Supernova Neutrino Detection with nEXO

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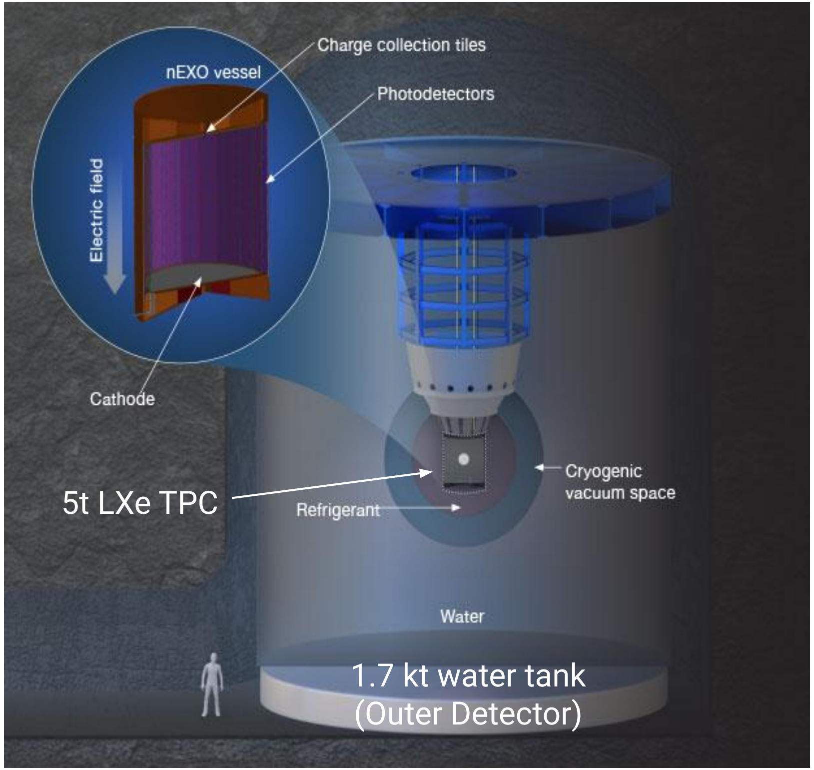
Canadian Multi-Messenger Astrophysics Workshop

nEXO Overview

- A neutrinoless double beta decay search in Xe-136
- Anticipated to be placed at SNOLAB (6 km w.e. depth) in Sudbury, ON.
- A **5t LXe Time Projection Chamber (TPC)** optimized to measure ionization and scintillation signals at MeV scales
- A **1.7 kt water tank**: shields against external backgrounds, and acts as an active muon veto.



nEXO Experiment Concept

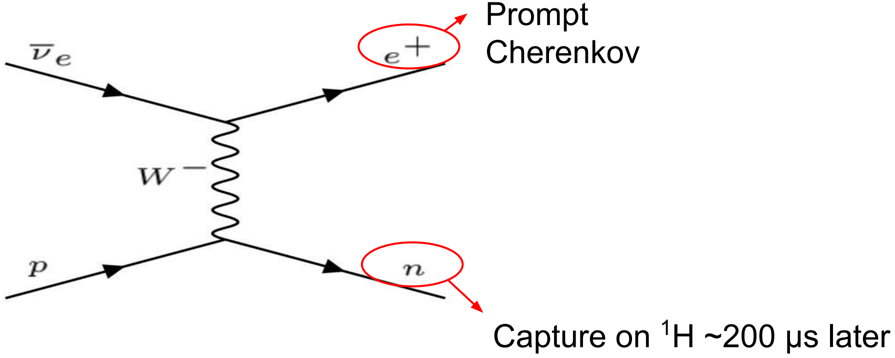
Supernova Neutrino Interactions in nEXO

- In the LXe
  - Charged current events
  - Coherent Elastic Neutrino Nucleus Scattering (CEvNS)
- In the water
  - Inverse beta decay (~90% of interactions)
  - Other charged current events

$$\nu_e +^{136}\mathrm{Xe} \rightarrow e^- +^{136}\mathrm{Cs}^*$$

$$\bar{\nu}_e +^{136}\mathrm{Xe} \rightarrow e^+ +^{136}\mathrm{I}^*.$$

$$\nu_x +^{136}\mathrm{Xe} \rightarrow \nu_x +^{136}\mathrm{Xe}^*$$



Supernova Neutrino Interactions in nEXO

- In the LXe
  - ~~Charged current events~~ cross sections too small for nEXO LXe mass
  - Coherent Elastic Neutrino Nucleus Scattering (CEvNS)
- In the water
  - Inverse beta decay (~90% of interactions in water)

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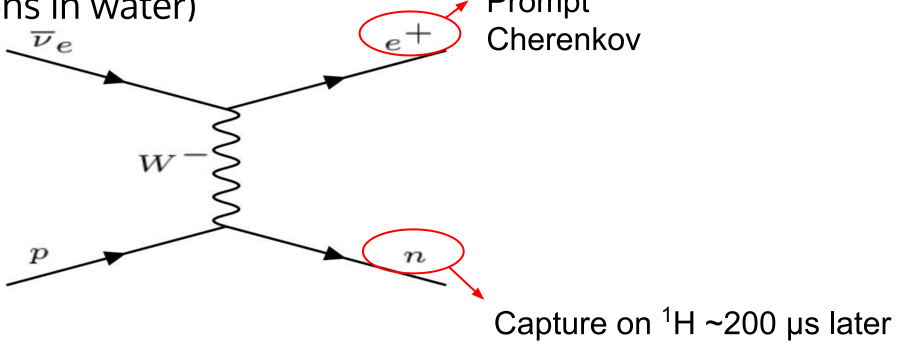


CEvNS in nEXO

- Coherent Elastic Neutrino Nucleus Scattering (CEvNS) cross sections scale as ~N^2
- The interaction is flavour-blind (sensitive to total neutrino flux evolution/neutrino calorimetry)

$$\nu_x + {}^{136}\mathrm{Xe} \rightarrow \nu_x + {}^{136}\mathrm{Xe}^*$$

So what numbers do we expect for nEXO?

