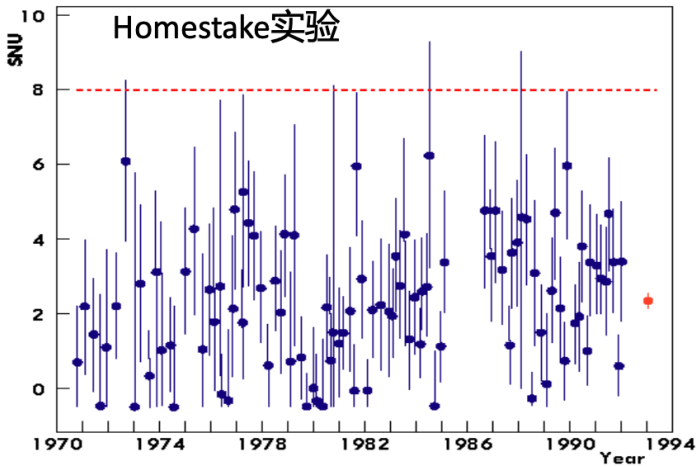
Event-by-Event Direction Reconstruction of Solar Neutrinos in a High Light-Yield Liquid Scintillator

张洋　山东大学

2024. 01. 20

Who is SNO?

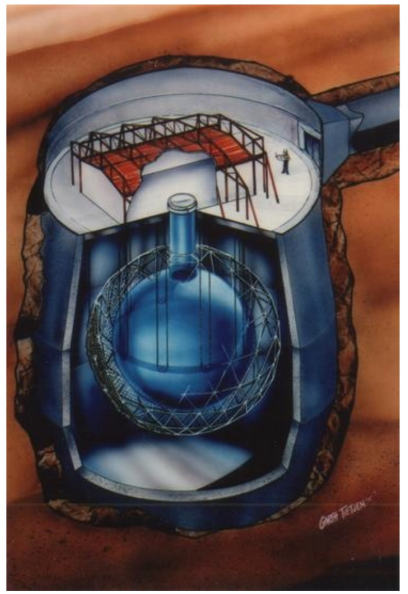
$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$



首次观测到太阳中微子，但与预期不符！

$$\text{CC: } \nu_e + d \rightarrow p + p + e^- - 1.442\,\text{MeV}$$
$$\text{NC: } \nu_x + d \rightarrow p + n + \nu_x - 2.224\,\text{MeV}$$
$$\text{ES: } \nu_x + e^- \rightarrow \nu_x + e^-$$

Herbert H. Chen（陈华生）
(1942 - 1987)



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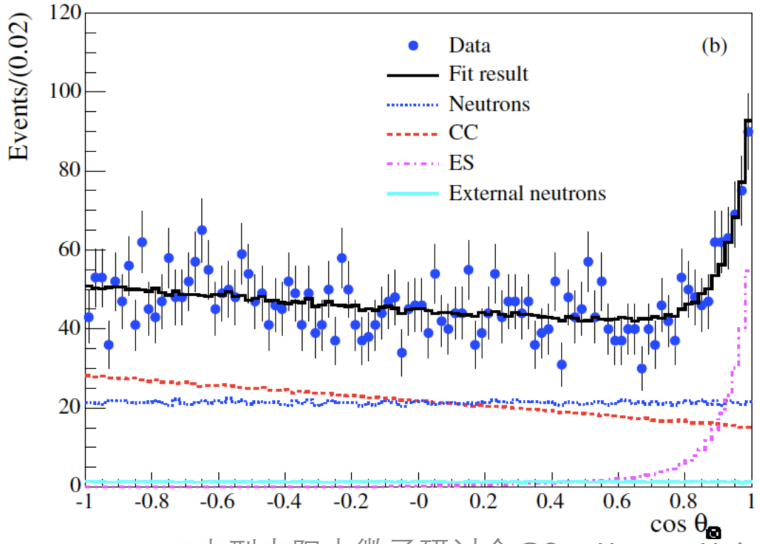
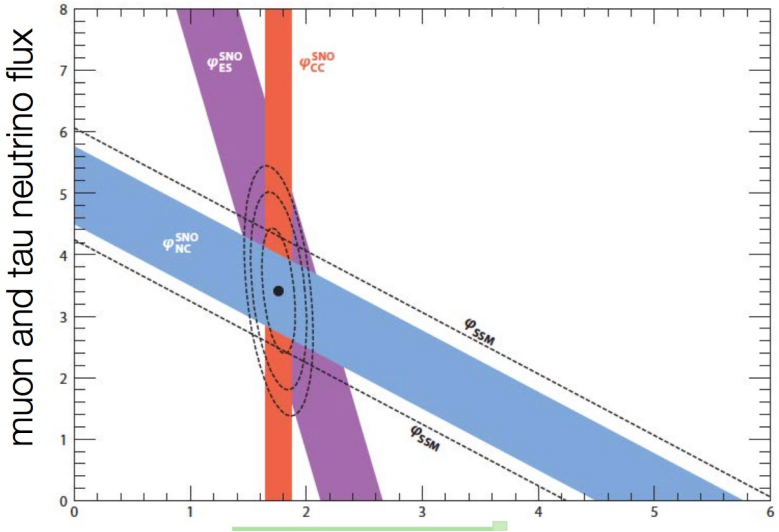
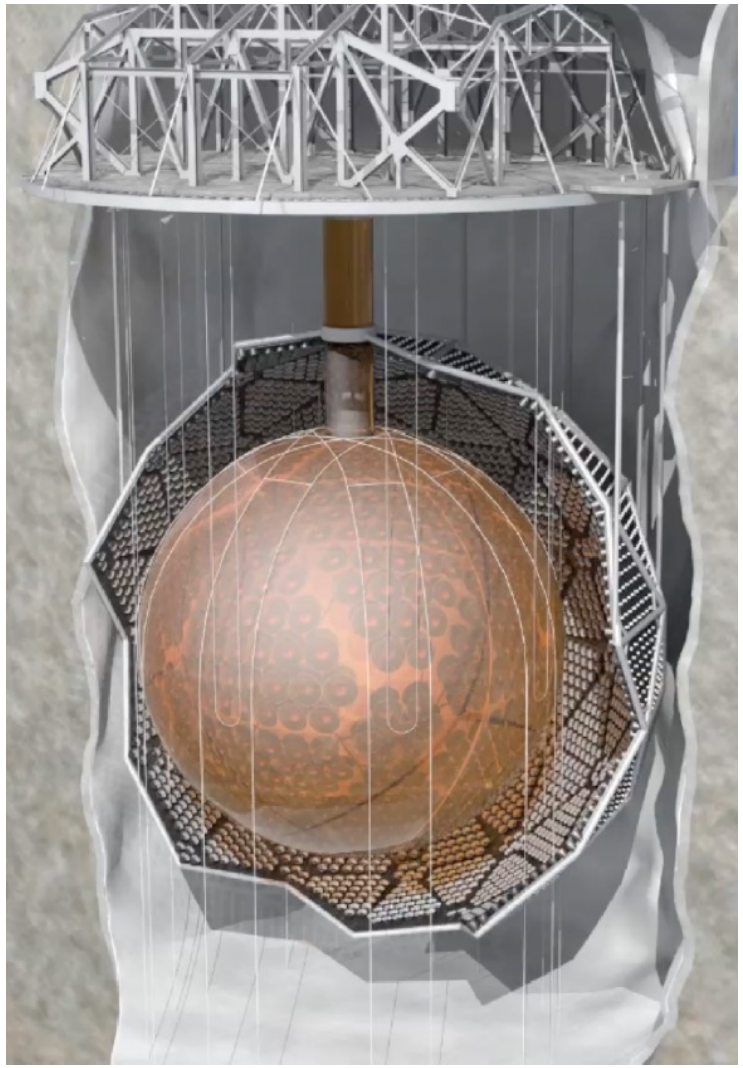
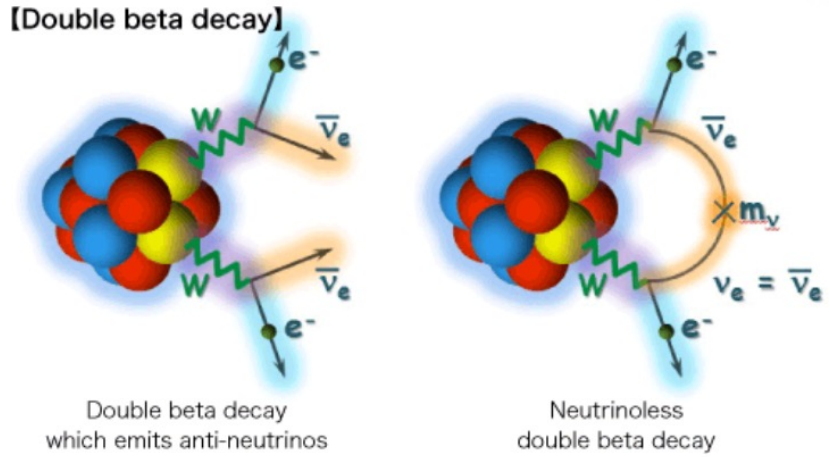
Arthur B. McDonald





