Scintillation/Cherenkov Separation in SNO+

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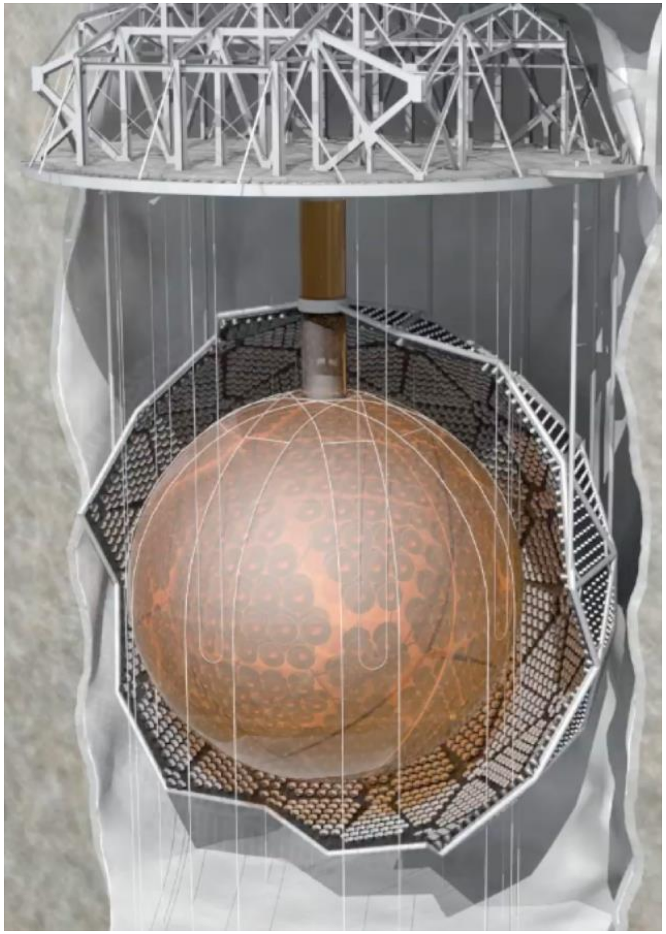
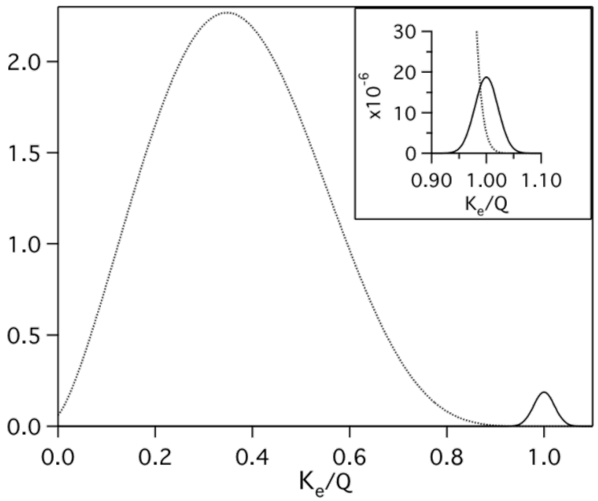
SNO+ Overview

- 780 tonnes LAB/PPO in 12m diameter acrylic vessel
- Surrounded by ~9400 PMTs
- Loaded with ~1300 kg of ^{130}Te
- Hope to observe neutrinoless double beta decay

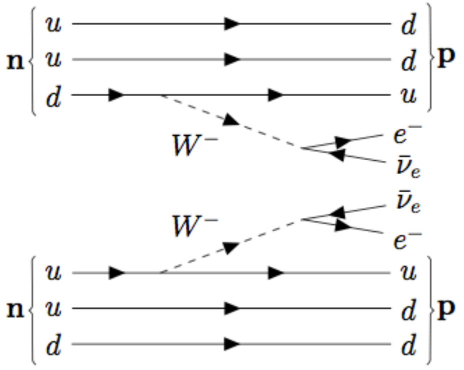


Neutrinoless Double Beta Decay

- If neutrinos are Majorana, neutrinoless double beta decay may be observed
- Extremely long half life - $T_{1/2} > 10^{25}$y
- Entire decay energy is taken away by electrons, no neutrinos emitted



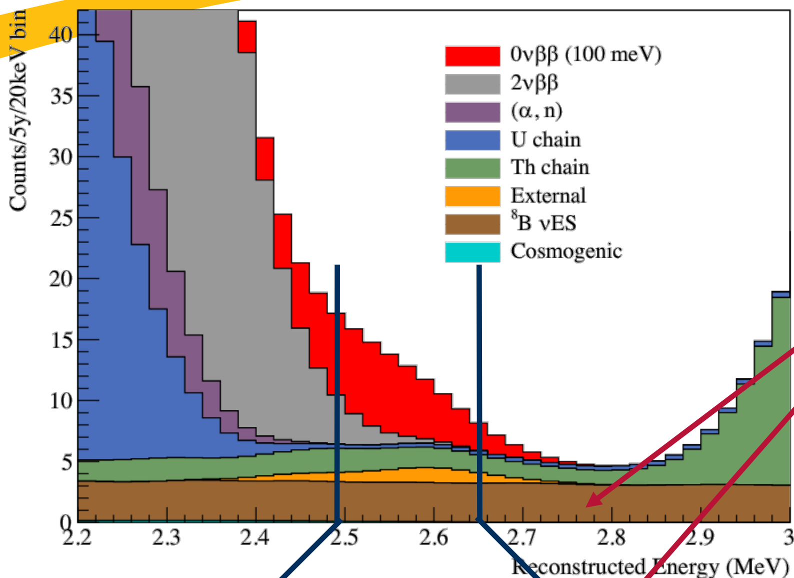
http://next.ific.uv.es/next/experiment/physics.html

