Simulating the kinematics of supernovae neutrino interactions in the three phases of SNO+

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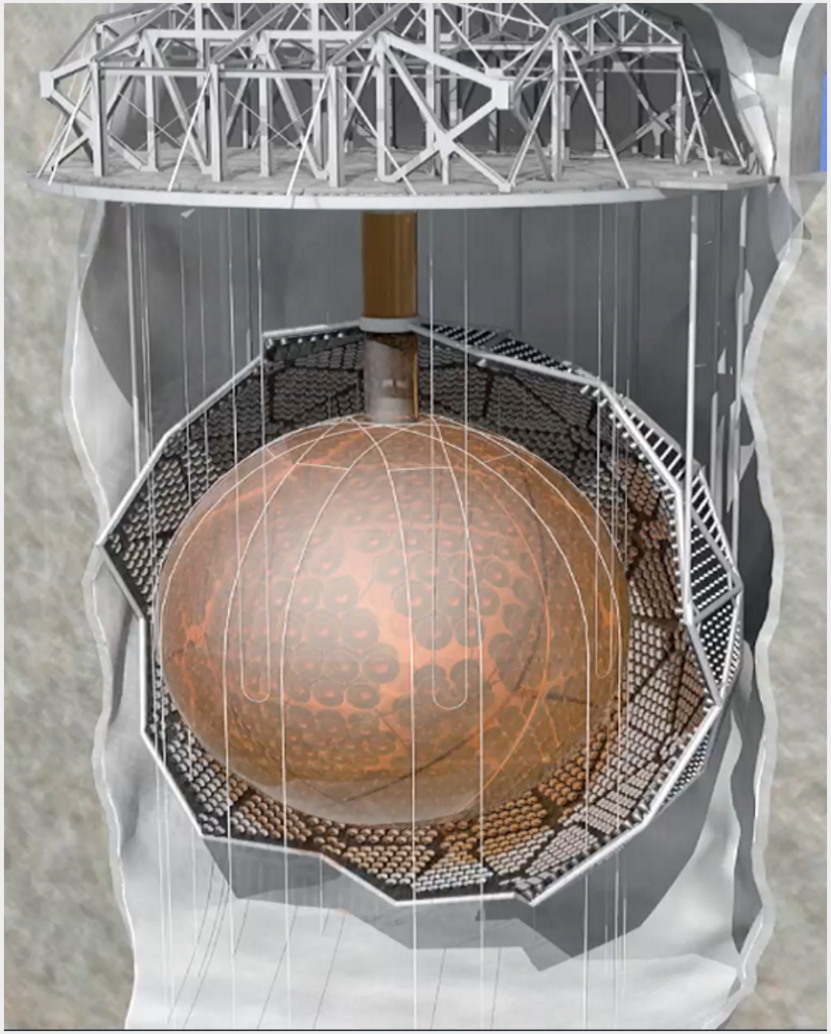
Introduction

- When measuring a supernovae burst it is important to understand the detector response to the burst.
- Detectors are not perfect.
  - Misreconstruction of events in position and energy.
  - Random background coincidences.
  - Supernovae events occurring outside fiducial volume.
- By simulating the final states of SN interactions within detector MC we obtain a better understanding of the detector response to the burst.

SNO+

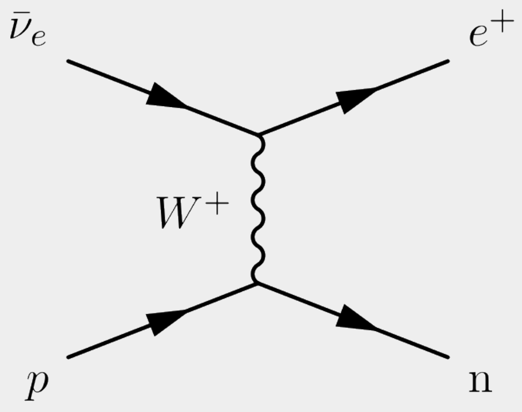
- Neutrino experiment
  - Focus on 0νββ
- Improved electronics from SNO
  - Lower trigger threshold
  - Higher data rate
- Three phases
  - Pure H_2O (Started running 4th May 2017)
  - Pure Scintillator (Early 2018)
  - Scintillator + Te (Late 2018)
- Sensitive to a SN burst during all phases of running.

