Reactor Anti-neutrinos

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Applied Antineutrino Physics 2016

1st - 2nd December

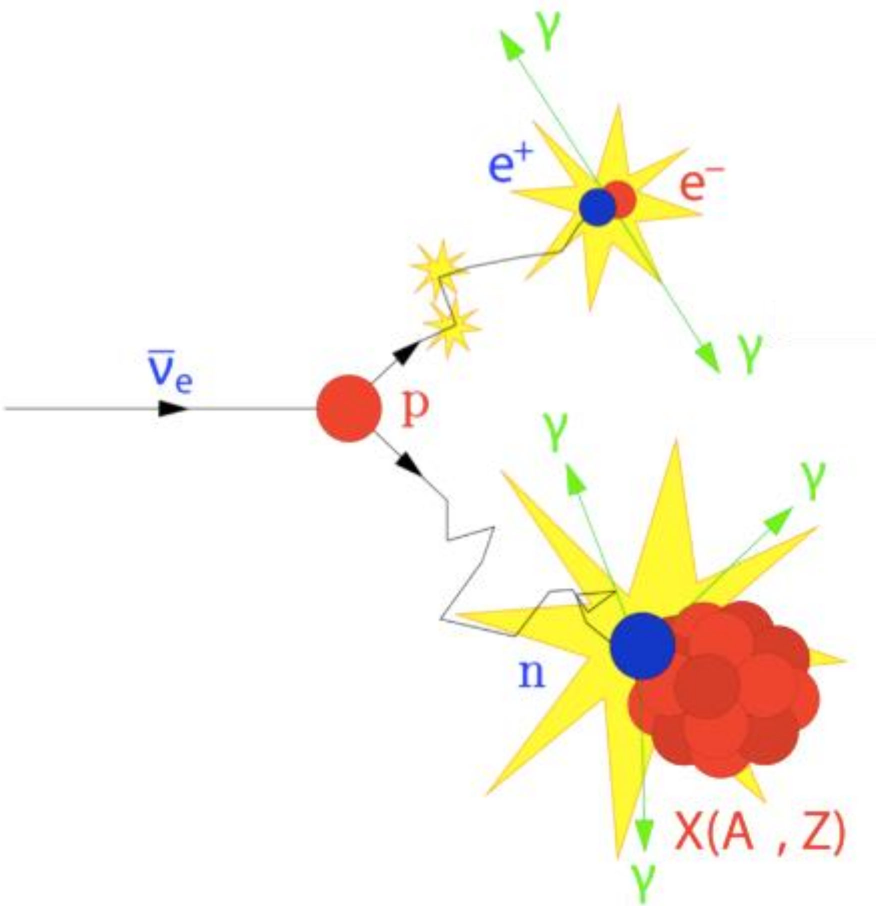
UNIVERSITY OF LIVERPOOL

- Most results presented are from last weeks workshop in Liverpool
- “Precise predictions of the antineutrino spectra emitted by nuclear reactors is a key ingredient in measurements of reactor neutrino oscillations as well as of the recent applications to the surveillance of power plants in the context of non proliferation”

See http://hep.ph.liv.ac.uk/aap2016/

- Reactor Anti-neutrino Anomaly (RAA)
- The Reactor Shoulder at 5 MeV
- Sterile neutrinos from Reactors
- Experiments
- Applications

Anti-neutrino Interactions



Inverse β-decay:

$\nu_e + p \rightarrow n + e^+$

Distinct signal:

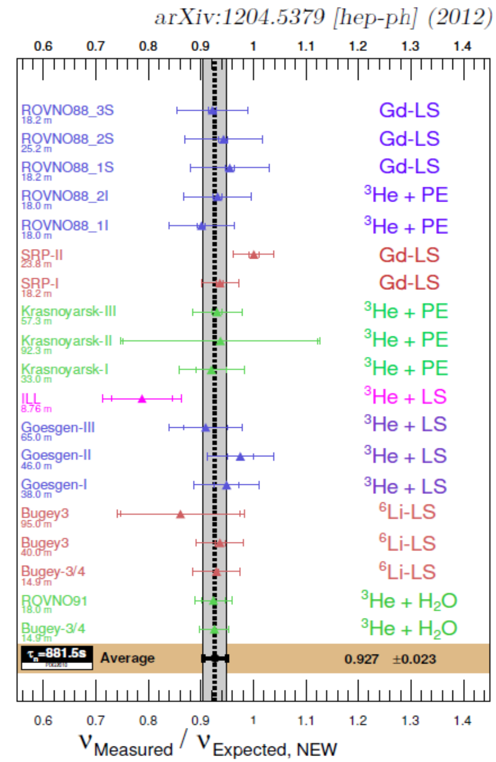
Prompt e^+ track

Delayed *n* capture releases γ-rays

- Efforts to use n_e scattering are also being addressed

Reactor Antineutrino Anomaly

- Rate recalculation leads to discrepancy between the detected and predicted number of antineutrinos coming from reactors
- Reactor Antineutrino Anomaly:
    - 6% flux deficit between
    - SBL reactor experiments
    - and new predictions (2011)
- Sugests a fourth, sterile-type neutrino may exist?
- Or perhaps nuclear effects?

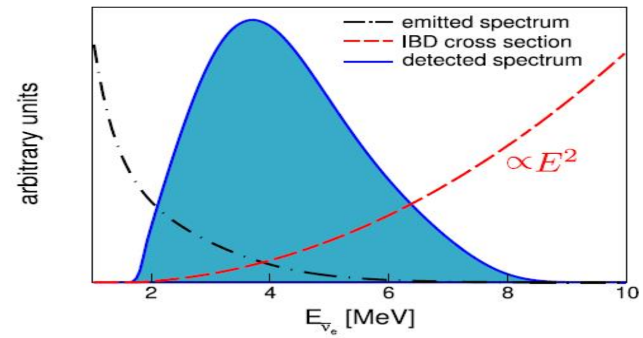


Slide from Julia Haser (MPI)