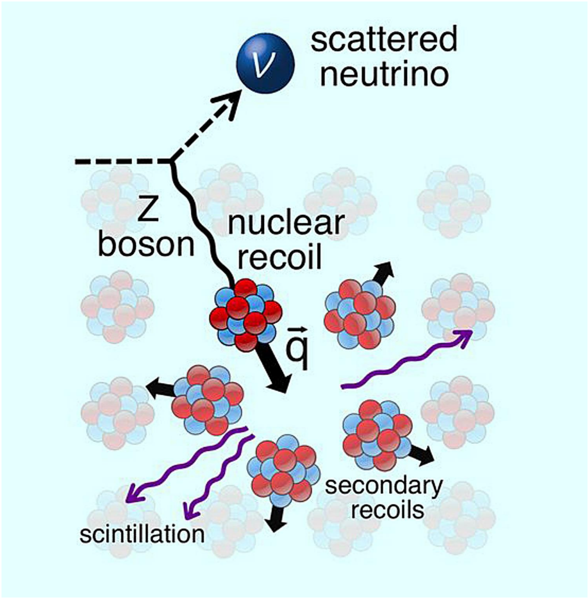
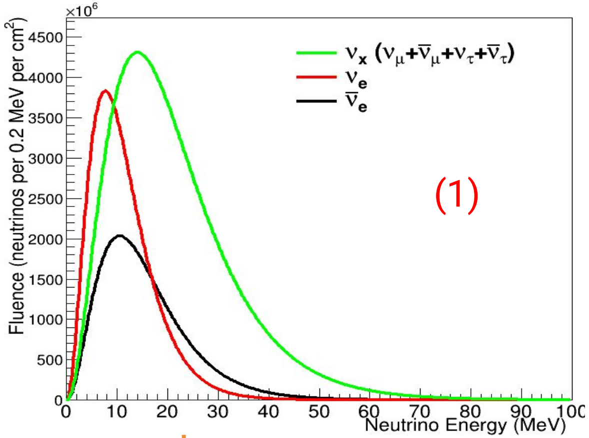
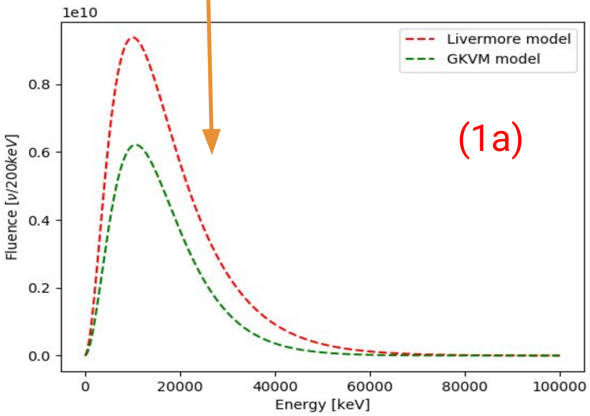


Image credit: COHERENT collaboration

Detecting CEvNS with nEXO

1. Use canonical SN fluxes from SNOwGLoBES (GKVM, Livermore)
    a. Integrate across all neutrino flavours
2. Take cross sections from Pirinen et al. (2018) for Xe-136
    a. Linearly interpolate, set to zero past either bound
3. Calculate recoil spectrum of interactions using modified methods from Lang et al., 2016 and XMASS Collaboration, 2016





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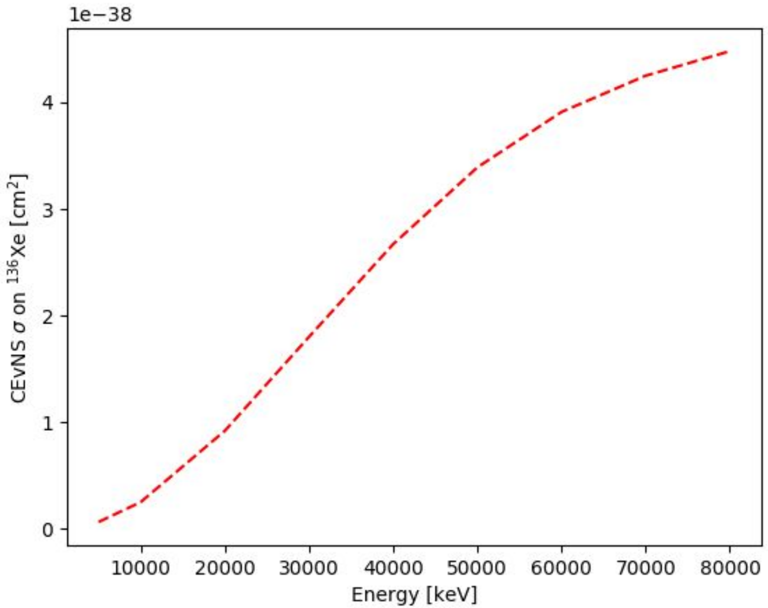