SNO+: upgrade of SNO





Te-loaded LS

- **The nature of neutrinos**
- **Probe of neutrinos mass hierarchy**
- **Lepton number violation & leptogenesis**
- **Matter-antimatter asymmetry**


Greater | Grand
Sudbury
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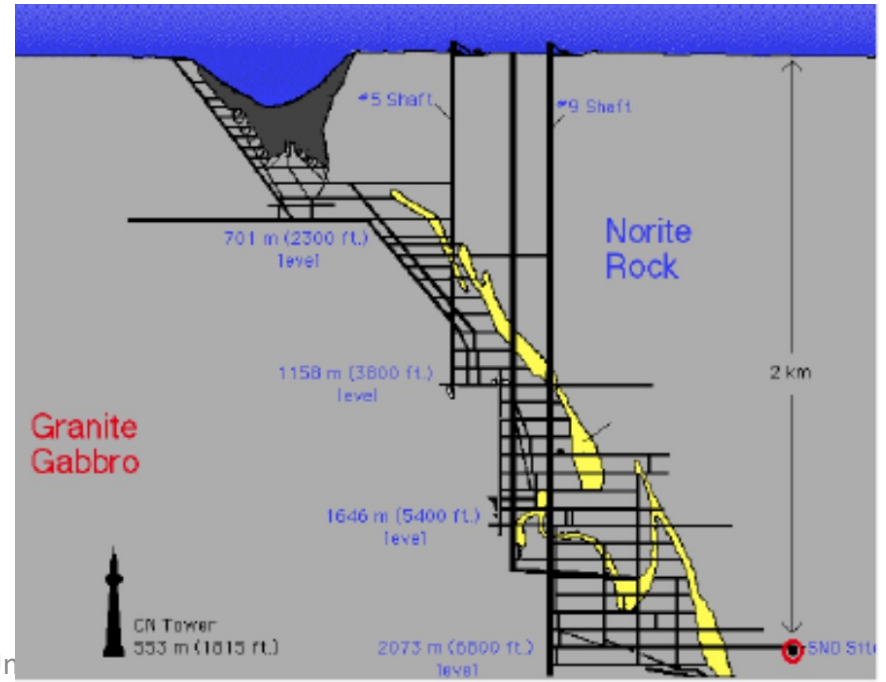
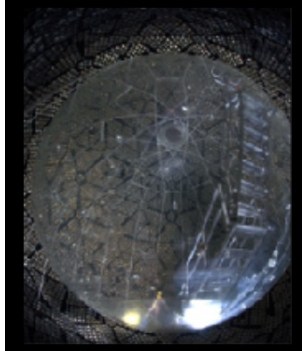
5
CENTS

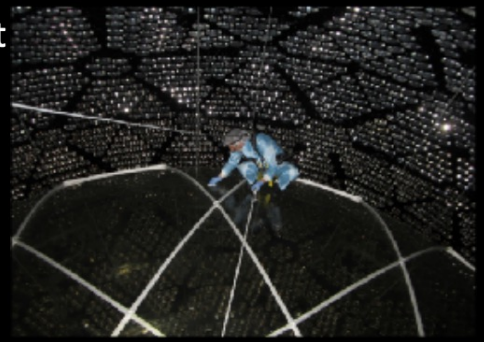

#5 Shaft
#9 Shaft
701 m (2300 ft.) level
Norite Rock
1158 m (3800 ft.) level
2 km
Granite Gabbro
1646 m (5400 ft.) level
CN Tower
553 m (1815 ft.)
2073 m (6800 ft.) level

SNO → SNO+



Cleaning the AV

Installed hold-down rope net

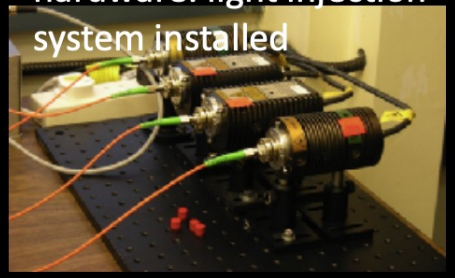


More cleaning

Filling with water

PMT repairs

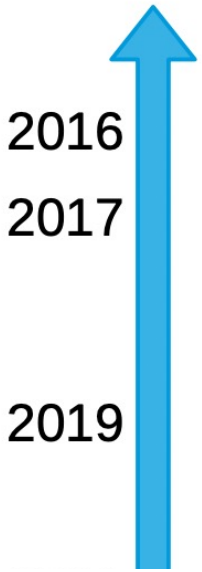
New calibration hardware: light injection system installed



Upgraded trigger electronics and DAQ

Courtesy: Mark Chen @清华

SNO+ timeline



- Dec 2016: start commissioning with water
- May 2017: start of water phase

  ^{8}B Solar neutrino flux: PRD 99 (2019) 012012
  Invisible nucleon decay modes: PRD 99 (2019) 032008, PRD 105 (2022) 112012
  Neutron-proton capture: PRC 102 (2020) 014002
  Reactor neutrinos: PRL 130 (2023) 9

- July 2019: start filling with scintillator (LAB+PPO fluor)

Courtesy: Jeff Tseng @LNGS

纯水中首次探测反应堆中微子

PHYSICAL REVIEW LETTERS

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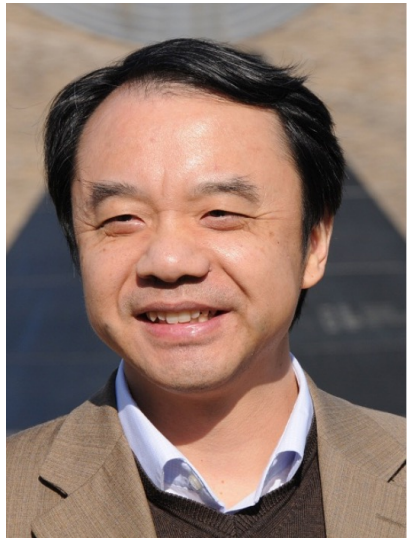
Evidence of Antineutrinos from Distant Reactors Using Pure Water at SNO+