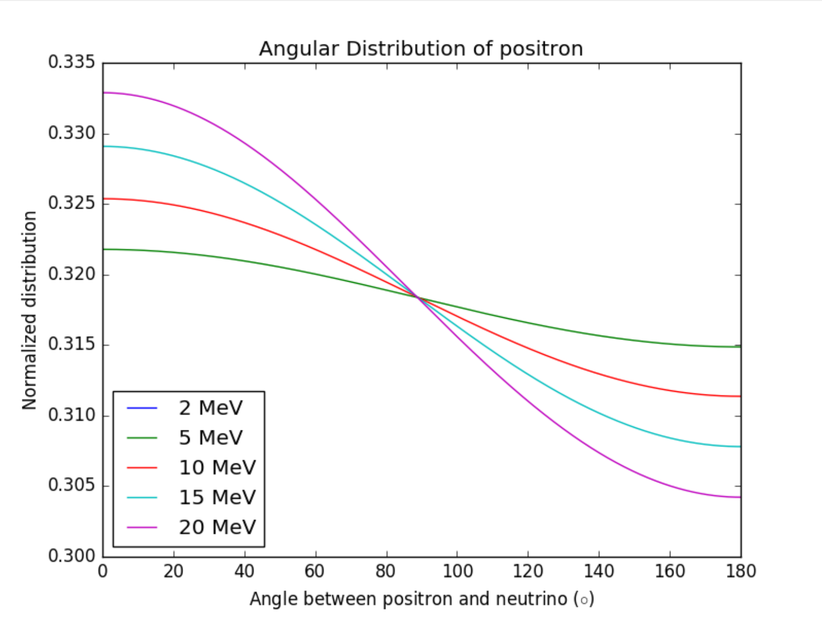


Inverse Beta Decay

- Signal in detector is prompt light from Cherenkov light
- Delayed signal from neutron capture (O(100 μs) 2.2 MeV)
- Both delayed and prompt signal are visible in scintillator phases of SNO+.
- SNO+ plans to measure detection efficiency of delayed signal in water phase with calibration source.

A. Strumia, F. Vissani, Precise quasielastic neutrino/nucleon cross-section https://doi.org/10.1016/S0370-2693(03)00616-6



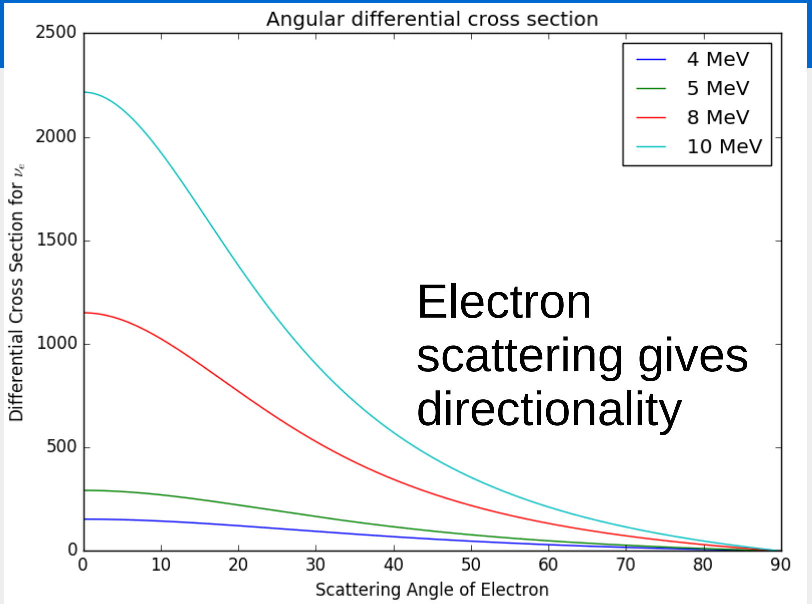


Neutrino electron/proton scattering

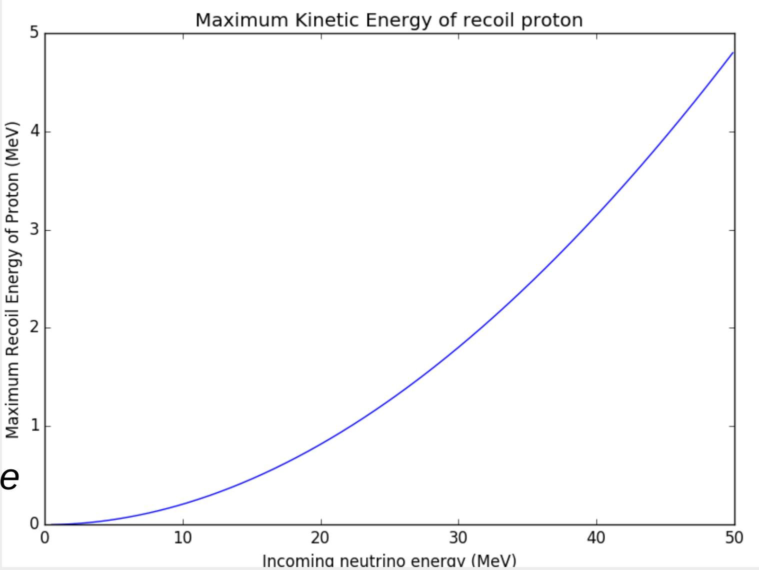
- Interactions accessible to all flavours of neutrino.
- Electron scattering produces Cherenkov light
- Proton scattering not visible in Cherenkov detectors
  - Will be visible in scintillator phase of SNO+
  - Spectrum is quenched in scintillator

