The Gadolinium Phase of the Super-Kamiokande Neutrino Detector

or:

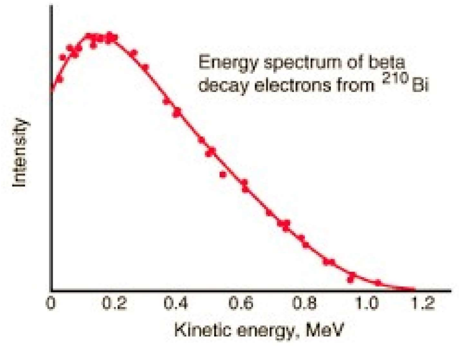
How I Learned To Stop Worrying And Love The Plumbing

Matthew Nicholson
University Of Warwick

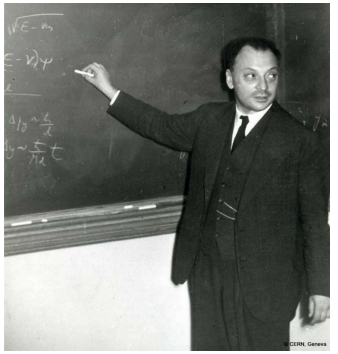
Summary

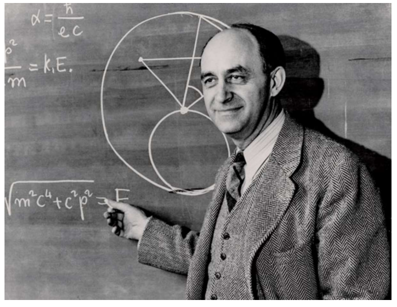
- Introduction to Neutrinos
- How to detect them
- The Super-Kamiokande detector
- Gadolinium phase of SK
- Gadolinium Absorbance Detector (GAD)
- Supernova Relic Neutrino (SRN) analysis

Introduction To Neutrinos



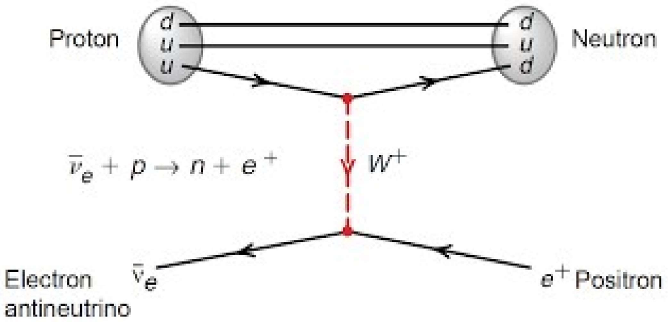
- Neutrinos were first proposed by Wolfgang Pauli to explain the continuous distribution of energies from the electron emitted in beta decay (1930)
- Beta decay was then formalised by Enrico Fermi into a four fermion point interaction (1933)
- Now find their place in the SM as 3 of 6 fundamental leptons, with electron, muon and tau flavours + antimatter counterparts
- Current outstanding questions of neutrinos include mass hierarchy and CP violation – can tell us about the matter-antimatter asymmetry of the universe





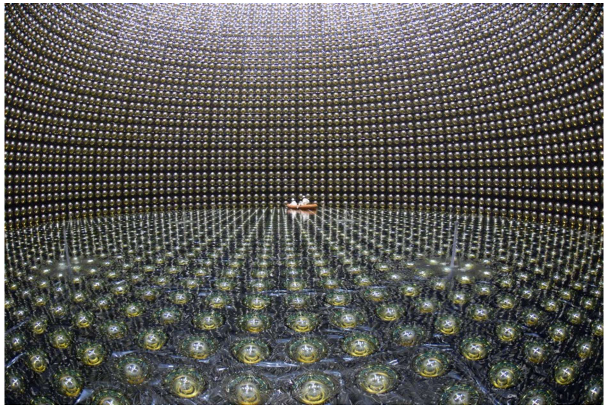
How To Detect Neutrinos

- Neutrinos were detected by Clyde Cowan and Frederick Reines with Project Poltergeist in 1956 by measuring *inverse beta decay*.
- Large tanks of water served as proton targets for the process, photomultiplier tubes detect the gamma signal from positron when it annihilates with a nearby electron.
- Doping water with Cadmium gives additional neutron capture signal – opens the door for Gadolinium.
- Where do you put the detector?