A. Allega *et al.* (The SNO+ Collaboration)
Phys. Rev. Lett. **130**, 091801 – Published 1 March 2023

Physics See synopsis: Reactor Neutrinos Detected by Water

325 More



中科院院士，高能所所长王贻芳院士

潘诺夫斯基实验粒子物理学奖-2014
基础物理学突破奖-2016
国家自然科学一等奖-2016
未来科学大奖“物质科学奖”-2019

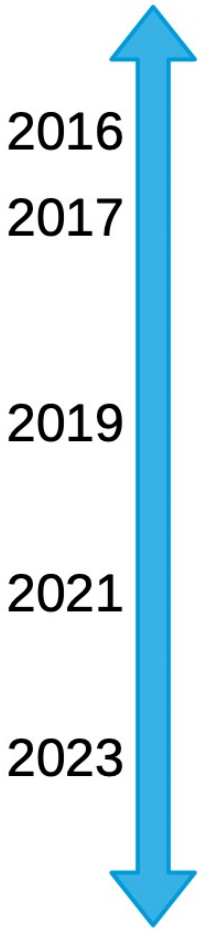
“通过纯水的切伦科夫效应测量反应堆中微子是一个全新的成就，实验技术上极其困难。这种新方法和技术为未来中微子实验开辟了一条新的道路。祝贺山东大学张洋教授及其团队！”

美国《物理》杂志：突破

Viewpoint: Probing Majorana Neutrinos). But while SNO+ team members prepare for that search, they have made another breakthrough by capturing the interaction with water of antineutrinos from nuclear reactors [1]. The finding offers the possibility of making neutrino detectors from a nontoxic material that is easy to handle and inexpensive to obtain, key factors for use of the technology in auditing the world's nuclear reactors (see **Feature: Neutrino Detectors for National Security**).

U.S. DEPARTMENT OF ENERGY
Science News

SNO+ timeline



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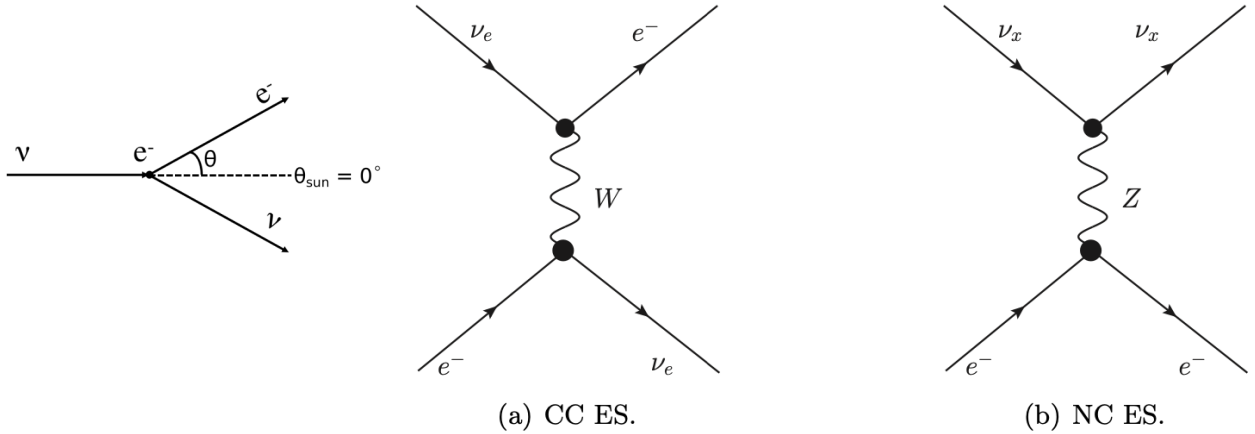
- July 2019: start filling with scintillator (LAB+PPO fluor)
  - "Partial fill" phase due to pandemic: 365T LS, 0.6g/L PPO
- April 2022 : start of scintillator phase
  - 780T LS, 2.2g/L PPO
- 2024: preparation for Te loading for 0νββ phase

Courtesy: Jeff Tseng @LNGS

Solar study in pure water



(a) CC ES. (b) NC ES.

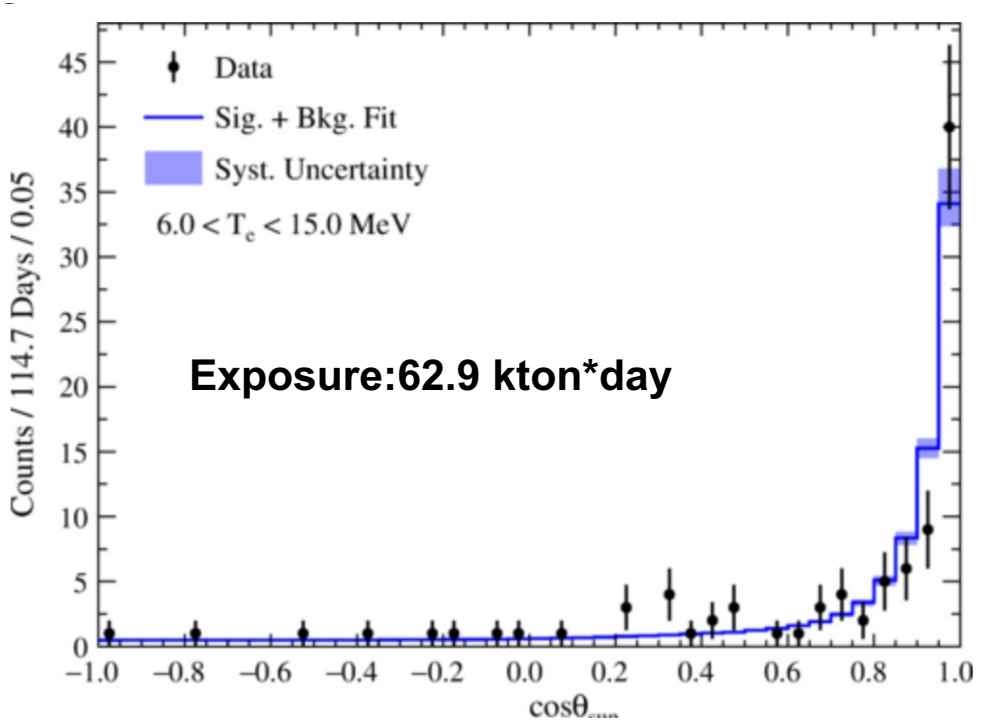
Courtesy: Jie's PhD thesis

$$\cos\theta_{sun} = \sqrt{\frac{T_e(m_e c^2 + E_\nu)^2}{2m_e c^2 E_\nu^2 + T_e E_\nu^2}},$$

$$= \left(1 + \frac{m_e c^2}{E_\nu}\right) \frac{1}{\sqrt{1 + \frac{2m_e c^2}{T_e}}}.$$

e.g, $E_\nu = 10$ MeV, T_e=6 MeV
→ $cos\theta_{sun} = 0.97 \sim 1$

Phys. Rev. D 99, 012012 (2019)

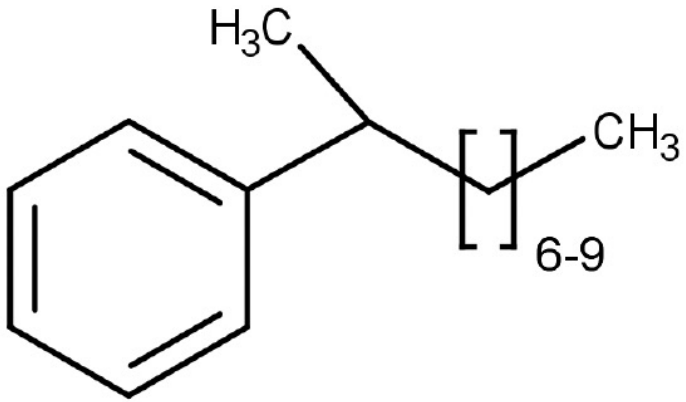


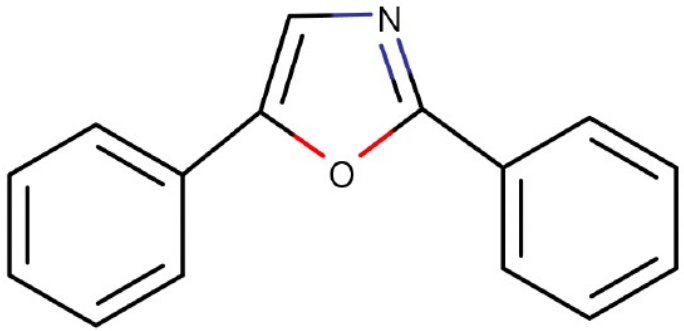
$$\Phi_{ES} = 2.53^{+0.31}_{-0.28}(\text{stat})^{+0.13}_{-0.10}(\text{syst}) \times 10^6 \text{ cm}^{-2}\text{ s}^{-1}.$$