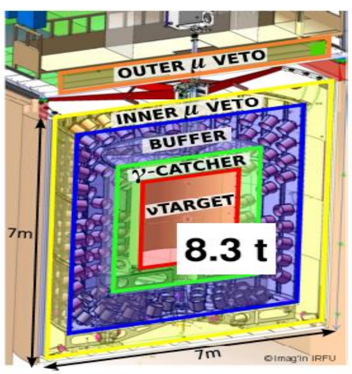
θ_{13} high Precision reactor Experiments

current high precision reactor experiments:

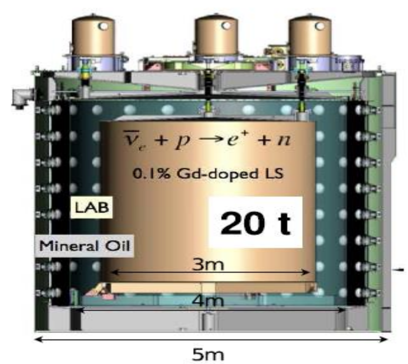
- inverse beta decay reaction
- organic liquid scintillator
- loaded with 1 g/L Gd
- measurement of θ_{13} using $\bar{\nu}_e$ rate and spectral shape



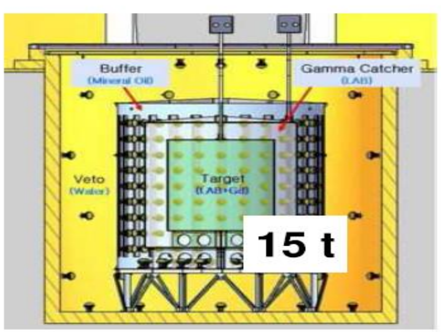
Double Chooz



Daya Bay



RENO



The Reactor Shoulder

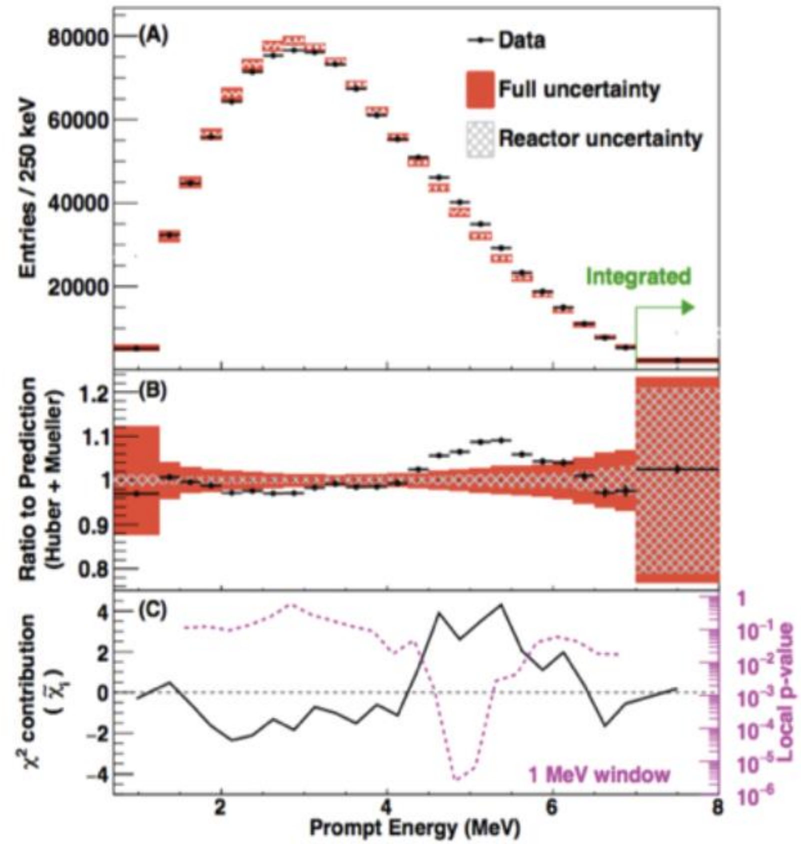
- All three Reactor Experiments, Daya-Bay, Double-Chooz and RENO are far enough away that sterile neutrino oscillations are averaged out
  - Hence no confusion between New Physics and Nuclear effects
- Statistics are approaching millions of events

Daya Bay

Measurements of neutron capture time, vertex distributions,delayed energy spectrum of events around 5 MeV region are consistent with the rest of IBD events

Theoretical predictions do not account for the excess of the 4-6 MeV excess in the prompt energy spectrum with a local significance of 4.4 sigma

Huber/Mueller prediction can not described the entire prompt energy spectrum at 2.9 sigma



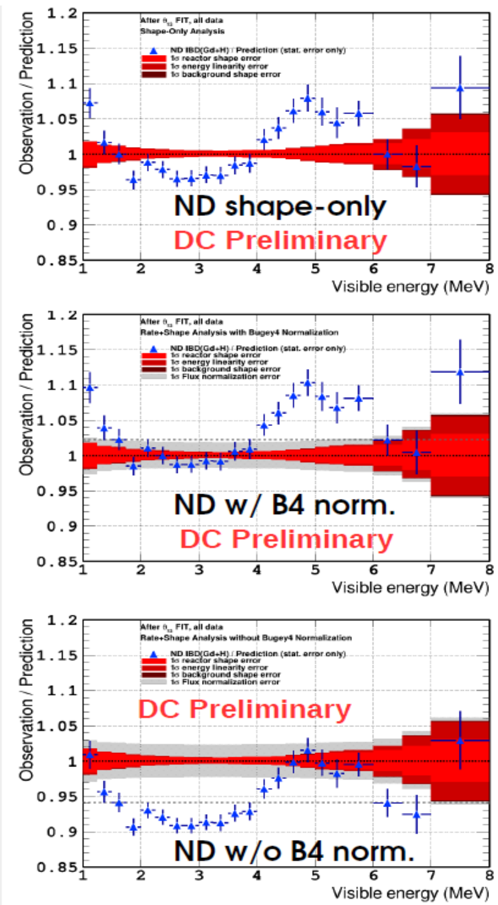
Double Chooz

- **Shape-only**:
  → Data and MC spectra **normalized to 1**
- **By definition**, in absolute over the energy range:
  → Integral(DATA) = Integral(MC)
  → Integral("Excess") = Integral("Deficit") !
  → values of the ratio depend of the statistics in the bin
- **But**:
  → What happens if I use a normalization?
  → **What is the real problem? Deficit? Excess? Both?**
  → "**Excess**" and " **Deficit**" notions are **driven by normalization**
  → In shape-only analysis, **only distortions remain !**