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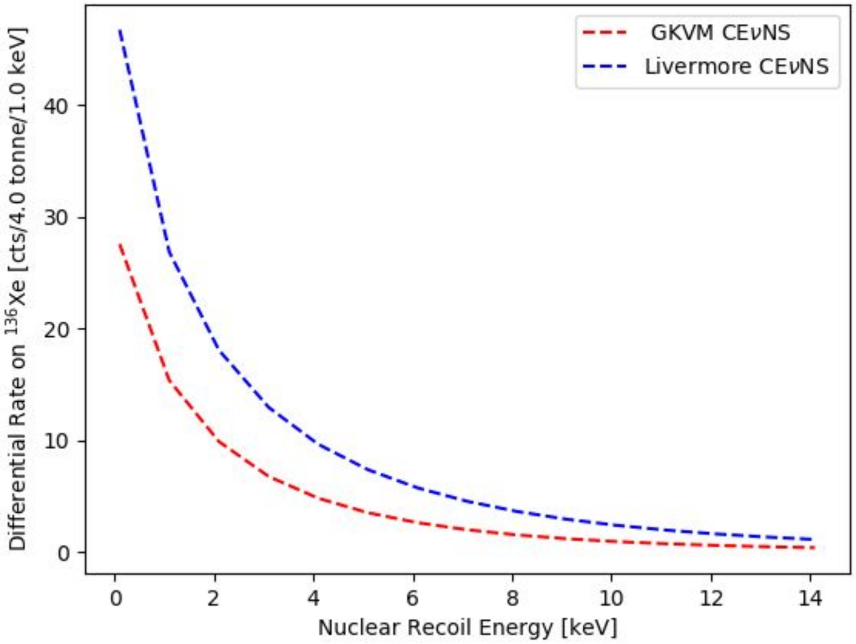

nEXO TPC is currently optimized for detecting ~MeV energy deposits!!

Neutrino Interactions in nEXO

- In the LXe
  - ~~Charged current events~~ cross sections too small
  - Coherent Elastic Neutrino Nucleus Scattering (CEvNS)
- In the water
  - Inverse beta decay (~90% of interactions in water)

$$\cancel{\nu_e + {}^{136}\mathrm{Xe} \to e^- + {}^{136}\mathrm{Cs}^*}$$

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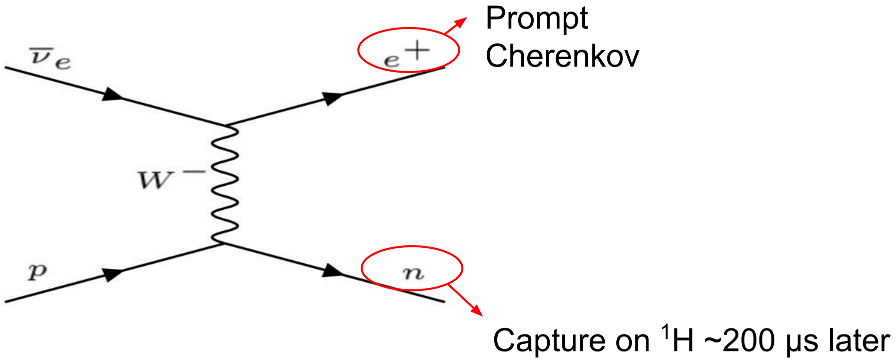

Neutrino Interactions in nEXO

- ~~In the LXe~~
    - ~~Charged current events~~ cross sections too small
    - ~~Coherent Elastic Neutrino Nucleus Scattering (CEvNS)~~ can't do it with baseline design (electronics noise is too high in charge-tile readout)
- In the Outer Detector
    - Inverse beta decay (~90% of interactions in water)

$$\cancel{\nu_e + {}^{136}\mathrm{Xe} \rightarrow e^- + {}^{136}\mathrm{Cs}^*}$$

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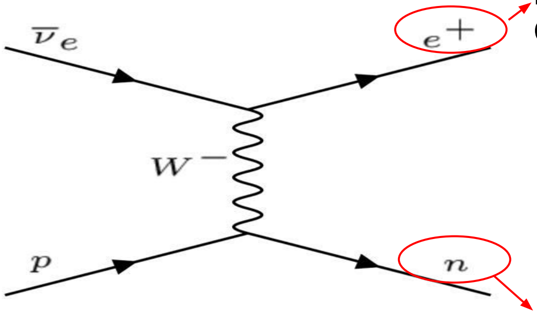
Inverse Beta Decay (IBD)

- Inverse beta decay (IBD) is a go-to in neutrino physics
  - Coincidence detection of positron cherenkov and delayed 2.2 MeV gamma (from neutron capture on hydrogen)

- Positron carries information about incoming neutrino energy
- Little triangulation capability, at SN energies IBD is not directional
- Kinematic threshold at ~1.8 MeV