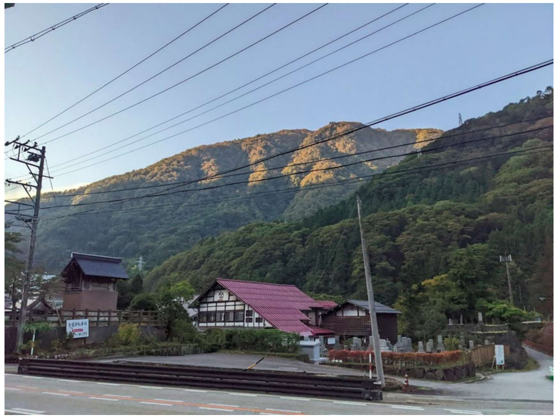


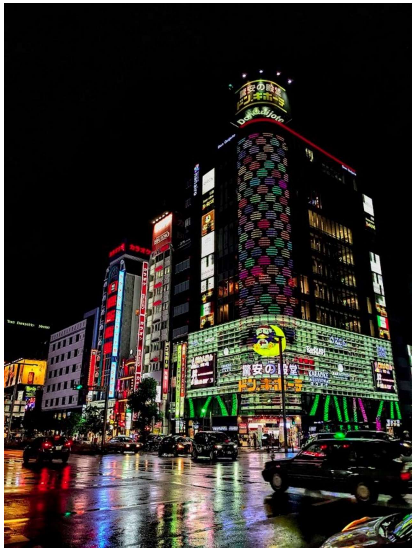
Super Kamiokande

- 21.5kton fiducial volume Water-Cherenkov detector located in Hida, Japan.
- 11,000+ Photomultiplier Tubes (PMTs) to capture light emitted from particle interactions.
- Successor to the "Kamioka Neutrino Detection Experiment"
- Physics goals: Proton Decay, Atmospheric + Solar Neutrinos, Supernova Early Warning System.
- The collaboration was awarded the 2015 Nobel Prize for experimental discovery of Neutrino Oscillation – implies neutrinos have non-zero mass.

