals

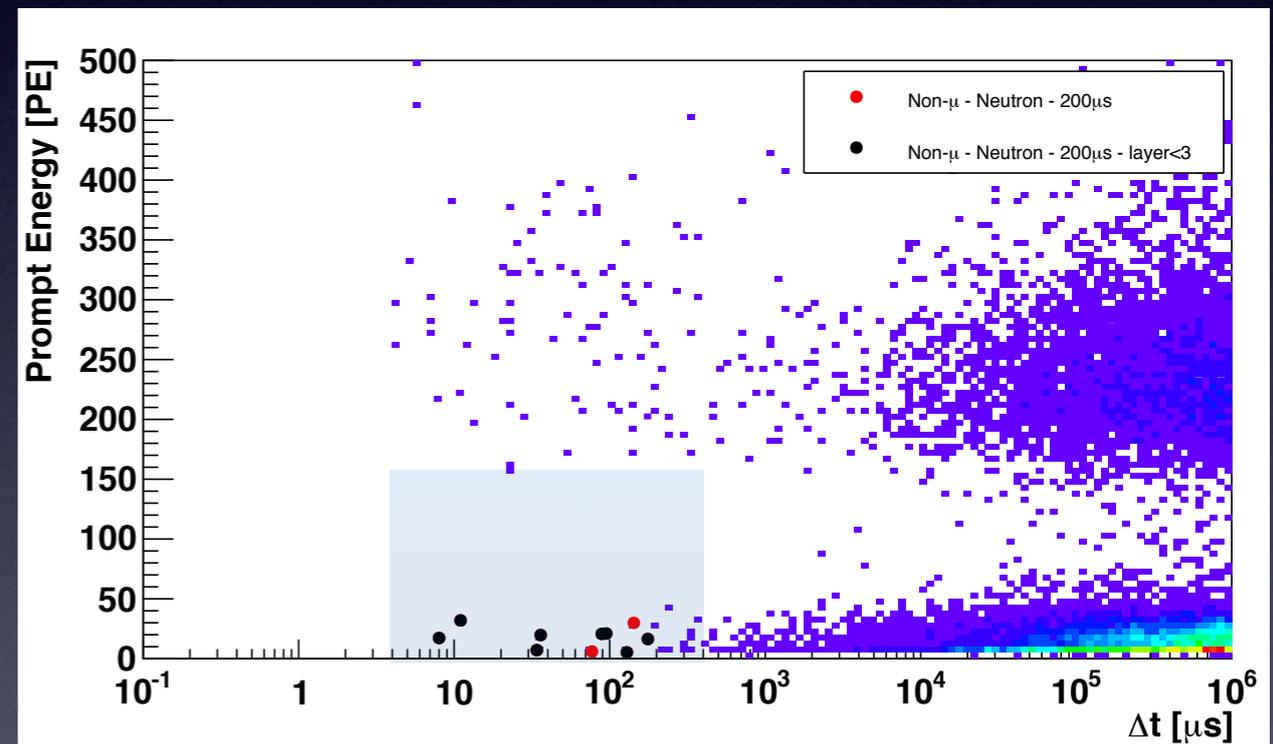


# Energy-Time correlations

*Reactor ON*



*Reactor OFF*



# Results

- Reactor ON :  $9.54 \pm 3.9$  candidates (BKG subtracted)
  - $5.46 \pm 0.87$  expected background
  - $2.44\sigma$  reactor ON signal excess ( SBR  $\sim 2.7$ )
- Low energy accidental background present (combination of muon and gamma-ray induced)
  - efficiently reduced using spatial topology
- Need more statistics to increase significance of result
- develop more sensitive analysis
  - waveform & likelihood analysis

