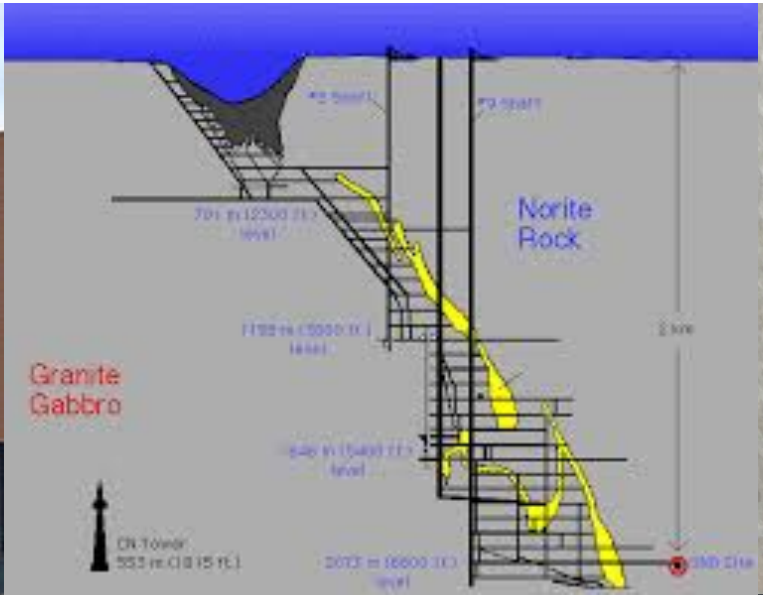
AmBe Source Calibrations in SNO+ Partial Scintillator Phase

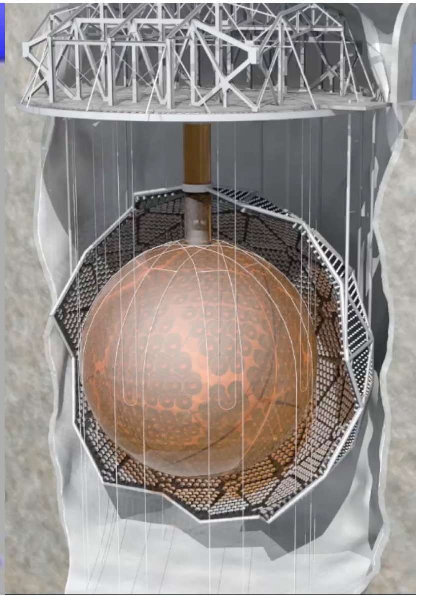
Ph.D. Candidate Jamie Grove

Supervisor: Dr. Christine Kraus

Introduction to SNO+

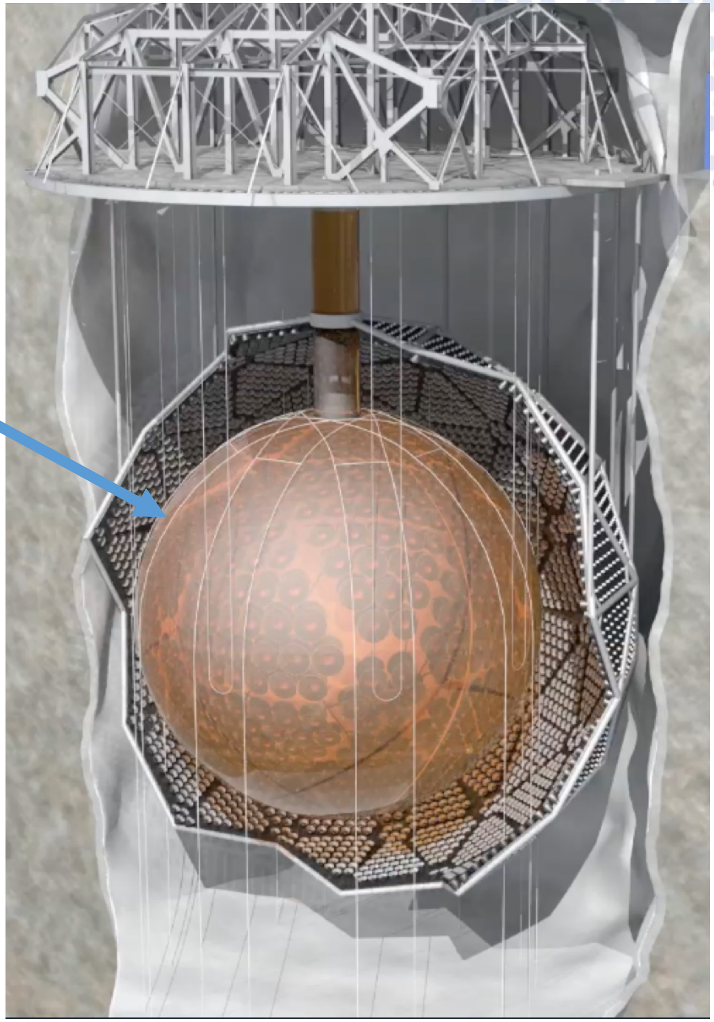
- SNO+ is located 2km underground (6000 w.m.e) in Creighton mine, Sudbury Ontario, Canada.
- The next generation of the Sudbury Neutrino Observatory (SNO).