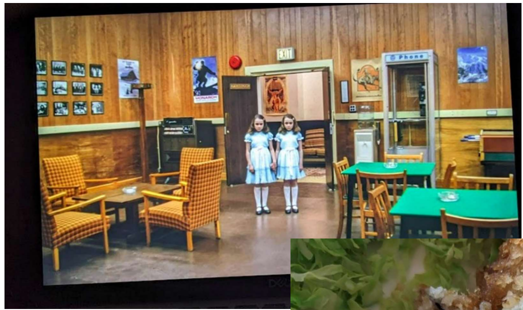


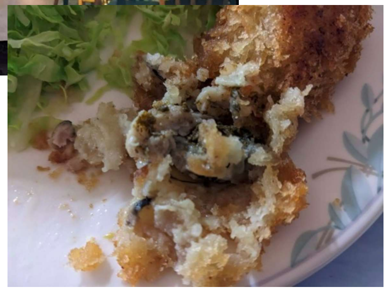
Some nice views from Japan…

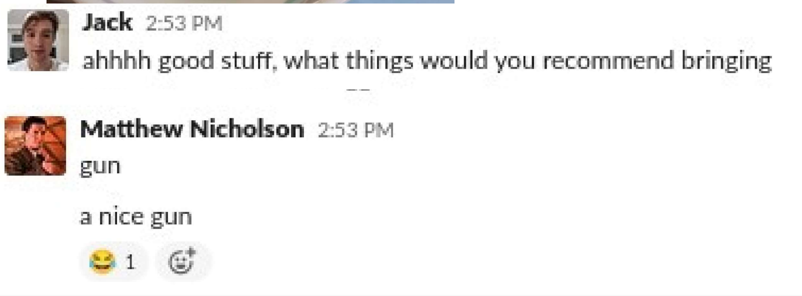


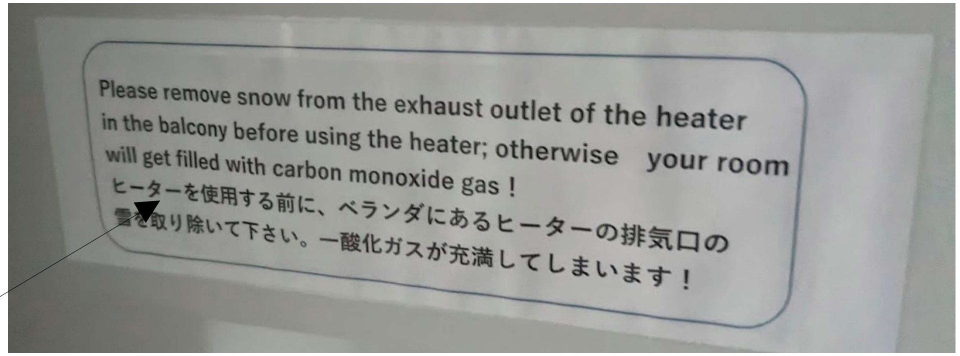


… and some not so nice views





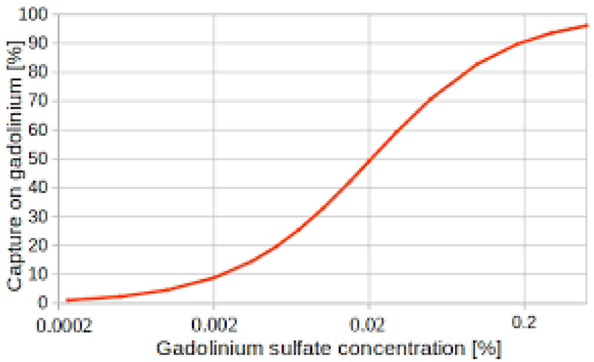


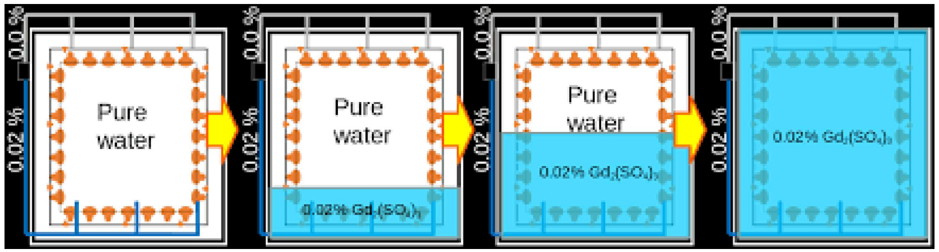


you say that like
it's a bad thing

Gadolinium Phase

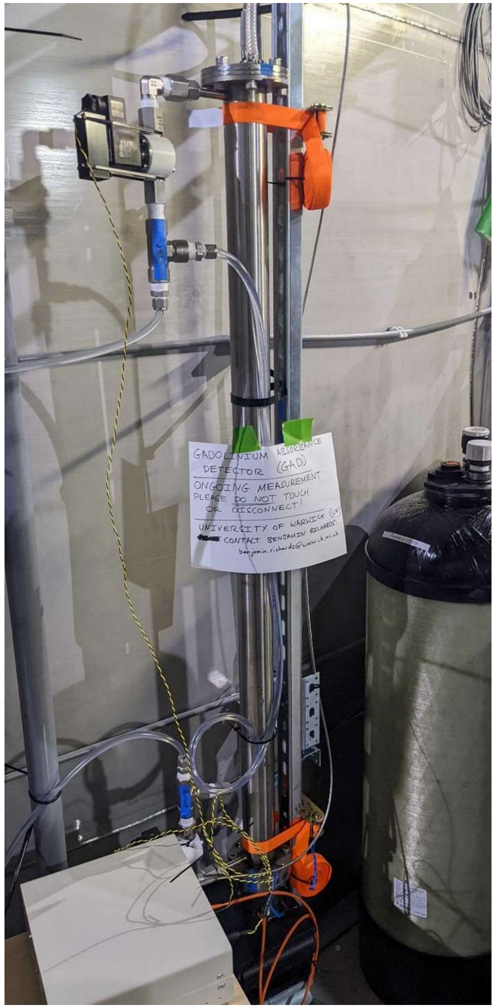
- Since 2020, SK been adding Gd2SO4 to its water. Gd is a rare earth element with a high affinity for neutron capture.
- SK's concentration of Gd2SO4 currently sits at 0.03%
- Motivation is similar to Poltergeist's Cd doped detector, delayed gamma burst from neutron capture can be detected by PMTs.
- SK has the largest order of Gd in human history.
- Great care has been taken to monitor transparency of the water + soak testing components





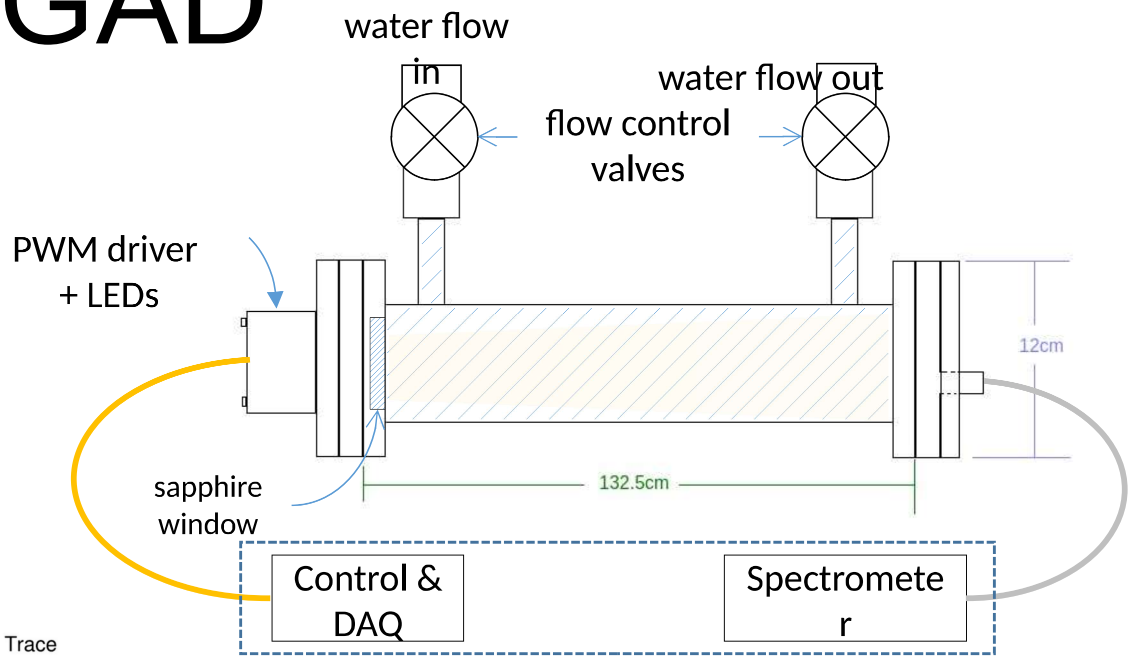
Gadolinium Absorbance Detector (GAD)

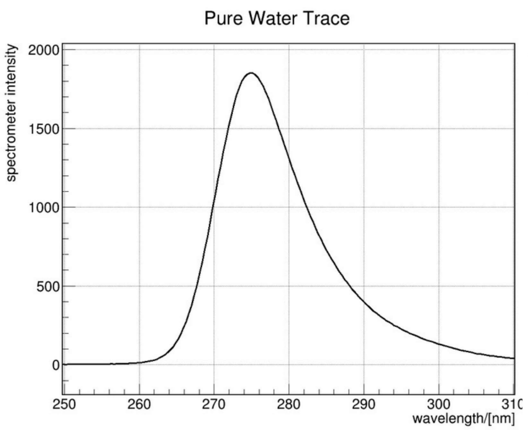
- In order to determine the rate of neutron capture precisely, and to ensure no Gd is being lost in filtration systems – measuring the concentration of Gd in the detector is crucial.
- Currently the concentration of Gd is determined by taking regular samples of water.
- The GAD is a device capable of measuring concentration of Gd with an accuracy of O(1%).
- GAD was installed in EGADS, the Super-K test-bed detector, in July 2022.