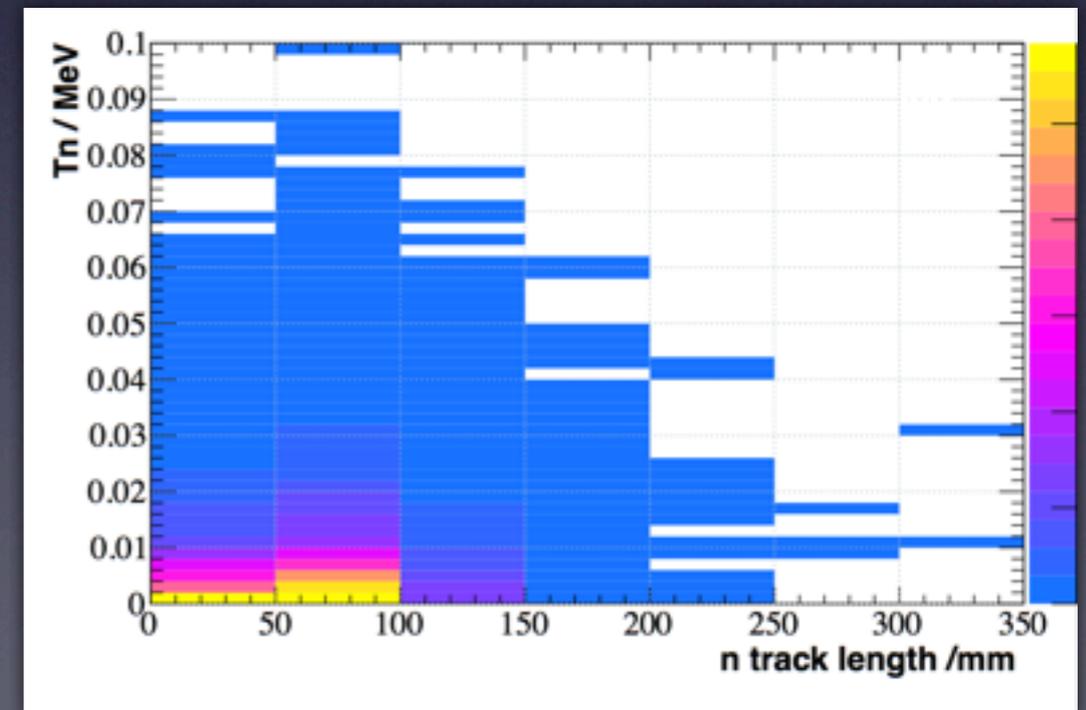
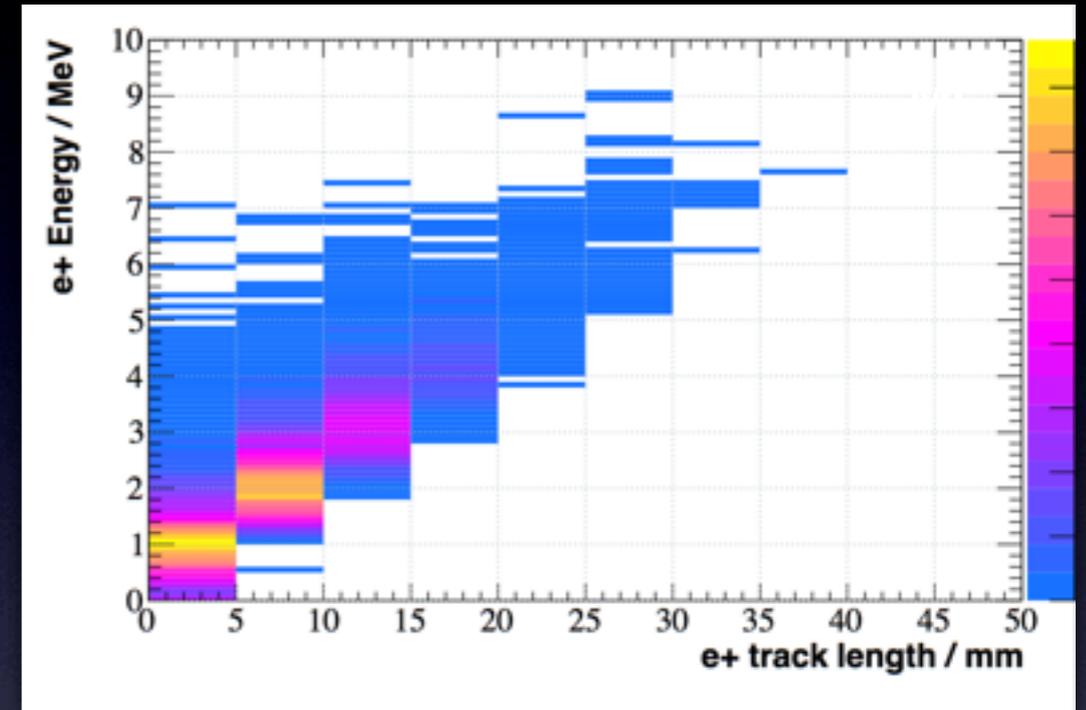
# Summary & outlook