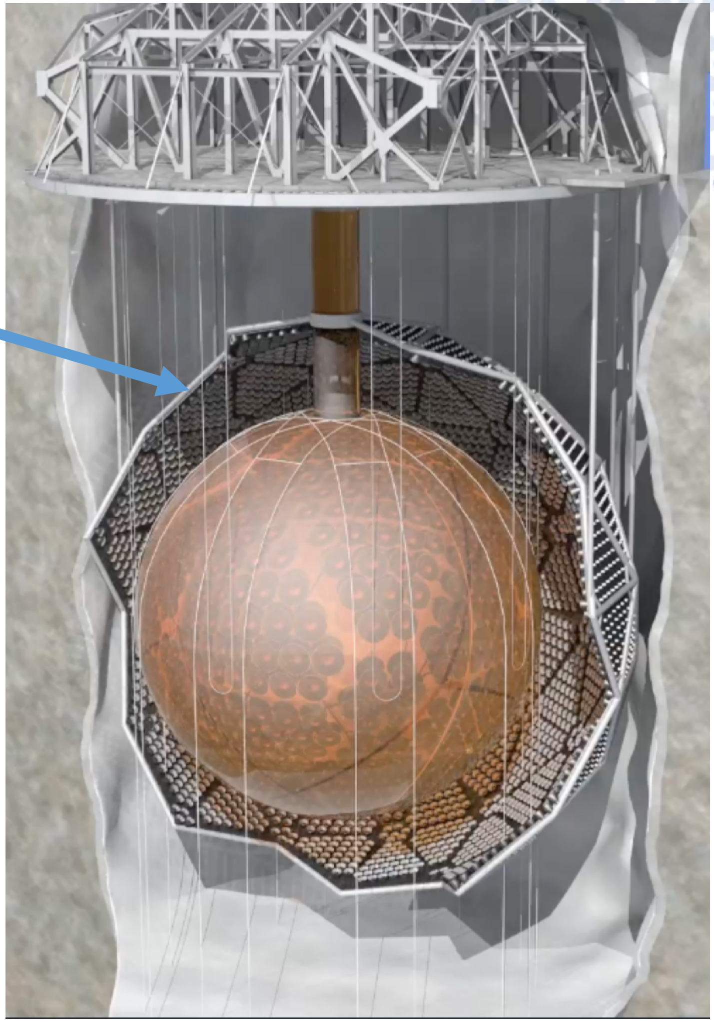
Introduction to SNO+

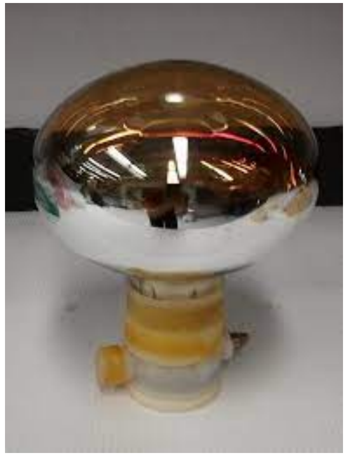
- 6m radius acrylic vessel (AV)

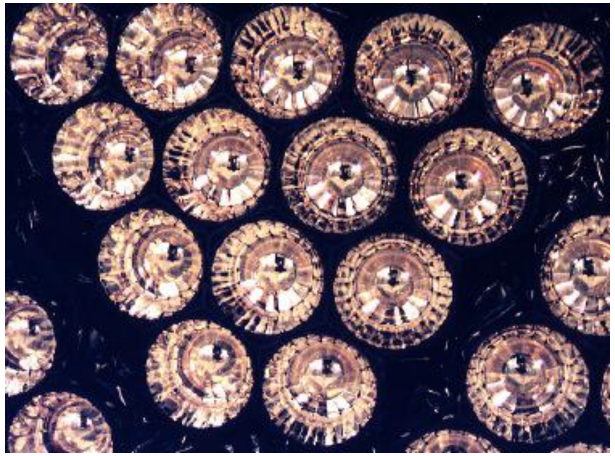


Introduction to SNO+

- 6m radius acrylic vessel (AV)
- 9m radius stainless steel structure, which houses ~9600 PMTs (PSUP)

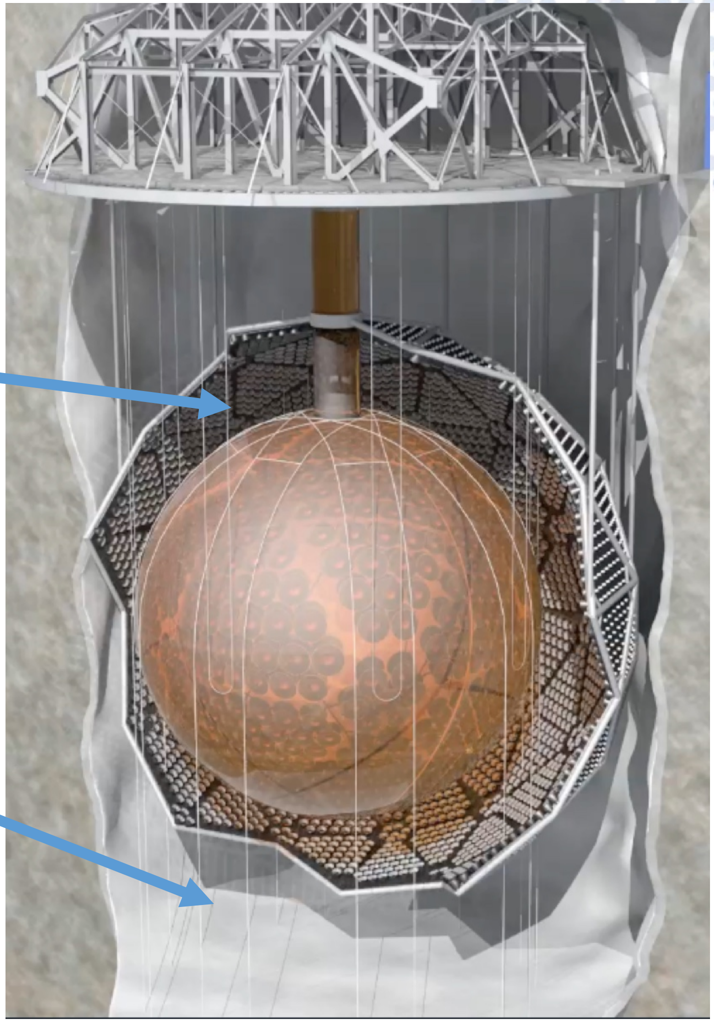






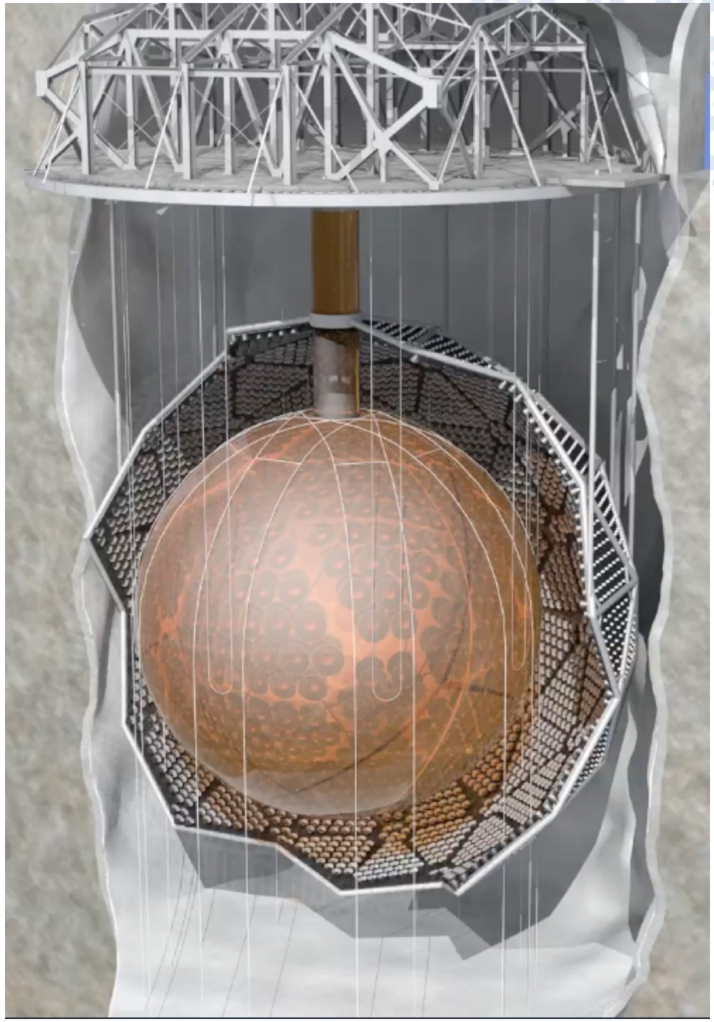
Introduction to SNO+

- 6m radius acrylic vessel (AV)
- 9m radius stainless steel structure, which houses ~9600 PMTs (PSUP)
- 1700 tonnes of inner shielding ultra-pure water (UPW)
- 5300 tonnes outer shielding UPW in the 26m tall by 22m length SNO cavern lined with Urylon



