TAUP 2023
Vienna, 29 August 2023

Neutrinoless double-beta decay search with SNO+

SNO+ Background Performance & Preparations for 0νββ

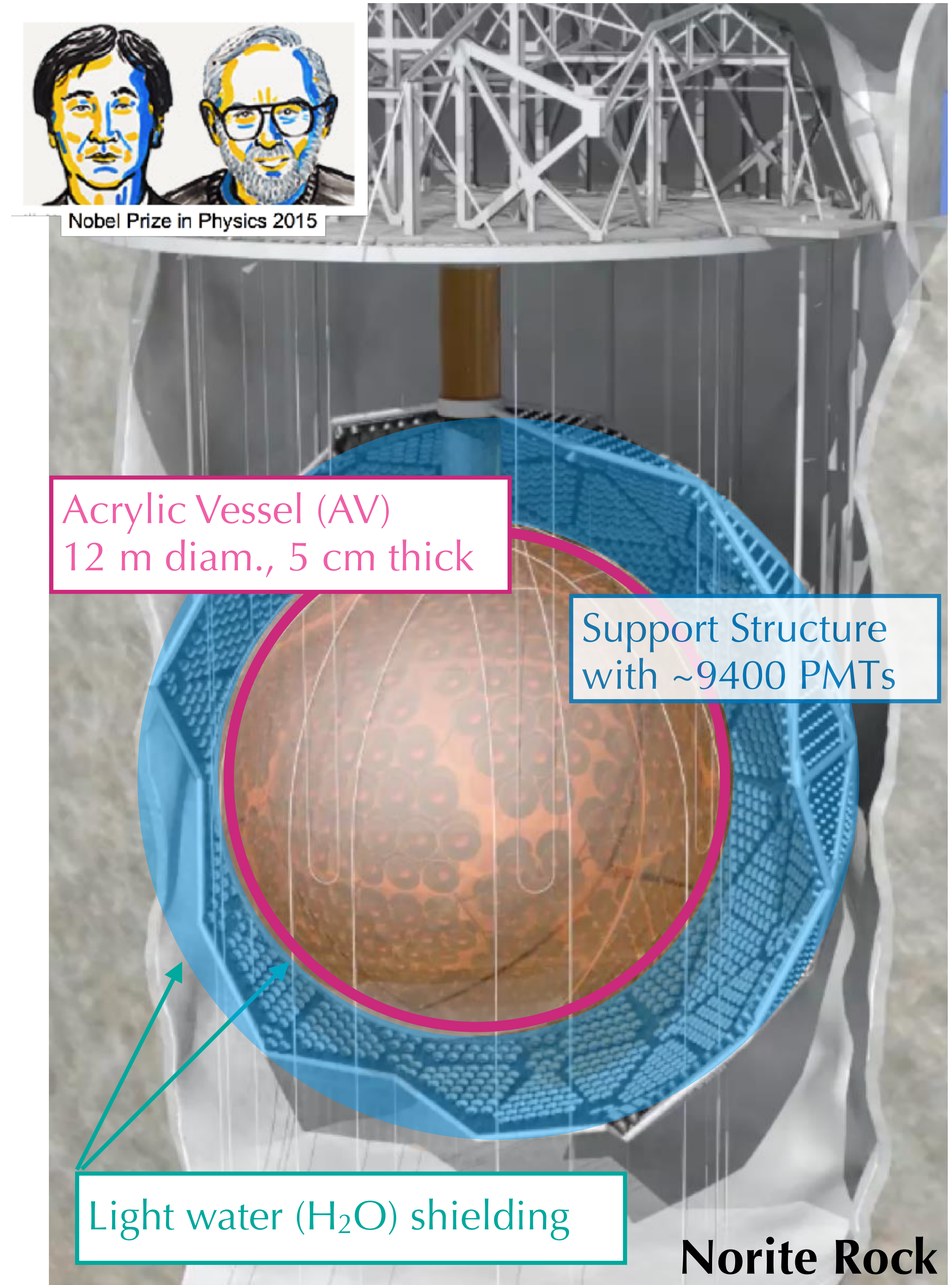
Valentina Lozza for the SNO+ Collaboration

FCT Fundação para a Ciência e a Tecnologia

LIP Lisbon

SNO+ DETECTOR

- Multi-purpose neutrino experiment with the primary goal to search for the neutrinoless double-beta decay of ^{130}Te.



JINST **16 (2021) 08, P08059**

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- Three target's materials:
  - 905 t of *ultra-pure water* (2017-2019);
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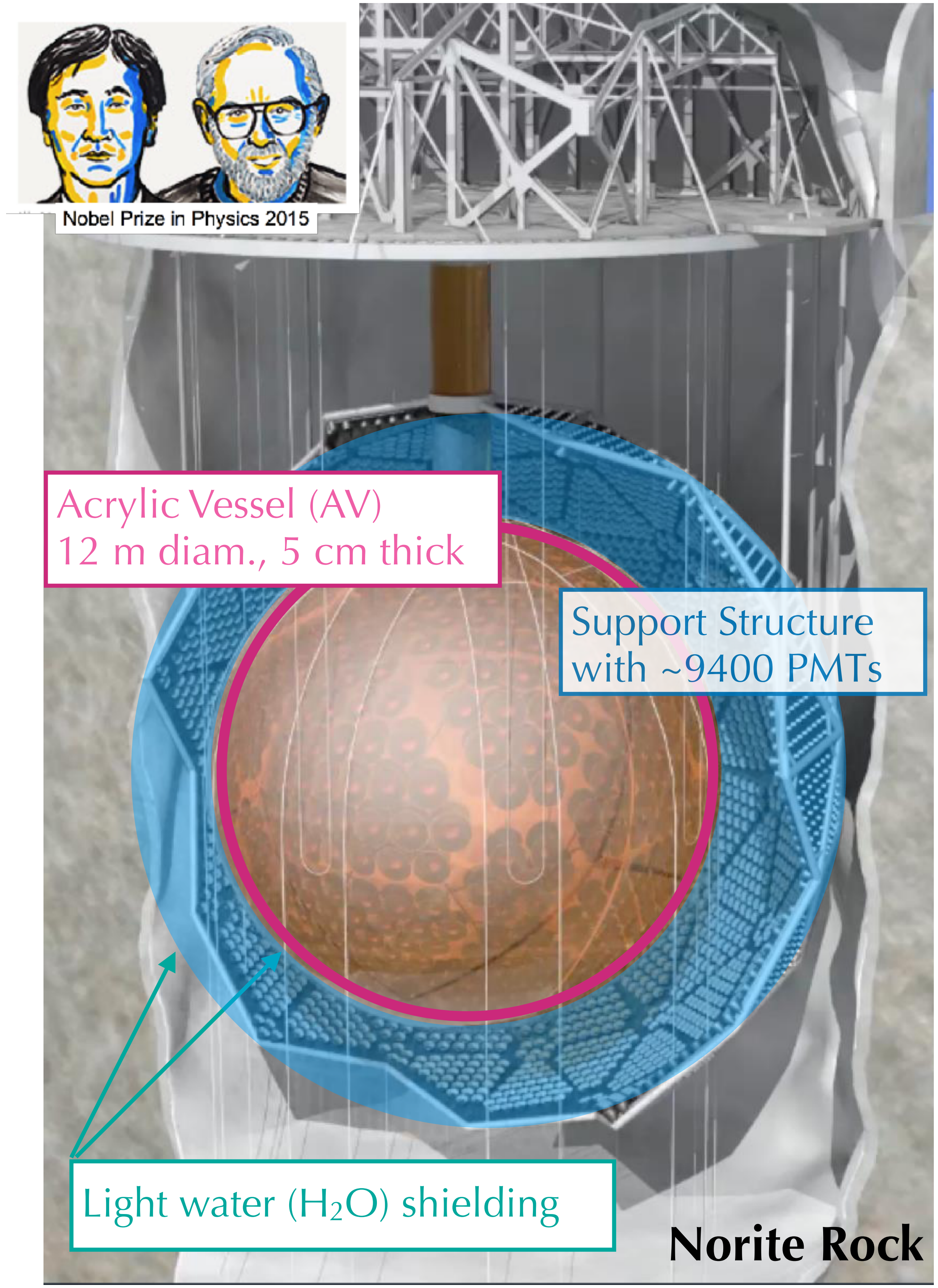
  - 3.9 t ^{nat}*Te-loaded scintillator* (2024 -).



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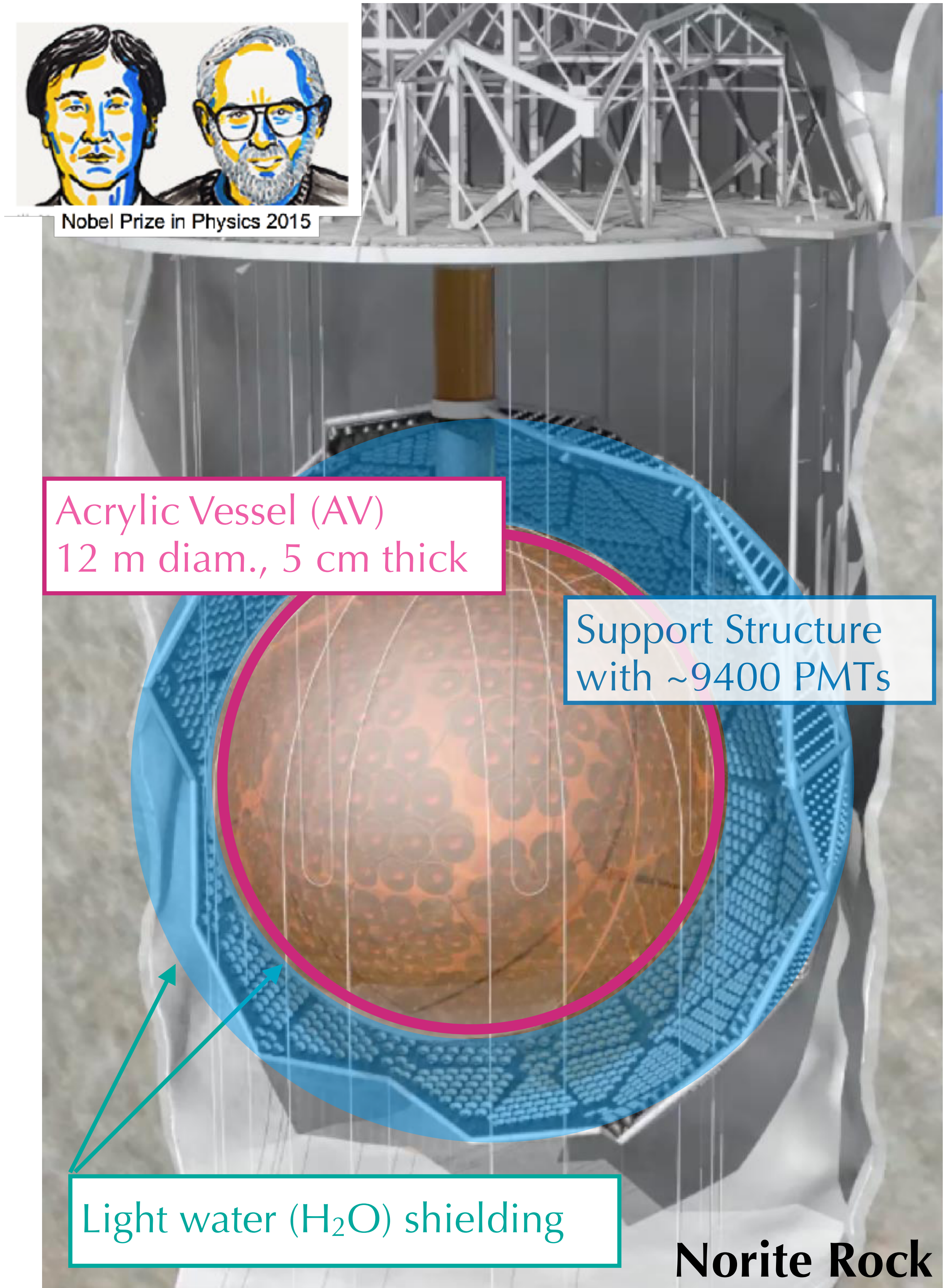
- Several background reduction layers:
  - 7 kt of high-purity water shield;
  - N_2 Cover Gas blanket across the entire detector;
  - Radon-impermeable plastic covering the cavity walls.



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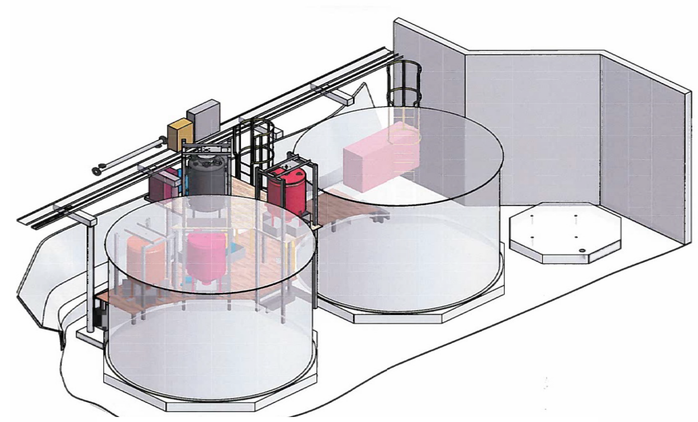
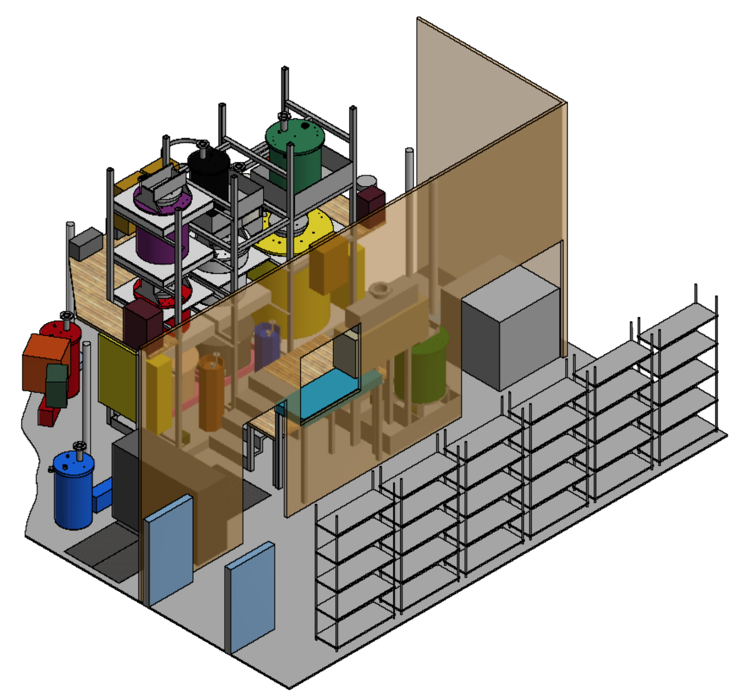
- Material purification:
  - 4 purification plants UG for water, scintillator and Te;
  - Possibility to recirculate and repurify water and scintillator;
  - Extensive QA campaigns before, during and after filling/loading.