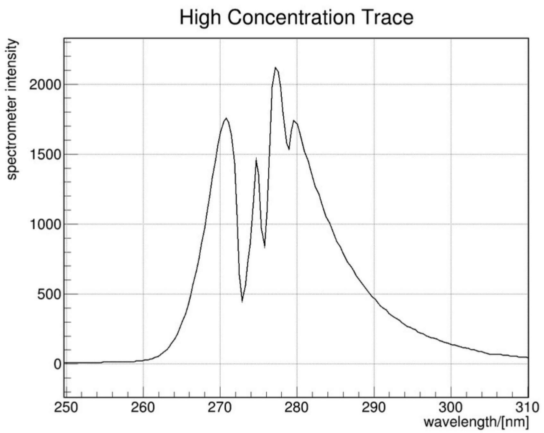


GAD

- GAD uses a UV source and spectrometer to measure characteristic Gd absorbance bands
- The body of the device is a 1.3 meter 316 stainless steel flow tube with removable endcaps
- At one end is a set of UV LEDs that illuminate Gd absorbace peaks at ~263nm – the other has a spectrometer for collecting and measuring light.

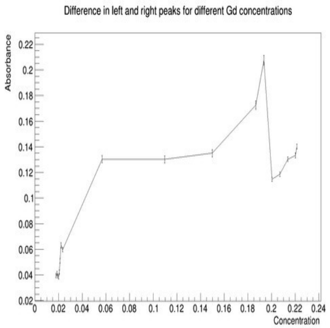


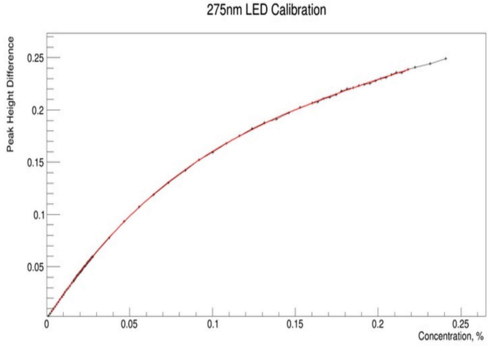


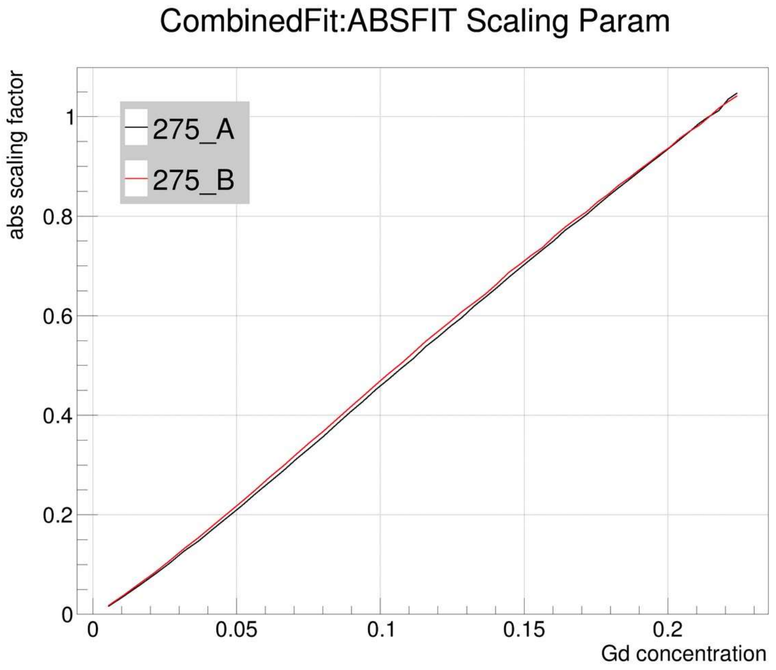


Calibrating GAD

- Calibrating GAD involves testing the device’s response to a range of different concentrations and building a calibration profile.
- We fill the GAD with a known quantity of pure water and then slowly raise it’s concentration by adding Gd solution – taking measurements along the way
- Doing this we extract from the measurements a “metric” that characterises the amount of absorbance in the sample and mapping it to its given concentration.
- Then, for an unknown sample of water we can invert the calibration profile and calculate the concentration from the metric.
- In practice, we have a lot plumbing considerations to make: rouge bubbles, leaks + varying LED intensities, spectrometer warm up times.
- Takes an awful long time!!!