Introduction to SNO+: SNO+ Goals and Phases

- Nucleon decay
- Water detection of reactor antineutrinos
- Low energy solar neutrinos (pep and CNO cycles)
- Geo and reactor antineutrinos
- Supernova
- Scintillator calibration and verification of scintillator optical model and detector response
- $0\nu\beta\beta$-decay of ^{130}Te



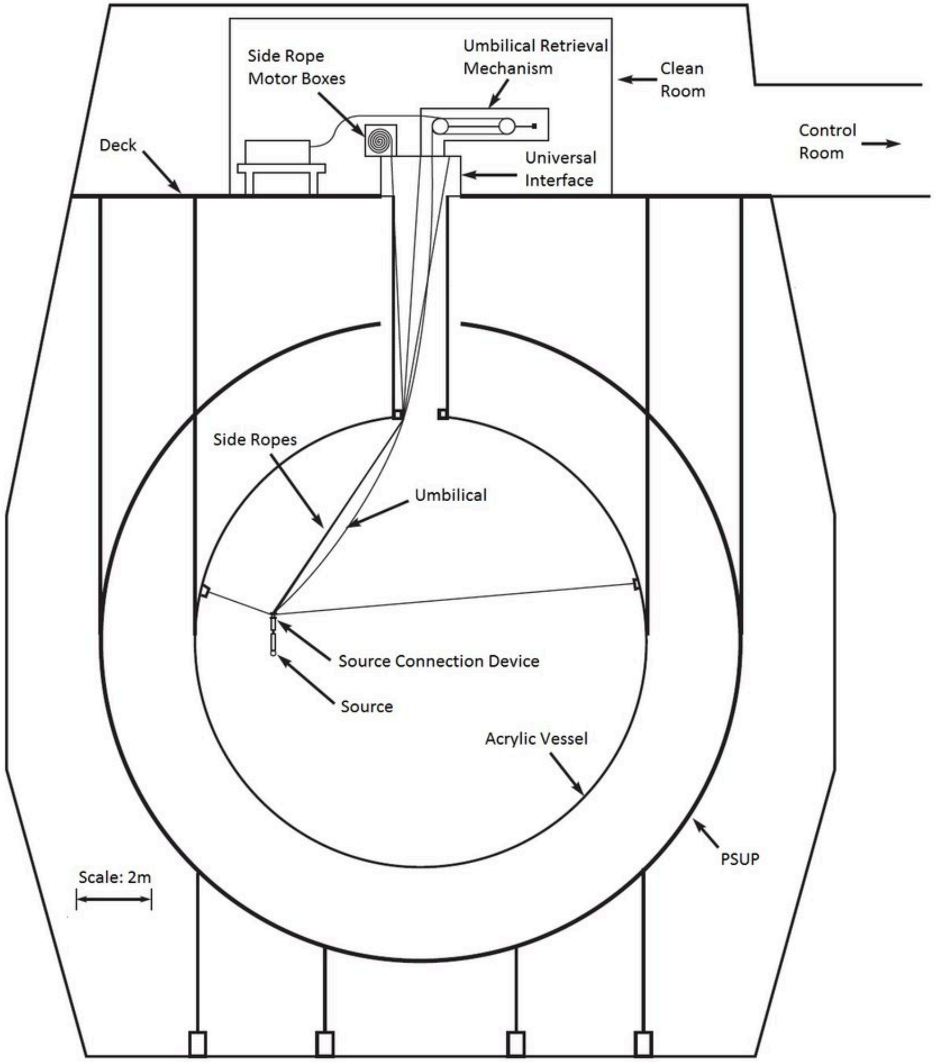
Introduction to Calibrations in SNO+

Calibration goals:

- Validate response at energies for $0\nu\beta\beta$-decay, low energy solar neutrinos, reactor antineutrinos, and geoneutrinos
- Validate position reconstruction
- Quantify PMT response and timing

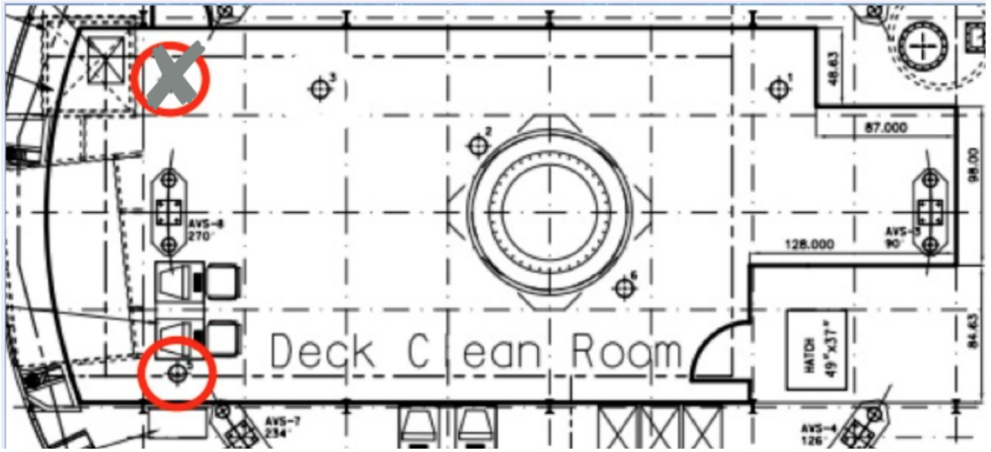
- Accomplished via optical and radioactive source deployments, both internally and externally.

Introduction to Calibrations in SNO+



[1] Matthew R. Walker

- Internal source deployments are done via a system of ropes and the umbilical retrieval mechanism (URM).
- Umbilical cable caries optical fibers, gas tubes, and wires for the PMTs for tagged source.
- Source position is adjusted using the side ropes.