TeDiol purification plant


LS purification plant


TeA purification plant

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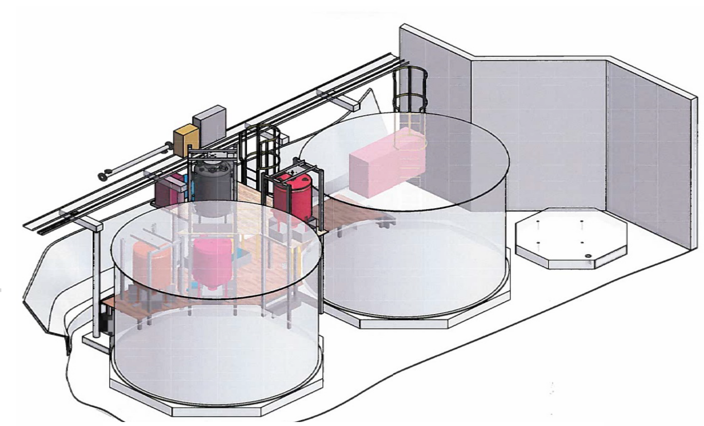
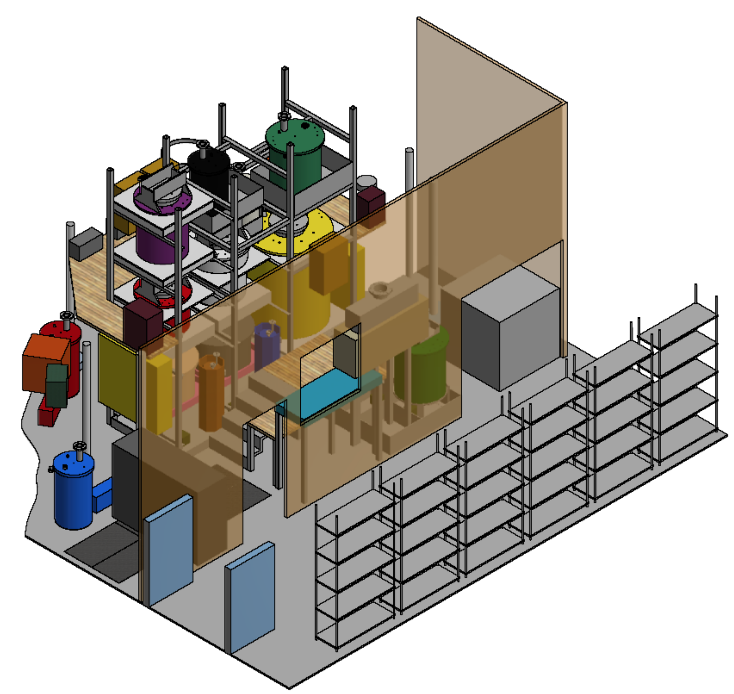
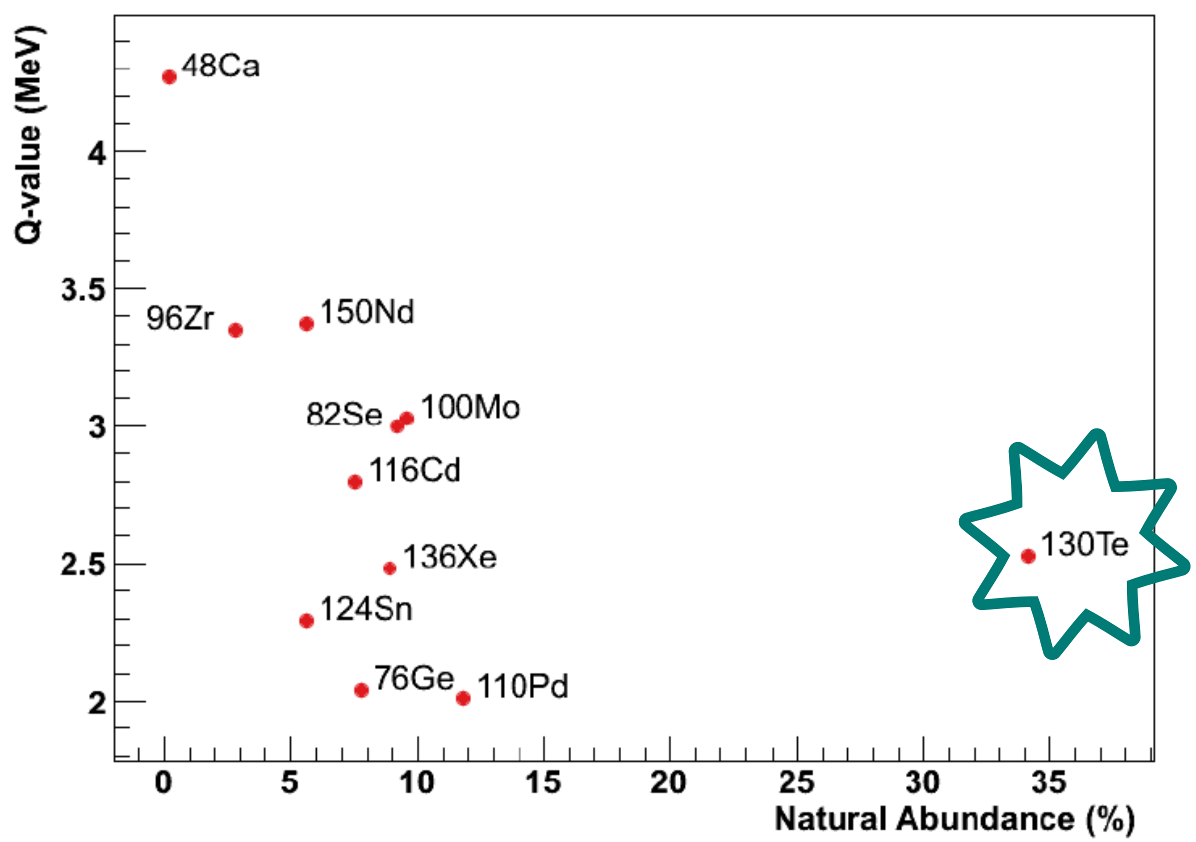
- Mater
  - 4 p
    scin
  - Possibility to recirculate and repurify water and scintillator;
  - Extensive QA campaigns before, during and after filling/loading.

See poster
S. Manecki, S. Biller
SNO+ Tellurium Purification and Loading for Neutrinoless Double Beta Decay Search


TeDiol purification plant


LS purification plant


TeA purification plant



Major Advantages of Te

- No need for enrichment
- Long 2νßß half-life (7.9x10^{20} yrs)
- High Q-value of 2.5 MeV

Major Advantages of SNO+

- Large size allows rejection of external backgrounds
- Fast timing allows rejection of U and Th chain background (+ alpha,n)
- High light yield for good resolution = targeting 460 PMT hits/MeV
- ***Target-out measurements before and while adding Te***

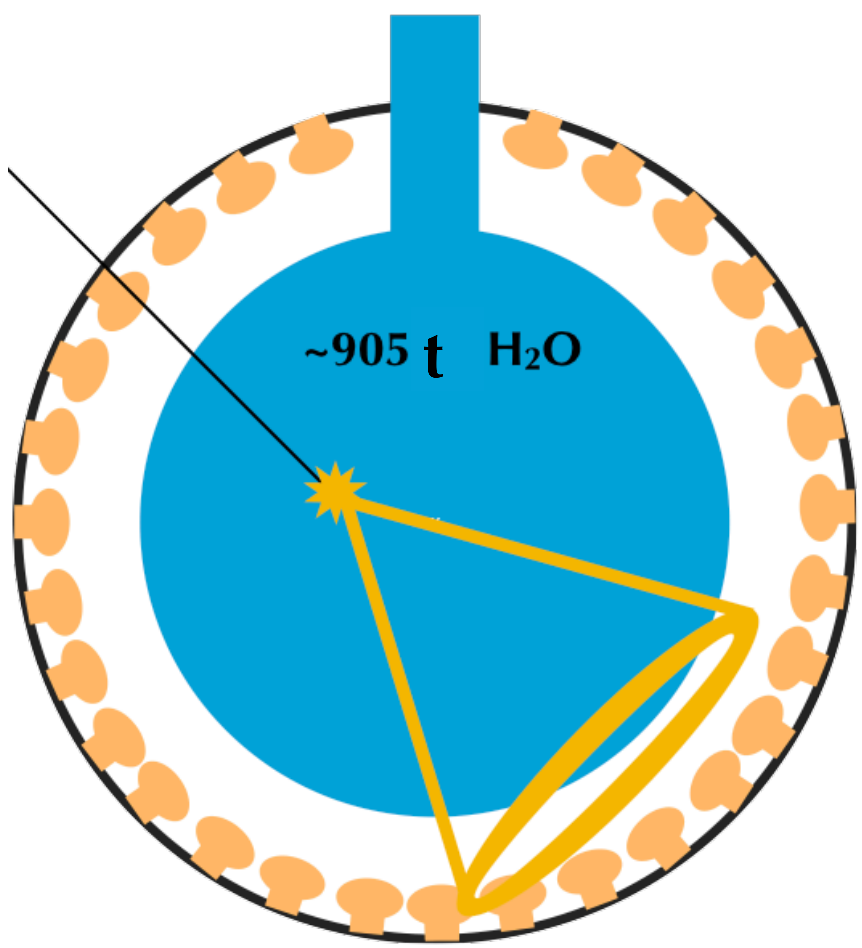
SNO+ WATER

2017 2018 2019

May - December 2017
(~115 gold physics days)
First SNO+ water phase
Phys.Rev.D 99, 032008 (ND)
Phys.Rev.D 99, 012012 (Solar)
Phys.Rev.C 102, 014002 (Antinu)

October 2018 - June 2019
(~185 gold physics days)
Second SNO+ water phase
Phys.Rev.D 105, 112012 (ND)

Additional Cover gas shielding to reduce Rn ingresses in water



Major Outcomes

- Nucleon decay modes into invisible channels
- Solar neutrinos
- Reactor antineutrinos
  - **First measurement** of reactor antineutrinos using pure water ***Phys.Rev.Lett 130, 091801***

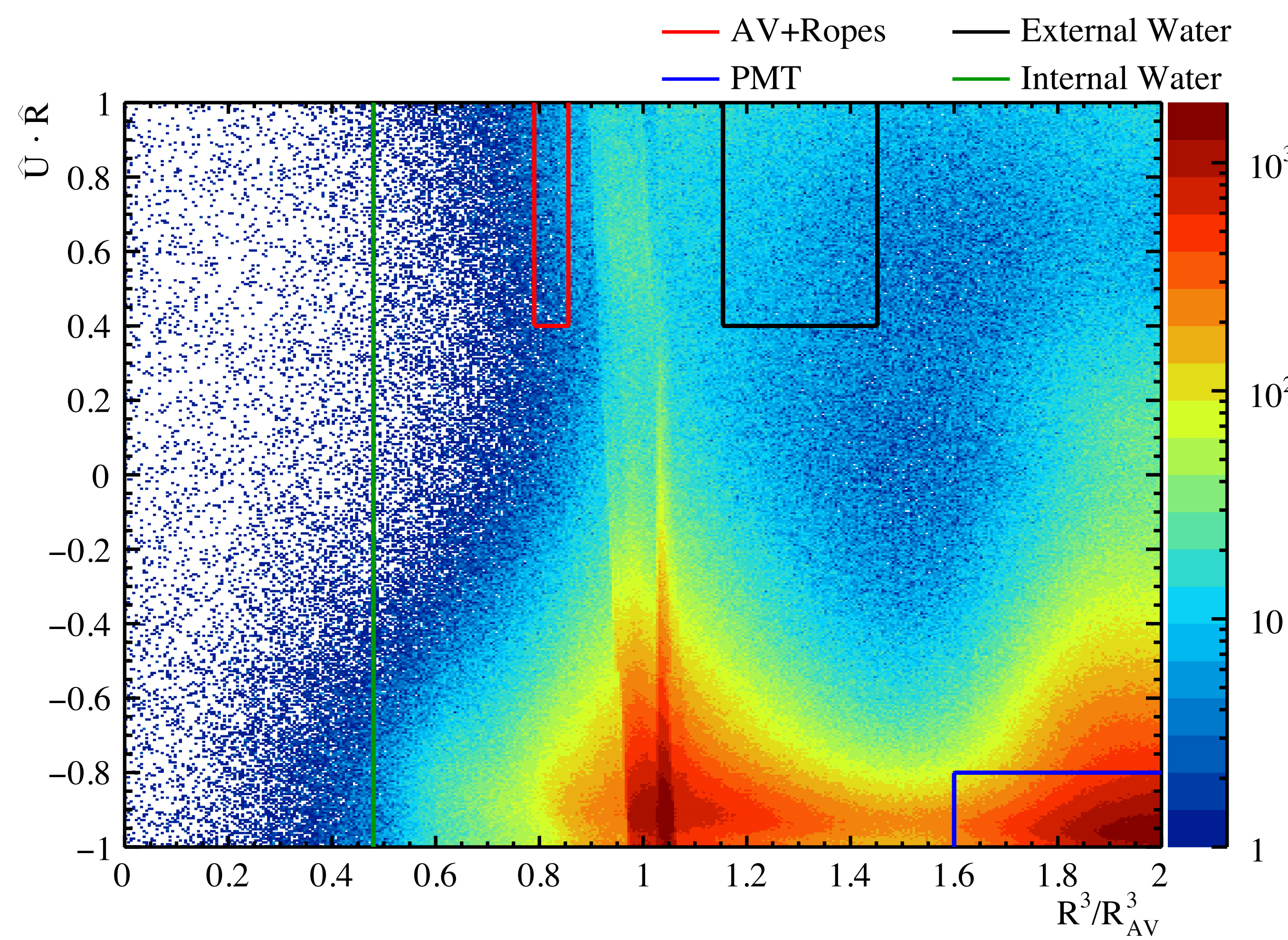
See talk
T. Kaptanoglu
Aug 31, 2023, 3:15PM
Hörsaal 21 lecture hall

SNO+ External Backgrounds

- External background measurement during the water phase allows to use a directional cut
  - 3.0 < E < 5.0
  - -5.0 m < Z < 5.0 m