J. Beacom, W. M. Farr, P. Vogel https://arxiv.org/abs/hep-ph/0205220

B. von Krosigk et al. https://link.springer.com/article/10.1140/epjc/s10052-013-2390-1.



Electron scattering gives directionality



Nuclear Interactions with oxygen

- Charged current interactions
  - $O(\nu_e, e^-)F$ (15.4 MeV threshold)
    - ^{16}F decays immediately via proton emission, ^{15}O then decays via (~1.7 MeV e^+) (Half life 120 s)
  - $O(\nu_e, e^+)N$ (11.4 MeV threshold)
    - ^{16}N decays via emission of e^- and 6.18 MeV γ (68% of the time) (Half life ~7 s)
    - What is the direction/energy of the scattered electron (positron)?
- Neutral current interactions
  - Higher energy neutrinos excite nuclei over particle emission threshold.
  - Often nuclei after particle emission are in an excited state and release a γ E > 5 MeV.

Neutrino Interactions with carbon

- Charged current interactions
  - $C(\nu_e,e^-)N$ (17.9 MeV threshold)
    - ^{12}N decays via β^+ decay to ^{12}C (endpoint 16.3 MeV) (half life ~11 ms)
  - $C(\bar{\nu}_e,e^+)B$ (13.9 MeV threshold)
    - ^{12}B decays via β^- decay to ^{12}C (endpoint 13.4 MeV) (half life ~20 ms)
- Neutral current interaction
  - Elevates nucleus to 15.11 MeV excited state that decays via γ emission.

Kinematics of nuclear interactions

- In scintillator detectors kinematics matter less
  - Directionality from Cherenkov light washed out by scintillation light
  - Still important to understand ejecta energies.
- In Cherenkov detectors simulating directionality is essential.
  - IBD/electron scattering interactions well defined.
  - In interactions with Oxygen the final state kinematics are not so well defined

Example: SNO+ Water Phase Sensitivity

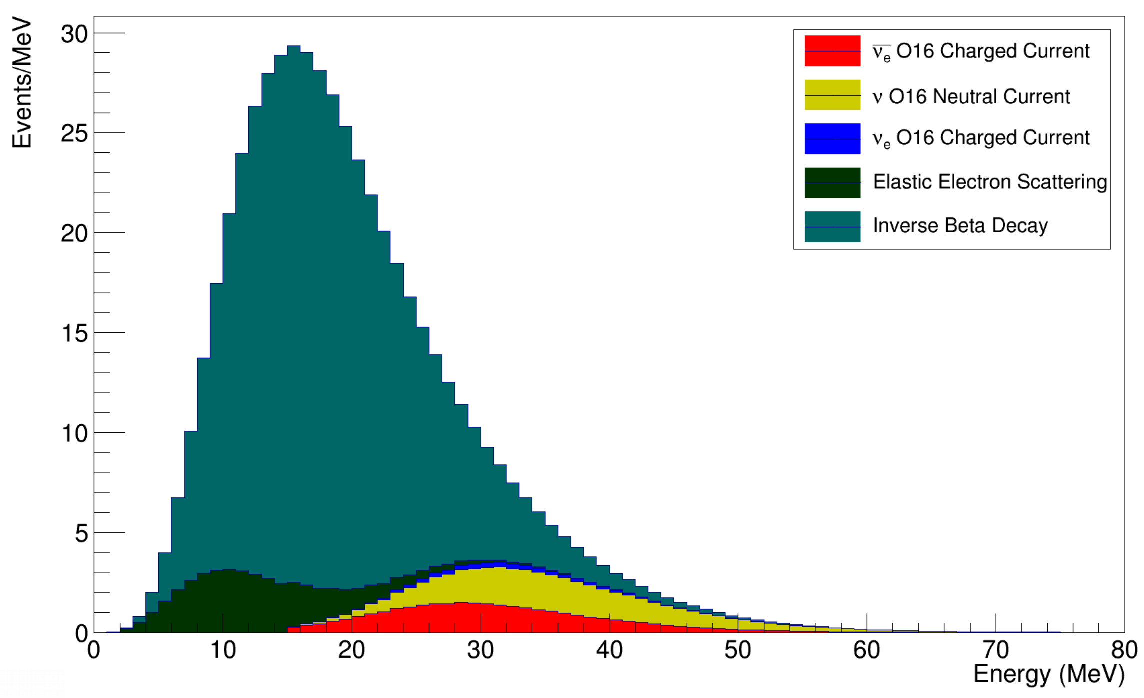
1) Convolute a SN burst spectrum with cross sections, multiply by number of corresponding targets inside detector