- A finely segmented solid scintillator anti-neutrino detector was built and tested at the SCK•CEN BR2 reactor
  - Background rejection capability demonstrated with prototype detector
  - very promising results from first run
    - reactor ON signal excess at  $2.44\sigma$  with consistent IBD topology anti-neutrino features
    - Backgrounds appear to be low (SNR  $\sim 2.7$ )
- NEMENIX plan to run until end of 2014
  - upgrade DAQ and trigger scheme before end of year
  - add muon veto planes to reduce further muon background
  - calibrate precisely neutron efficiency
- Very promising development effort in the UK towards near field anti-neutrino detector

Back up

# Detector optimisation

- Trade-off between granularity and distance of neutron capture
- Positron track length is  $\sim 1$  cm
  - Good energy containment ( $> 90\%$ )
- Neutron captured well within 15cm radius



# Backgrounds

## Background rates

- Neutrons
  - Large system to measure atm neutrons
  - Reactor ON : small neutron counter :  $R_n < 10^{-5}$  Hz
- Reactor ON gamma-rays
  - HPGe detector w and w/o shielding



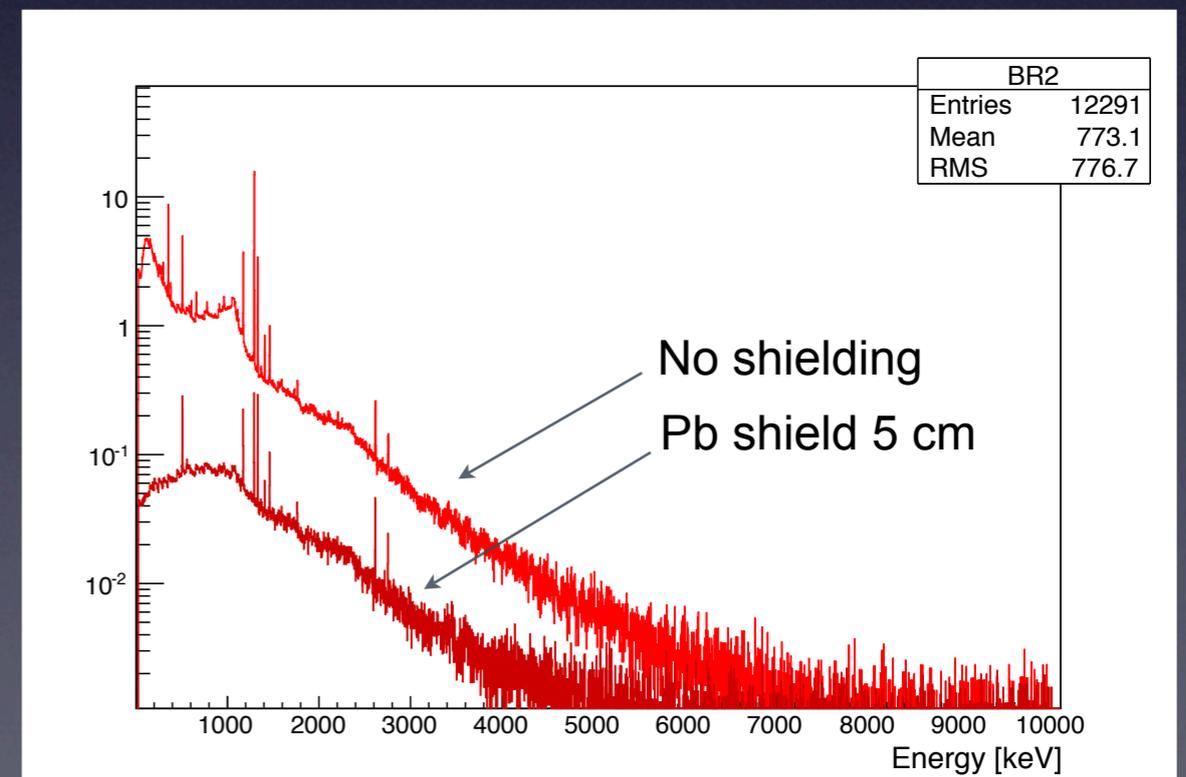
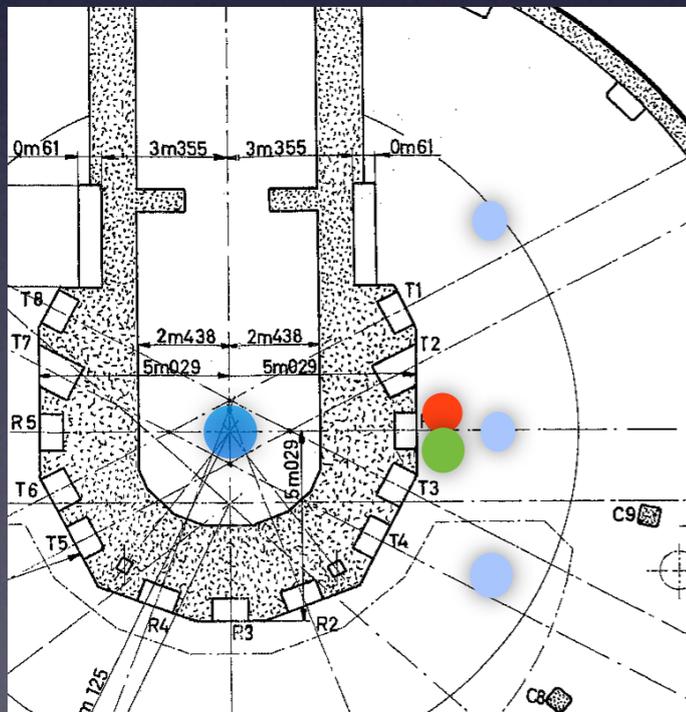
BR2 HPGe detector