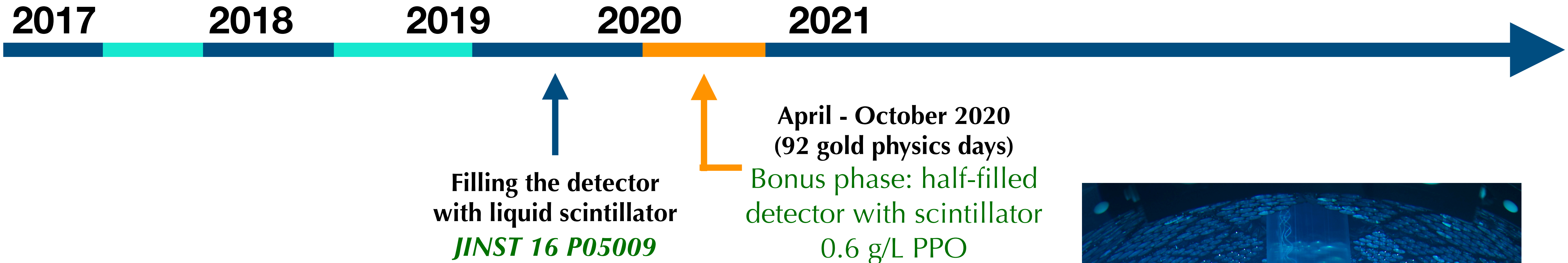
Box	Cuts
AV	$5.55\ \text{m} < R_{AV} < 5.7\ \text{m}$ $U \cdot R_{AV} > 0.4$
External Water	$6.3\ \text{m} < R < 6.8\ \text{m}$ $U \cdot R > 0.4$
PMT	$1.6 < R^3 < 2.0$ $U \cdot R < -0.8$
Internal Water	$R_{AV} < 4.7\text{m}$

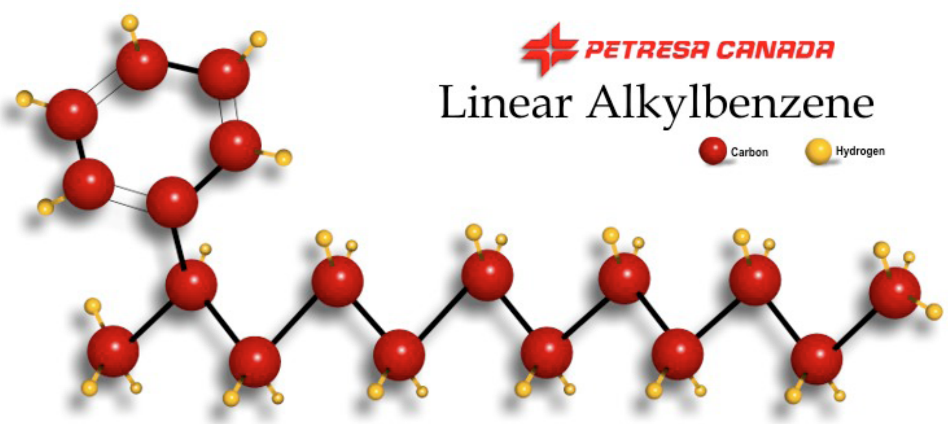
Background	Rate (Fraction of Nominal)
AV+Ropes	$0.21 \pm 0.009^{+0.64}_{-0.21}$
External Water	$0.44 \pm 0.003^{+0.32}_{-0.27}$
PMT	$1.48 \pm 0.002^{+1.65}_{-0.60}$



Contribution to the 0νßß ROI is 50% smaller than with nominal values

SNO+ Scintillator





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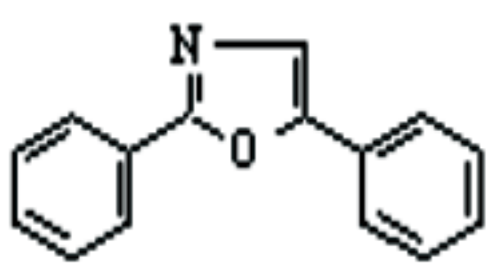
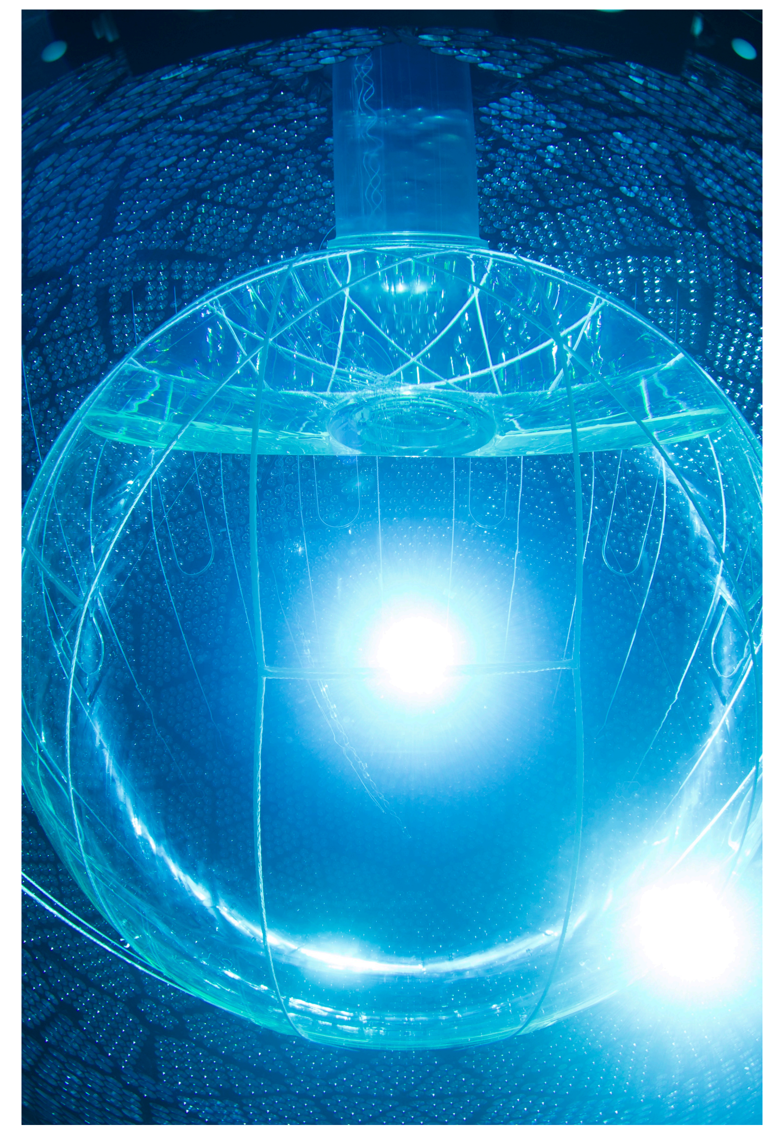


PPO

- Developed by SNO+
- From water Cherenkov detector to scintillator detector!
- Allows isotopic loading

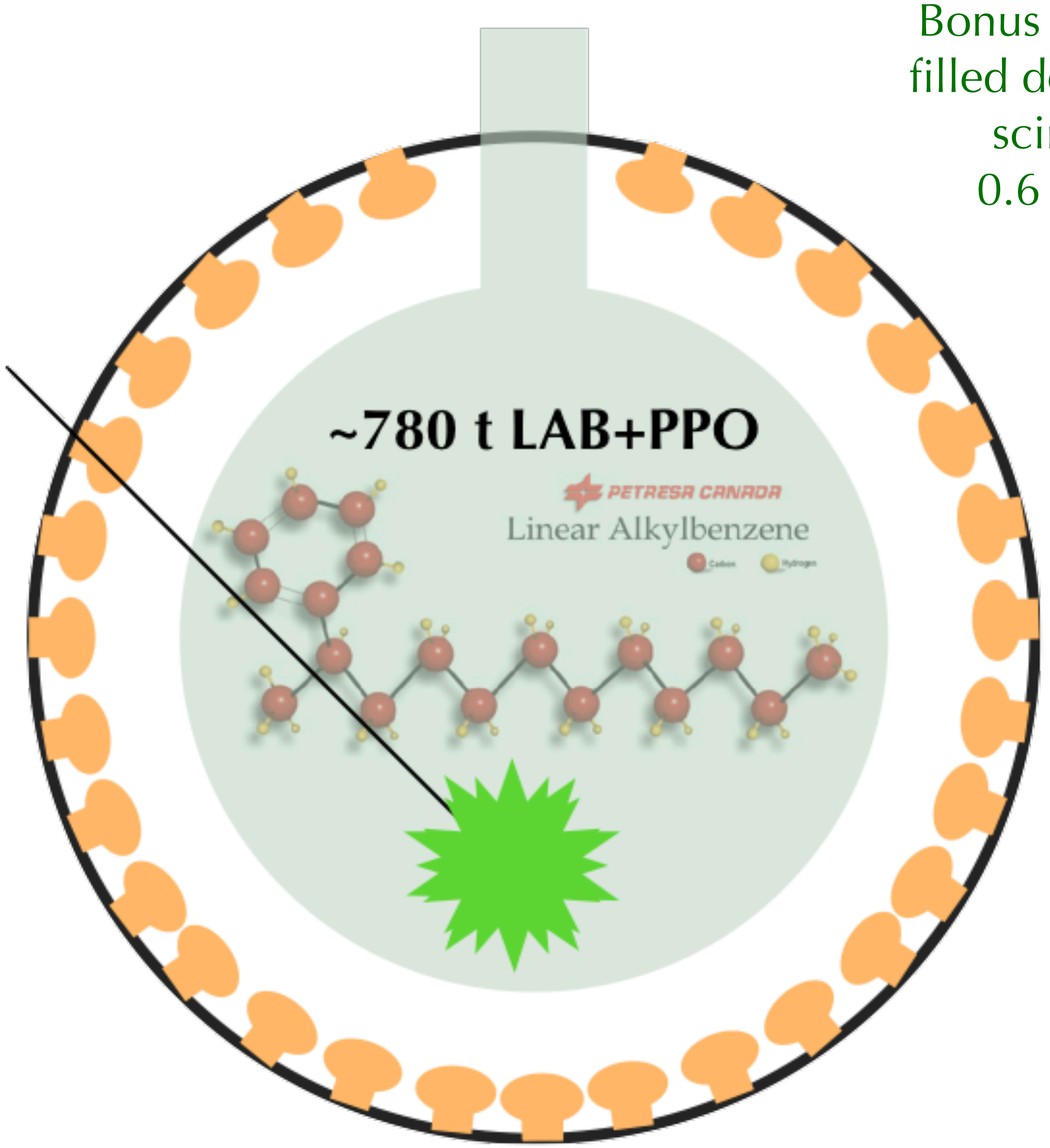


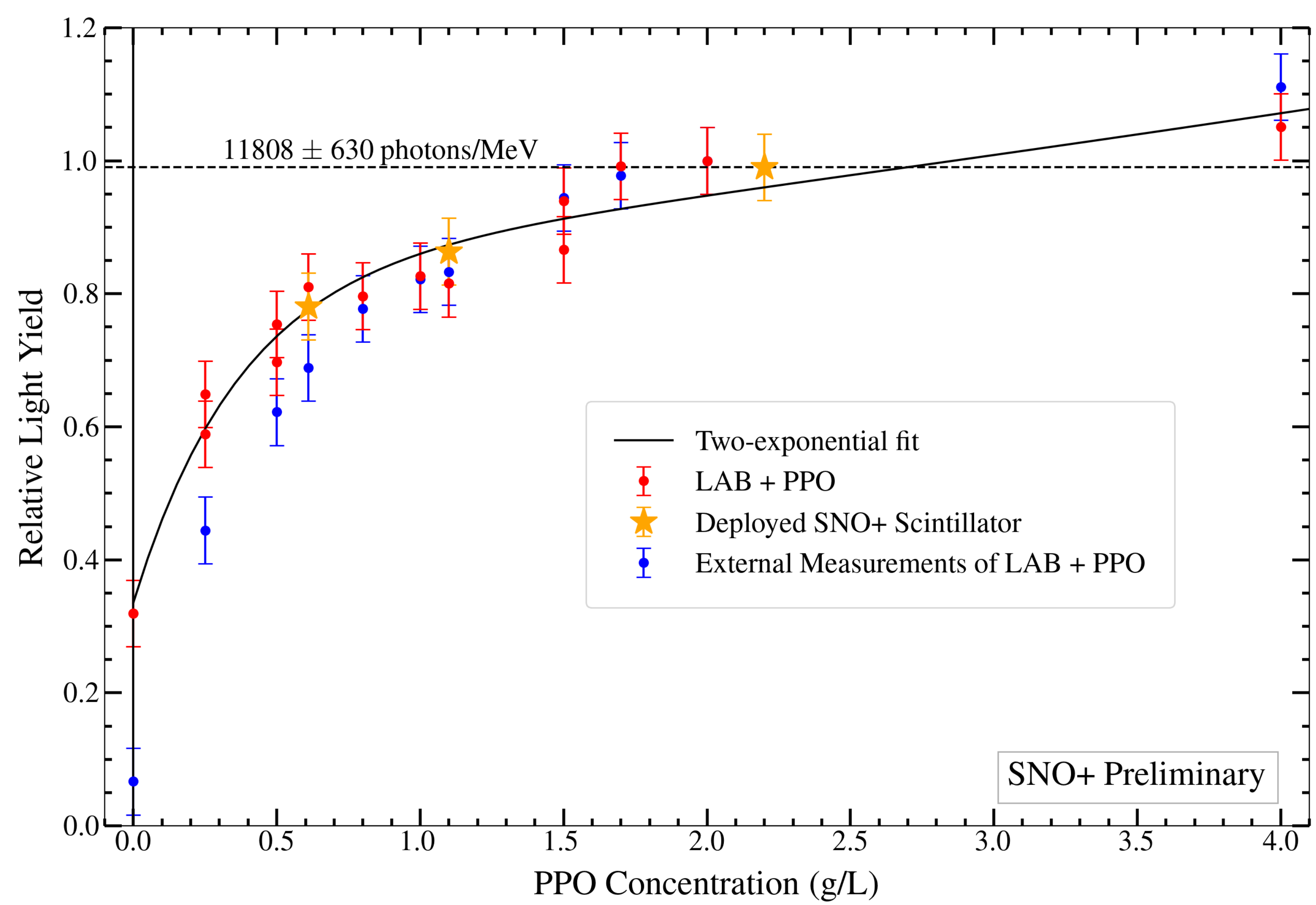
SNO+ Scintillator

2017 2018 2019 2020 2021 2022 2023

April - June 2021
Bonus phase: full-filled detector with scintillator
0.6 g/L PPO