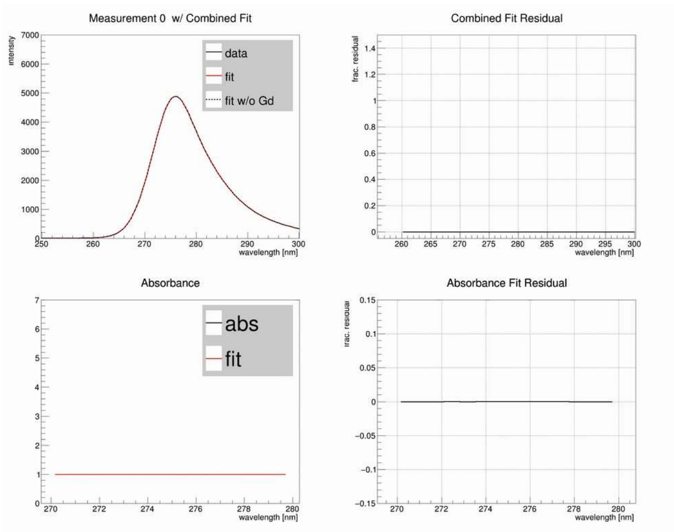


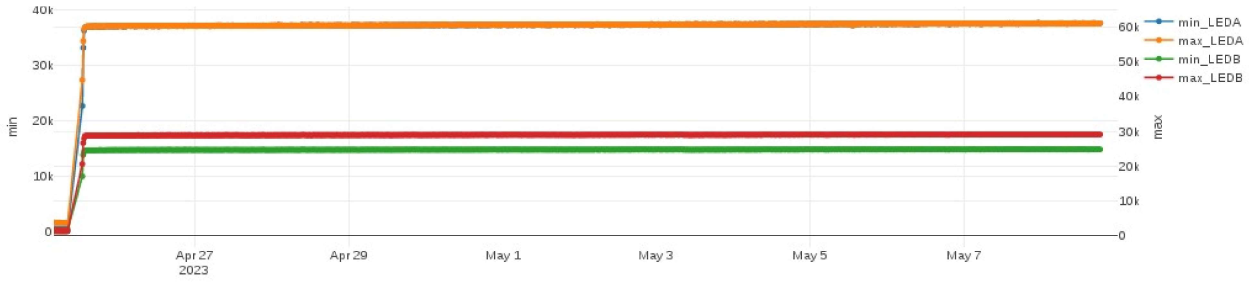


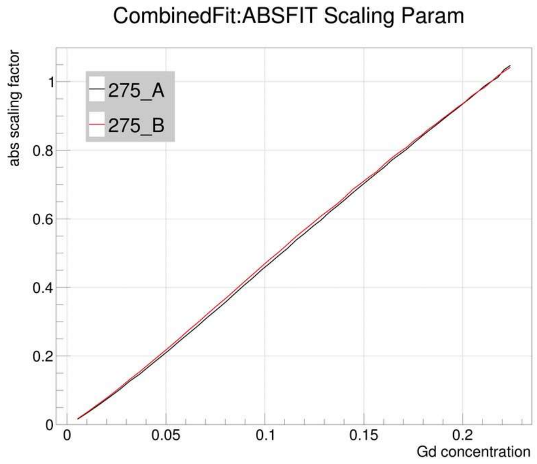


Most recent calibration

- Most recent calibration was done July 2023 in Mozumi – over two days due to Kamioka mine rules.
- We (we?) waited for approximately 2 weeks for filling bubbles to disperse before calibrating – this has produced overall stability in subsequent measurements.
- Warwick GAD team are currently onsite to install further upgrades to device.

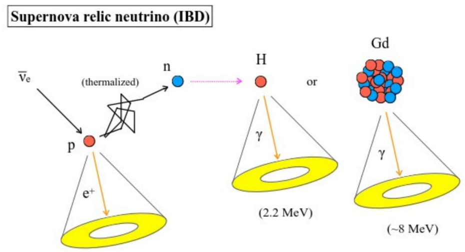


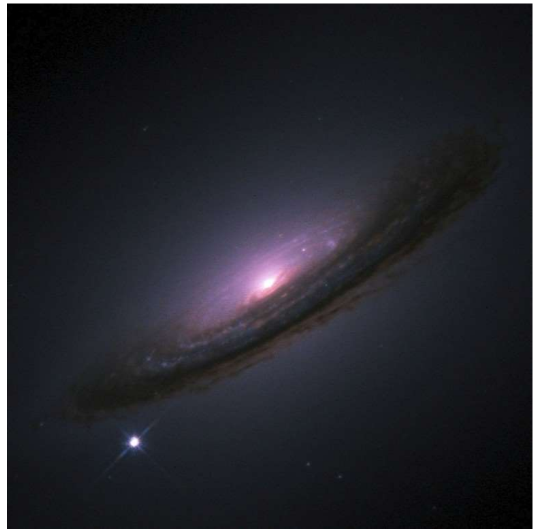




Supernova Relic Neutrinos (preliminary)

- Supernovae are immensely energetic yet incredibly rare astrophysical events.
- Only one galactic supernova 1987A has ever been recorded by neutrino detectors – considerable effort goes into providing early warning for others.
- However, a supernova is expected to occur in the universe roughly once a second – the neutrinos from these supernova constitute a collective flux called either the Diffuse Supernova Neutrino Background (DSNB) or Supernova Relic Neutrinos (SRN)
- Measuring the DSNB can tell us about supernova in general, the rate of star formation in the universe, and cosmology.





SRN flux

$$\frac{d\Phi(E_\nu)}{dE_\nu} = c\int_0^\infty \frac{dz}{H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} \times \left[R_{\rm CCSN}(z)\int_0^{Z_{\rm max}} \Psi_{\rm ZF}(z,Z)\left\{\int_{M_{\rm min}}^{M_{\rm max}} \Psi_{\rm IMF}(M)\frac{dN(M,Z,E'_\nu)}{dE'_\nu}dM\right\}dZ\right].$$