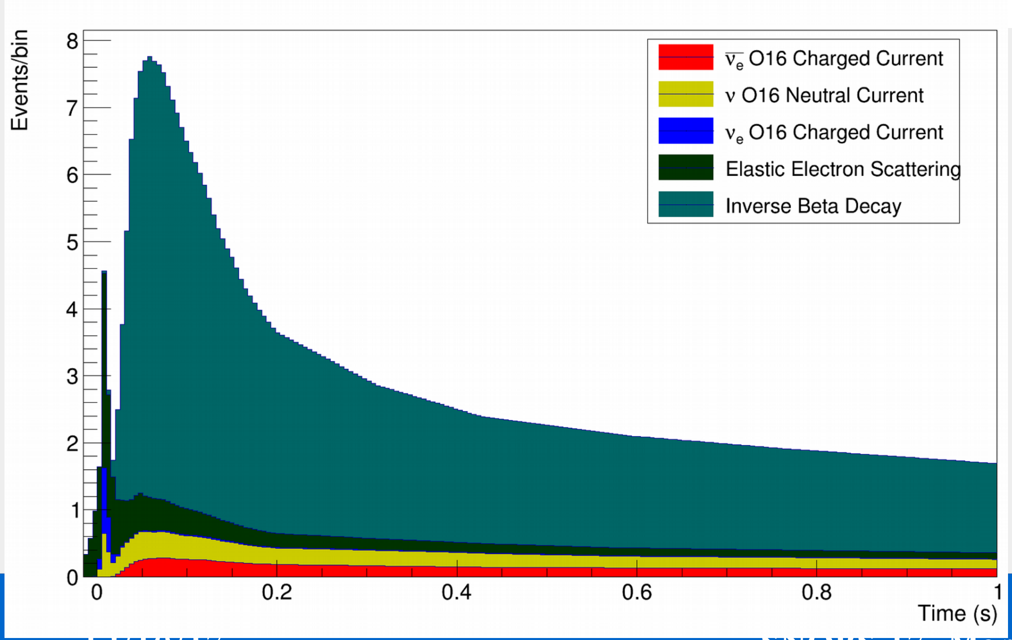
2) For each interaction channel sample differential cross section to obtain directions and energies of ejecta

3)Plug these into detector simulation via HEPEVT format

SNO+ water phase interaction distributions

- Distribution of interactions in time and energy
- Histograms sampled to obtain time and energy of individual interactions
- Peak at t=0 is neutronisation peak