April 2022 - March 2023
Full fill detector with scintillator
2.2 g/L PPO

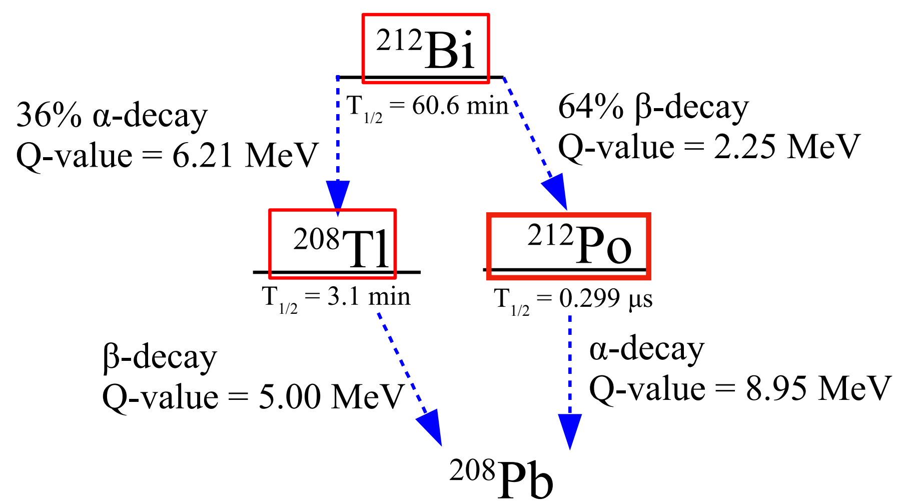


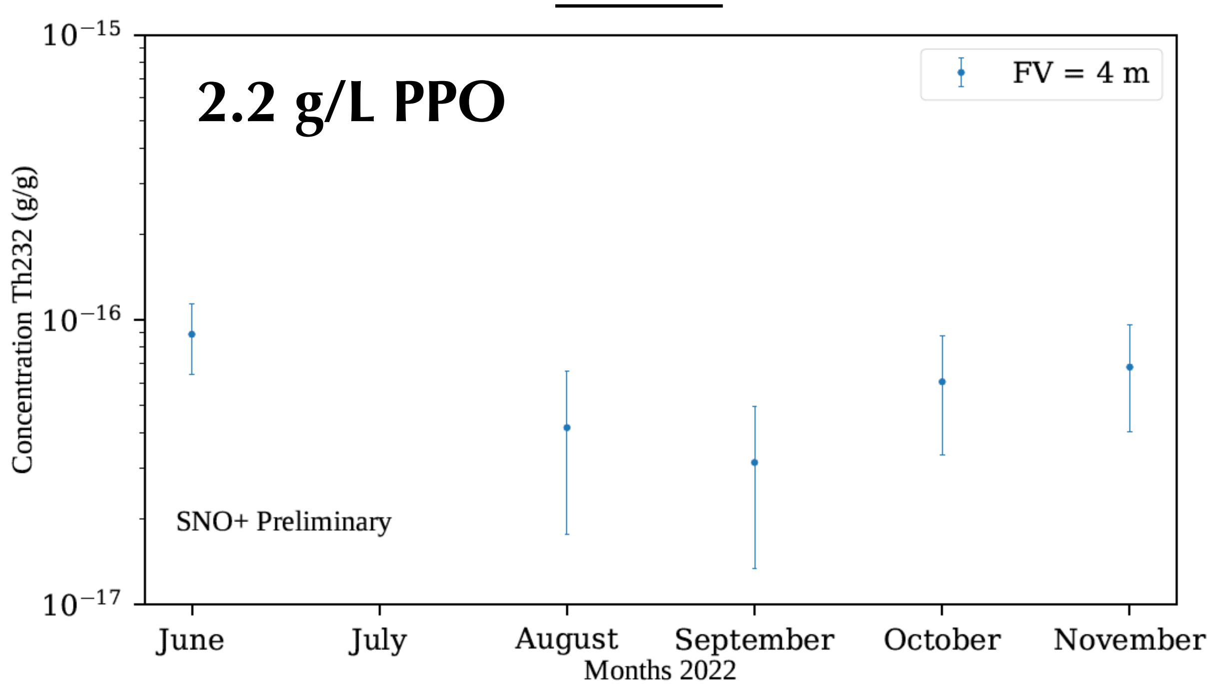


SNO+ Backgrounds

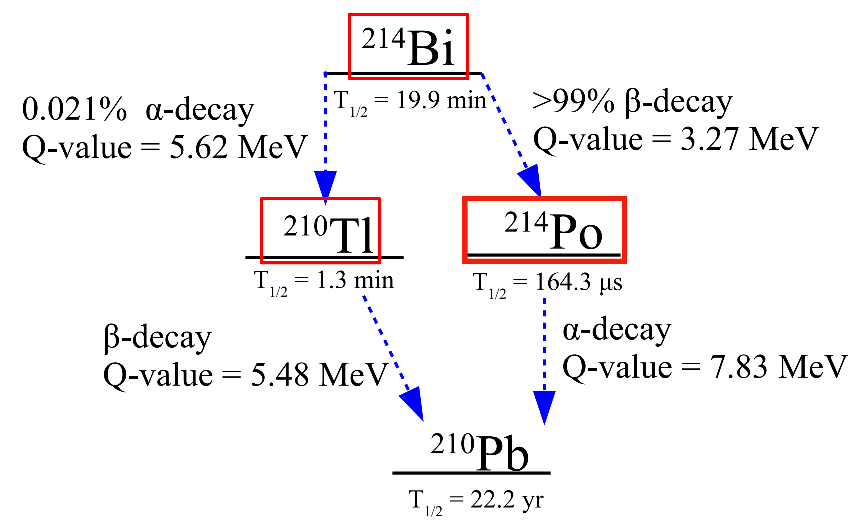
- Preparation for the double-beta decay phase: background and target-out measurement

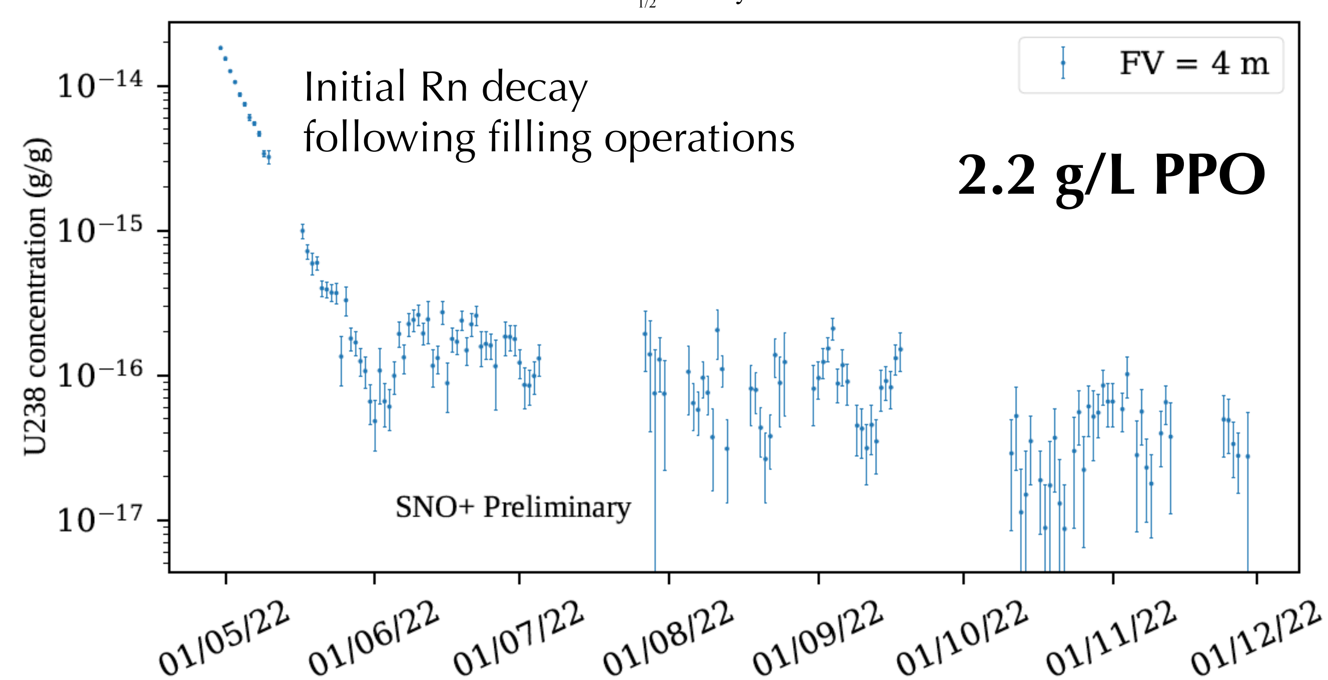
^{232}Th via ^{212}BiPo





^{238}U via ^{214}BiPo



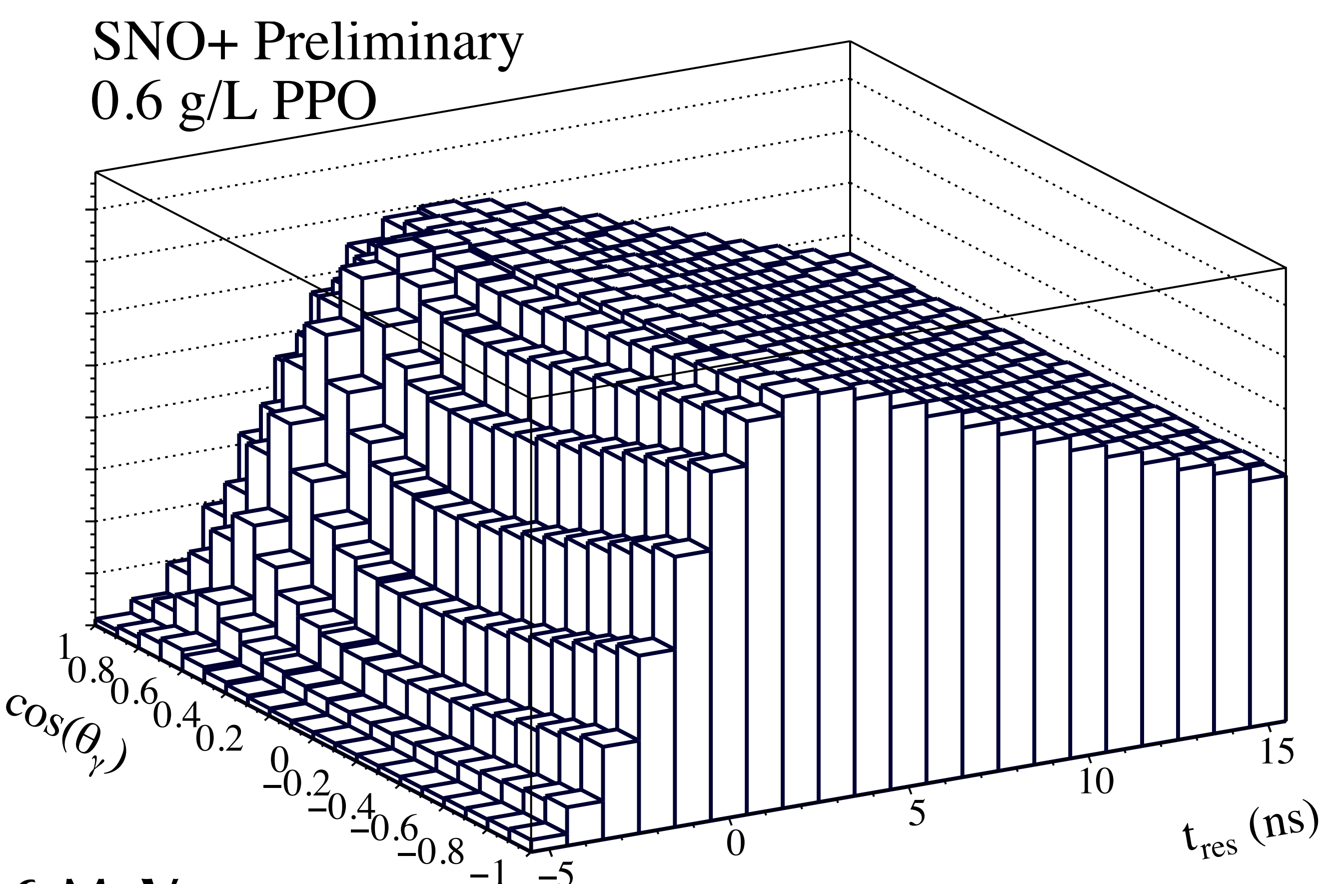


^{232}Th = $(5.7\pm0.3)10^{-17}$ g/g

Below DBD-phase requirements!

^{238}U = $(5.3\pm0.1)10^{-17}$ g/g

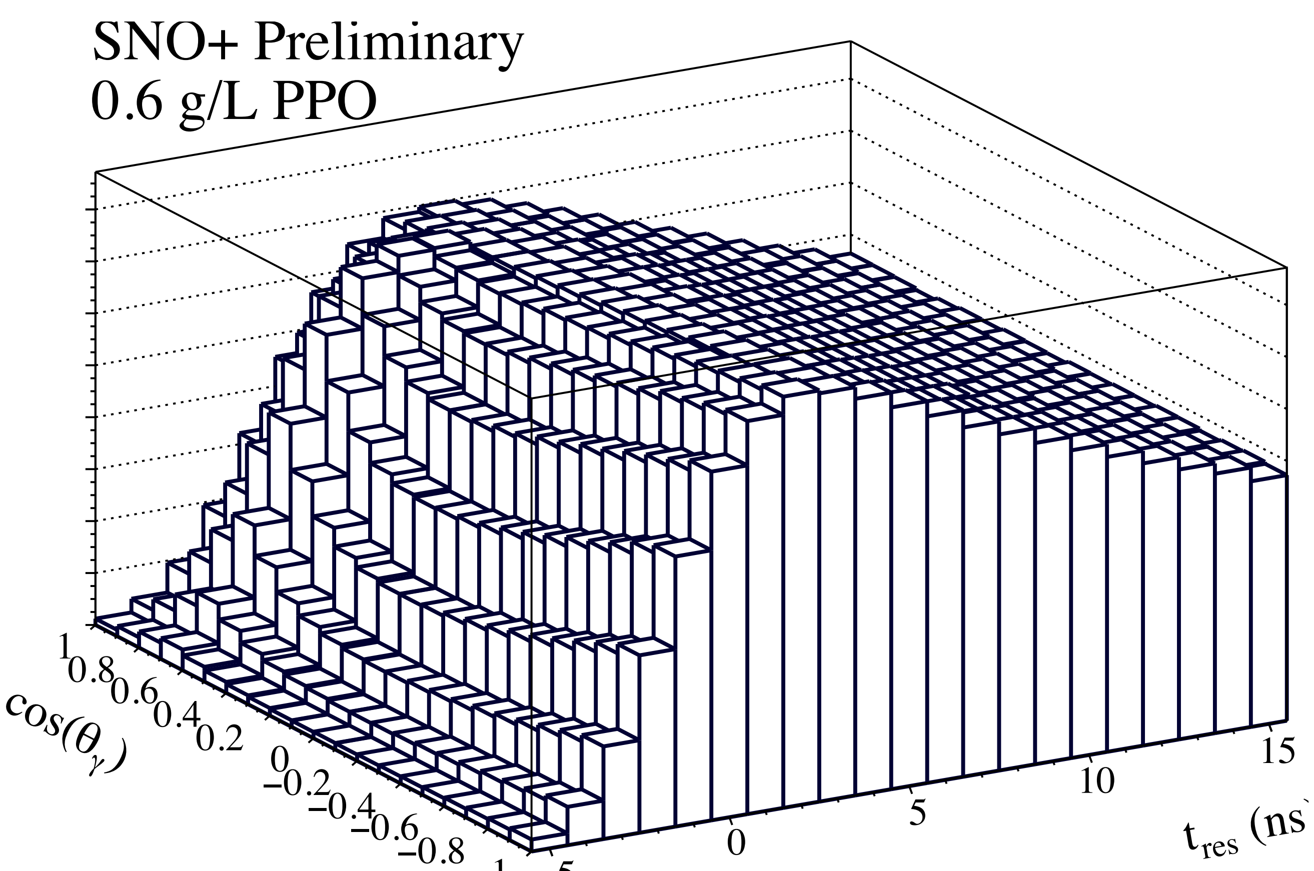
- Investigation of mitigation strategies for solar neutrinos: Directionality of ^{8}B
- Very promising results for the 0.6 g/L PPO scintillator:
  - Determined by fitting prompt timing profiles to combined Cherenkov-scintillation 2D PDFs