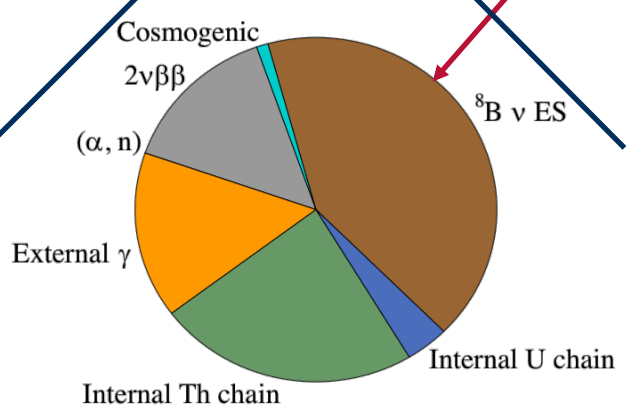


(a) Double beta decay ($2\nu\beta\beta$)

(b) Neutrinoless double beta decay ($0\nu\beta\beta$)

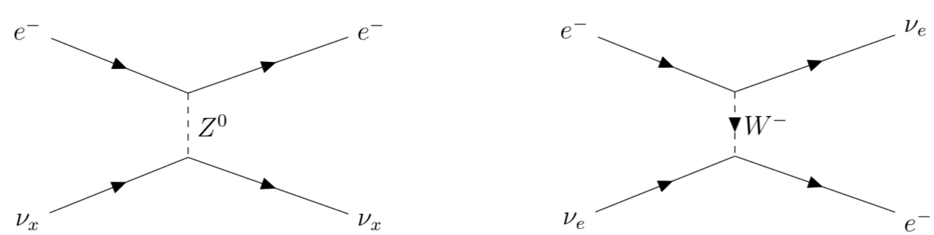
Solar Neutrinos as Background





SNO+ Document #5009

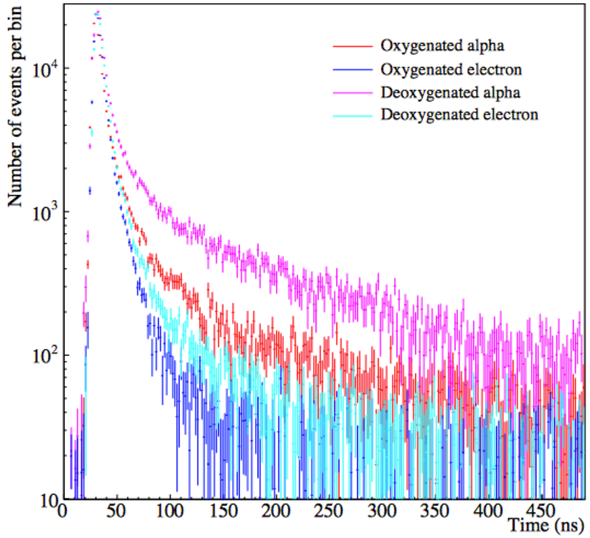
- Main background of SNO+
- Solar neutrinos interact and produce electron signals in the detector
- These look similar to DBD electron signals



Scintillation vs Cherenkov Light

Scintillation

- Emitted isotropically around electron
- Delayed light emission



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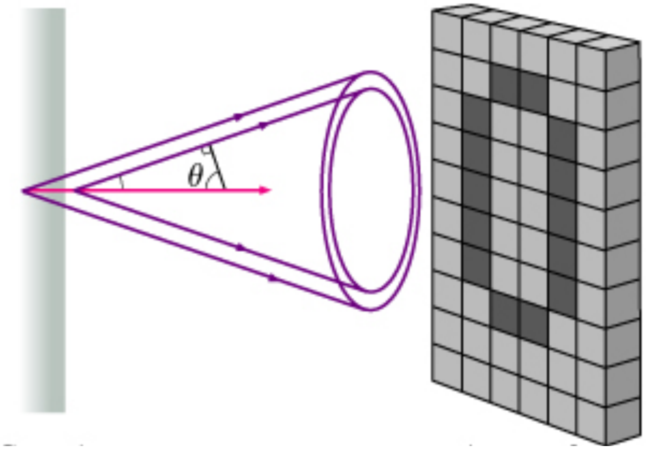
Cherenkov