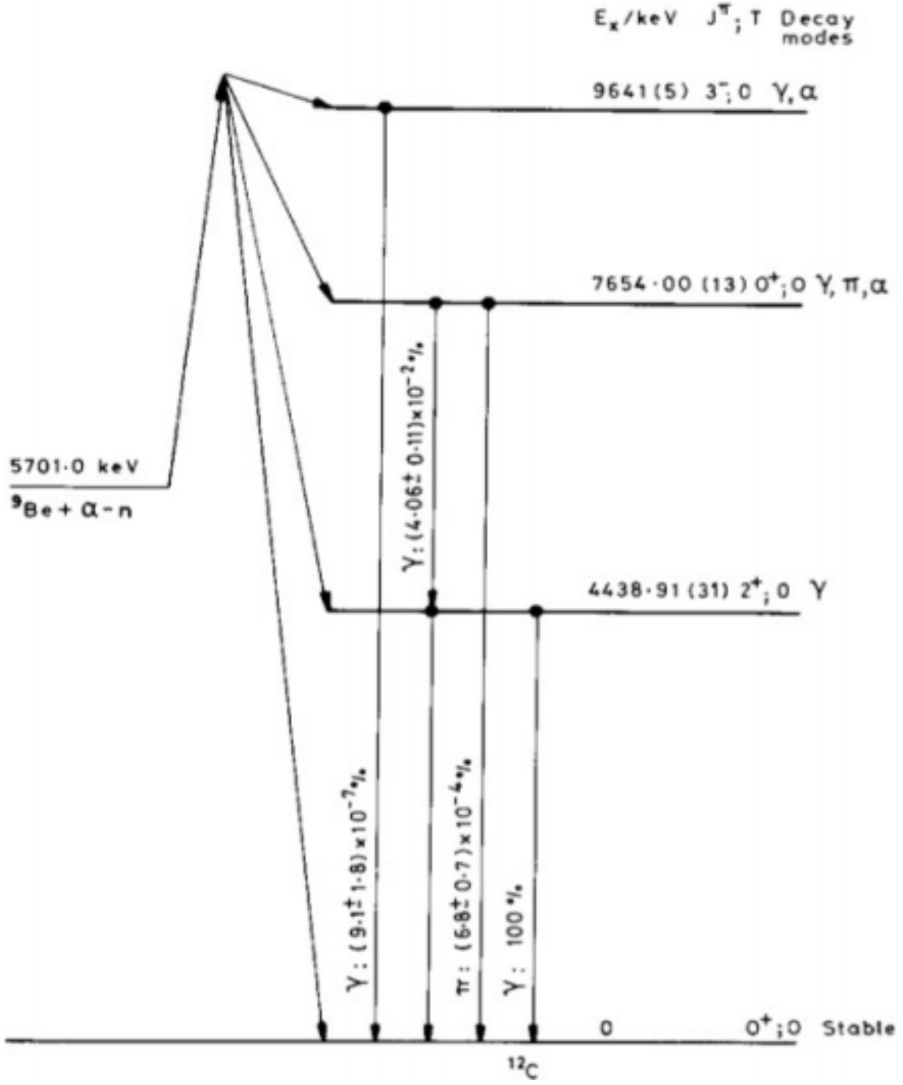
- External deployment carried out via guide tubes that pass outside the AV.

AmBe Source Signal

- ^{241}Am decays via α emission
- The α induces a ^{9}Be(α, n)^{12}C reaction

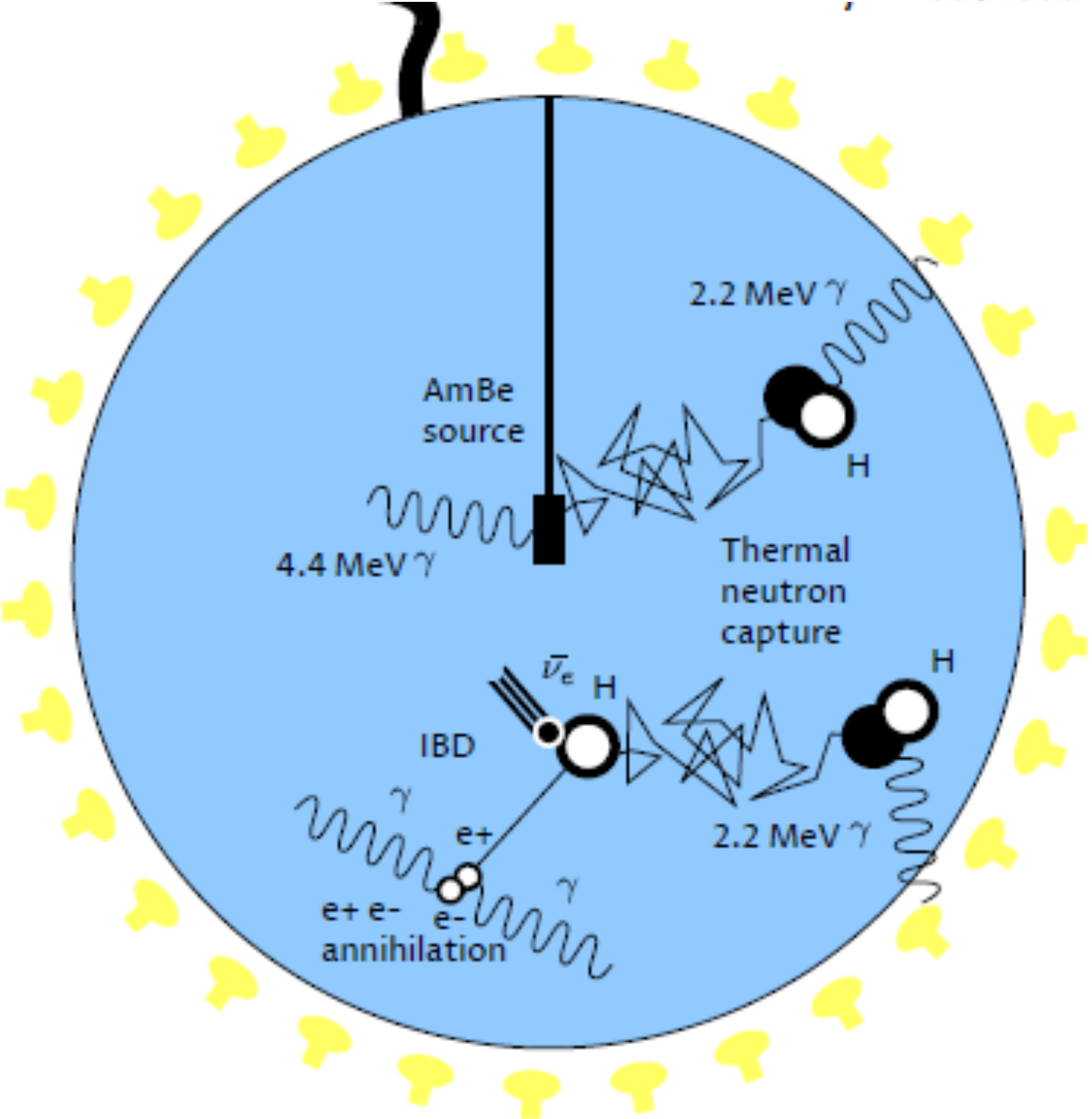
$$^{9}\mathrm{Be} + \alpha \rightarrow n + ^{12}\mathrm{C}^{*}$$

- The ^{12}C* de-excites and produces a 4.4 MeV γ ~60% of the time.
- Neutron is thermally captured on a hydrogen atom and produces a 2.2 MeV γ



AmBe Source Signal

- 4.4 MeV γ is released within ns
- 2.2 MeV γ is released ~$200\mu s$
- Able to use a coincidence trigger on the time difference, Δt, between the 4.4 MeV γ and the 2.2 MeV γ of the captured neutron.