- **Conclusion**:

→ **In Shape only, some characterizations of the distortions can be done:** scaling with reactor power, fission fraction dependence, …

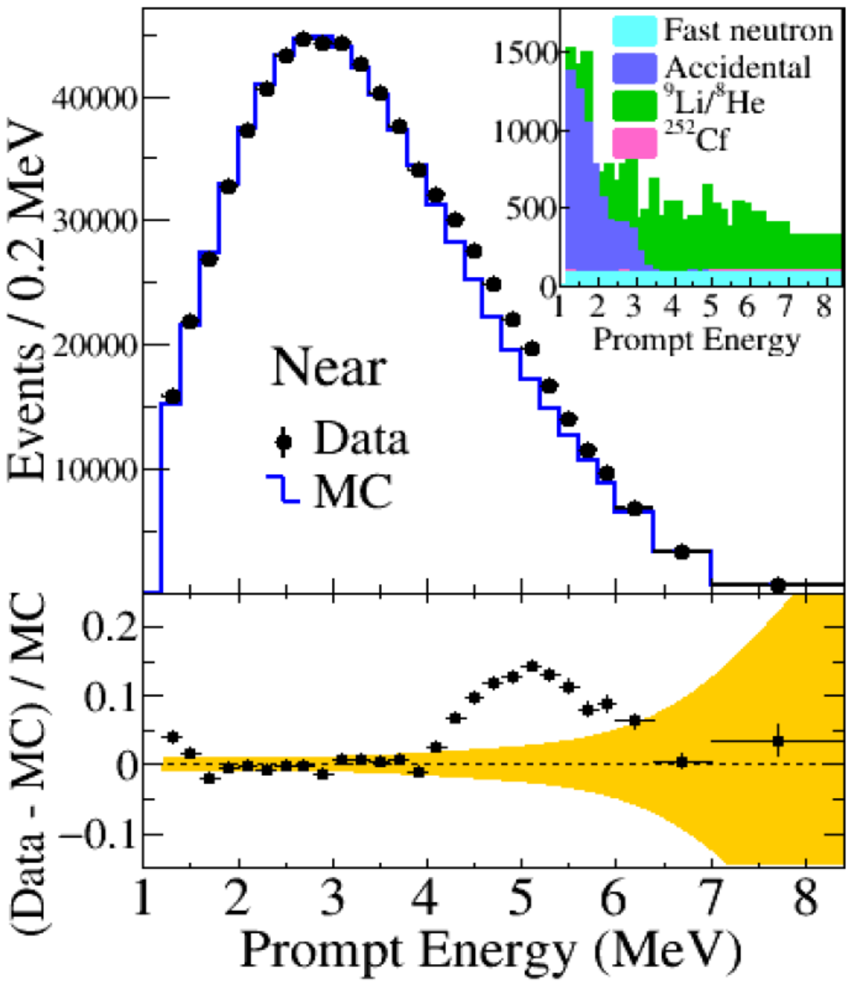
→ **But normalization + shape is a must** for physics interpretation, and the uncertainties associated to the normalization has to be taken into account.



RENO

1400 days of data (Aug. 2011 – Sep 2015)

(Preliminary)



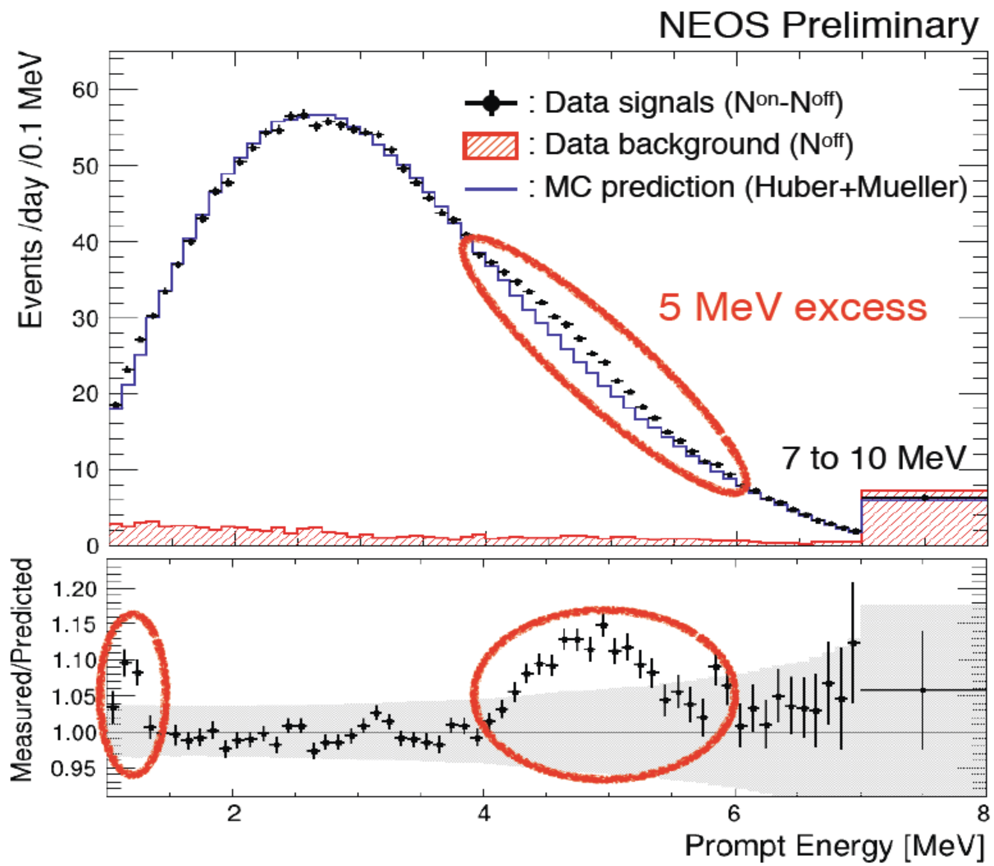
The measured near spectrum is compared with prediction using χ^2-square test.