BR2 portable neutron detector

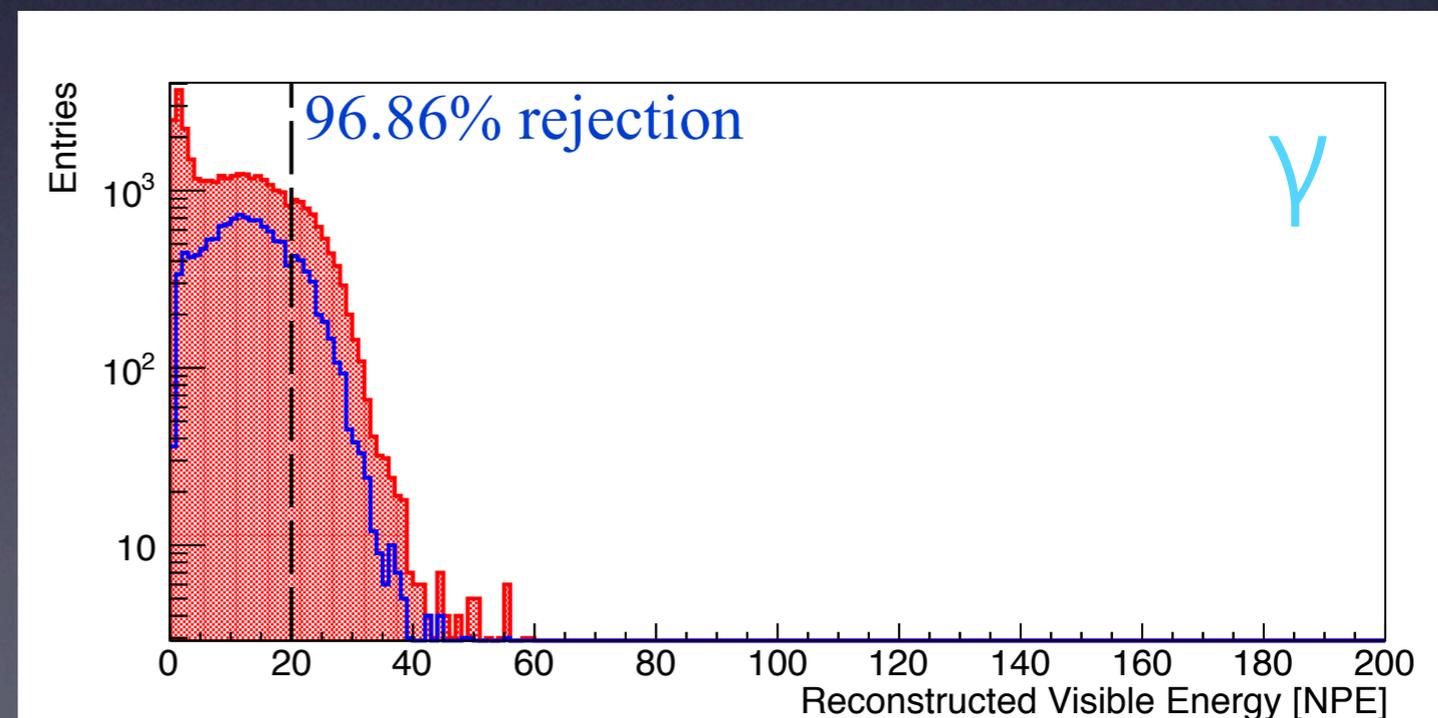