- **Solar ^{8}B flux is measured with extremely low background.**
  - ✓ **Signal rate ~1 evt/(kton*day) vs bkg 0.25 evt/(kton*day)**

Liquid scintillator: LAB + PPO

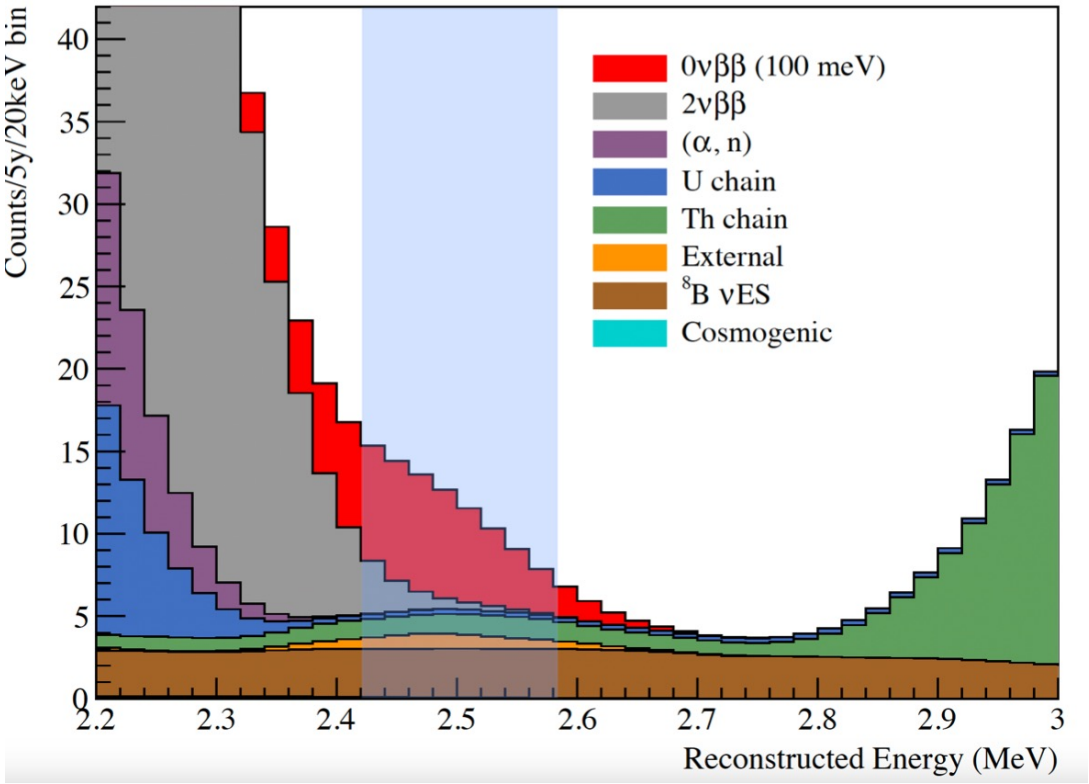
JINST 16 (2021) 05, P05009

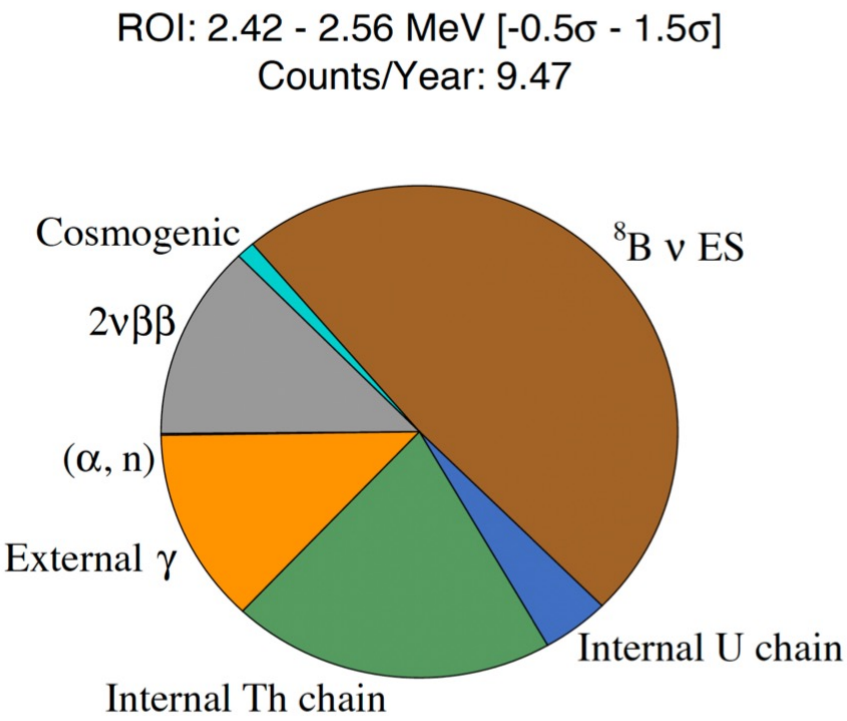




- **Developed for SNO+, used by many LS experiments.**
- **Generally high LY of isotropic emission, with only ~5% Cherenkov light.**