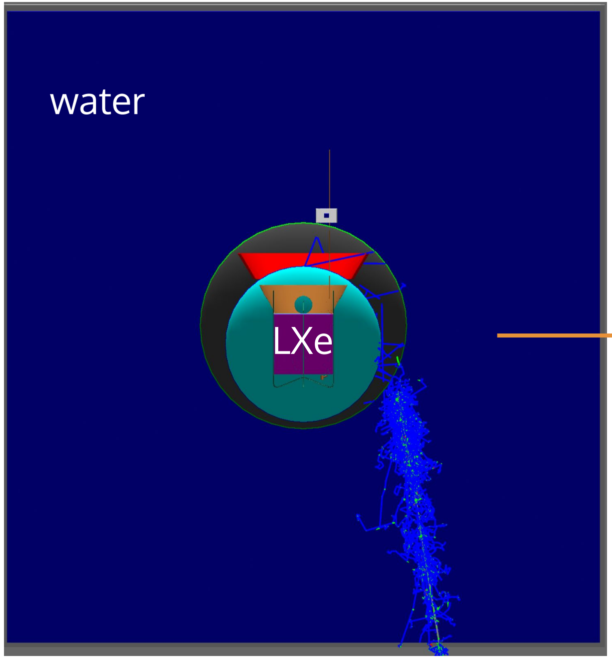
Prompt
Cherenkov light

Delayed capture on ^1H ~200 μs later

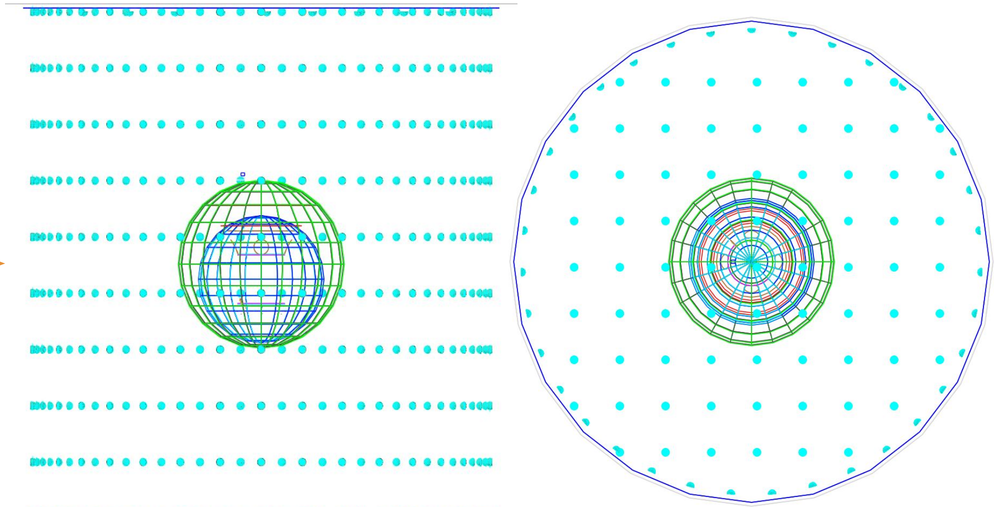
These events can come from the SN burst itself, or even a few days prior
[K. Asakura et al (Kamland Collaboration), 2016]

IBD Simulations in the Outer Detector

nEXO Outer Detector is instrumented with PMTs to detect Cherenkov radiation of passing muons (or positrons!)



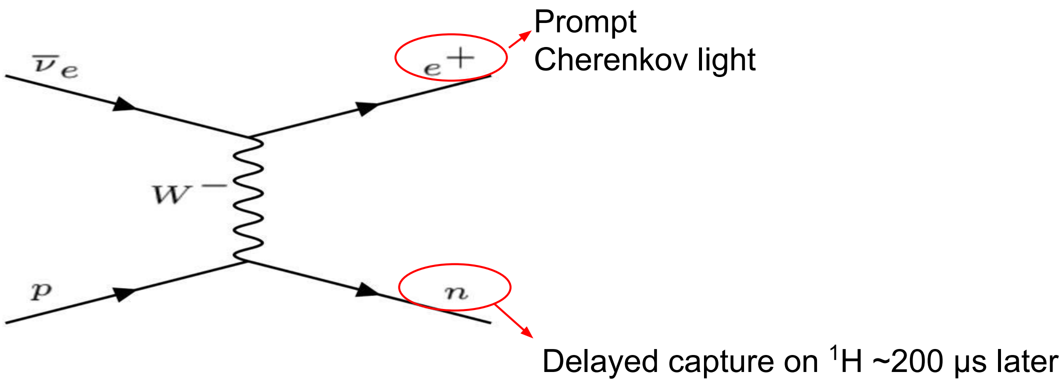
Example of a muon track traversing nEXO

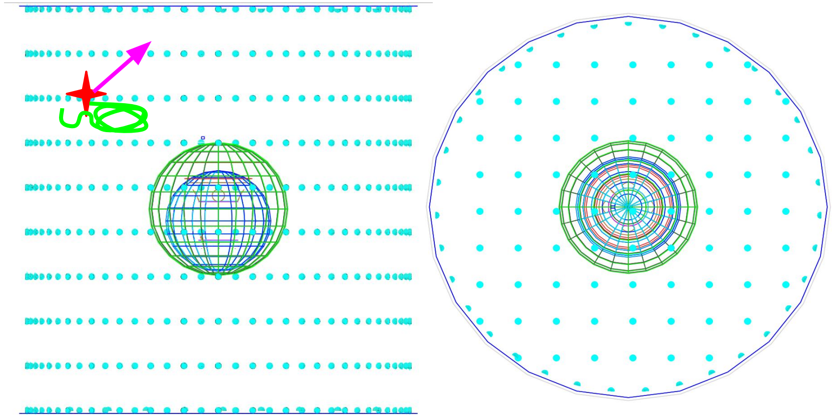


Top and side view of the PMTs in the nEXO Outer Detector simulation (Geant4)

IBD Simulations in the Outer Detector

- Implemented realistic detector responses (charge collection, dark rates, quantum efficiency, optics) in Geant4
- Simulated ~10^6 IBD events according to GVKM spectrum uniformly and isotropically throughout the nEXO Outer Detector





Top and side view of the PMTs (R5912) in the nEXO Outer Detector simulation (Geant4)