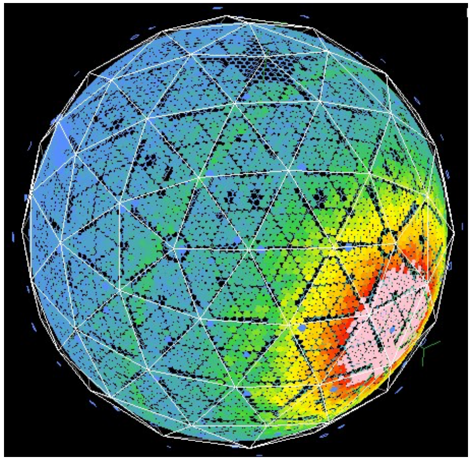
- Emitted in cone ahead of electron
- Prompt light emission

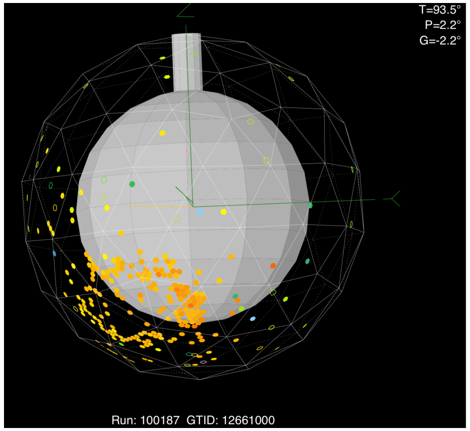


http://www.masteringphysicssolutions.net/wp-content/uploads/2013/03/MP_Ch22_Q15_1.jpg

Cherenkov/Scintillation Separation

- Cherenkov light is directional
- So if we can separate Cherenkov from scintillation, might be able to reconstruct direction of neutrinos
- Correlating this with the Sun's direction allows the solar neutrino background to be reduced





Motivation

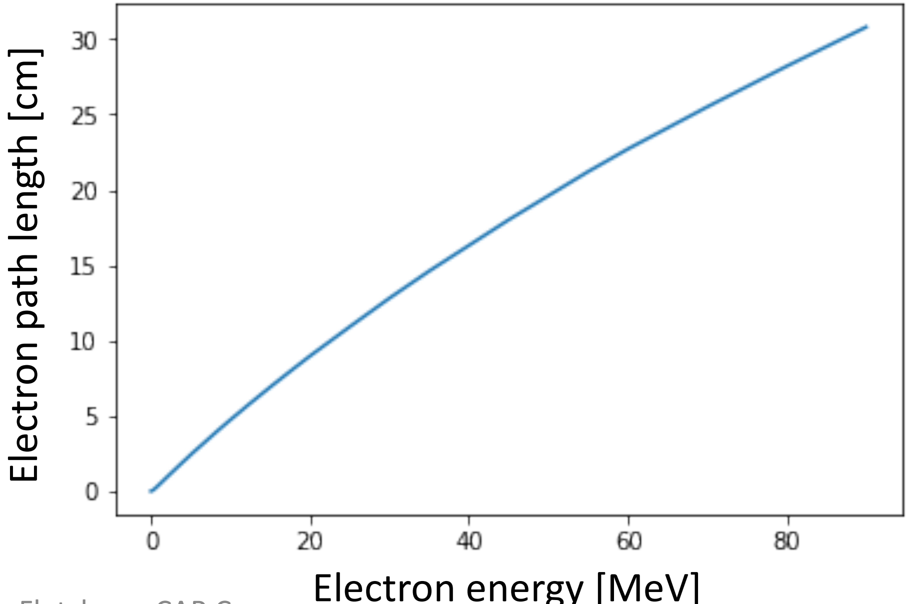
- Experiments have shown it is possible to separate scintillation and Cherenkov
  - Separation of cosmic muon light in LAB (Li et al. 2015)
  - CHESS experiment reported ~70% efficiency for identifying Cherenkov photons in LAB with 2g/L PPO (Caravaca et al. 2016)
- SNO+ collaborators have shown the same in simulations
  - RAT seems to indicate that we can separate scintillation from Cherenkov (Mottram 2014)
  - Separate simulation using GEANT4 was able to reconstruct positions of electrons in centre of liquid scintillator detector (Aberle et al. 2014)
- Other large liquid scintillator experiments don't use this technique… why?

Monte Carlo Simulation

- Simulate detector as sphere of LAB+PPO tiled with PMTs at surface
- Ignoring: AV, neck, PSUP
- Physics processes mainly based on RAT, GEANT4
- Very fast!
- Allows for easy modelling and changing of fundamental aspects of the problem