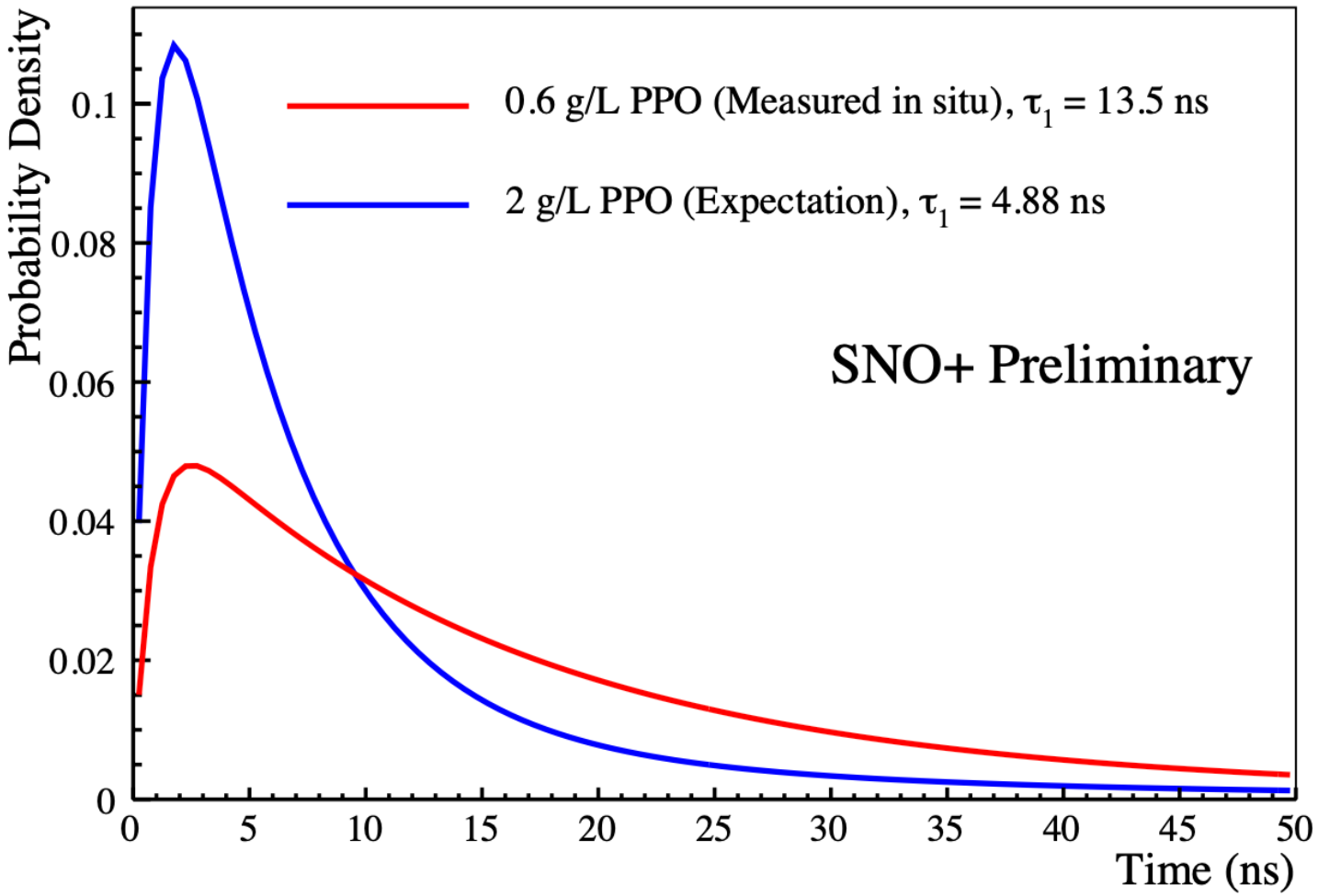
Background budget for $0\nu\beta\beta$





Is it possible to reconstruct the direction of Solar ^{8}B neutrinos?

Time profile of LS



Empirical formula,

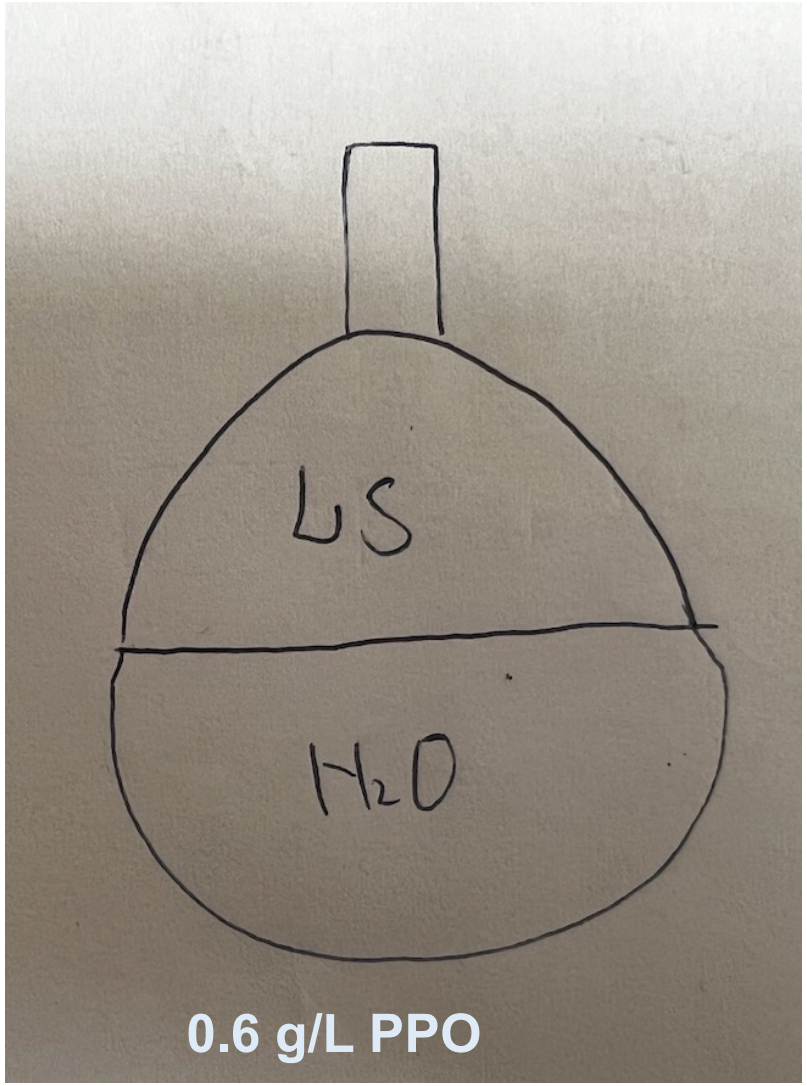
$$P(t) = \sum_{i=1}^{3} A_i \frac{e^{-t/\tau_i} - e^{-t/\tau_r}}{\tau_i - \tau_r}$$

LAB + PPO (singlet + triplet)

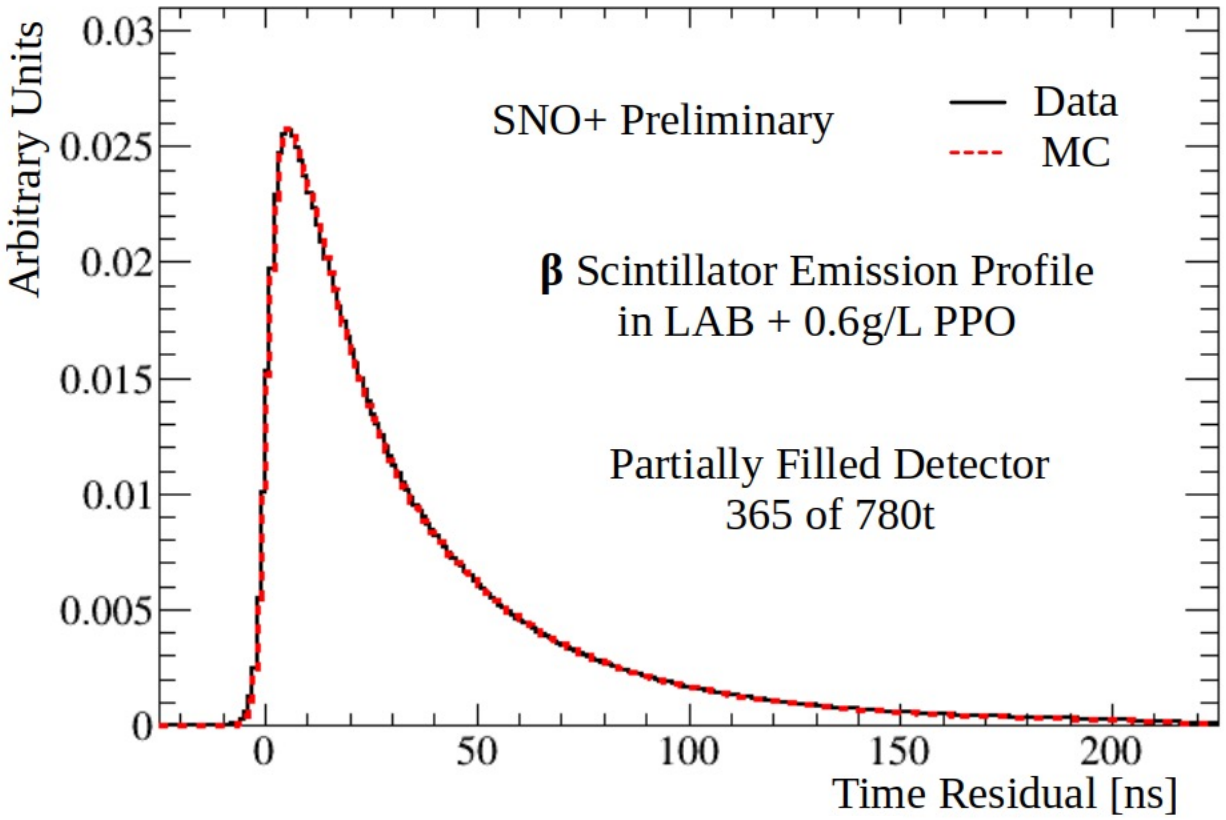
Fraction of singlets dependent on dE/dx, thus α/β classfication

Lower PPO concentration would facilitate the $\check{C}$ separation.