6 MeV e-

SNO+ Directionality

- Investigation of mitigation strategies for solar neutrinos: Directionality of ^{8}B
- Very promising results for the 0.6 g/L PPO scintillator:
  - Determined by fitting prompt timing profiles to combined Cherenkov-scintillation 2D PDFs
  - Event-by-event direction reconstruction compared to Borexino Correlated and Integrated Directionality
    - **first time in liquid scintillation experiment —> Paper in preparation!**



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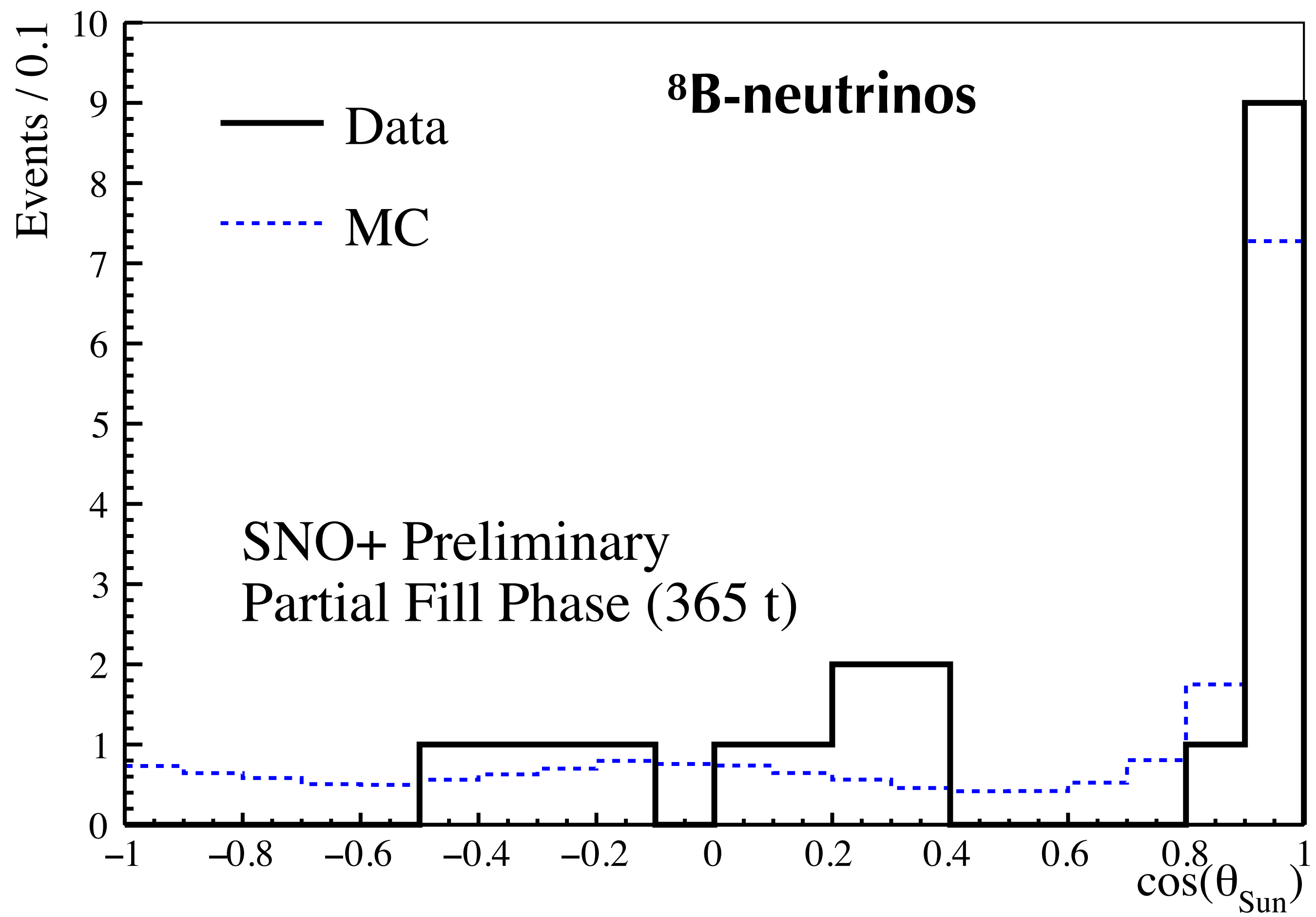
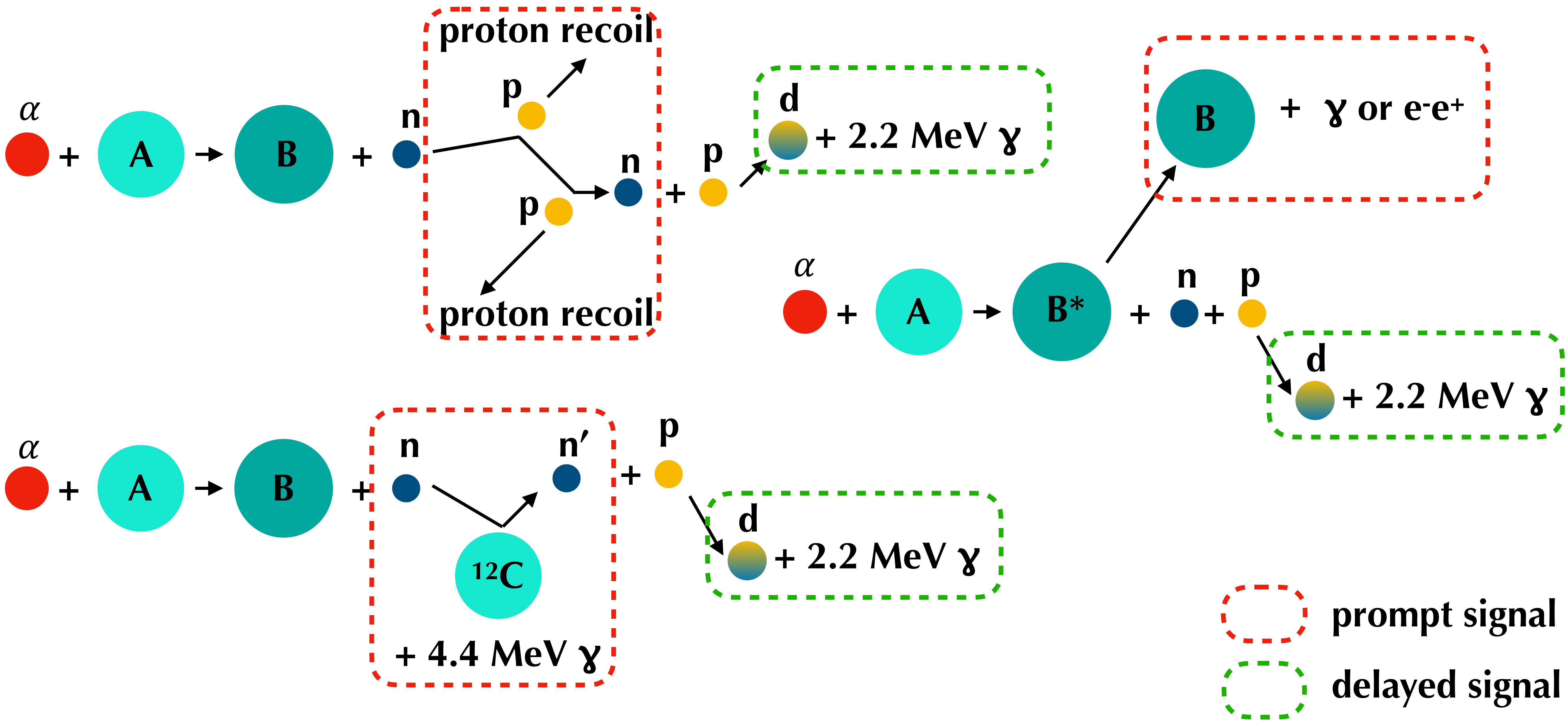


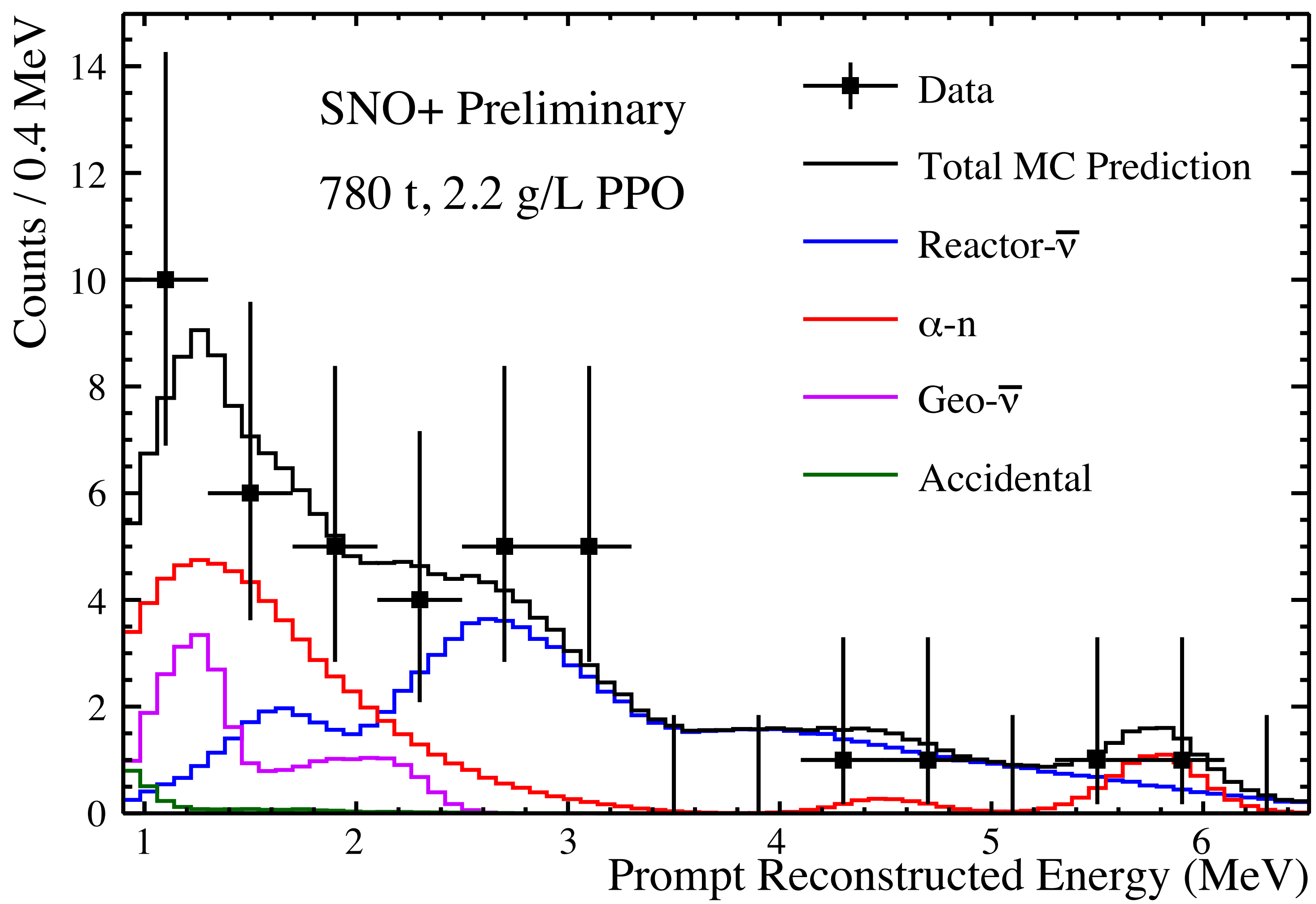
SNO+ Alpha,n Reactions

- Major background for the antineutrino analysis
- Prompt (scattered off protons) and delay (2.2 MeV gamma from neutron capture) can fall in the DBD ROI



SNO+ Alpha,n Reactions

- Major source of alphas is ^{210}Po
  - Highly reduced (70%) ^{210}Po background from partial fill to the 2.2 g/L full fill phase
- Developed a classifier to separate ^{13}C(alpha,*n*) reactions from anti-neutrinos



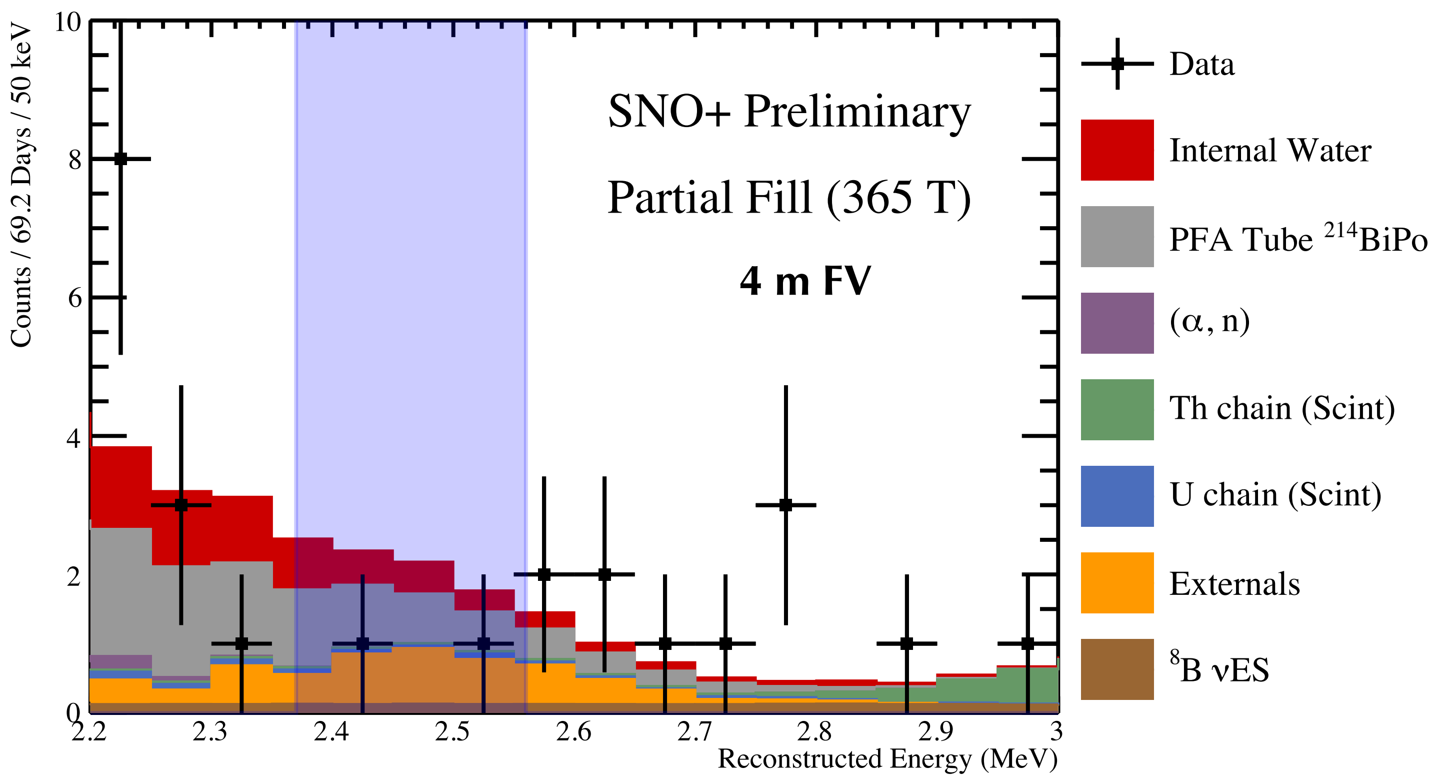
See talk
T. Kaptanoglu
Aug 31, 2023, 3:15PM,
Hörsaal 21 lecture hall