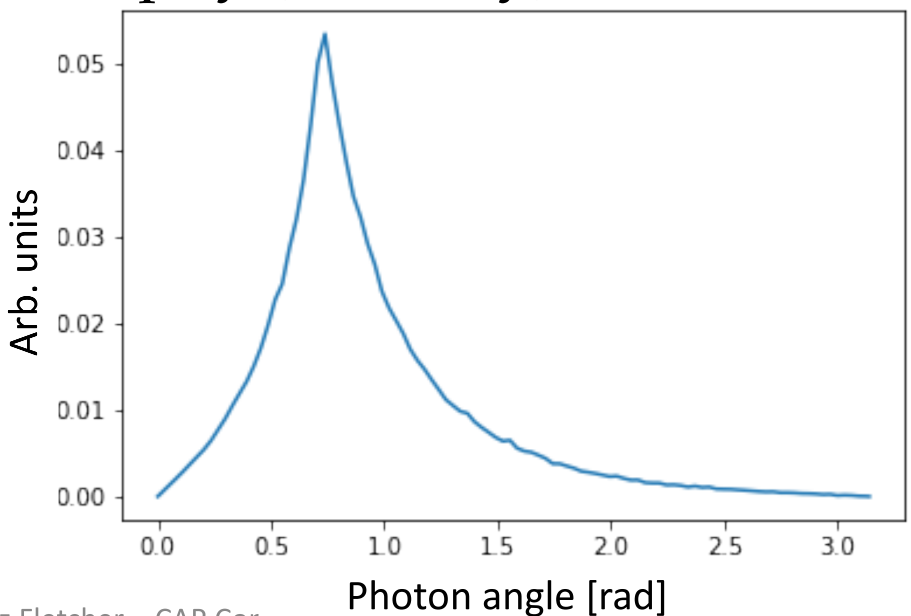
Electron Physics

- Electron launching and stepping
  - CSDA step length
  - No explicit multiple scattering
- Photons distributed uniformly along electron track



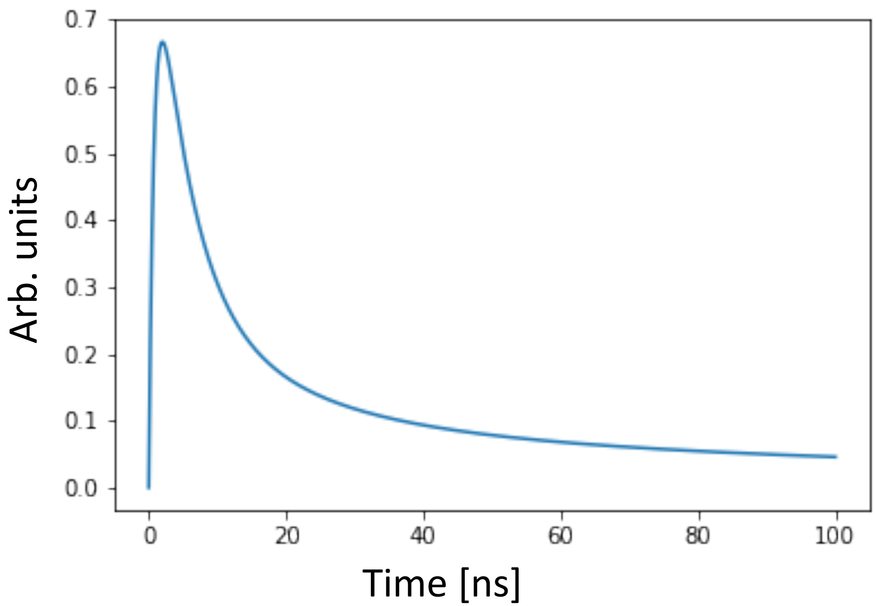
Cherenkov Physics

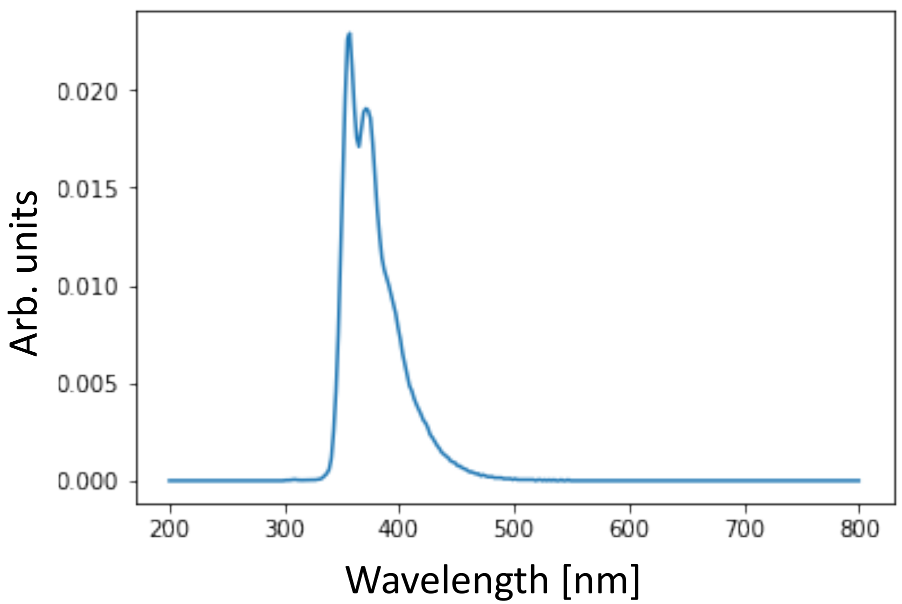
- Cherenkov photons distributed with angular distribution below relative to electron direction to account for multiple scattering
- Cherenkov photons emitted uniformly in azimuth
- Emitted promptly (no delay)



Scintillation Physics

- Uses measured scintillator cocktail time distribution, and measured emission spectrum
- Scintillation photons emitted isotropically about electron path