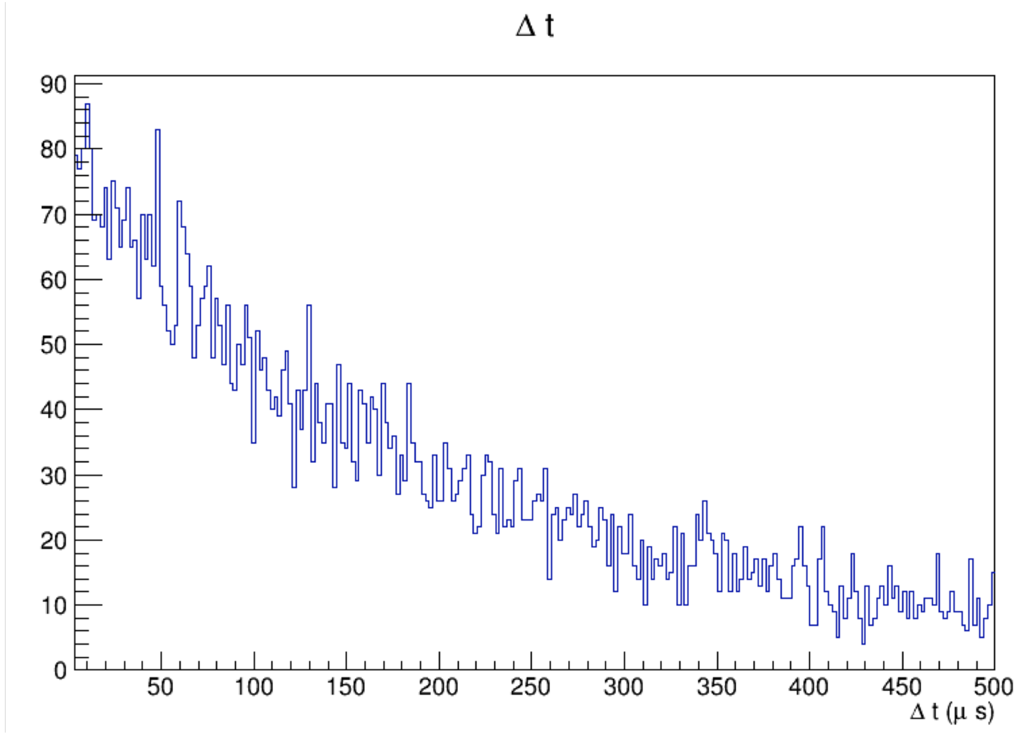


AmBe Source Partial Scintillator Deployments

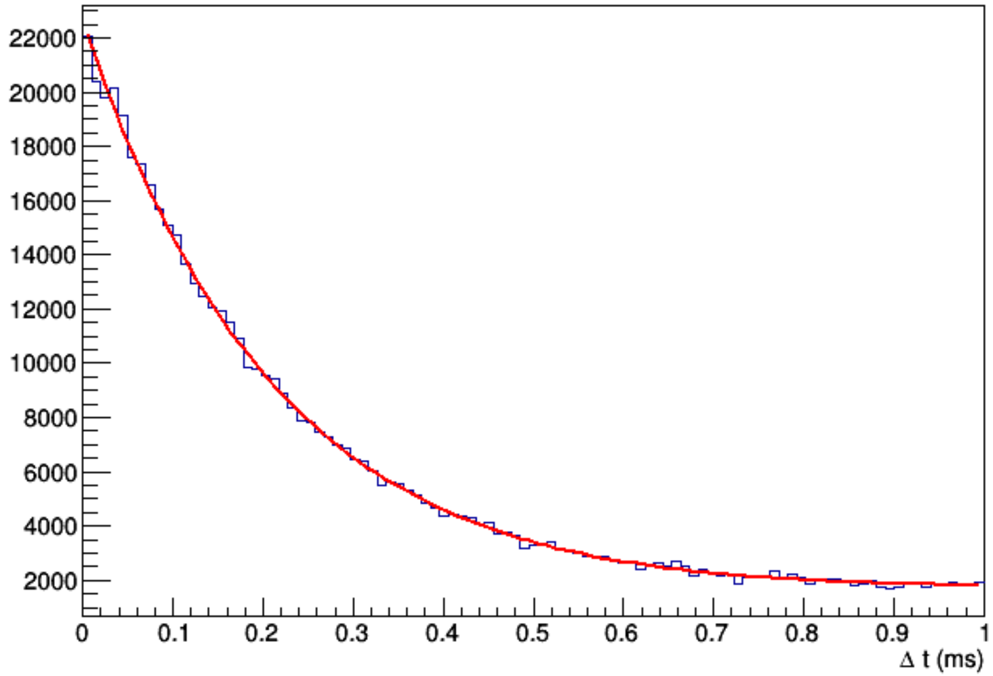
Date	# of runs	Deployed	Scintillator
January 15, 2020	17	External	Partial (~20%)
January 16, 2020	7	External	Partial (~20%)
August 4, 2020	3	External	Partial (~50%)
August 18, 2020	12	External	Partial (~50%)
September 15, 2020	5	External	Partial (~50%)
September 16, 2020	7	External	Partial (~50%)
April 23, 2021	6	External	Full
May 22, 2021	8	External	Full

Detector Response: Neutron Capture Time

Partial Scintillator Deployments



Water Data



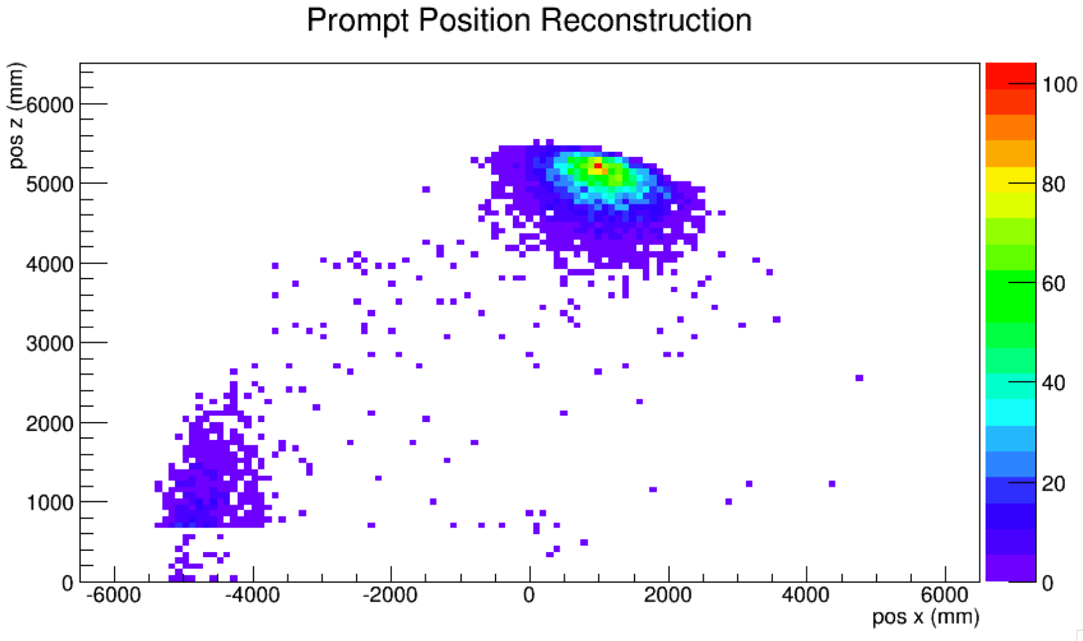
$$F(\mathrm{t}) = N \cdot R_1(P \cdot E \cdot (\lambda + R_2)e^{-(\lambda+R_2)\mathrm{t}} + (1 - P \cdot E) \cdot R_2 e^{-R_2\mathrm{t}})$$