Reactor IBD oscillated using:

- Δm^2_{21} = 7.53x10^{-5} eV^2
- $\sin^2(\theta_{12})$ = 0.307

SNO+ Target out

- Preparation for the double-beta decay phase: background and target-out measurement



June - October 2020
(~69 gold physics days)

Bonus phase:
partial fill
0.6 g/L PPO

Partial fill:

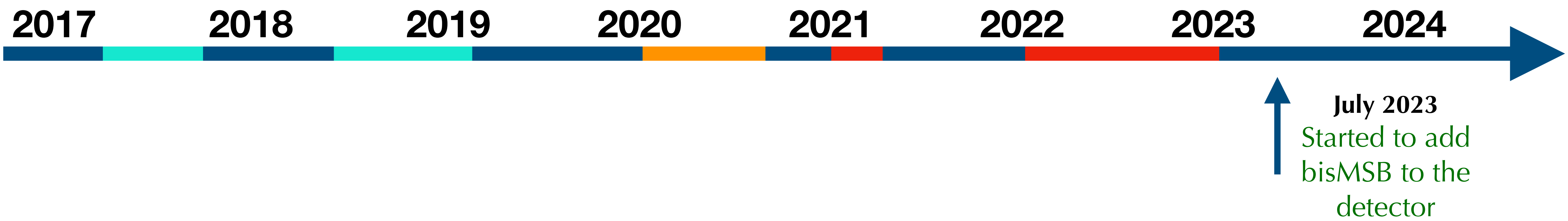
- Expected 8 events, seen 2

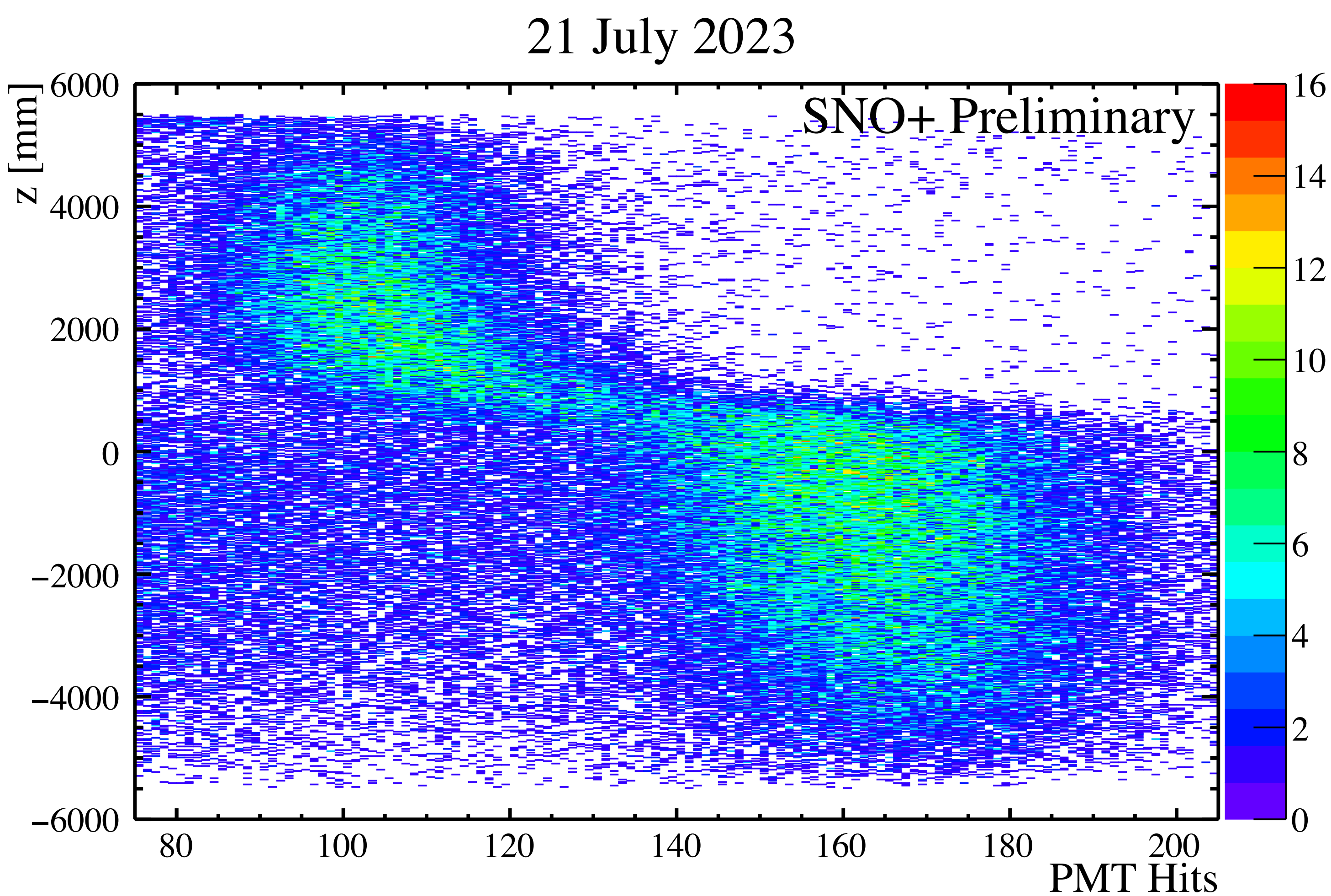
Full fill + 2.2 g/L PPO:

- Analysis in progress

See poster
B. Tam
0νββ Target Out Analysis for the SNO+ Experiment

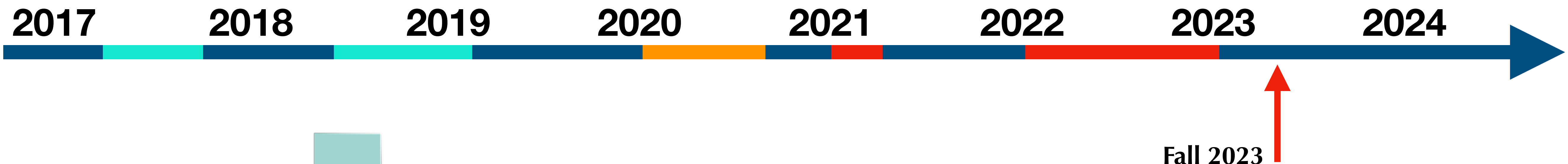
SNO+ BisMSB

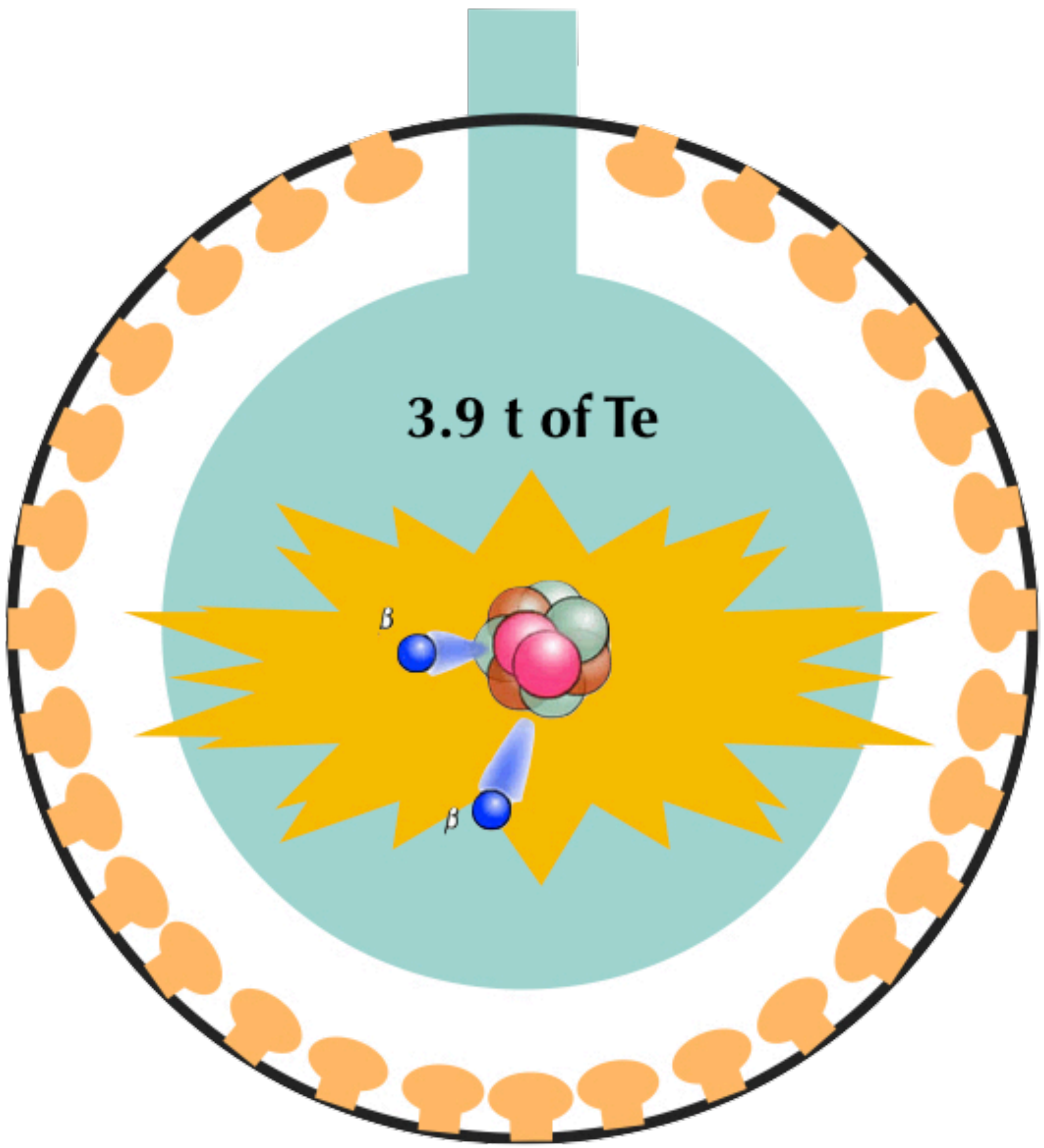


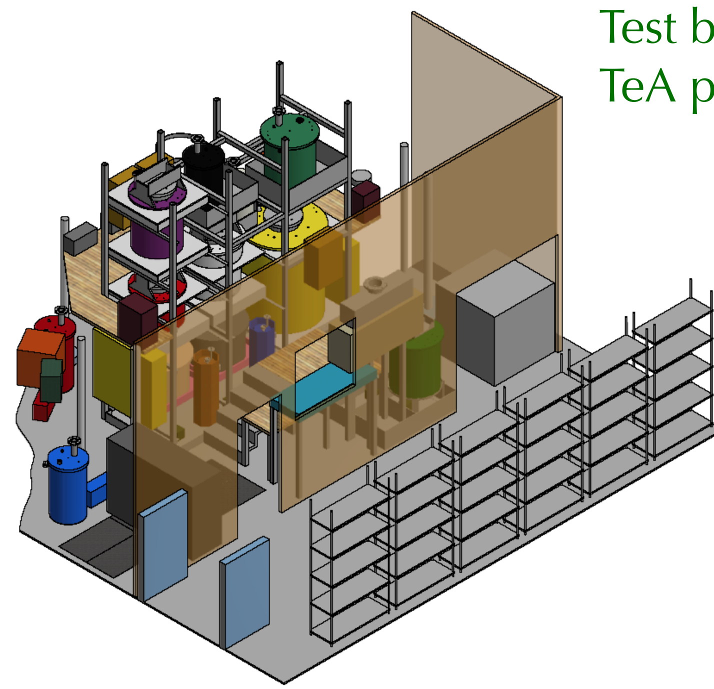


- Tracking ^{210}Po decays
- BisMSB added at the bottom of the detector (0.5 kg) and started to mix
- **Clear improvement (~1.5x) in light output**

SNO+ TeLS



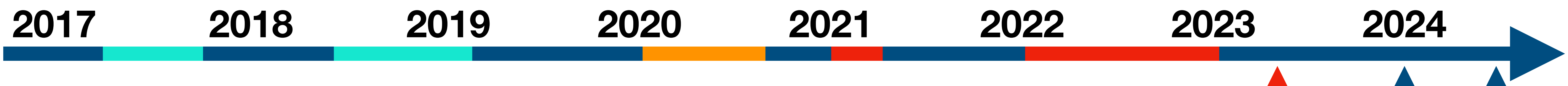




Fall 2023
Test batch (~200 kg) of the TeA purification plant

- **Important milestone:**
  - First full-scale tests of SNO+ Te purification and loading systems
  - Samples will be collected for off-site ICP-MS analysis (U/Th)