Photon Physics

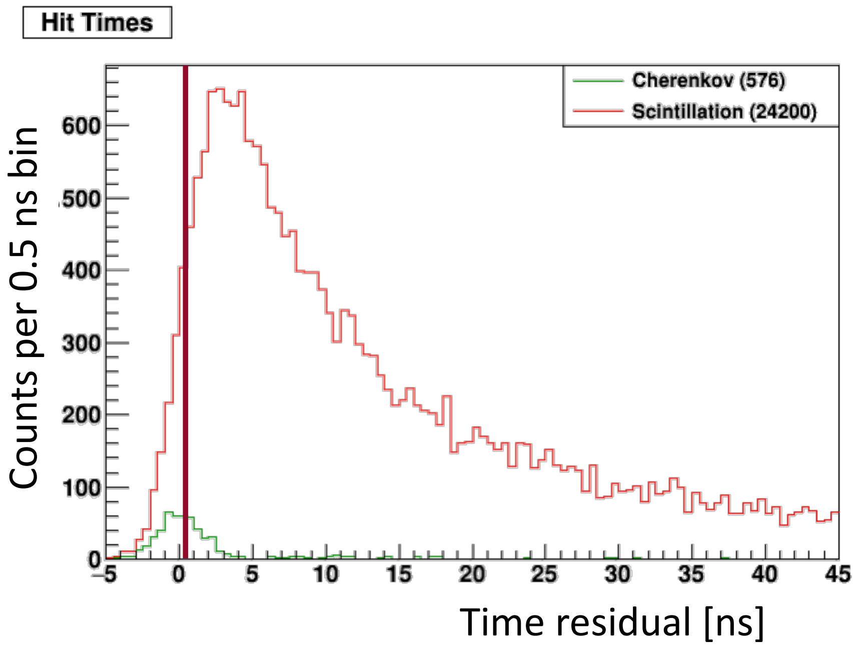
- Photon step length calculated using inverse distribution method
- Check to see if step reaches boundary
  - If so, detected
  - If not, determine if photon was scattered or absorbed
    - If scattered, step again
  - If absorbed, see if photon reemitted
    - If reemitted, step again
- If photon is detected, PMT timing resolution added
- All photons that reach the boundary are considered detected

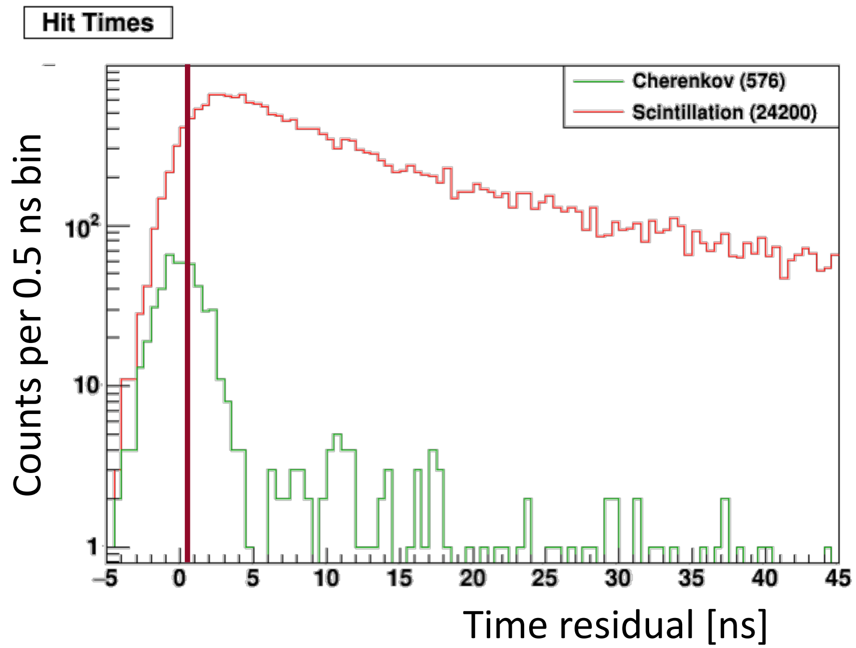
Fundamental Factors to Study

- Pixelization
  - Somewhat analogous to PMT coverage
- Scintillation timing
  - Slow scintillators can help to separate Cherenkov and scintillation distributions
- PMT time resolution
  - The better the resolution, the more separable the distributions