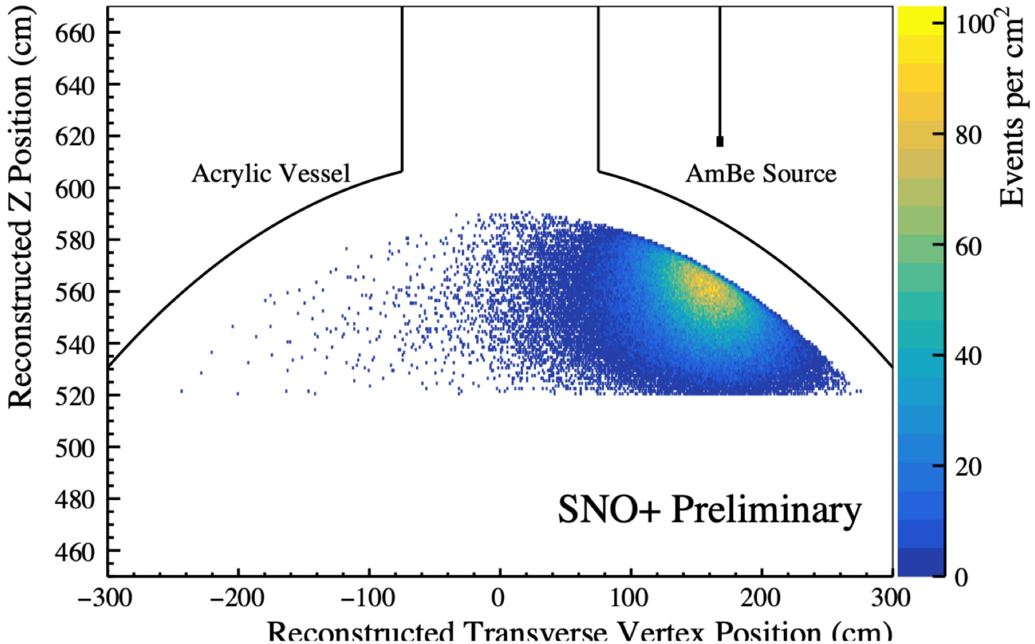
Water Data results: Neutron capture time of 208.2 μs

Neutron detection efficiency of 46%

[2] Yan Liu et al.

Detector Response: Position Reconstruction





[3] Ryan Bayes

- Validation of position reconstruction.
- Analysis project:
  - Bayesian analysis to calculate the AmBe source rate at different positions
    - Neutron detection efficiency
    - Branching ratio of the ^{12}C de-excitation
    - Cross sectional area of detector to flux from AmBe source
    - AV refractive index
  - AmBe source strength is ~1683 kBq and 62 Hz neutron rate

$$^{9}\text{Be} + \alpha \rightarrow n + {}^{12}\text{C}^{*}$$

SNOLAB Future Work

- Position reconstruction validation
  - Quantifying PMT timing offset, hit time residuals
- Nhit distributions and light yield studies
  - PPO concentration proportional to the # photons / MeV
  - Energy reconstruction
- Cross section of neutron capture on hydrogen and carbon
- Potential Cherenkov light
  - Potential for directional analysis
  - Understanding the mechanisms of $0\nu\beta\beta$-decay

Conclusion

- Multiple deployments of the AmBe source externally during the partial and full scintillator phase.
- Look into the analysis of the mean capture time, and neutron detection efficiency.
- Verification of the position reconstruction
  - AmBe source rate calculation at various source positions
- Framework of future analysis

References

[1] – *Calibration Hardware Research and Development for SNO+,* Matthew R. Walker

https://www.researchgate.net/publication/262911707_Calibration_Hardware_Research_and_Development_for_SNO

[2] – *Neutron Detection in the SNO+ Water Phase,* Y. Liu, J. Grove et al. (for the SNO+ Collaboration)

https://arxiv.org/abs/1808.07020

[3] – *Status of the SNO+ Experiment, talk at CAP 2021, TS4-2 June 8,* Ryan Bayes

https://indico.cern.ch/event/985448/contributions/4295799/

[4] - *Calibration of the SNO+ experiment,* J. Maneira et al. (for the SNO+ Collaboration)

https://iopscience.iop.org/article/10.1088/1742-6596/888/1/012247

[5] - *Multi-site Event Discrimination in Large Liquid Scintillation Detectors,* Jack Dunger and Steven D. Biller

https://arxiv.org/abs/1904.00440

[6] - *Development, characterisation, and deployment of the SNO+ liquid scintillator,* Ben Tam and the SNO+ Collaboration

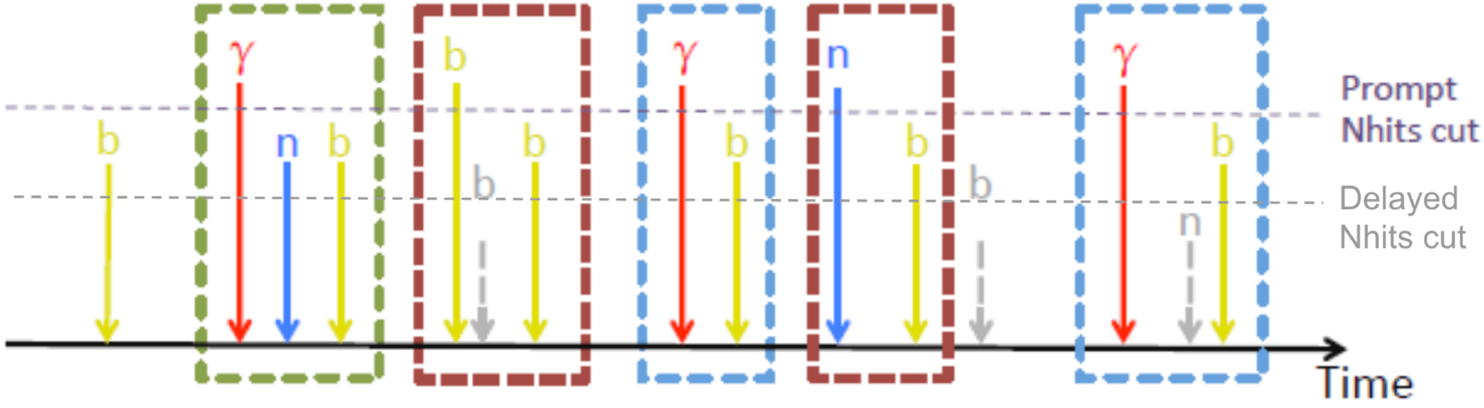
https://iopscience.iop.org/article/10.1088/1748-0221/16/05/P05009/pdf