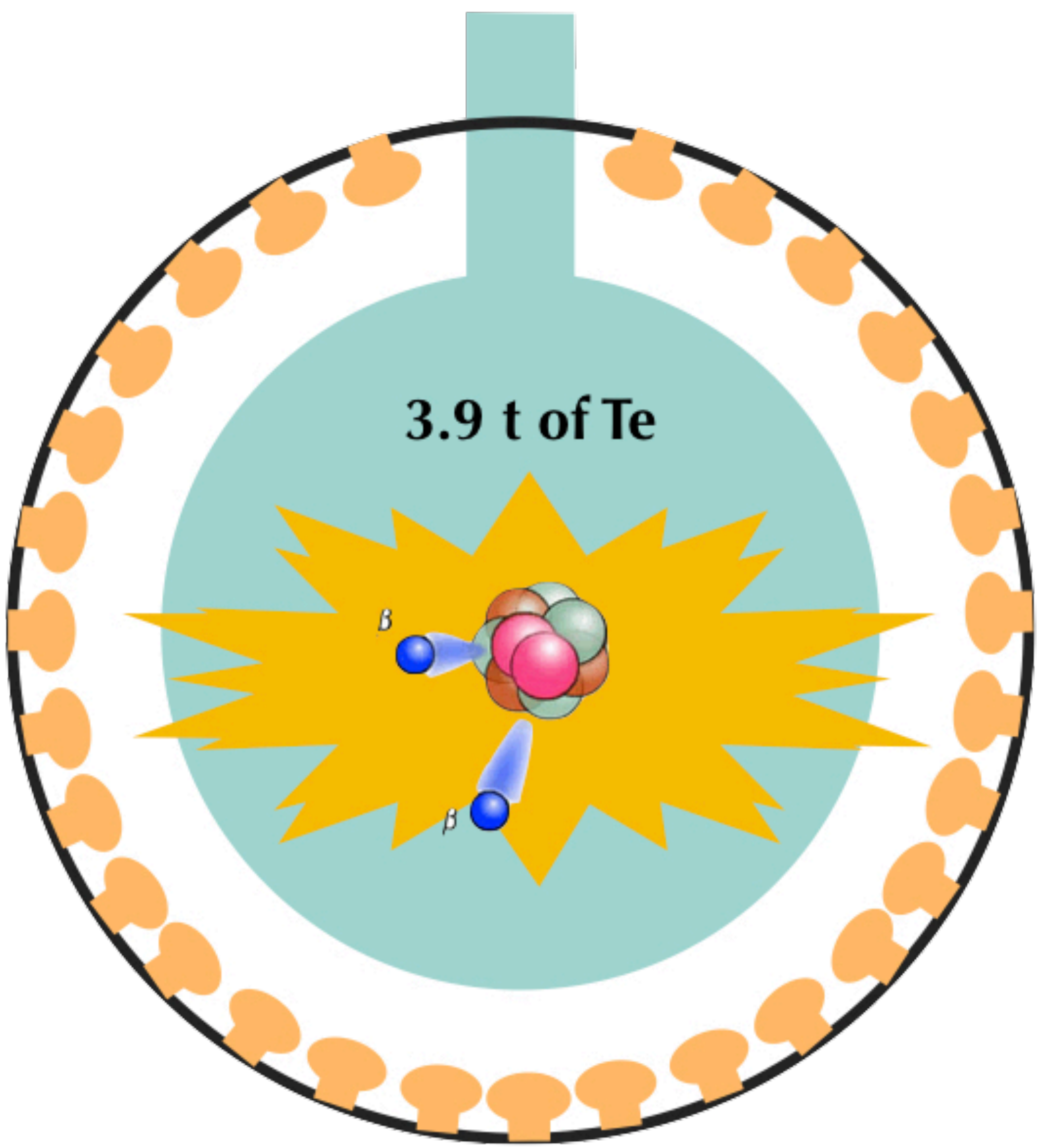
SNO+ TeLS

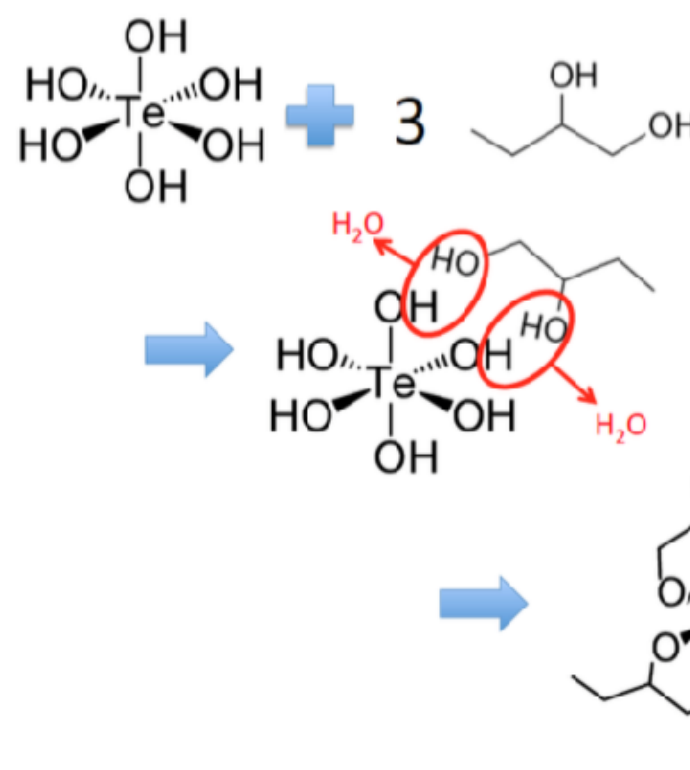


Fall 2023
Test batch (~200 kg) of the TeA purification plant

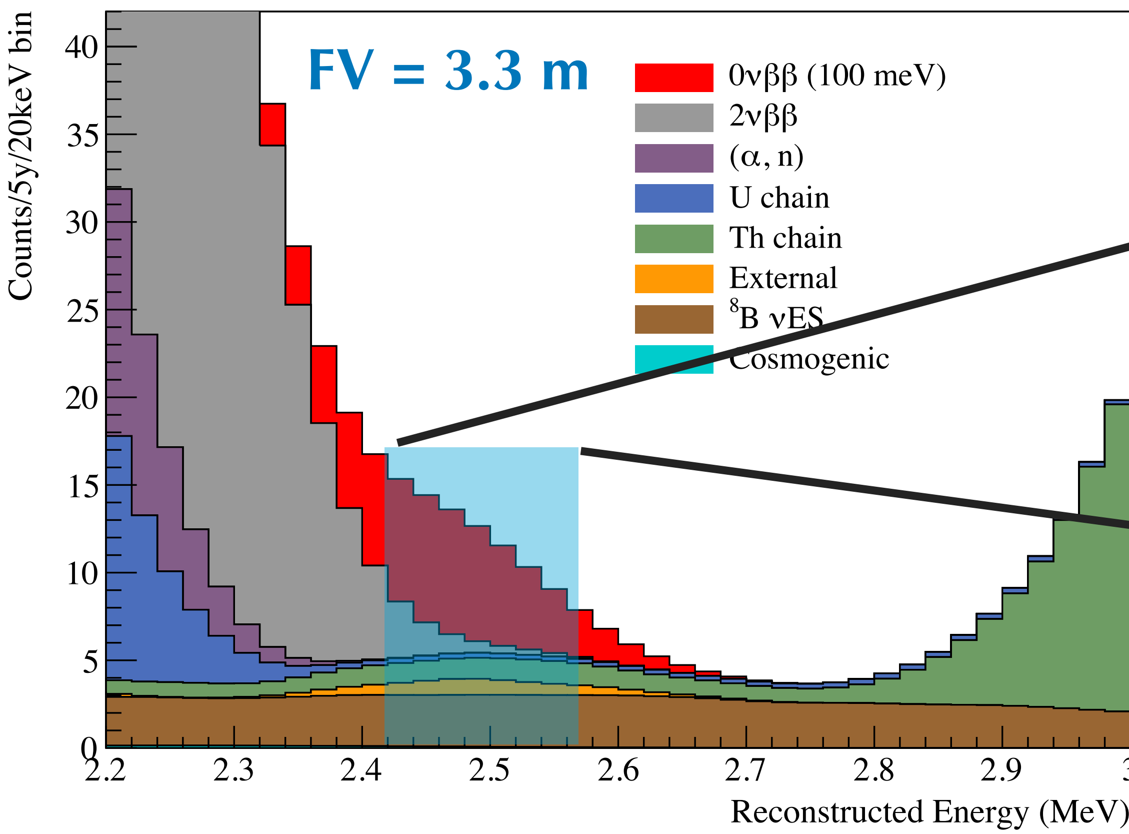
From 2024
Start to add TeLS cocktail components

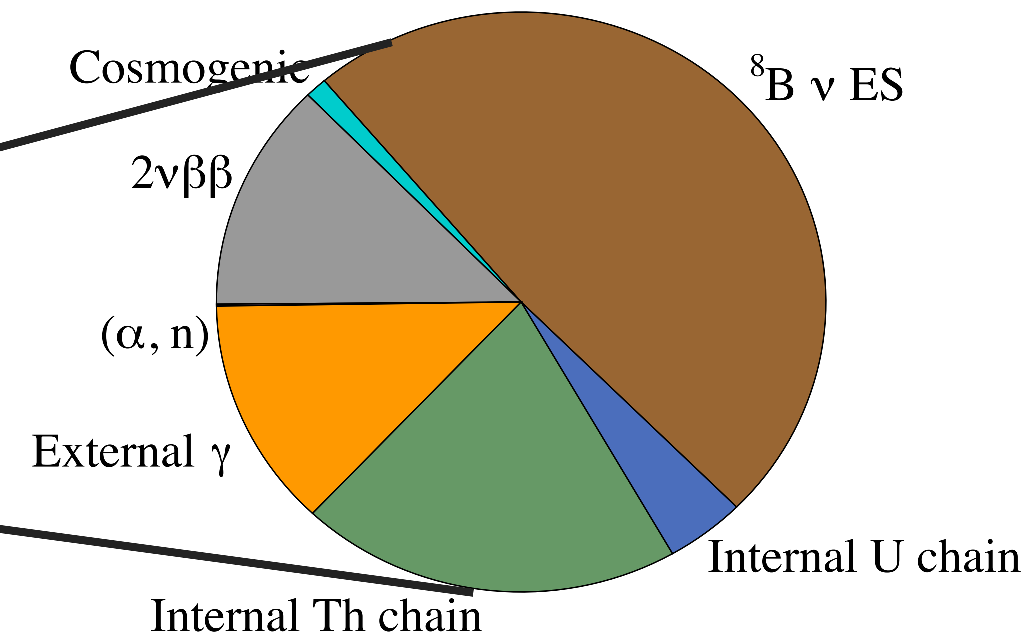
From 2025
Start count with Te





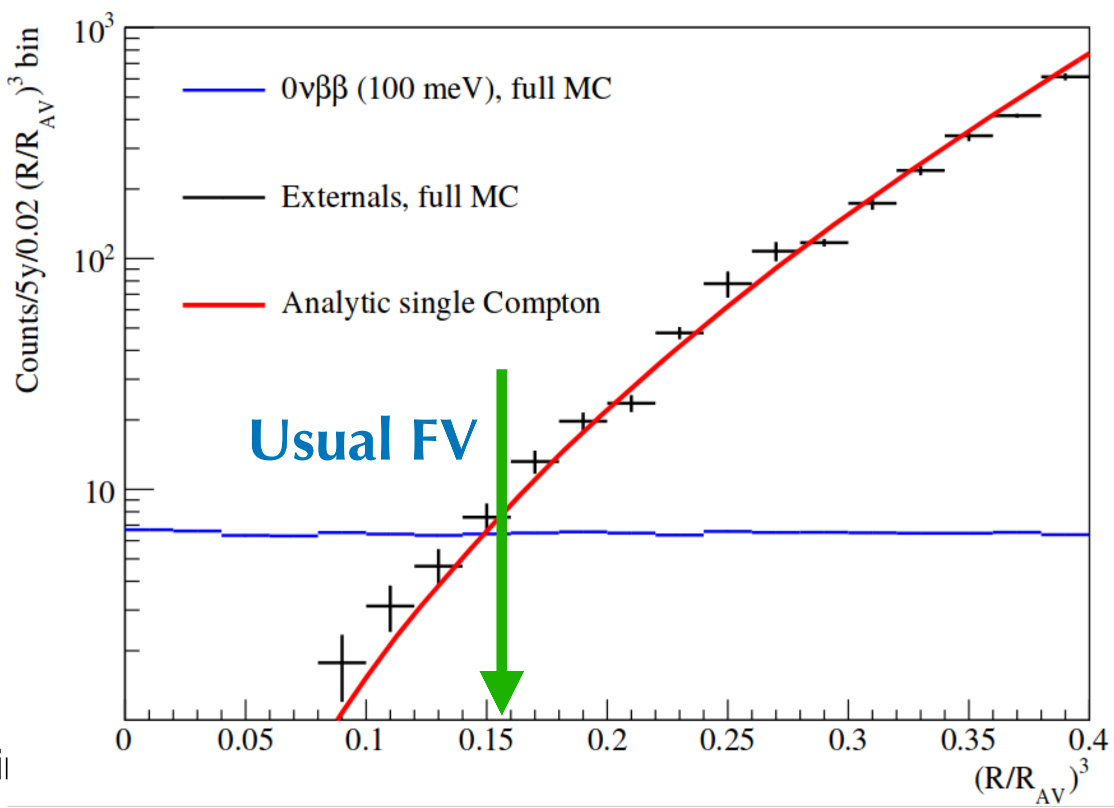
Expected Signal/Background





Events in the Region Of Interest
+ Fiducial Volume

9.47 events/yr (at nominal backgrounds)

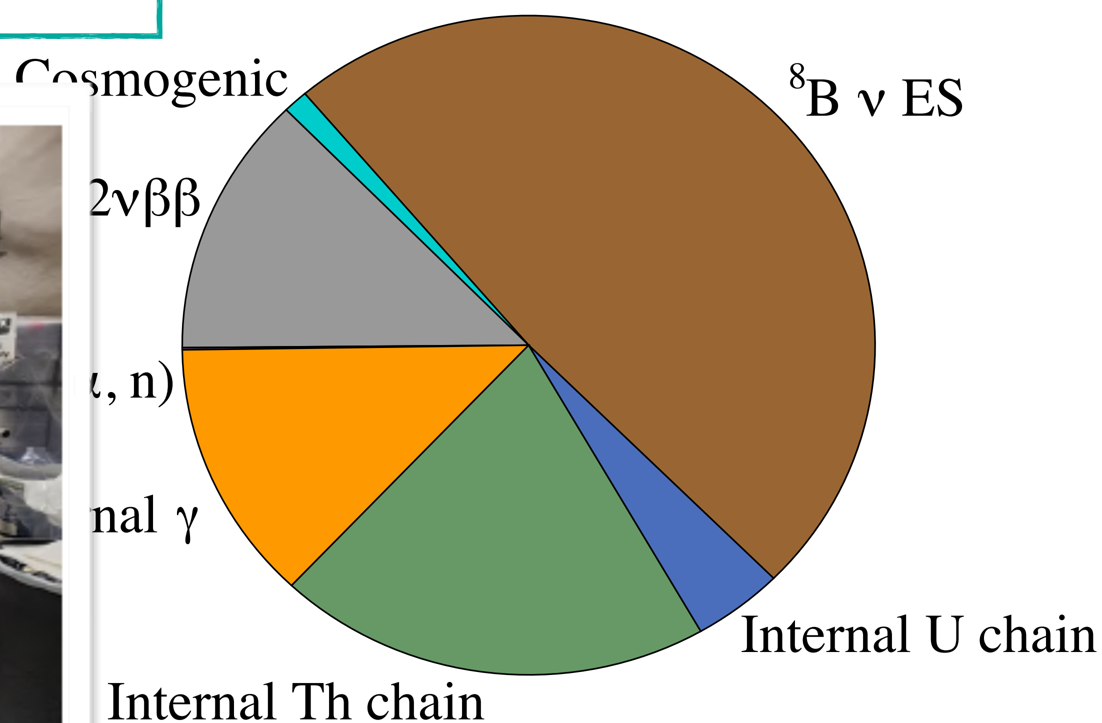


Mitigation Strategies

Cosmogenic:
- ^{60}Co, ^{110m}Ag, ^{88}Y, ^{22}Na
- mitigation: purification + "cool-down" UG
- First Te UG since 2015
- multi-site classifier