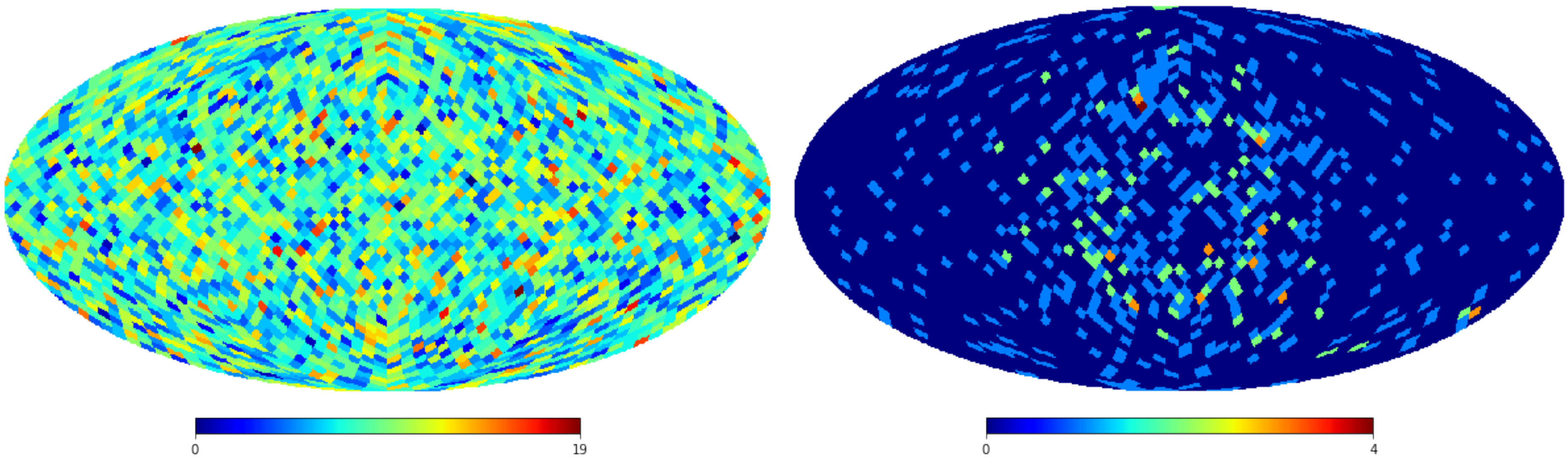
Timing

- First few ns are most Cherenkov-rich
- So cutting on first few ns helps to pick out Cherenkov-rich hits





Timing

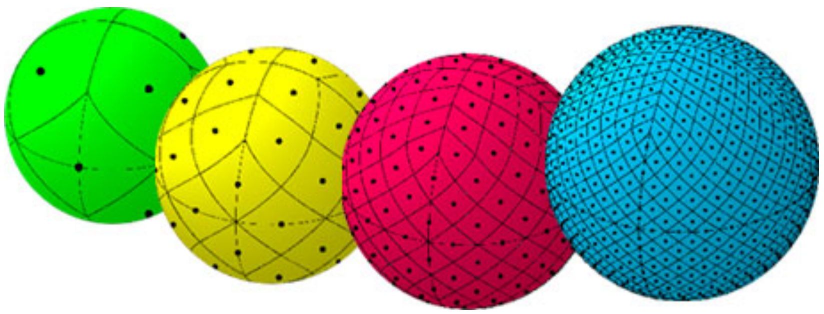


2.5 MeV event at (0,0,0) in (1,0,0) direction

Left: no time cut　　Right: t<0.5ns

Pixelization

- Found HEALPix, software from for CMB analysis[1]
  - Hierarchical, Equal Area, and iso-Latitude Pixelation
- Pixelization scheme for data on the sphere
- Also a few analysis tools (spherical harmonics, power spectra, etc)
- Each generated hit is binned into a pixel



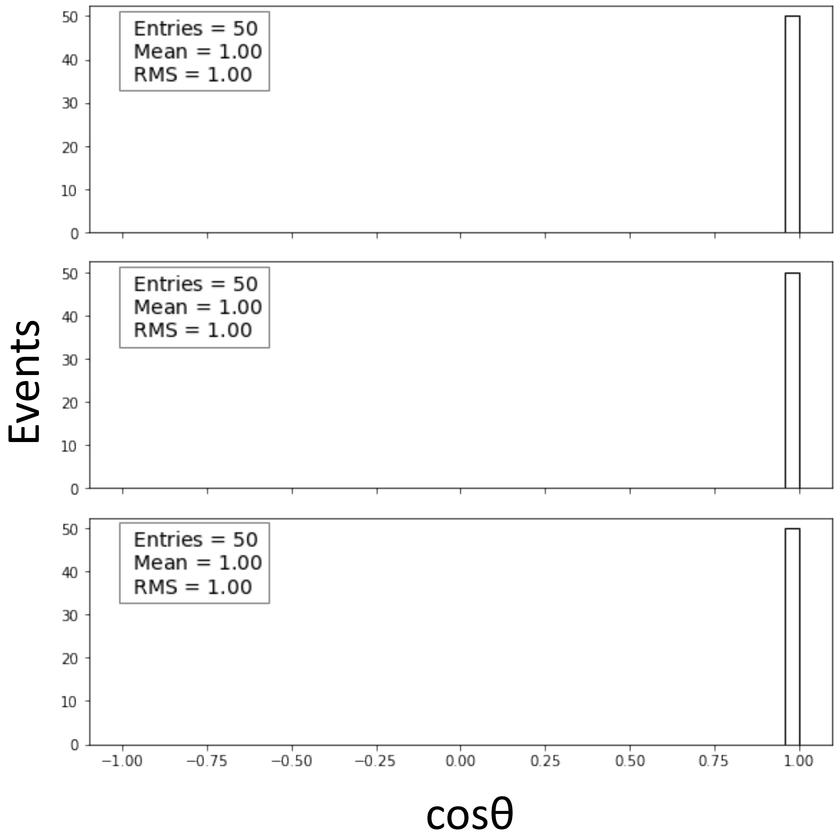
[1]K.M. Gorski et al., 2005, Ap.J., 622, p.759