Fraction of 5 MeV excess:
2.50 ± 0.21 (%)

Significance of the 5 MeV excess: **~12.7 σ**

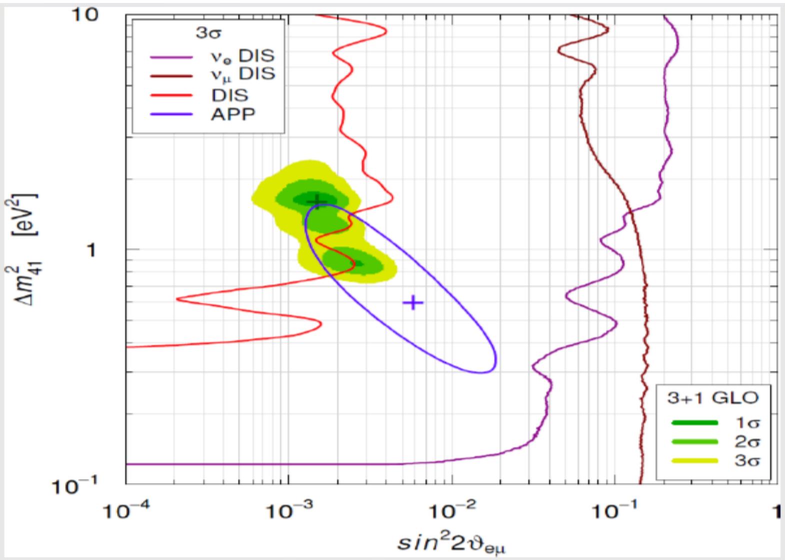
NEOS

- Measured spectrum
  - Reactor-on period:
    - signal + background
  - Reactor-off period:
    - background only
  - **Signal to background ratio ~23**
- Comparison with Huber and Mueller's flux model
  - **5 MeV excess is clear**
  - Disagreement around 1 MeV



Sterile's

- **Global and Pragmatic 3+1 fits**
  - **Not yet included ICECUBE and MINOS**

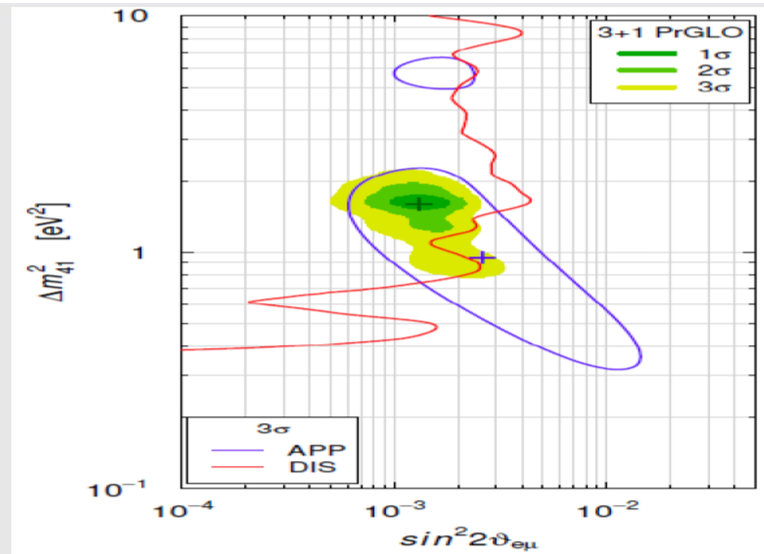


Best Fit: $\Delta m^2_{41} = 1.6\,\mathrm{eV}^2$

$|U_{e4}|^2 = 0.028 \qquad |U_{\mu 4}|^2 = 0.014$

GoF $= 6\%$ ($\chi^2_{\mathrm{min}}/\mathrm{NDF} = 304.0/268$)

$\mathrm{GoF_{PG}} = 0.06\%$ ($\chi^2/\mathrm{NDF} = 15.0/2$)



GoF $= 24\%$ PGoF $= 7\%$

No Osc. disfavored at $\approx 6.2\sigma$

$\Delta\chi^2/\mathrm{NDF} = 46.6/3$

➢ **With (left) and without (right) MiniBooNE low energy bins (<475 MeV)**

What's Next

- Resolving the existence of the anomalies determining whether new-physics exists.
- Any improvements in understanding the quantity and nature of antineutrinos emitted from nuclear reactors will help in non-proliferation monitoring of those reactors.