cosmological parameters

neutrino number spectrum per CCSN

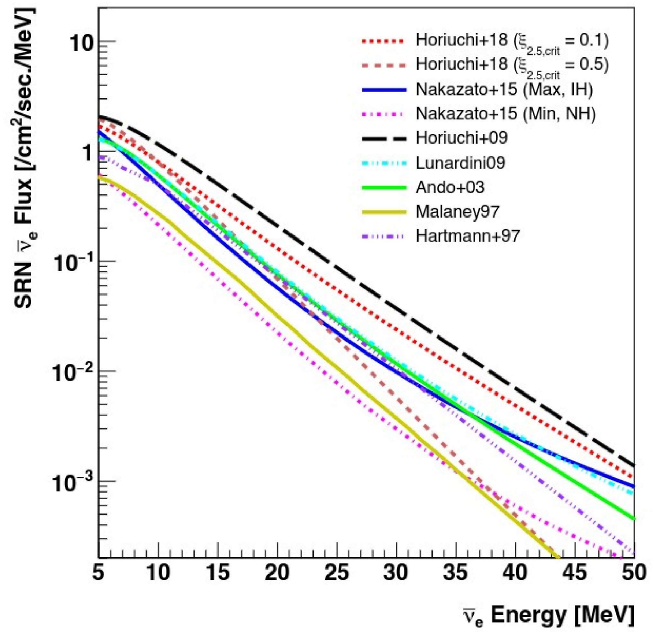
CCSN rate

metallicity distribution of progenitors

initial mass function of progenitors

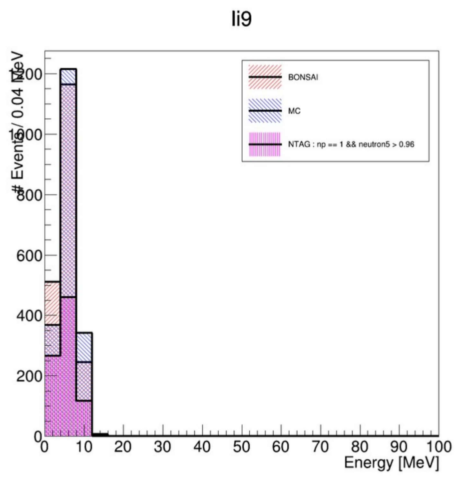
SRN Analysis

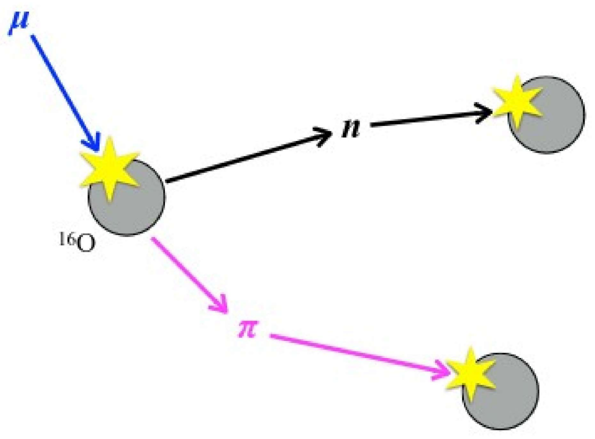
- Measuring the DSNB is practically very difficult due to a) very low event rates and b) irreducible backgrounds.
- These are mainly atmospheric, muon spallation events and reactor neutrinos that are normally indistinguishable from relic candidates.
- Gd + Neutron tagging allows for better rejection of some these backgrounds.
- Warwick are doing their own SRN analysis, largely written by ourselves – not a small task.



Background #1 : Muon Spallation

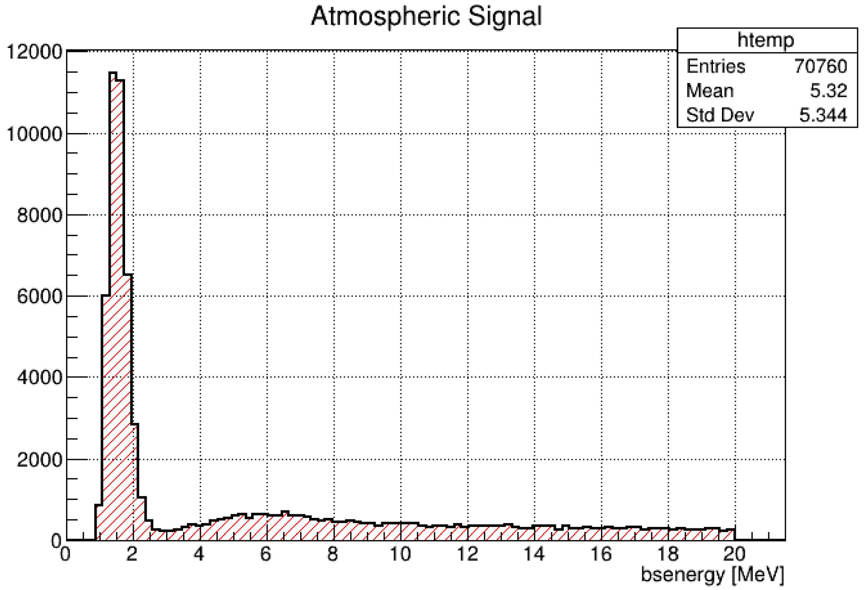
- High energy muons collide with isotopes in detector that produce pions and neutrons.
- Main spallation inducing isotope is Li9.
- Rejection of these events is performed by a) neutron cloud cuts and b) data-driven spallation likelihood cuts.