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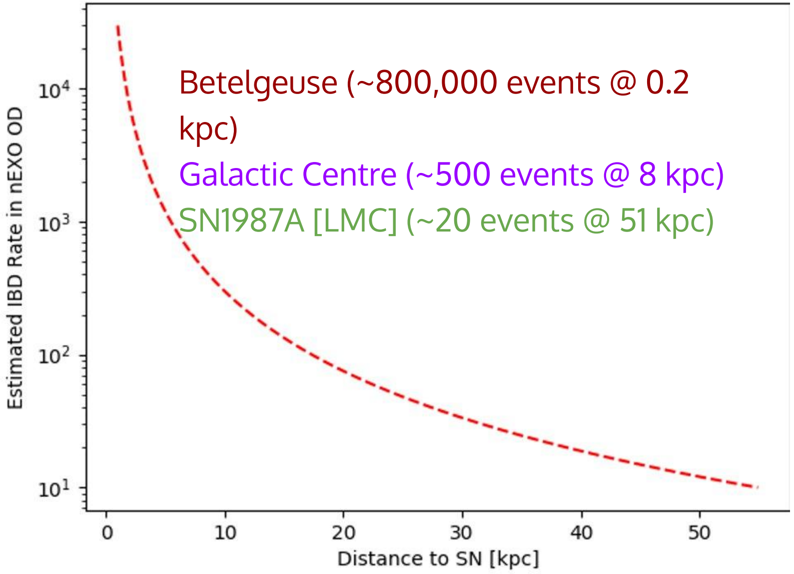
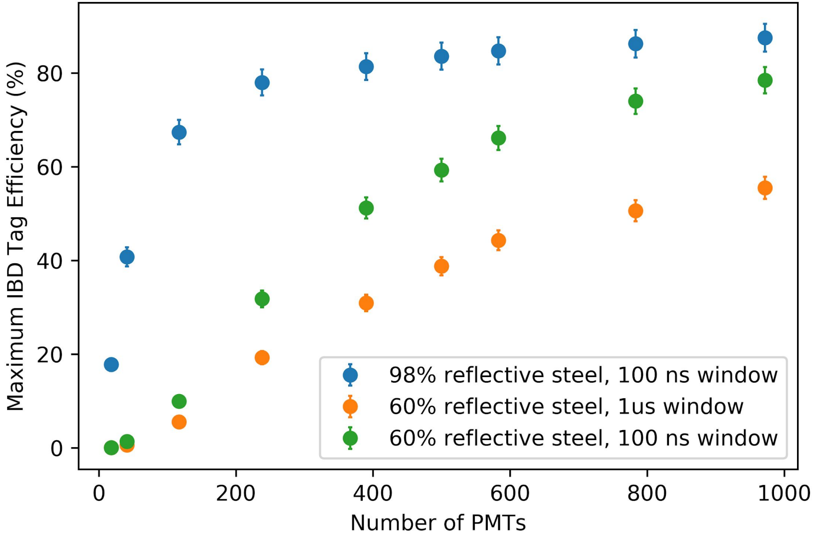
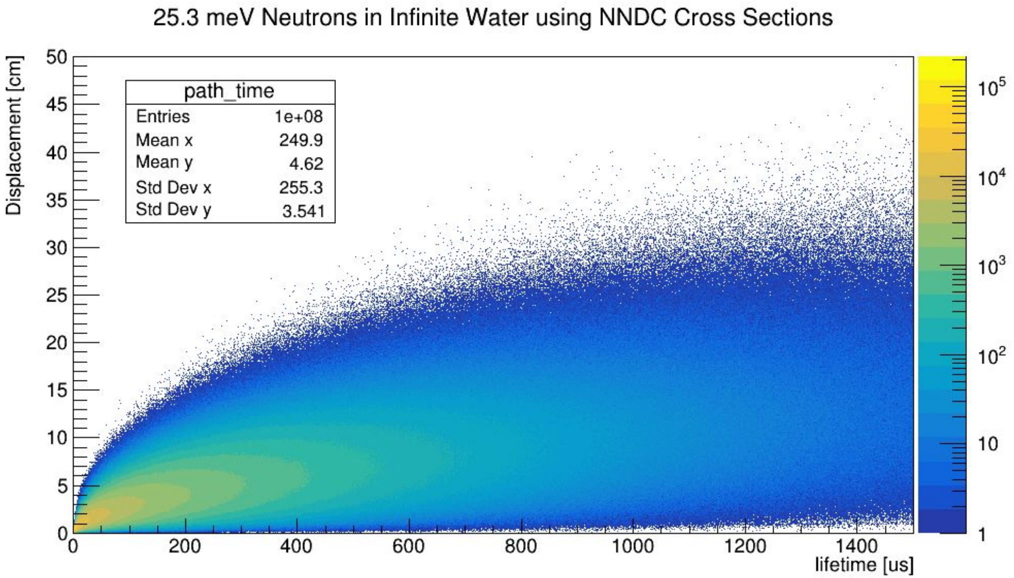
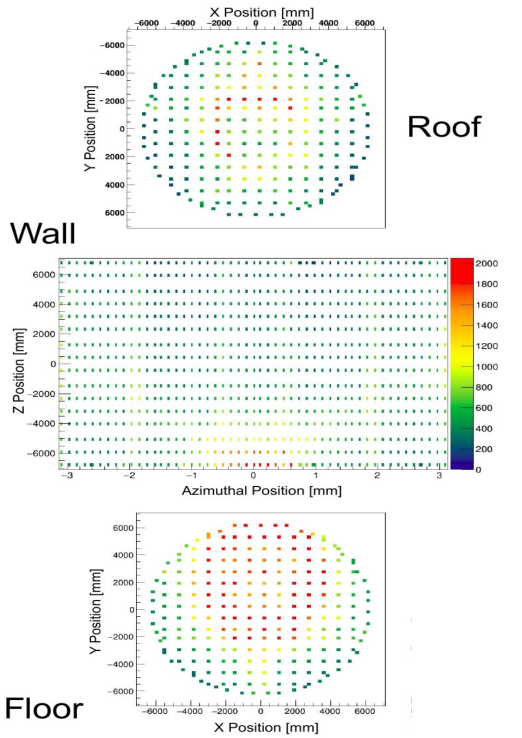