[7] – *Status of Juno Experiment, talk at International Workshop on Neutrino Telescopes, 2019,* A. Paolini

https://indico.cern.ch/event/768000/contributions/3275073/attachments/1815708/2967448/Paoloni_JUNO.pdf

Extra Slides

Fitting Neutron Capture Time, Δt



$$F(\mathrm{t}) = N \cdot R_1(P \cdot E \cdot (\lambda + R_2)e^{-(\lambda+R_2)\mathrm{t}} + (1 - P \cdot E) \cdot R_2 e^{-R_2\mathrm{t}})$$

N: Normalization (run time × histogram binning)

R_1: Rate of single candidate prompt events

P: Probability of selecting a true 4.4 MeV γ, $P(\gamma|4.4MeV)$

E: Neutron detection efficiency

$\implies P \cdot E$: Neutron capture efficiency

λ: Neutron capture time

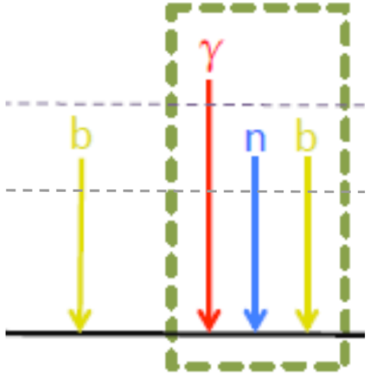
R_2: Rate of single candidate delayed events

Fitting Neutron Capture Time, Δt

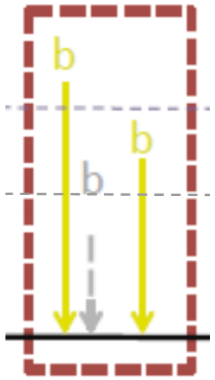
$$F(\mathrm{t}) = N \cdot R_1 \left(P \cdot E \cdot (\lambda + R_2) e^{-(\lambda+R_2)\mathrm{t}} + (1 - P \cdot E) \cdot R_2 e^{-R_2 \mathrm{t}}\right)$$

$$P \cdot E \cdot \lambda e^{-(\lambda+R_2)\mathrm{t}}$$

True – True event



Fake – Fake event

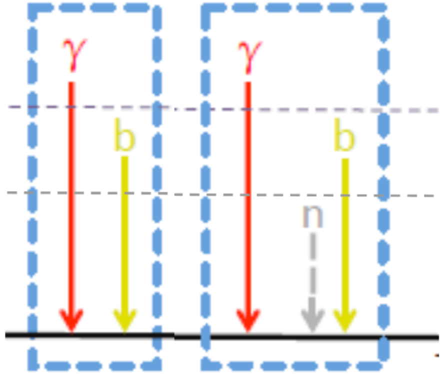


Fitting Neutron Capture Time, Δt

$$F(t) = N \cdot R_1(P \cdot E \cdot (\lambda + R_2)e^{-(\lambda+R_2)t} + (1 - P \cdot E) \cdot R_2 e^{-R_2 t})$$

$$P \cdot E \cdot R_2 e^{-(R_2+\lambda)t}$$

True – Fake event



Introduction to Calibrations in SNO+

- SNO+ has a number of installed and deployed calibration sources.
  - Installed: A LED light-injection system via installed optical fibres on the PSUP.
  - Deployed: A variety of optical and radioactive sources.

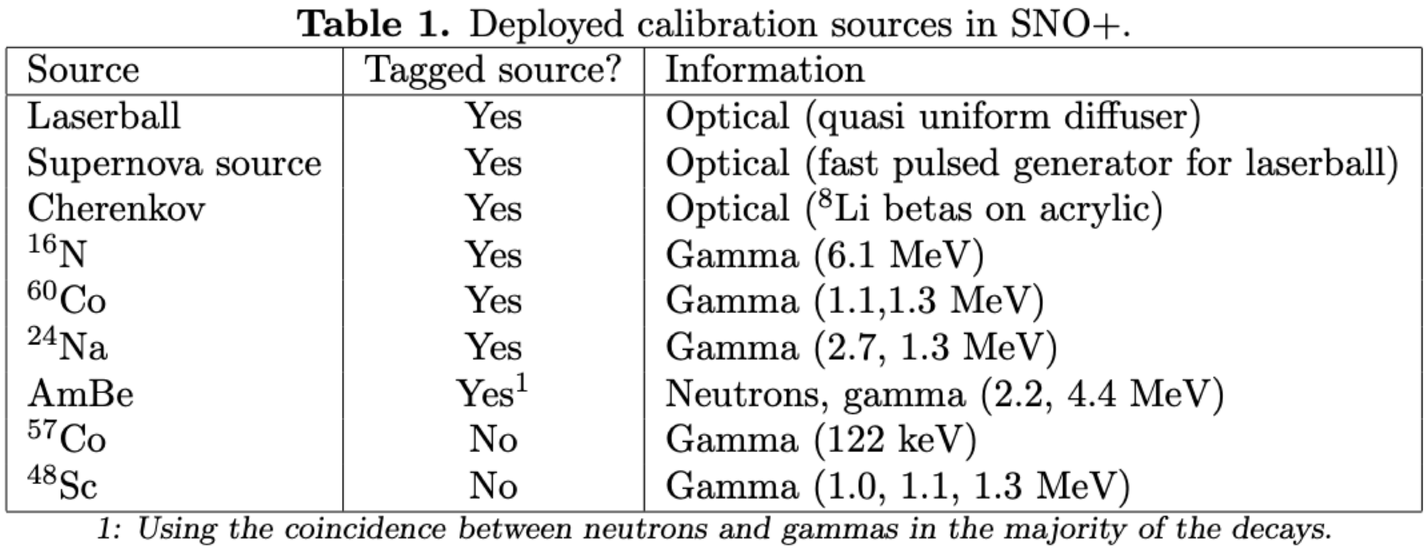


Table 1. Deployed calibration sources in SNO+.