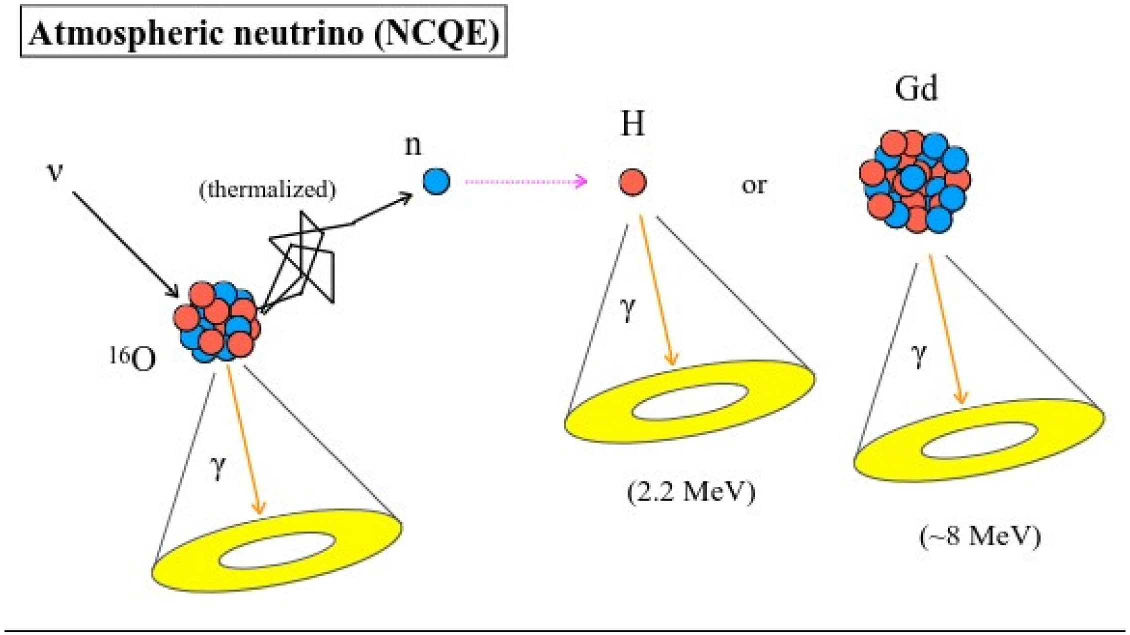




Background #2 : Atmospheric Neutrinos

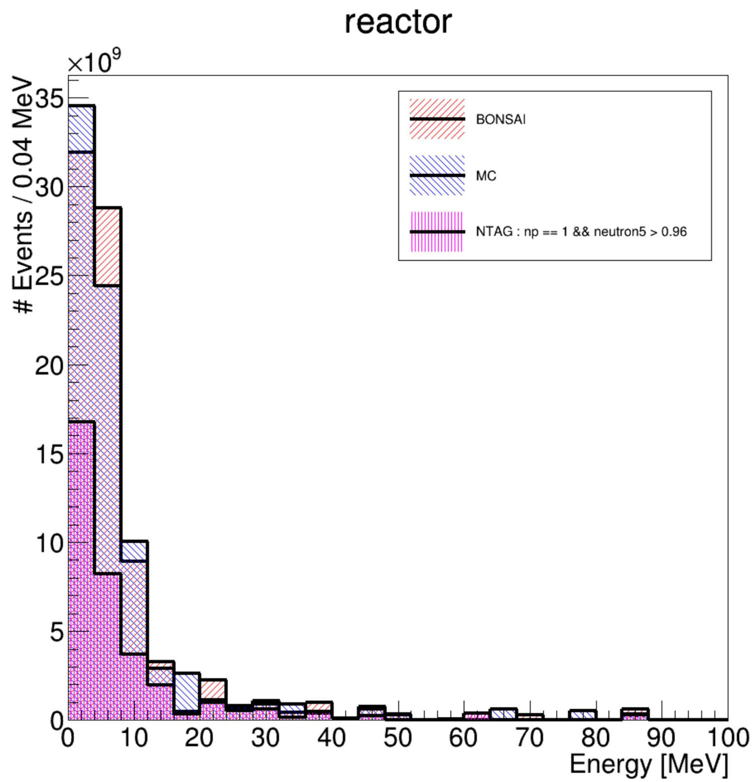
- We have NQCE – mimicking IBD interaction with gamma + n and CC induced muons
- Both are removed through MC modelling, relying on sideband of theta_c > 30.





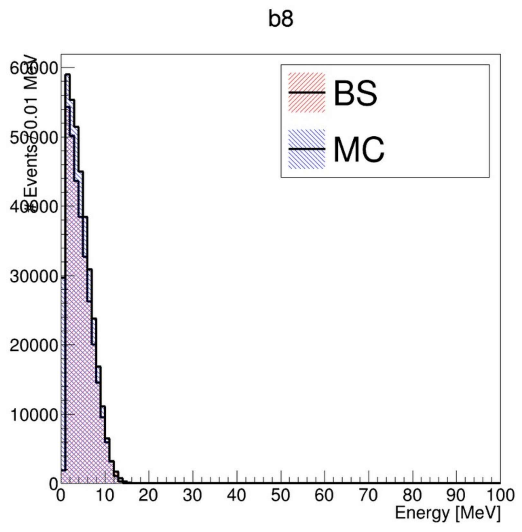
Background #3 : Reactor Neutrinos

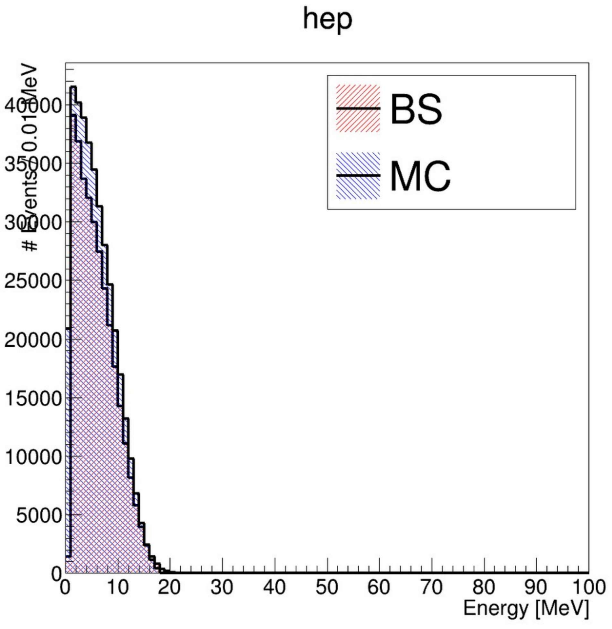
- Electron IBD from nuclear reactor plants
- Irreducible , since identical from signal
- Again removed by MC method