Backgrounds to IBD Tagging

- Decay rate estimates of various isotopes in the SNOLAB cryopit walls give ~500 kHz of ~2.5 MeV gammas (neutrons negligible)
- Background is too high to do IBD coincidence over 100's of μs without good localization (< 1 m)





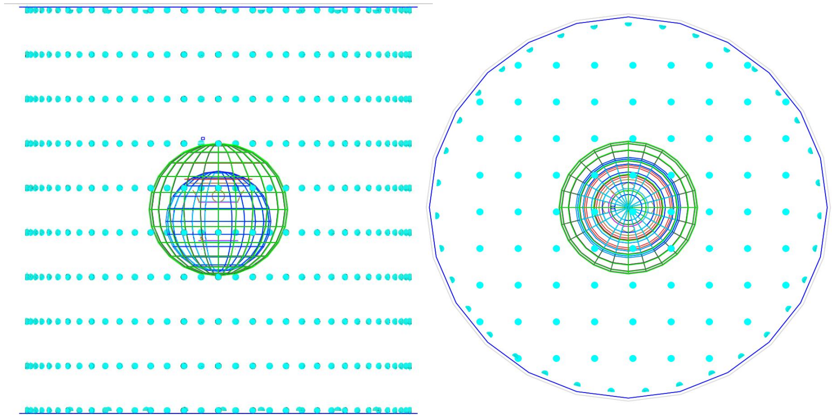
Positron localization in nEXO OD (work by E. Klemets)

Backgrounds to IBD Tagging

- With available PMTs, localizing ~2.2-2.5 MeV events via Cherenkov emission alone is extremely difficult
- This produces an inefficient neutron (and therefore IBD) tag
- pre-SN neutrinos will be undetectable in the Outer Detector without external shielding from gammas

nEXO, in its current design, will likely see a rise in energy read out by all the PMTs during the first couple of seconds of a supernova burst at distances ~ 10 kpc

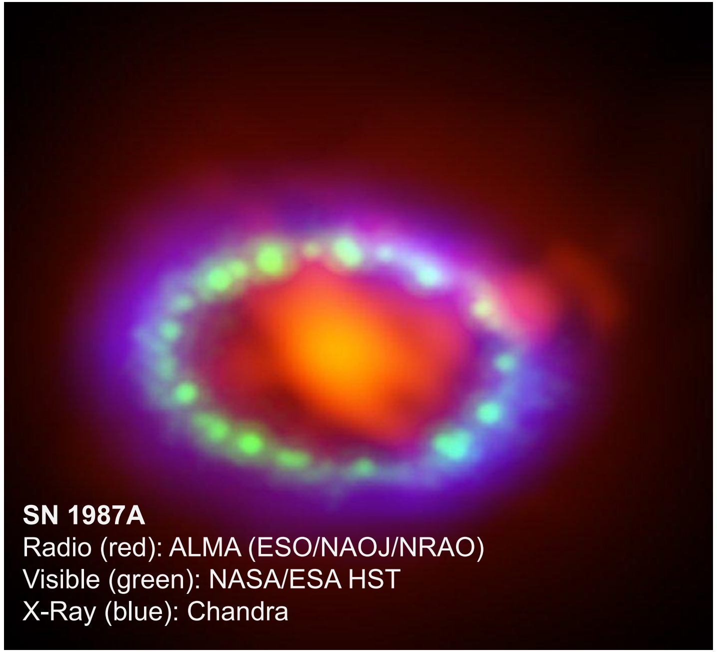
This will only be from positron cherenkov emission



Top and side view of the PMTs in the nEXO Outer Detector simulation (Geant4)

Conclusions

- Particle/nuclear physics experiments are now becoming large enough to consider SN neutrino signals
- CEvNS is unlikely to be detected in nEXO due to noise in the charge-readout system
- nEXO will likely notice a SN burst out to ~ 10 kpc in its Outer Detector via IBD interactions
- Shielding against radiogenic gammas would aid SN neutrino detection efficiency in the Outer Detector (and potentially in detection of pre-SN neutrinos)



Thank you!

And many thanks to: L.J. Kaufman (SLAC), H.M. Tsang (PNNL), T. McElroy (McGill) and the nEXO Collaboration

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nEXO

Institut Spatial de McGill
McGill Space Institute

Mitacs

CEvNS Methods: Recoil Spectrum

Calculate recoil spectrum of interactions using modified methods from Lang et al., 2016 and XMASS Collaboration, 2016

I integrated this term out and used the total neutrino flux from earlier to normalize to my event rate

Differential Rate

$$\frac{d^2R}{dE_R dt_{pb}} = \sum_{\nu_\beta} N_{Xe} \int_{E_\nu^{min}} dE_\nu \, \underline{f^0_{\nu_\beta}(E_\nu, t_{pb})} \frac{d\sigma}{dE_R}$$

Differential cross section/nuclear recoil energy

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m_N}{4\pi} Q_W^2 \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

Helm form factor

$$F(E_R) = \frac{3j_1(qr_n)}{qr_n} \exp\left(-\frac{(qs)^2}{2}\right)$$

CEvNS Expected Readout

- pCDR RMS noise level of each charge tile is ~200 e^- (1 us window)
- Ionization yield is O(1) e^- /keV ignoring E-field variation (E. Aprile, T. Doke 2009)
- Scintillation yield is also O(1), considering photon detection efficiency of nEXO (~3%)