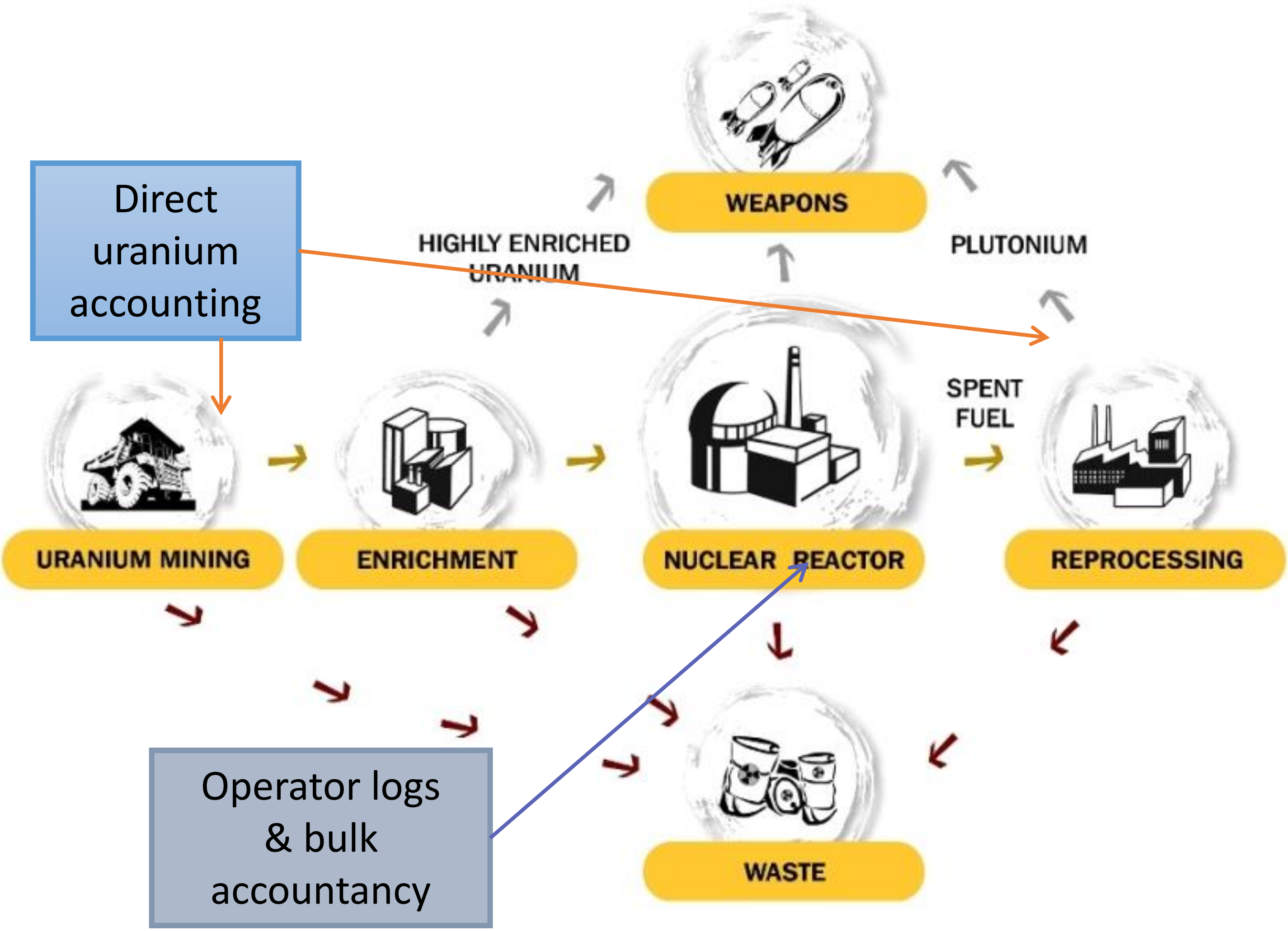
Need for spectral measurements

- Directly test the hypothesis of a new oscillation with Δm2 ~ 1 eV2,
  - i.e. oscillation length of few meters
- Provide new tests of reactor models by making precision measurements of 235U fuel

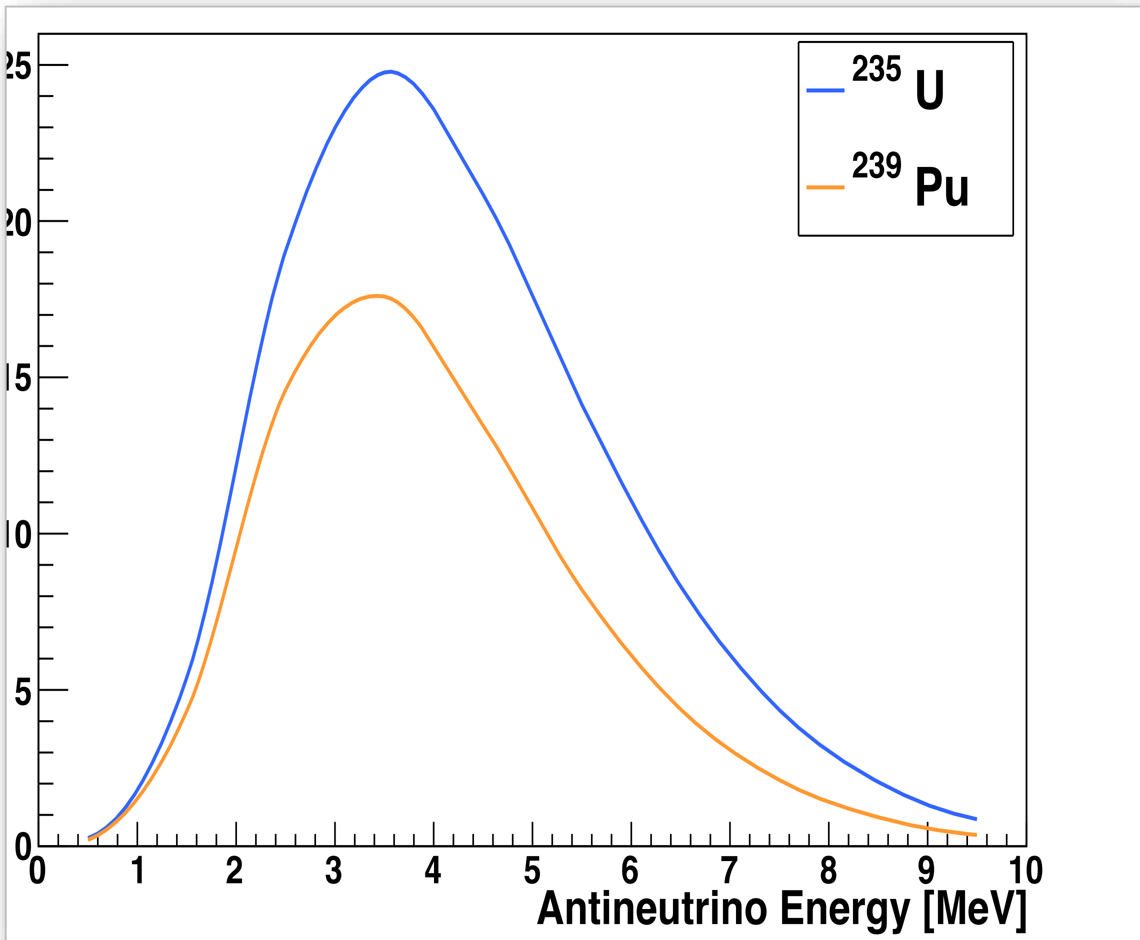
Applications

- Used to better determine the interior of a reactor from a stand-off distance
  - Decoupled from Power plant operation
- Work is underway to demonstrate deployable detectors with spectral capability
  - Rate and Spectral Anomalies add more information