Validation of the models

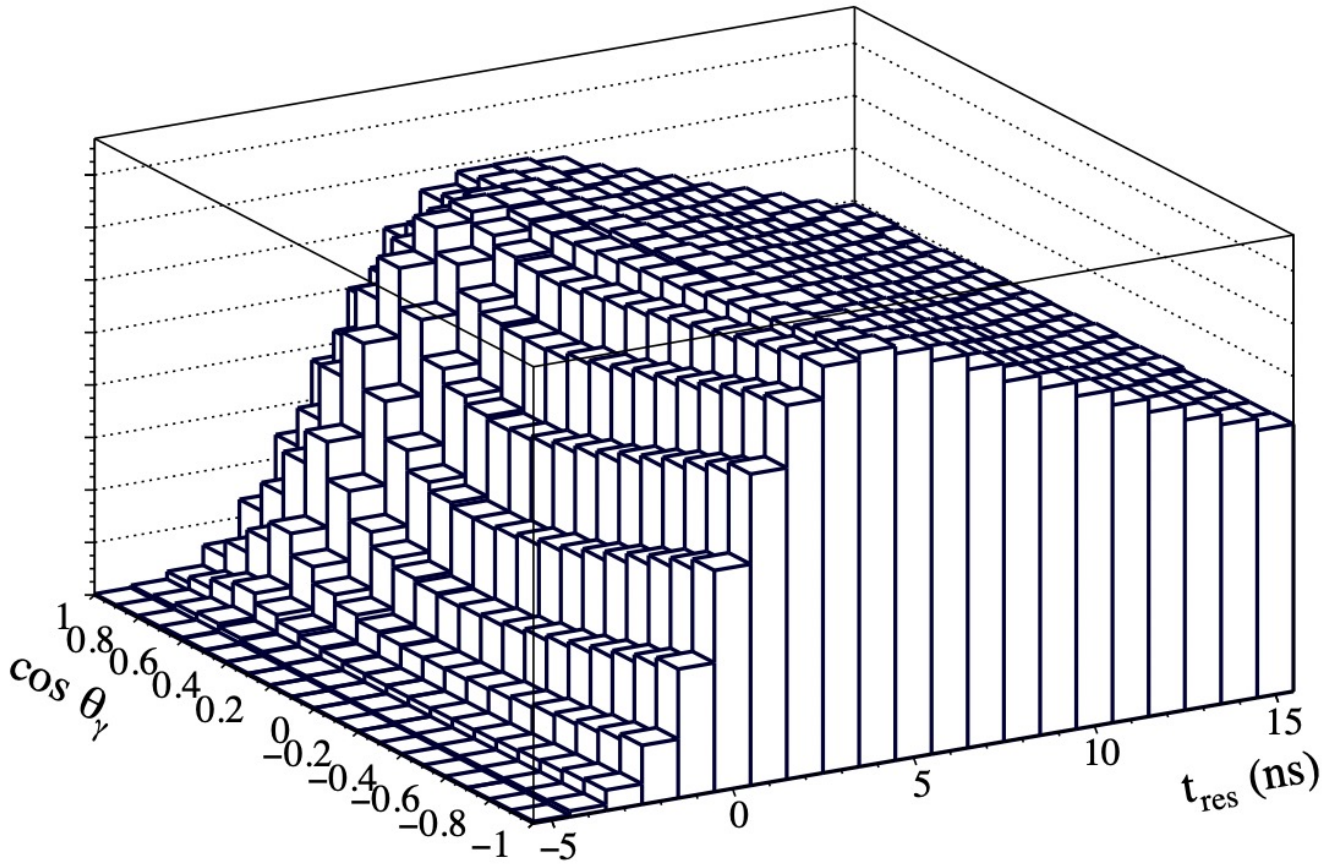


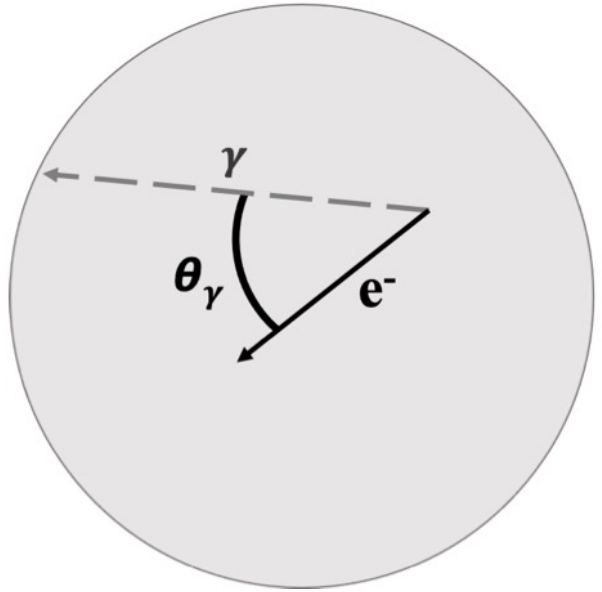
Bi-Po214 tagging



$$t_{\text{res}} = t_{\text{hit}} - t_{\text{event}} - t_{\text{flight}}$$

Extraction of $\check{C}$ light



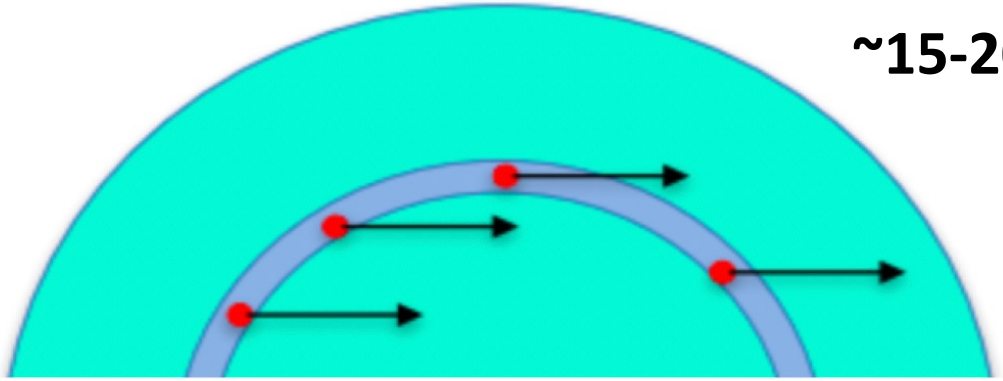


i	1	2	3
τ_i (ns)	13.5	23	98.5
A_i	0.55	0.335	0.115

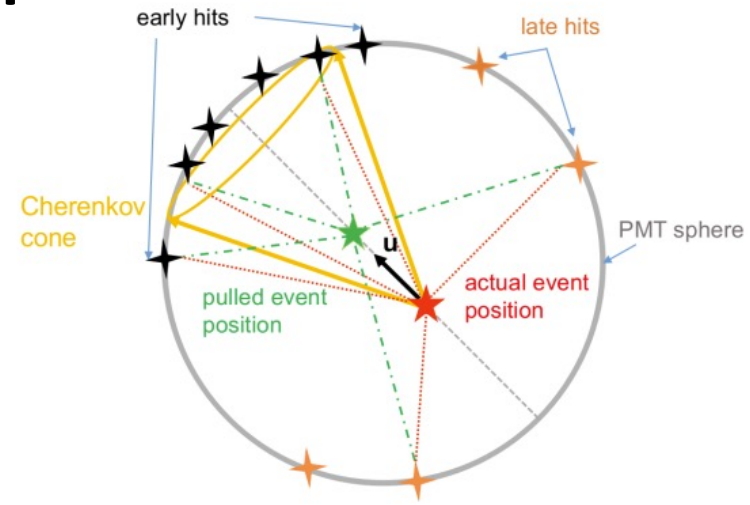
$\check{C}$ light can be extracted using early time.