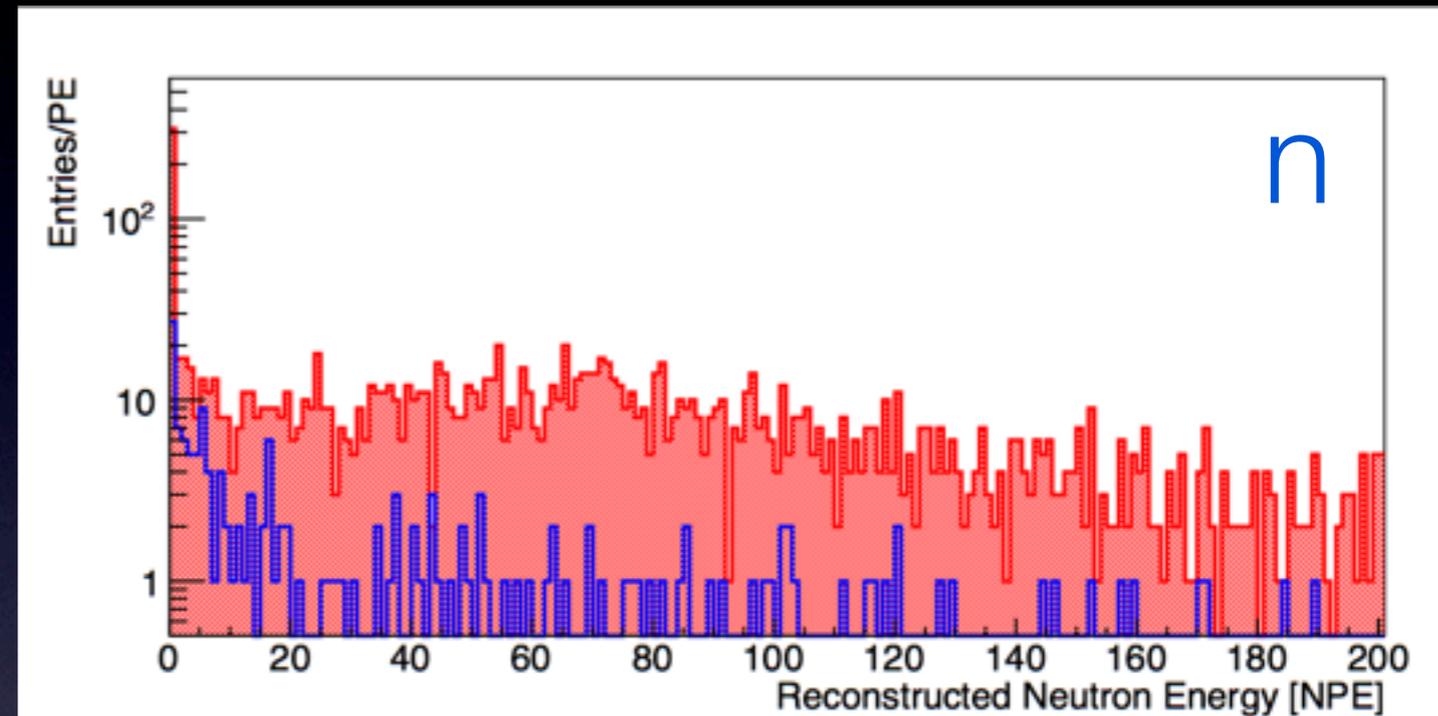