Background #4 : Solar neutrinos

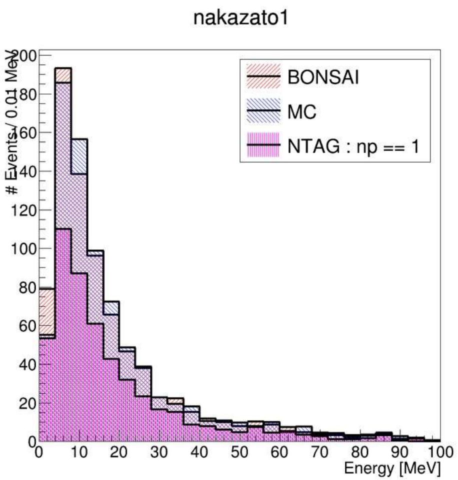
- Electron neutrinos from the sun
- Totally removed by neutron tagging

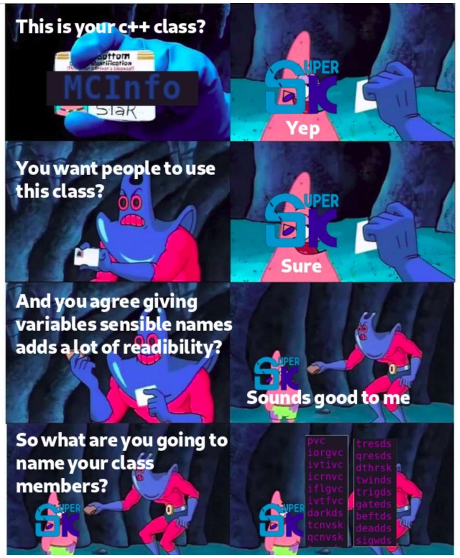


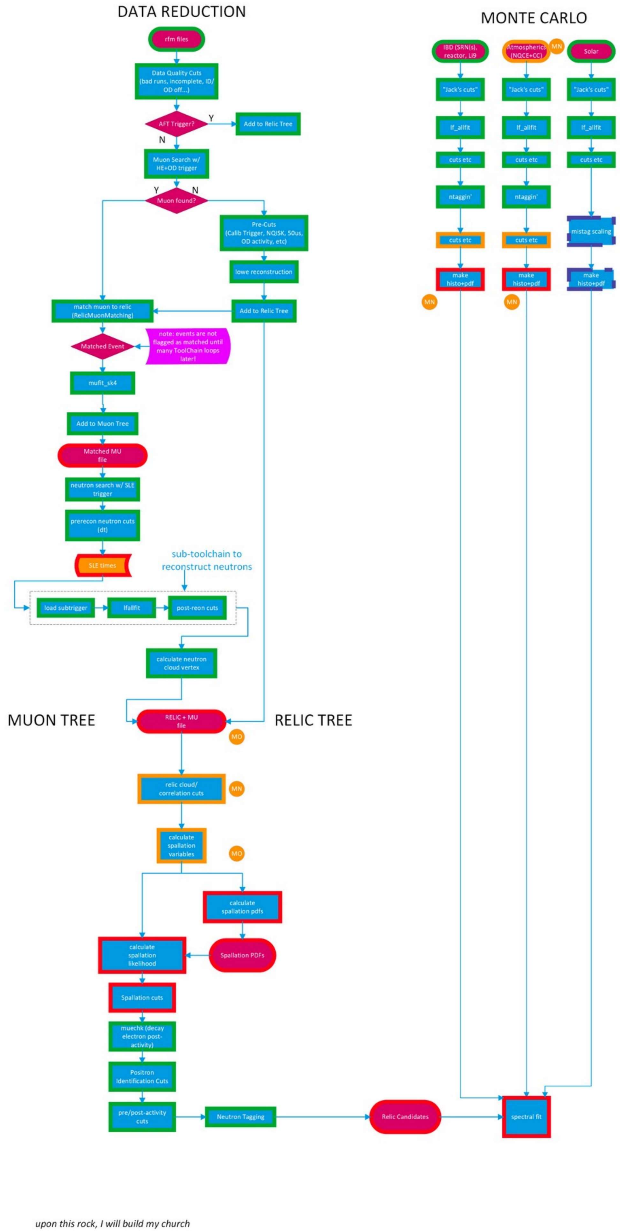


Analysis Pipeline

- In principle the analysis is relatively simple, however with current SK tools – it proves very difficult.
- We are gearing up (fingers crossed) to performing the first pass of the analysis
- Testing a variety of different SRN models with SK6+7 data.







Conclusion

- The addition of Gd to Super-K gives a new lease of life to the detector, particularly in the context of SRN analyses.
- GAD is performing stably in EGADS, maybe will sit in Super-K one day.
- Hopefully the first measurement of DSNB comes soon! With Warwick’s analysis pipeline!

THANKS FOR LISTENING!