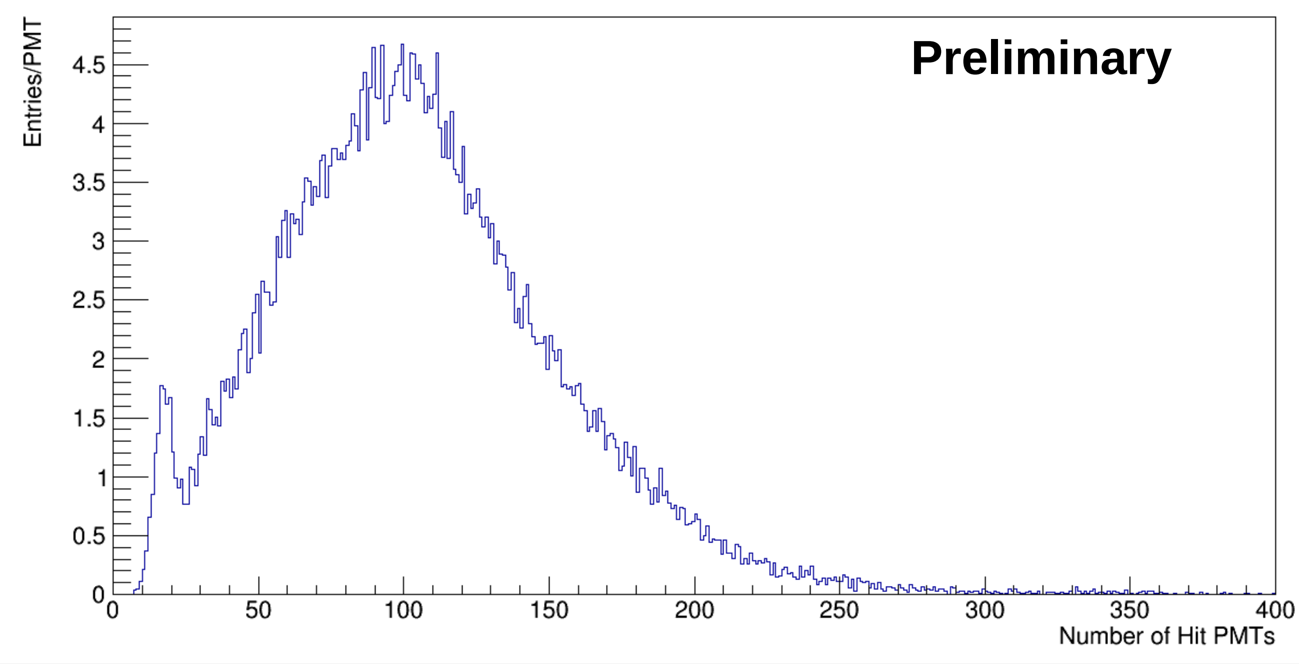


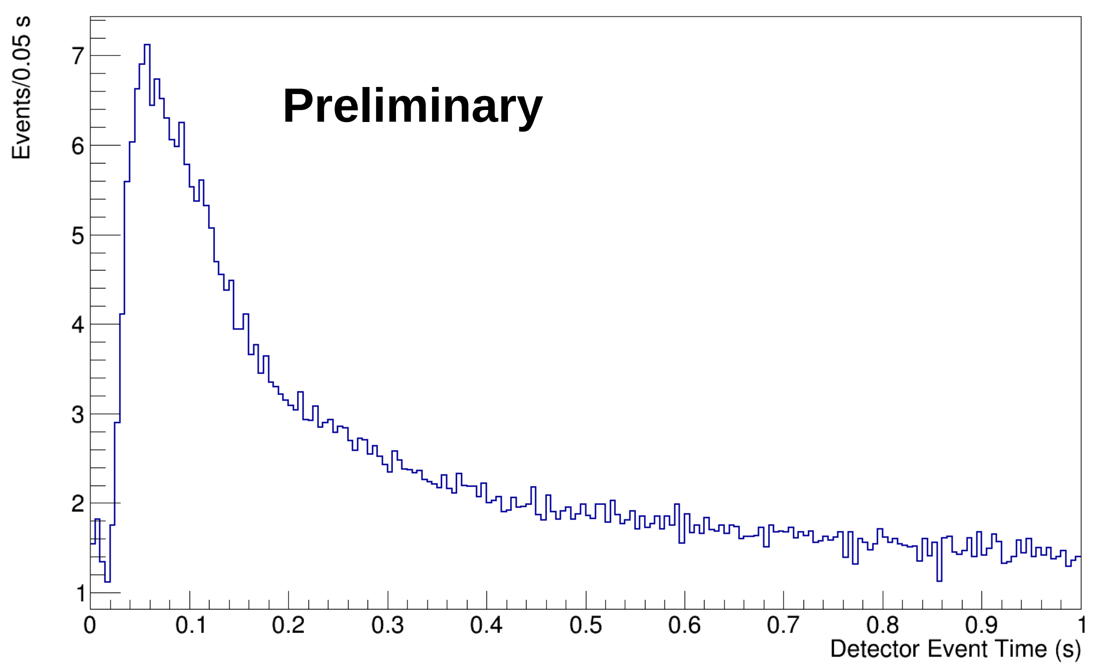
- Using “Garching” Model

Phys. Rev. Lett. 105, 249901 (2010)

- Distance: 1 kpc
- Volume 1 kt of Water

Simulated detector response





- Using “Garching” Model

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- Distance: 1 kpc
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Conclusion

- Simulating Kinematics of neutrino interactions is important to understand the detector response to a SN neutrino burst.
- Misreconstruction can have a systematic effect on burst spectrum
- Kinematics of interactions with electrons / nucleons can be calculated analytically
  - Kinematics of neutrino interactions with nuclei require numerical evaluation