Fissile material Accountancy



Energy Spectrum differences in fuel

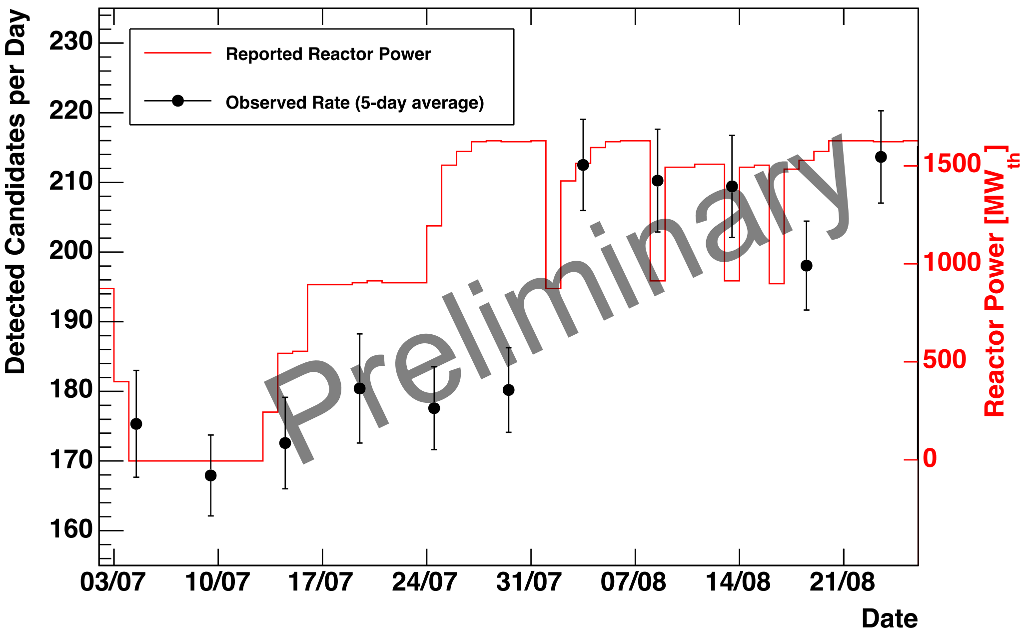


Vidarr: an example

- Modified design from T2K-Ecal Module
  - Demonstrate design and fit-for-purpose


Vidarr Deployment

- Least favourable conditions
  - At least 60m from a reactor core
  - No overburden
- Working on:
  - upgrades to hardware
  - spectral measurement
  - Complete Isotope model of reactor core



Robert Mills (NNL), et al.

Vidarr: Reactor Model

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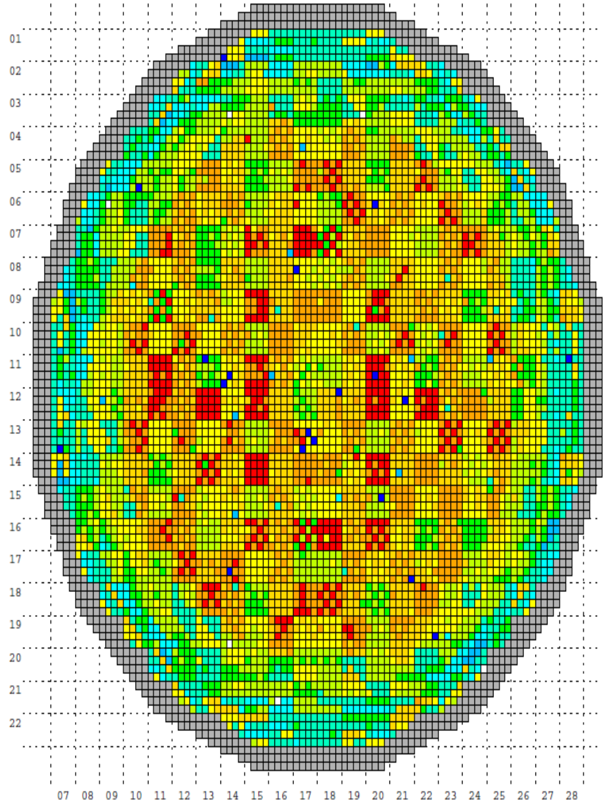
Irradiation GWd/t



Wylfa reactor 1

- 6156 fuel channels containing up to 8 elements.
- 0.711 or 0.8% 235U enriched fuel.
- Online refuelling.
- Complete power history (per day)
- PANTHER models for power at monthly intervals

Robert Mills (NNL), et al.

Anti-neutrino calculation

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- Work done so far used FISPIN to generate inventories for all 49248 rods in core during each day of irradiation with irradiation/cooling history.
- Then used bespoke code to generate anti-neutrino spectra for each rod during each day.

Future work:

- Use these data to generate an anti-neutrino flux over detector (magnitude and angular distribution Φ and Θ)- codes developed and tested but yet to be applied.
- Support University of Liverpool in modelling detector using GEANT4.

A whole series of experiments aimed at reactor monitoring and spectral measurements

- NEOS
- NuLat
- Nucifer
- PANDA
- VIDARR
- WATCHMAN
- Solid
- Chandler
- PROSPECT
- miniTimeCube
- Stereo
- Efforts also at
  - BARC, India
  - Akkyu, Turkey

See http://hep.ph.liv.ac.uk/aap2016/ for more info

Summary

- RAA is being addressed by improved experiments
- Parameter space for Sterile neutrinos is reduced
- Reactor Shoulder at 5 MeV
  - Measured in multiple high-resolution experiments
  - Not understood
- New generation of compact detectors
  - Precision spectral measurements
  - Deployable

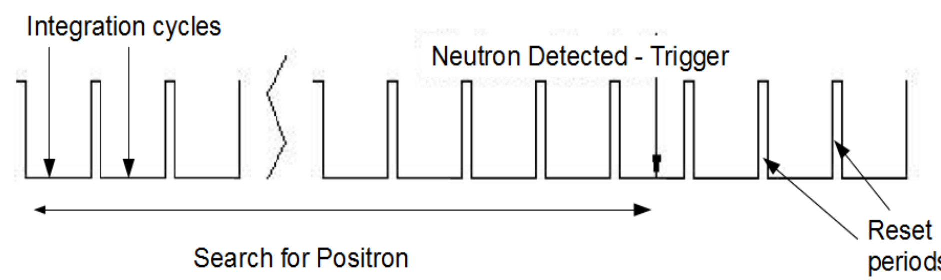
Thanks and Acknowlegements

- Robert Mills, David Mountford, Matt Ryan - NNL
- George Holt, Carl Metelko, Matt Warburton, Yan-Jie Schnellbach – U. of Liverpool