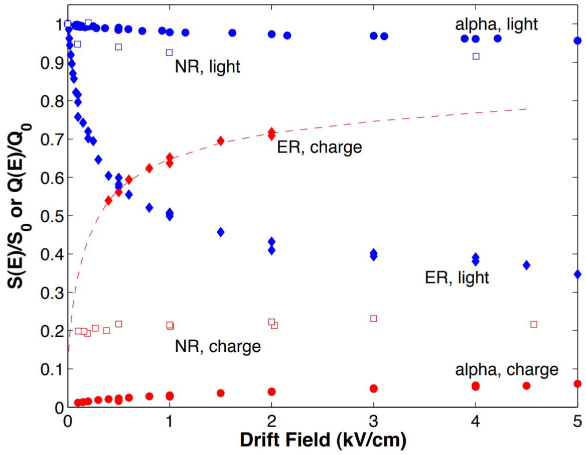


FIG. 6 Field dependence of scintillation and ionization yield in LXe for 122 keV electron recoils (ER), 56.5 keVr nuclear recoils (NR) and 5.5 MeV alphas.(Aprile, 2006).

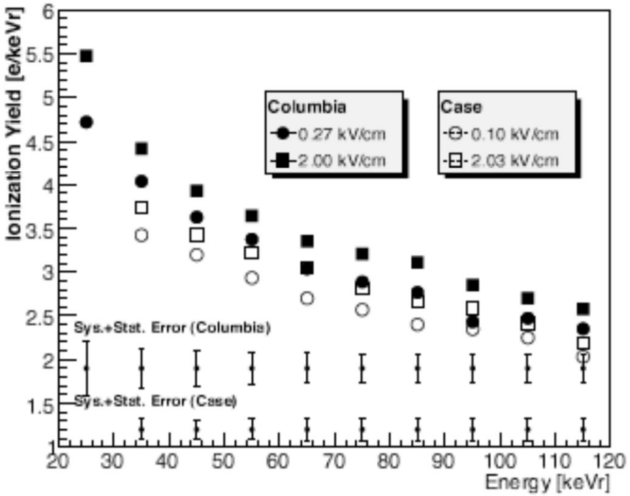
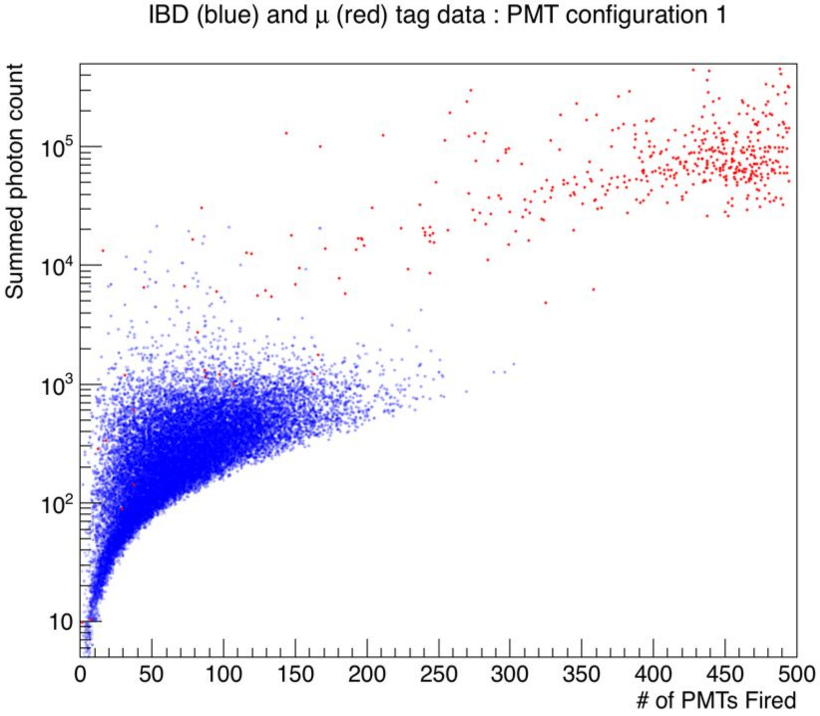


FIG. 5 Ionization yield from nuclear recoils measured with small scale two-phase xenon detectors (Aprile, 2006).

Separation of Muon and Neutrino Events

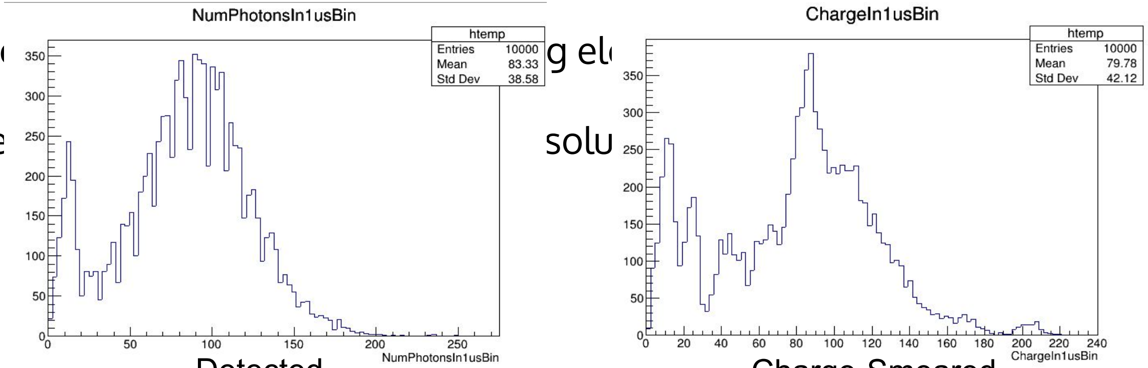
- Number of detected photons corresponds to
  - Particle track length in water
  - Energy of particle
- Only very high energy (~100 MeV) IBD events can be mistaken for muons
- Can easily distinguish between traversing muons (GeV - TeV) and other types of events with a simple cut



Results for 10^4 IBD events (blue) and 10^3 muon events (red)

Energy Resolution?