Circle Fitting

- HEALPix has a function to find pixels inside disk defined by a vector and an angle
- Use this to find ring at Cherenkov angle ± 5°
- Count number of hits inside disk
- Repeat with each pixel as centre
- Ring with max number of hits is fitted direction

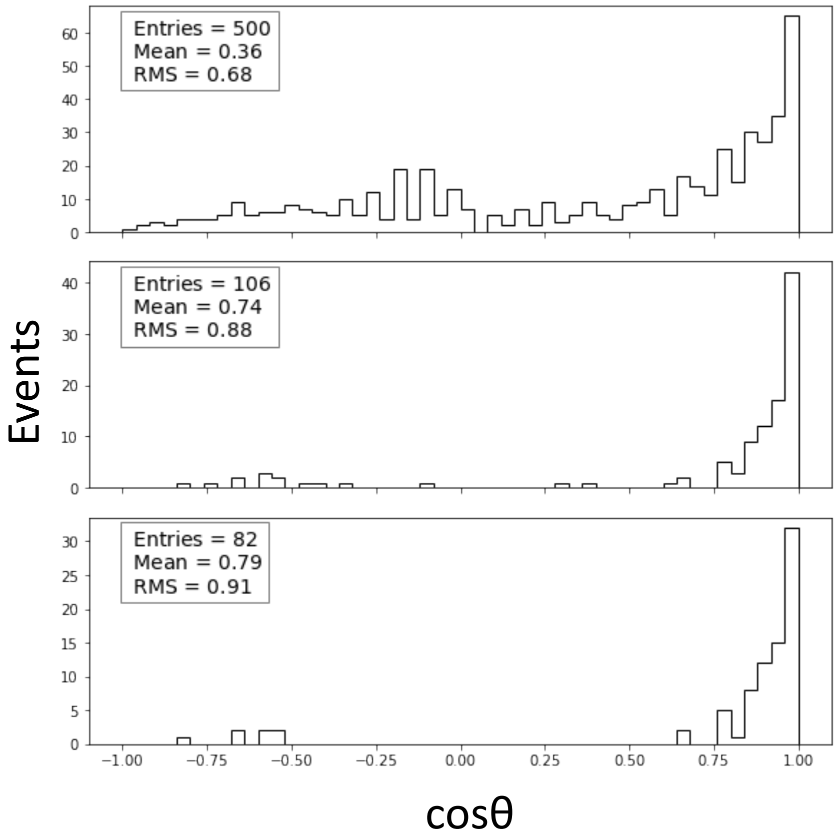
Circle Fitting

- 50 2.5MeV electrons launched at (0,0,0) with random directions
- Time cut of t < 0.5 ns
- Cut out events with number of ring hits < 60
- 100% of events pass both cuts
- 100% have accurate reconstructed position



Circle Fitting

- 500 2.5MeV electrons, random positions and (1,0,0) direction
- Time cut of t < 0.5 ns
- Fiducial volume cut of r < 3500 mm
- Cut out events with number of ring hits < 60
- 21% of events pass FV cut, 16% pass hits cut
- 83% cosθ >= 0.8, 67% cosθ >= 0.9



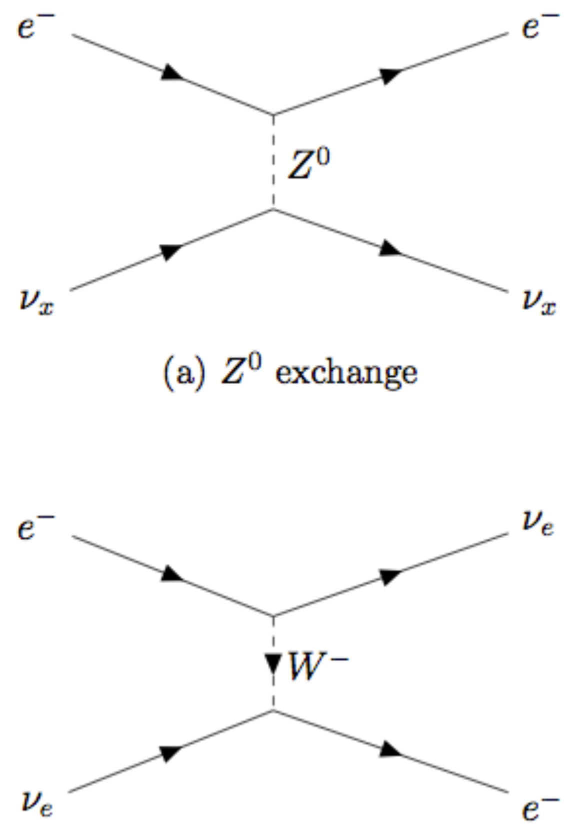
Next Steps…

- Look at dependence on energy, PMT quantum efficiency, PMT timing, pixel number/coverage
- Look at different scintillators e.g. slow fluors
- Compare to simulation results from SNO+ RAT

Questions?

SNO+ Signal

- Neutrinos scatter elastically off of electrons in the scintillator
- Then electrons interact with scintillator to produce light – scintillation and Cherenkov
- Same electron interactions as with electrons produced via $0\nu\beta\beta$ and $2\nu\beta\beta$



(a) Z^0 exchange

(b) W^- exchange

Is it Actually Possible?