Oxford Large neutron detector

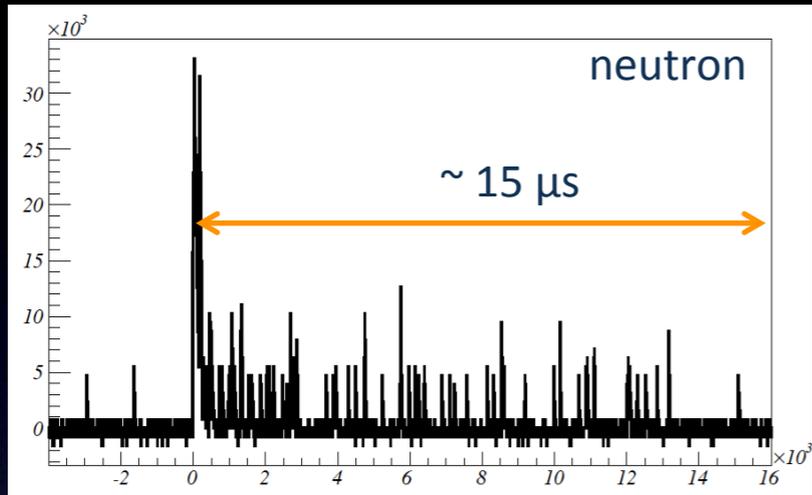


# Background rejection

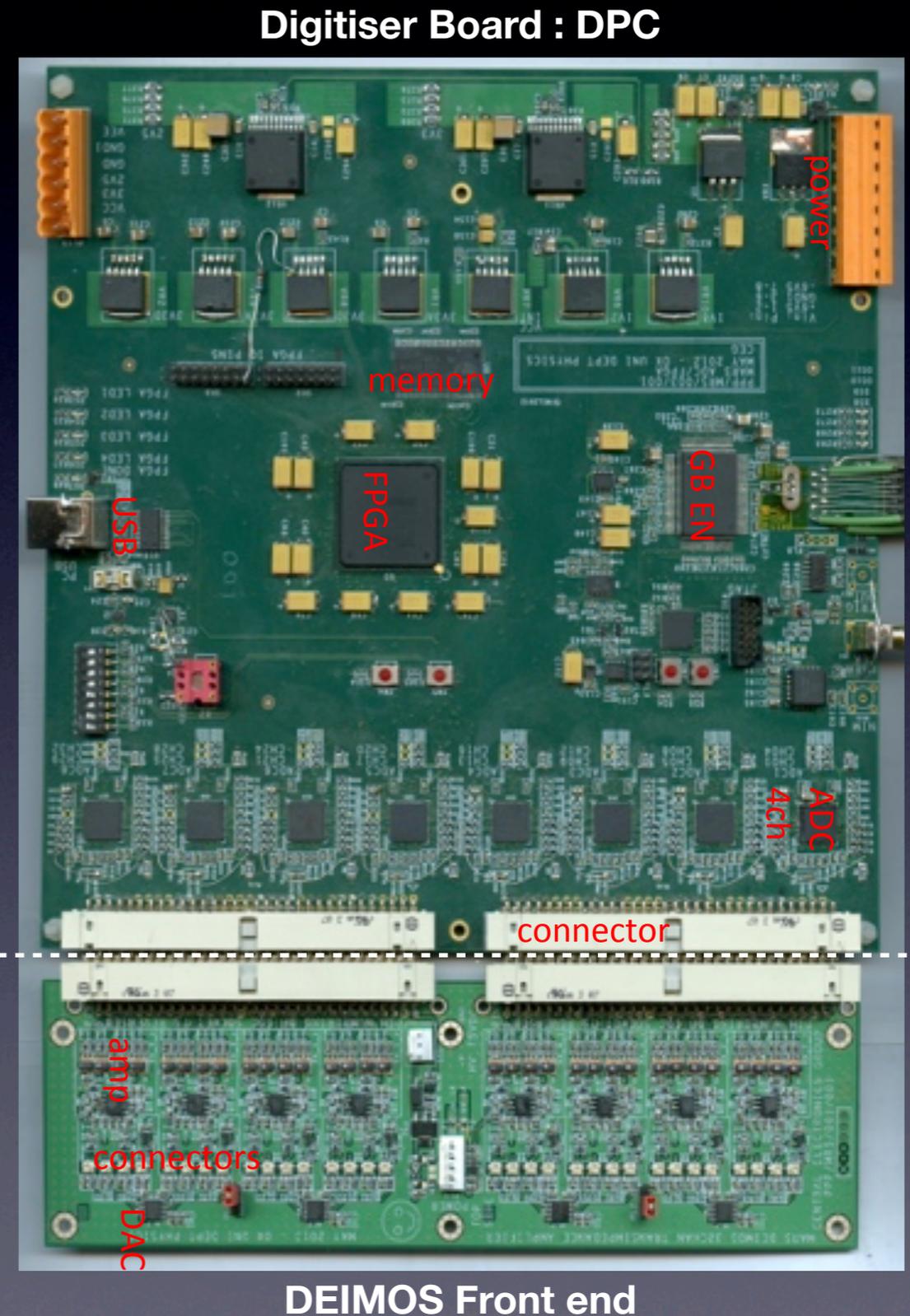
- Timing and spatial cut efficient at reducing accidentals
- Multiplicity (Compton scatter) cut
- **unprecedented background rejection capability !**