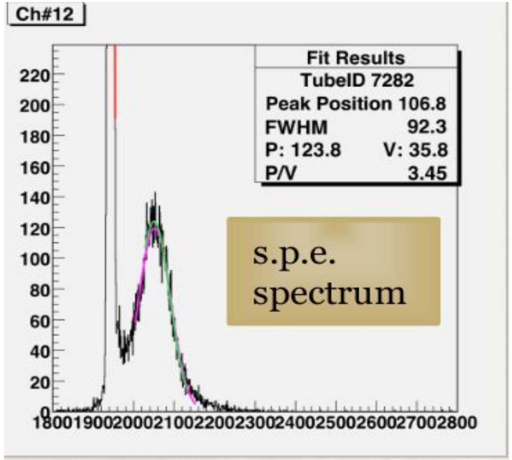
- Simulate 10^4 IBDs uniformly in tank at fixed energy
- Each event will give some photon count distribution for a given event window
- Assumed charge collection from PMTs goes like a Gaussian
  - Std = 0.5*sqrt(numPhotons) - see right
  - Mean = num photons detected for that event
- Sm… g el…
- Use … solu…



500 PMTs, 98% reflective, 15MeV positron

Detected

Charge-Smeared



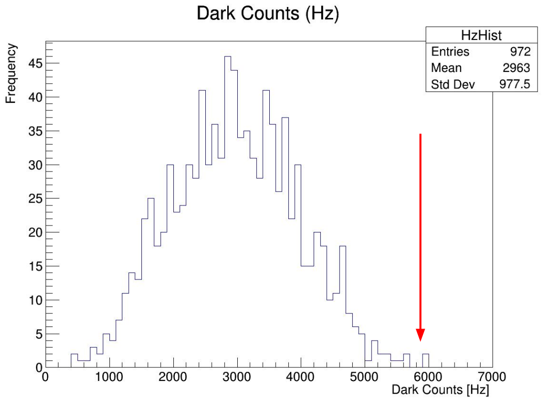
Daya Bay measured R5192 single photoelectron spectrum

Setting the IBD Trigger Level

1. Scale *worst* dark rate [counts/sec] to 100 ns, 1 μs and 10 μs bins
    a. This is how many dark counts we will we have in an event window
2. Multiply by the number of PMTs (500, 250, 125, 25 ...)
    a. This is how many dark counts will be summed over all PMTs in an event window for a particular configuration on average ($\lambda_{expected}$ in Poisson)
3. Calculate probability of obtaining N_{Dark} counts in any given event win
4. Calculate probability that dark counts exceed trigger $X_{trigger}$
5. Repeat until:

$$P(N_{DarkCounts} > X_{trigger}) < 1 / NumberBinsIn1Day$$

i.e. on average, we expect 1 false event per day

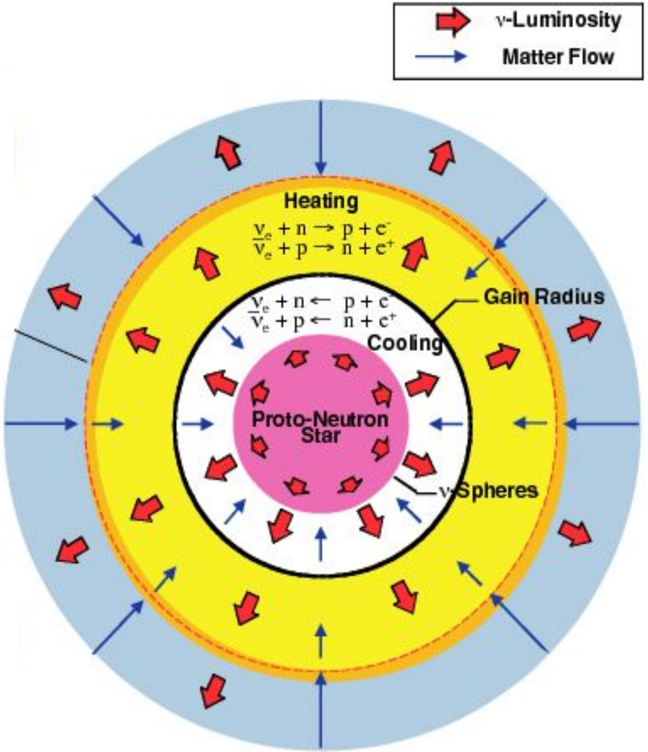


Hamamatsu R5912 dark counts
(courtesy of Daya Bay collaboration)

SN 1987A: Dawn of Multi-Messenger Astronomy

Neutrinos help constrain models of core collapse

1. Core collapse and deleptonization/neutronization burst
   - ($e^- + p \rightarrow n + \nu_e$)
2. Infalling matter bounces off core
3. Shock stalls
4. Proto-neutron star cooling
   - neutrino pair production
5. Shock re-acceleration



Tharrington, Arnold & Messer, Bronson & Hoffman, Forrest. (2006). Overview of NLCF FY 2006 Allocations. CUG Proceedings. 1.