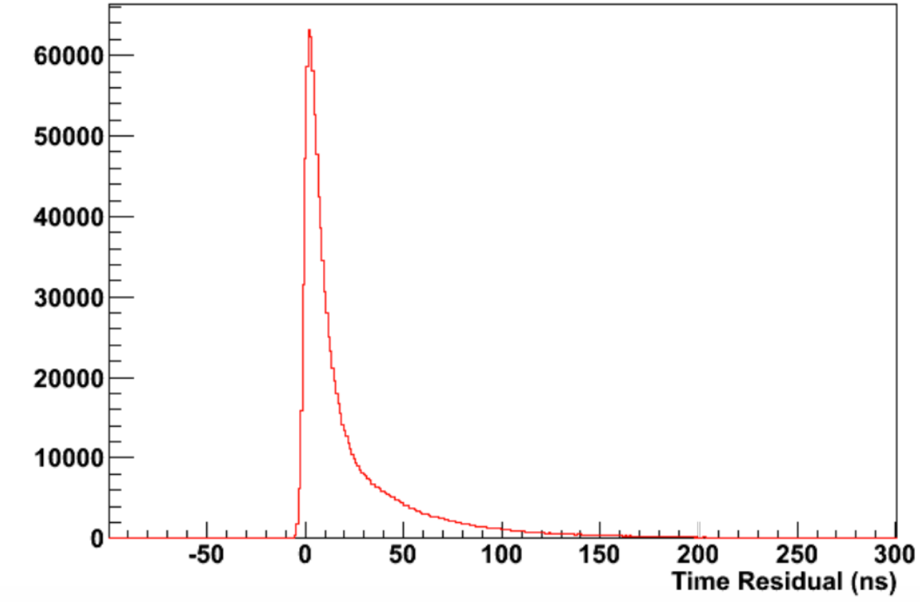
Source	Tagged source?	Information
Laserball	Yes	Optical (quasi uniform diffuser)
Supernova source	Yes	Optical (fast pulsed generator for laserball)
Cherenkov	Yes	Optical (^{8}Li betas on acrylic)
^{16}N	Yes	Gamma (6.1 MeV)
^{60}Co	Yes	Gamma (1.1,1.3 MeV)
^{24}Na	Yes	Gamma (2.7, 1.3 MeV)
AmBe	Yes[1]	Neutrons, gamma (2.2, 4.4 MeV)
^{57}Co	No	Gamma (122 keV)
^{48}Sc	No	Gamma (1.0, 1.1, 1.3 MeV)

1: Using the coincidence between neutrons and gammas in the majority of the decays.

[4] J Maneira et al

Detector Response: Hit Time Residuals

- Hit time residuals are critical to
  - Position reconstruction validation (event fitting, vertex fitting).
  - Background rejection (single site vs, multi-site deposition).
- Time offset of each PMT is caused by individual delays in the electronics.



$$t^i_{res} \equiv t^i_{hit} - t_0 - t^i_{flight}$$

t_0 - global event time, relative to the trigger
t_{hit} - hit time
t_{flight} - calculated time of flight, using the maximum likelihood position fit and vertex fitters on energy depositions

[5] Jack Dunger and Steven D. Biller

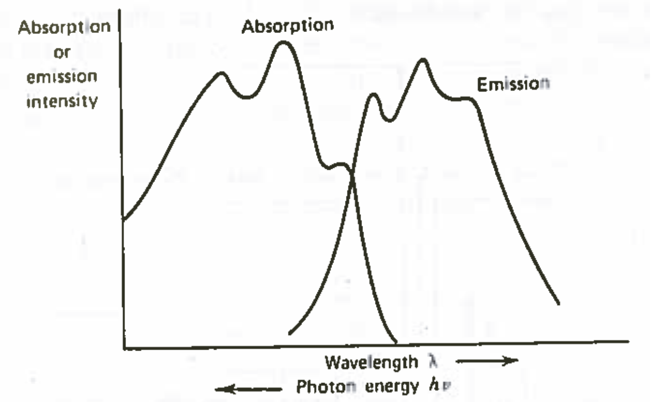
Scintillation Light

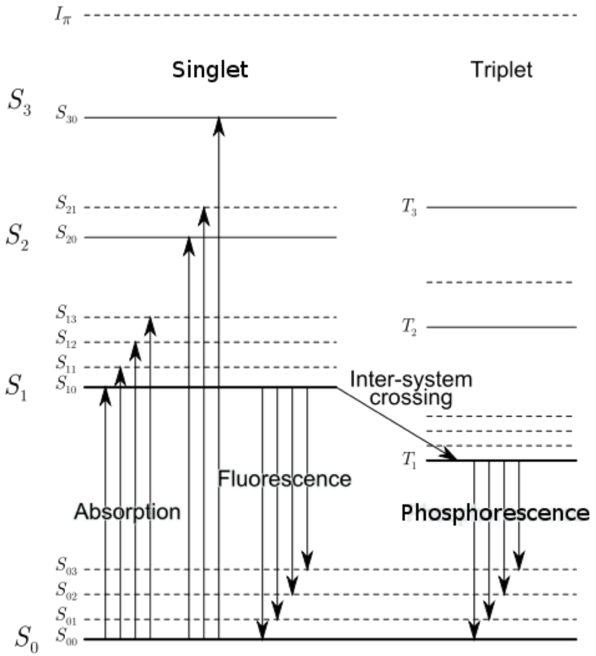
- Scintillator phase: 780 tonnes Linear Alkyl Benzene (LAB) and ~2g/L 2,5-diphenyloxazole (PPO)
  - It's long time stability
  - Compatibility with the acrylic
  - High purity levels
  - Long attenuation and scattering length
  - High light yield
  - Linear response in energy
  - High flash point
  - Environmentally safe (non-toxic)
  - PPO advantage of low light absorption of metals in region of interest for $0\nu\beta\beta$-decay

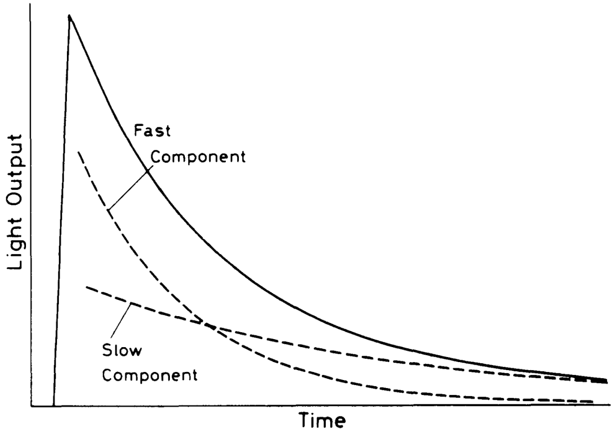
[6] Ben Tam, SNO+ collaboration

Scintillation Light

- Scintillator phase: 780 tonnes LAB and ~2g/L (PPO)
- Emission mechanism that depends on the excitation and subsequent deexcitation of benzene rings
- The structure has singlet (S_0, S_1, ..) and triplet states (T_1, T_2, …)
- The singlet de-excitation and subsequent fluorescence is fast (nsec).
- Goal: maximize light yield and transparency, optimize emission times, minimize self-absorption, and tune the emission spectra to match the quantum efficiency curves of the observing PMTs







[7] A. Paoloni, Juno Experiment