BACK-UP

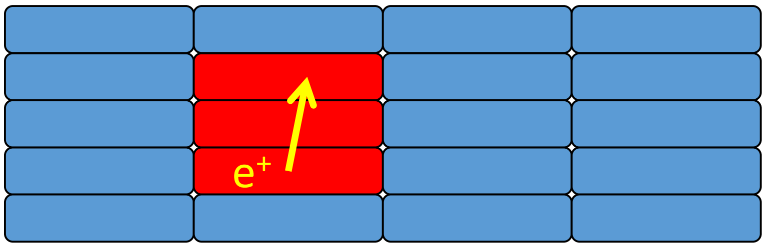
Liverpool Detector: Adapting T2K Tech

- Pb ➔ Gd sheets for neutron capture
  - High cross-section
  - 8 MeV γ-rays cascade
- Pulsed operation ➔ triggered operation
- Cosmic ray veto
- Adapted housing, cooling and shielding



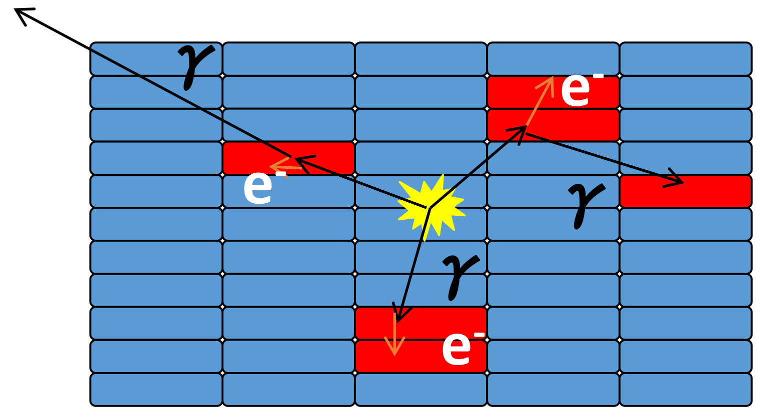
Liverpool Detector: Particle Signature

Positron



- Contained track
- Concurrent in time
- dE/dx ≈ 1.8 MeV/cm
- E_{max} ≈ 8 MeV
- Immediately after inverse β-decay

Neutron



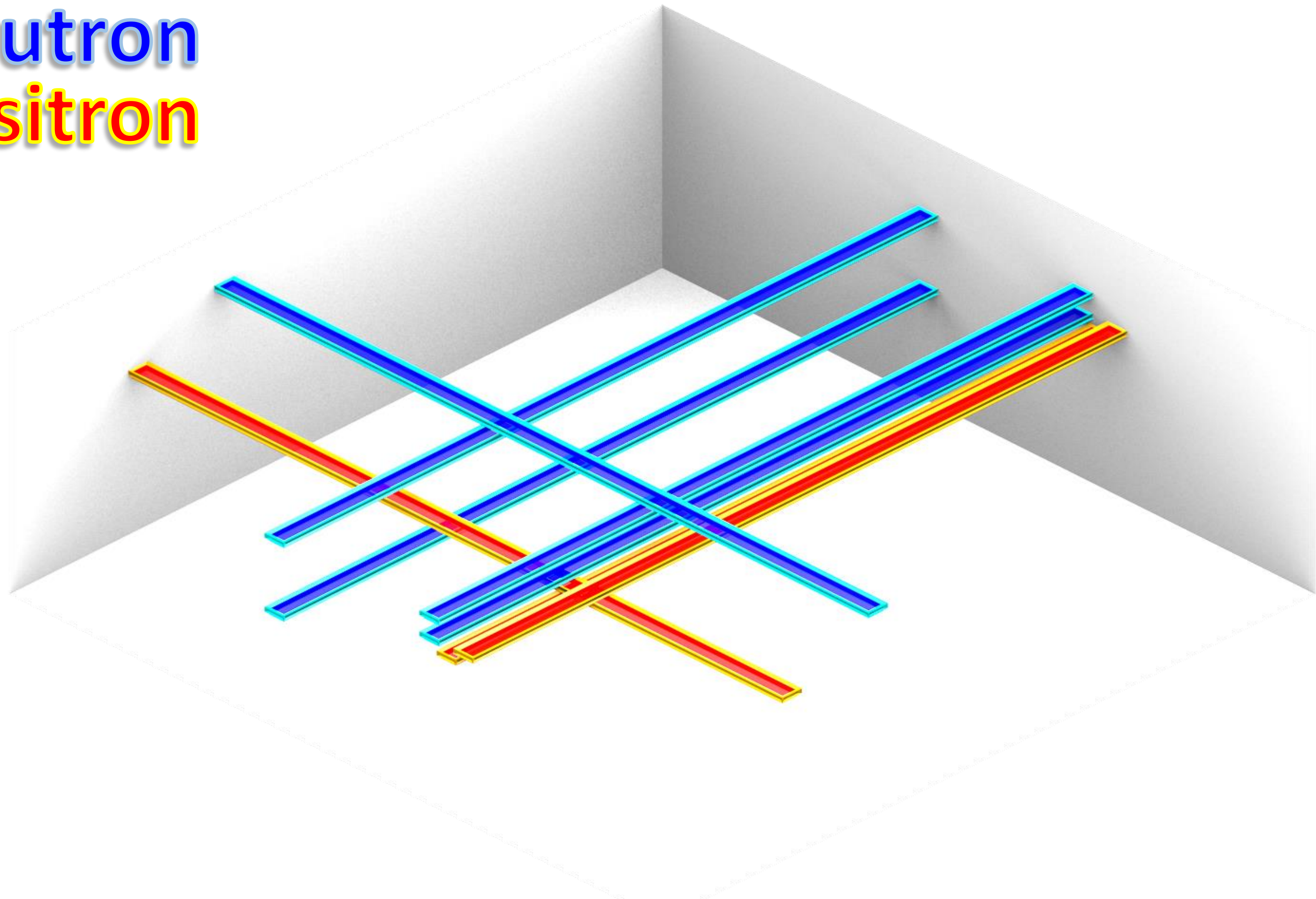
- 8 MeV γ cascade upon capture
- Multiple Compton scatters
- Spatially diffuse hits coincident in time
- Ca. 10 μs after positron

Distinct double co-incidence signal

Results: Candidate Event

Neutron

Positron



Outlook: Current Work

- Post-Wylfa Work:
  - Wylfa was shutdown permanently 31st Dec 15
  - Mobile lab & detector returned to Liverpool
  - Background studies underway

- Collaboration with National Nuclear Laboratory (NNL)
  - See presentation by Robert Mills tomorrow!