- Seems possible theoretically, but no scintillator experiment has been able to do so in practice
- Is there something that makes SNO+ ″special″?

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LSND/MiniBooNE

LSND

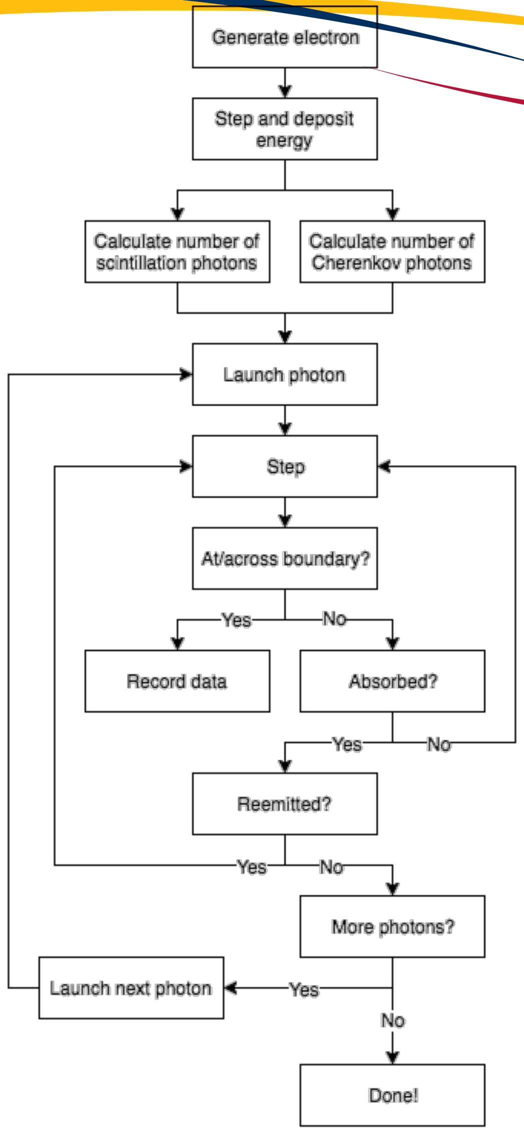
- Cylindrical detector using 167 tons of mineral oil and 0.031 g/l of b-PBD organic scintillator
- Mainly used Cherenkov/scintillation for particle identification
- Also reconstruction of vertex and angle

Athanassopoulos, C. et al. (1997). The liquid scintillator neutrino detector and LAMPF neutrino source. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 388(1–2), 149–172. https://doi.org/10.1016/s0168-9002(96)01155-2

MiniBooNE

- 12m diameter mineral oil Cherenkov detector
- Scintillation time constants on the order of ~20ns

MC


Generate electron
Step and deposit energy
Calculate number of scintillation photons
Calculate number of Cherenkov photons
Launch photon
Step
At/across boundary?
Yes
No
Record data
Absorbed?
Yes
No
Reemitted?
Yes
No
More photons?
Launch next photon
Yes
No
Done!

Electron Launching

- User can input starting position/direction or have them generated randomly
- Inputted or random starting energy
- Electron path length calculated from CSDA distribution

Scintillation Generator

- Mean number of scintillation photons:
$$N = Y * dE$$
- Y measured to be 11900 photons/MeV (Kaptanoglu et al. 2016)
- Then actual number gets calculated from a Poisson distribution
- Energy drawn for each photon from scintillation spectrum, then position chosen isotropically and stepped
- Delay time for each photon is chosen from hyperexponential distribution shown earlier

Cherenkov Generator

- Cherenkov angle is

$$\cos\theta = \frac{1}{n\beta}$$

- Given angular distribution to account for multiple scattering
- Distributed uniformly in azimuthal angle
- Photons emitted per unit length:

$$\frac{dE}{ds} = 370q^2\left[\epsilon_{max} - \epsilon_{min} - \frac{1}{\beta^2}\int_{\epsilon_{min}}^{\epsilon_{max}} \frac{d\epsilon}{n^2(\epsilon)}\right]$$ (GEANT, 2015)

Photon Propagation

- Photons propagated using the inverse distribution method
- Step size is:

$$s = \frac{ln\xi}{\frac{1}{L_s} + \frac{1}{L_{abs}}}$$

- Then calculate if this goes outside detector radius
- Then calculate if photon is scattered

$$p_s = \frac{L_s}{L_s + L_{abs}}$$

- If scattered, given new direction
- If absorbed, determine which component absorbed and whether reemitted given by comparing random number to reemission probability (0.59 for LAB and 0.8 for PPO)

Photon Propagation cont'd

- If reemitted, photon given new isotropic direction and energy chosen from reemission spectrum of material
- All numbers used in this are taken directly from RAT

REFERENCES

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M. Li, Z. Guo, M. Yeh, Z. Wang, S. Chen. Separation of Scintillation and Cherenkov Lights in Linear Alkyl Benzene. 30 Nov 2015. arXiv:1511.09339

M. Mottram. Survival of Cherenkov photons in the scintillator phase of SNO+ and implications for direction reconstruction. 30 Jan 2015. SNO+ Document #2906

K.M. Gorski et al., 2005, Ap.J., 622, p.759