# SoLid electronics



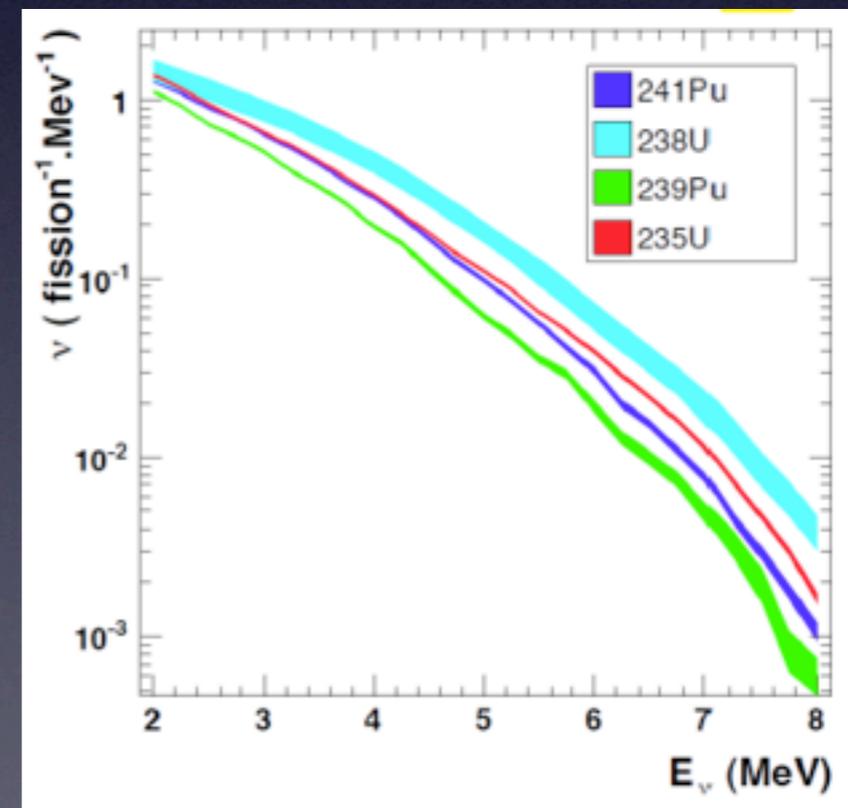
- Developed in Oxford
- Front-end cards : **DEIMOS 32chan amplifier card**
  - first board produced and under tests
- Back-end card : **DPC 32chan Digital Processing card**
  - fast digitisation : 80MS/s 12bit cADC
    - 200-400 us memory buffer
  - dead-timeless
  - on board digital processing : pedestal suppression, readout threshold, PSD etc..
  - use neutron signal features to trigger on IBD event
  - version 0 of card used to develop basic functionalities



# Reactors anti-neutrinos

- produced in beta decay of neutron riched fission nuclei
- small amount of total energy
  - by-product of fission
- main isotopes (U, Pu) spectra have different shape
  - contribution of U only in HEU fuel used at Research reactors
  - main four isotope in LEU power reactors
- Intense flux :  $\phi \sim 10^{12}/\text{MW/s}$