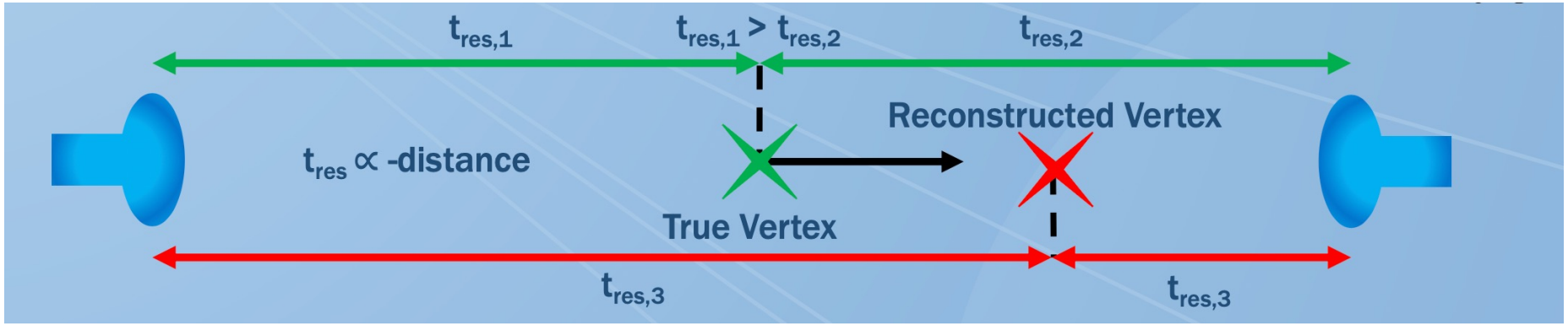
Backward peak

- **If we use true position, there is no backward peak.**
  - ✓ **The peak is due to the reconstruction effect.**