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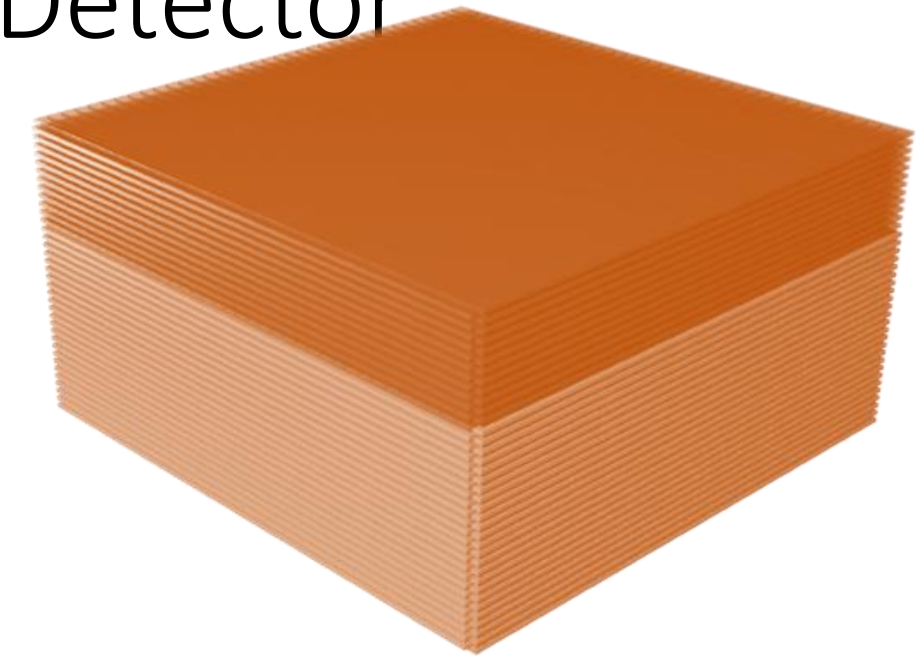
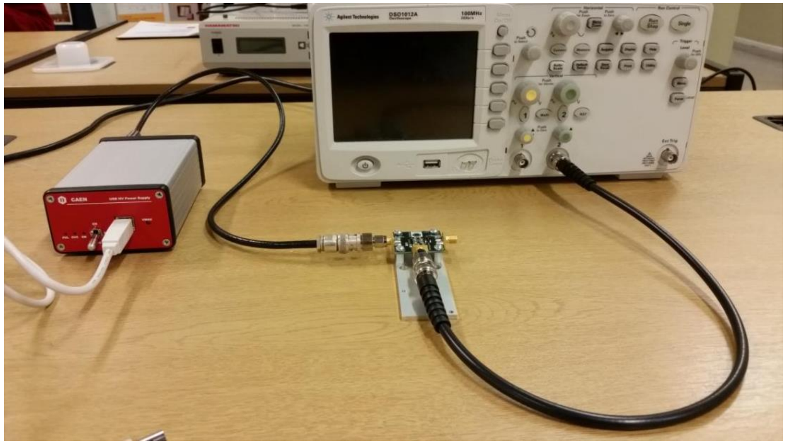
Outlook: VIDARR Detector Upgrade

- Extra mass upgrade:
  - 50% more target mass
  - c. 2000 ➔c. 3000 channels
  - Full replacement of WLS fibre

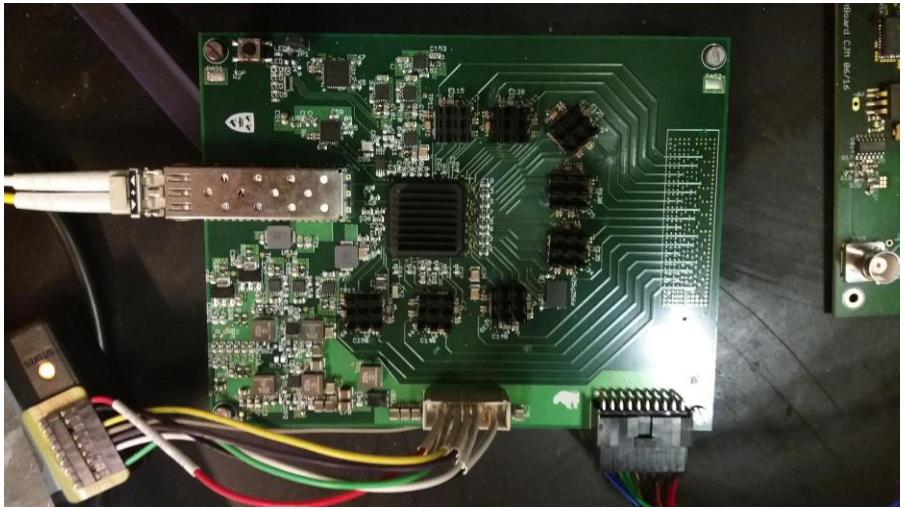


- MPPC upgrade:
  - Switch to latest-gen Hamamatsu MPPC
  - c. 10x larger gain
  - c. 10x less dark noise
  - c. 2x photo diode efficiency



Outlook: VIDARR Electronics Upgrade

- Electronics upgrade:
  - Match dynamic range to signals (0-10 MeV)
  - Low threshold (1 PE) and <10ns timing
  - Increase coincidence window to c. 100 µs



- Architecture:
  - 64-channel analogue board
  - 64-channel Fast ADC mezzanine board
  - ADC boards read out via optical link by backend board