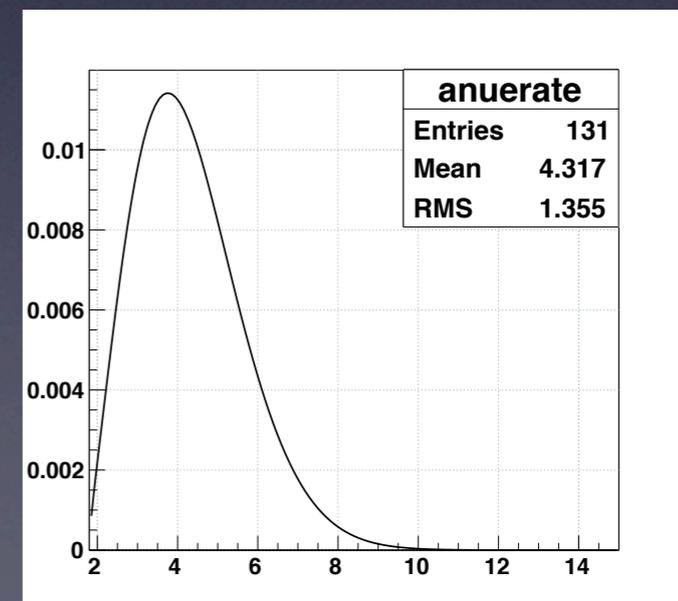
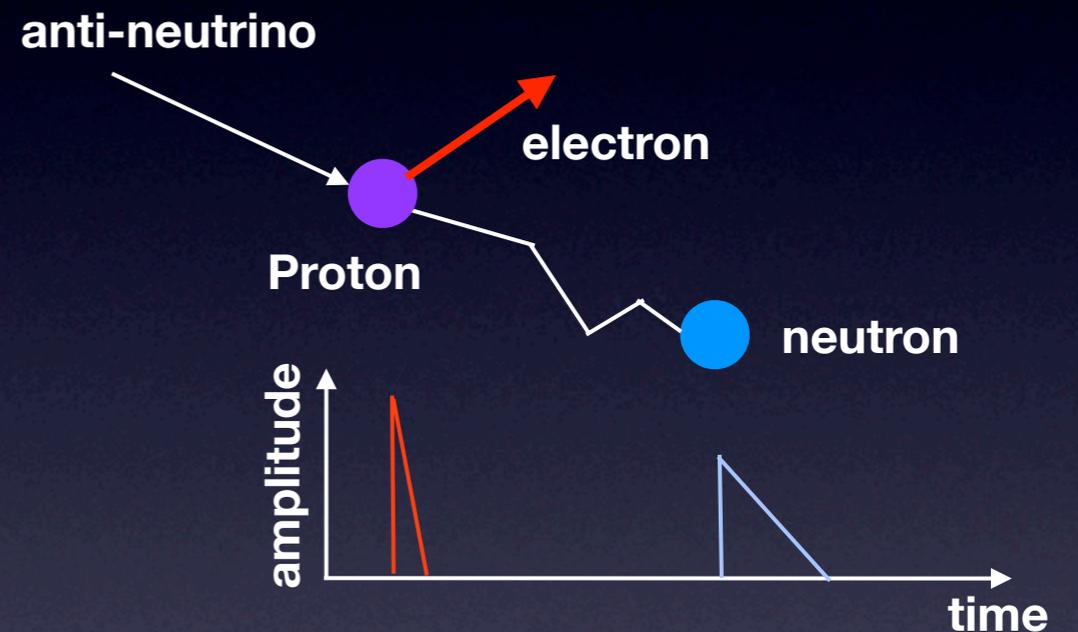
	<sup>235</sup> U	<sup>239</sup> Pu
$E_{\text{fission}}$ [MeV]	201.9	210.0
$\langle E_{\nu} \rangle$ [MeV]	1.46	1.32
$N_{\nu}$	5.58	5.09
( $E_{\nu} > 1.8$ MeV)	1.92	1.45



# Detecting anti-neutrinos



- Anti-neutrinos are detected via the Inverse Beta Decay IBD reaction
- look for time coincidence  $e^+ - n$ 
  - $\Delta t \sim 100\mu\text{s}$
- Small cross section compensated by  $N_{\text{Avogadro}}$  : liquid or solid target
- Sensitive to  $\sim 25\%$  of total flux
- Mean energy  $\sim 4 \text{ MeV}$
- 0.3 Hz at 30m from 3GWt reactor
- equivalent to detecting and monitoring a  $\sim 3 \text{ nCi}$  source !



# Detection challenges

- Signal ( $[10^{-5} - 0.1]$ Hz)
- Large natural background at the surface
  - cosmic rays ( $\sim 100$  Hz)
- Reactor backgrounds
  - gamma-rays  $[1-1k]$ Hz
  - neutrons  $[0.1-10]$ Hz
- Orders of magnitude higher background
  - overburden
  - large fiducial mass



- Correlated background
  - fast neutron (atm, muons)
  - beta-n reactions



- Uncorrelated background