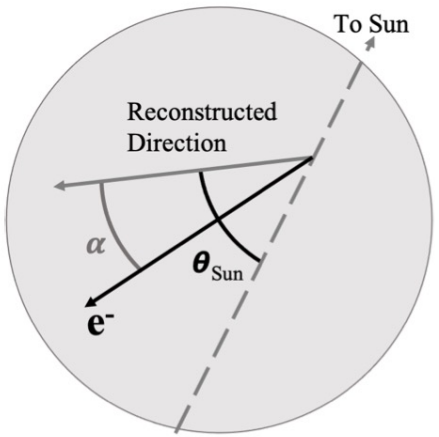
~15-20 cm

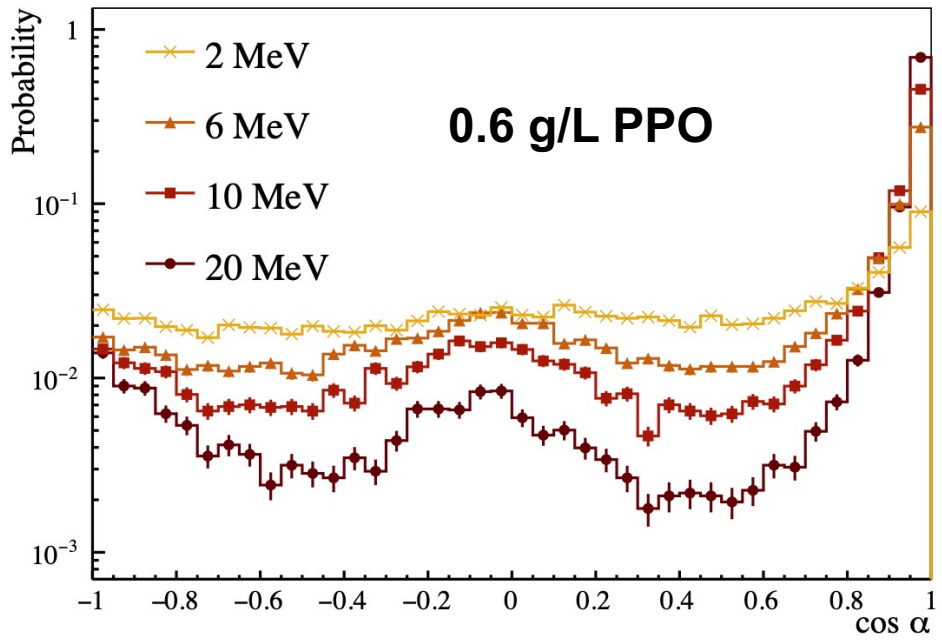


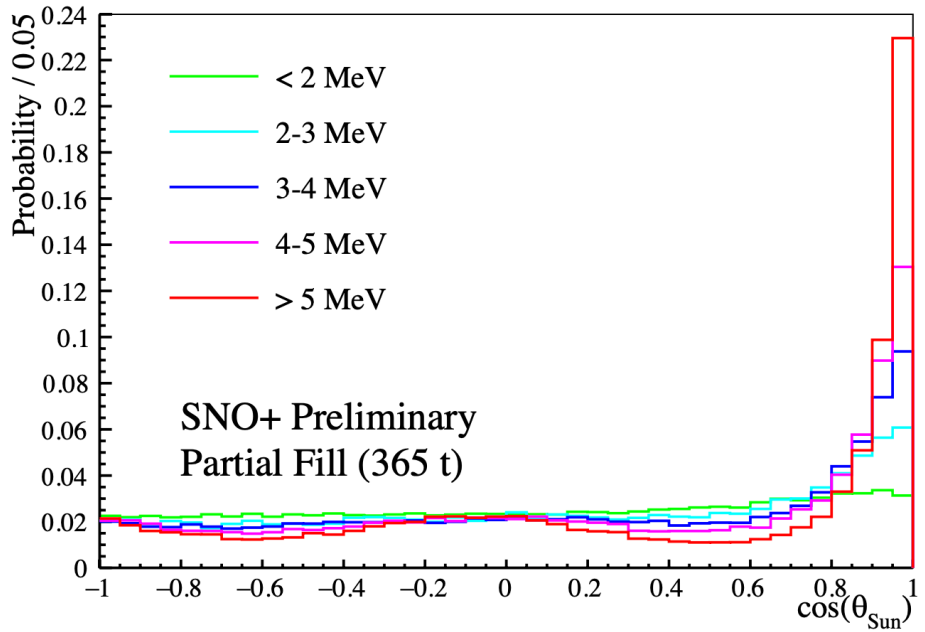


Courtesy: Josie @IOP HEPP & APP

Reconstruction based on MC



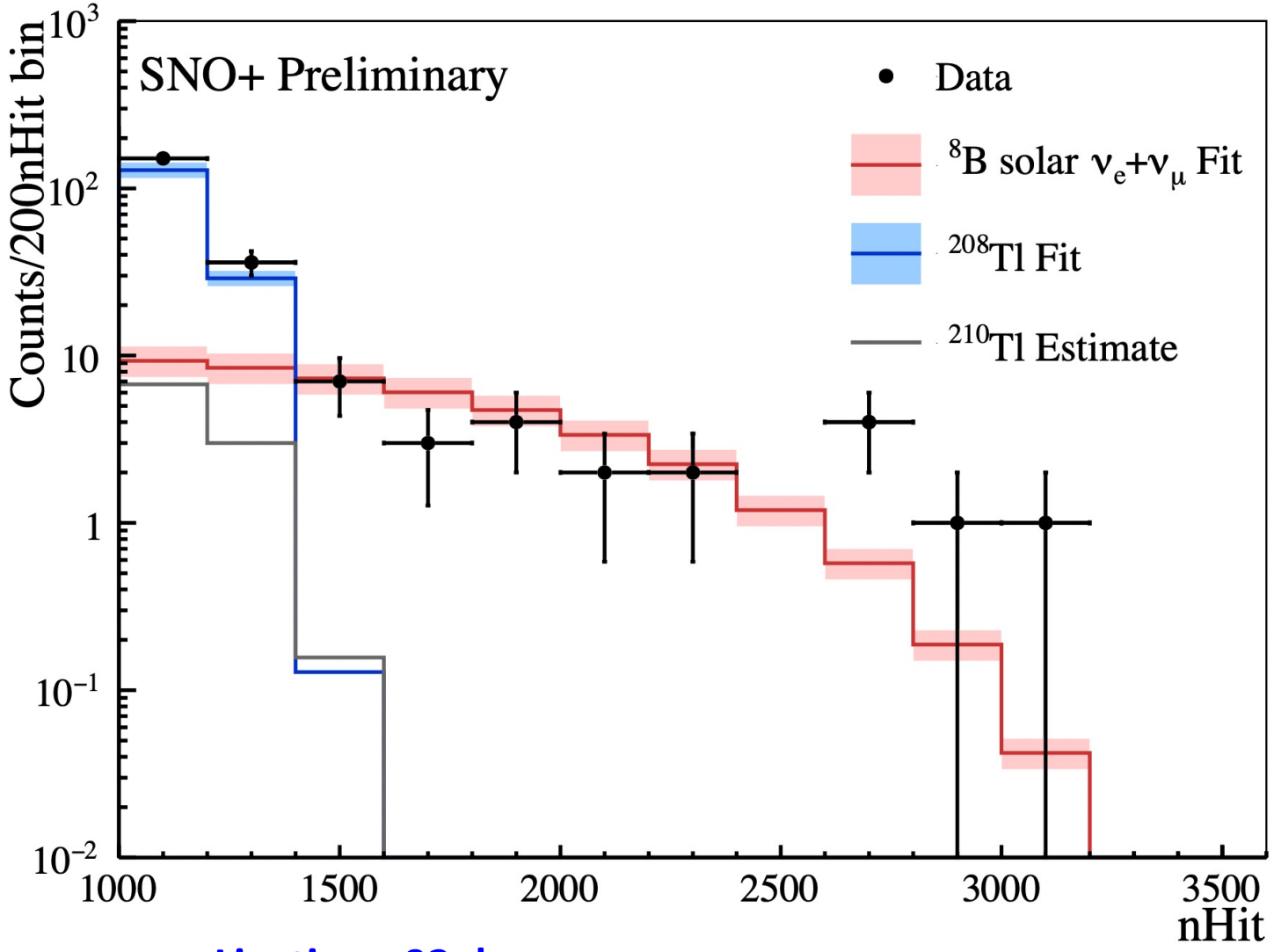




- **Direction can be reconstructed better with higher energy.**

Electron Energy (MeV)	% with $\cos\alpha > 0.8$
2	21.9 ± 0.4
6	45.6 ± 0.6
10	64.6 ± 0.7
20	83.0 ± 0.8

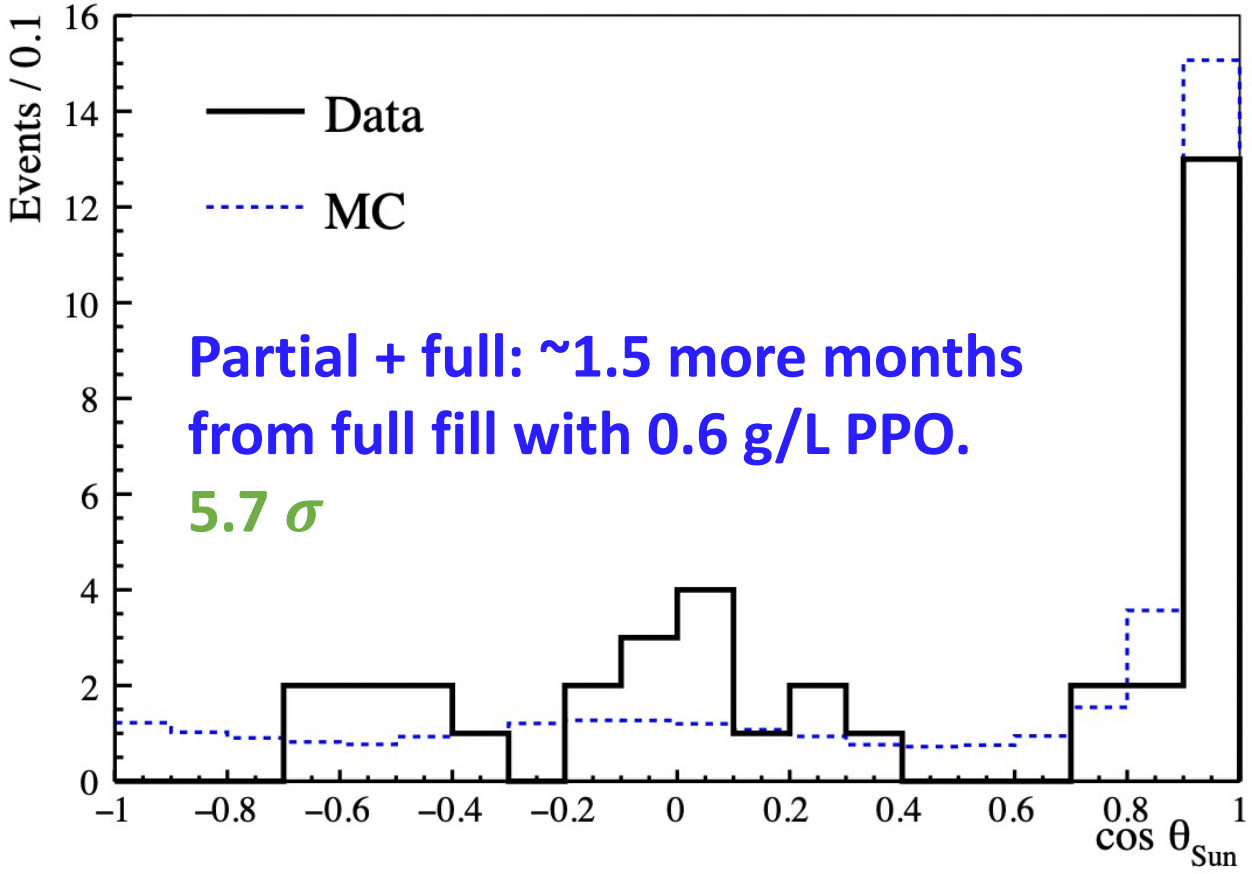
Solar ^{8}B in partial fill



Livetime: 92 days

- **1500 nHit ~ 5 MeV**
- **Select a pure solar sample by E>5 MeV**

What do we actually see?



~40% events have $cos\theta_{sun}$>0.8

First event-by-event directional recon. in a large-scale HLYLS (MeV energies)

Summary

- **First event-by-event directional reconstruction of solar neutrinos in a large-scale High-LY LS detector (5<E<10 MeV).**
  - **arXiv:2309.06341**

- **Further study with lower energy & 2 g/L PPO is underway.**

BACKUP