TeA cooling UG since 2015

Background breakdown in 0νββ ROI



See Poster
T. Kroupova
Event Reconstruction in the SNO+ Experiment

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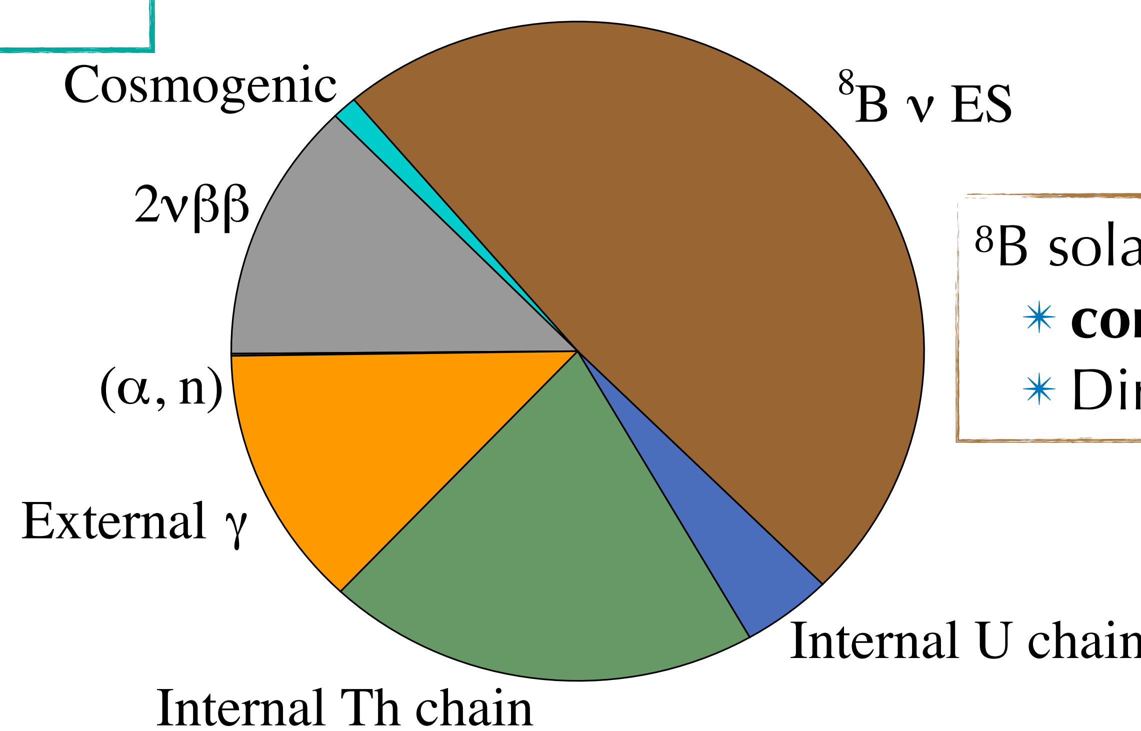
Background breakdown in $0\nu\beta\beta$ ROI



^{8}B solar neutrinos:
- **constrained by SNO/SK data**
- Directionality?

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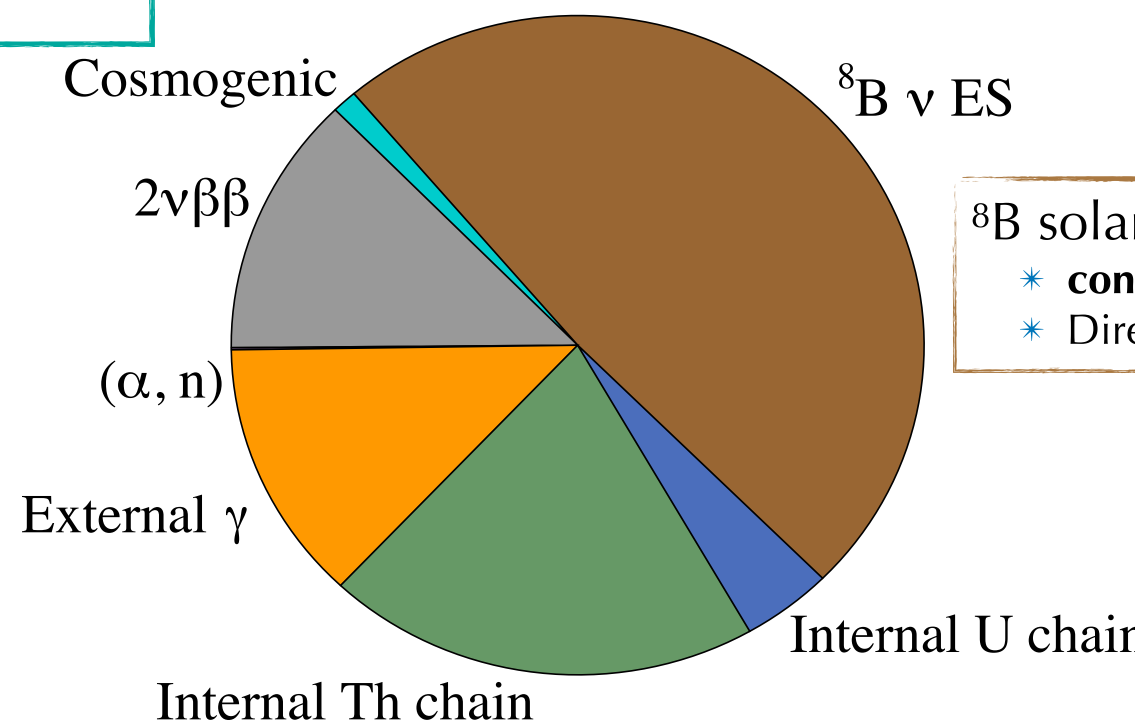

^{8}B solar neutrinos:
- **constrained by SNO/SK data**
- Directionality?

Internal U/Th chain:
- $^{214}BiPo$, $^{212}BiPo$, ^{210}Tl
- **LAB components below requirements for the TeLS phase**
- **Constantly monitoring the contribution from the scintillator before and while adding Te**
- ß – α delayed coincidence tagging + in-window rejection (expected more than 98% rejection on in-window events)

Mitigation Strategies

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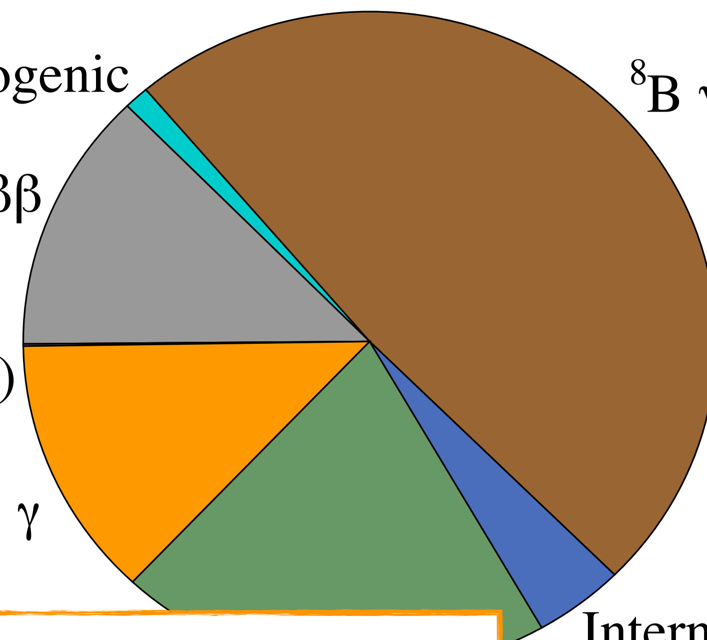

^{8}B solar neutrinos:
- **constrained by SNO/SK data**
- Directionality?

External gammas:
- from AV, ropes, water, PMTs, mainly ^{208}Tl
- **Measured in water phase, below nominal values**
- Fiducialization to minimize the leak in ROI

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Mitigation Strategies

Background breakdown in $0\nu\beta\beta$ ROI

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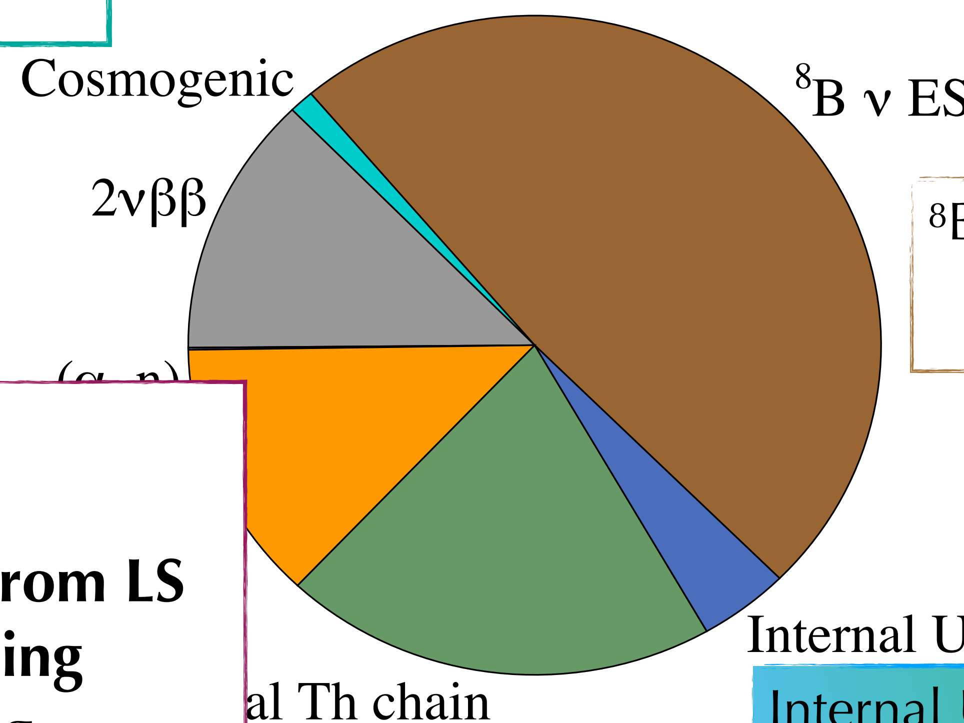

^{8}B solar neutrinos:
- **constrained by SNO/SK data**
- Directionality?

(a,n):
- alpha-capture on ^{13}C (^{18}O)
- **Measure the contribution from LS components before Te loading**
- delayed coincidence tagging

Internal U/Th chain:
- ^{214}BiPo, ^{212}BiPo, ^{210}Tl
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- **Constantly monitoring the contribution from the scintillator before adding Te**
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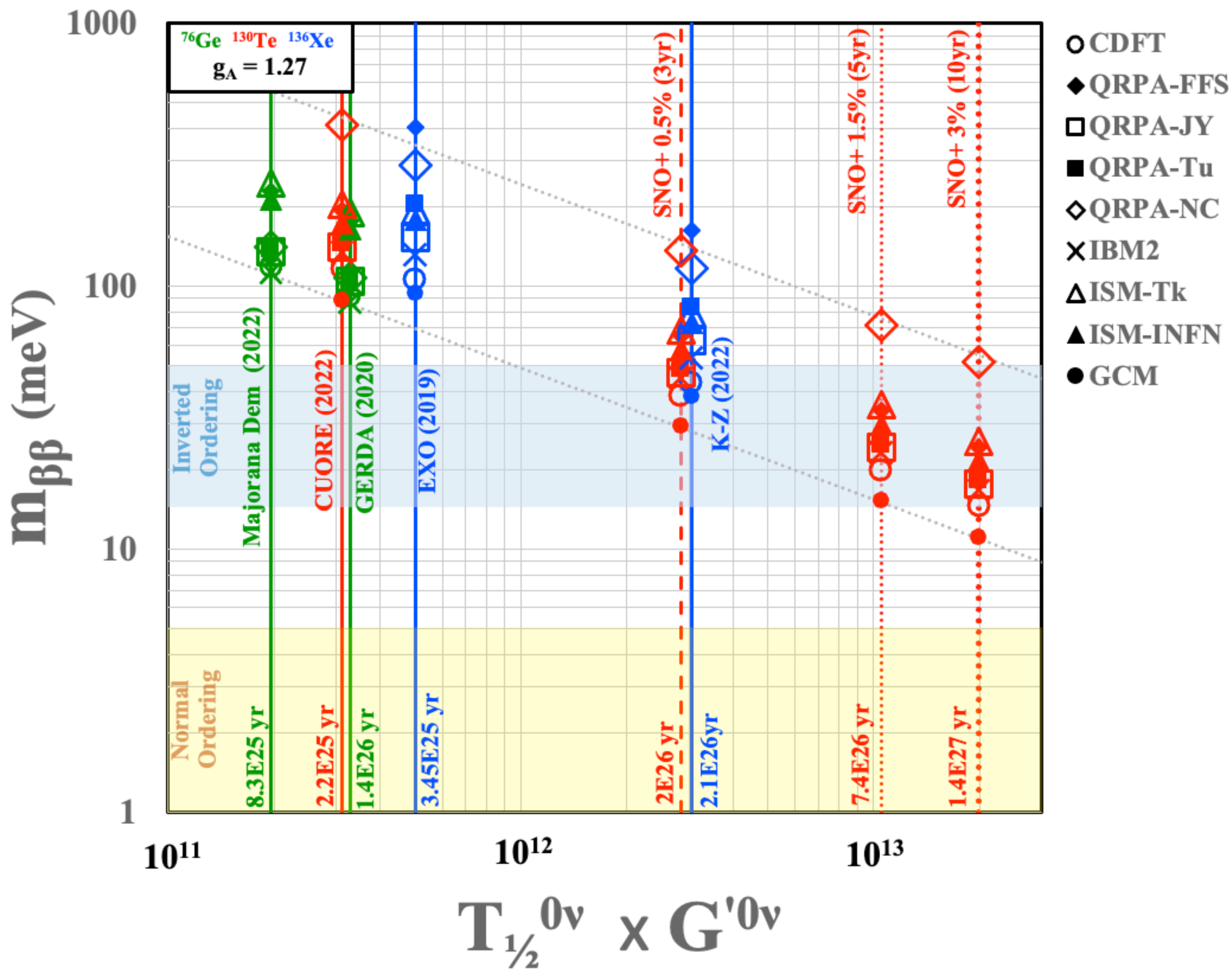
Projections



Summary

- SNO+ has successfully completed its scintillator loading and is taking data with 2.2 g/L PPO as of April 2022
- Initial measurements show radioactive backgrounds at or below the targeted values
- Many exciting physics publications are expected in the very near future!

LIP Coimbra
LIP Lisboa

SNOLAB
TRIUMF
University of Alberta
Queen's University
Laurentian University

TU Dresden

UNAM

Boston University
BNL
University of California Berkeley
LBNL
University of Chicago
University of Pennsylvania
UC Davis

Oxford University
Kings College London
University of Liverpool
University of Sussex
University of Lancaster

Shandong University

LIP Coimbra
LIP Lisboa

SNOLAB
TRIUMF
University of Alberta
Queen's University
Laurentian University

TU Dresden

UNAM

Thank you for your attention

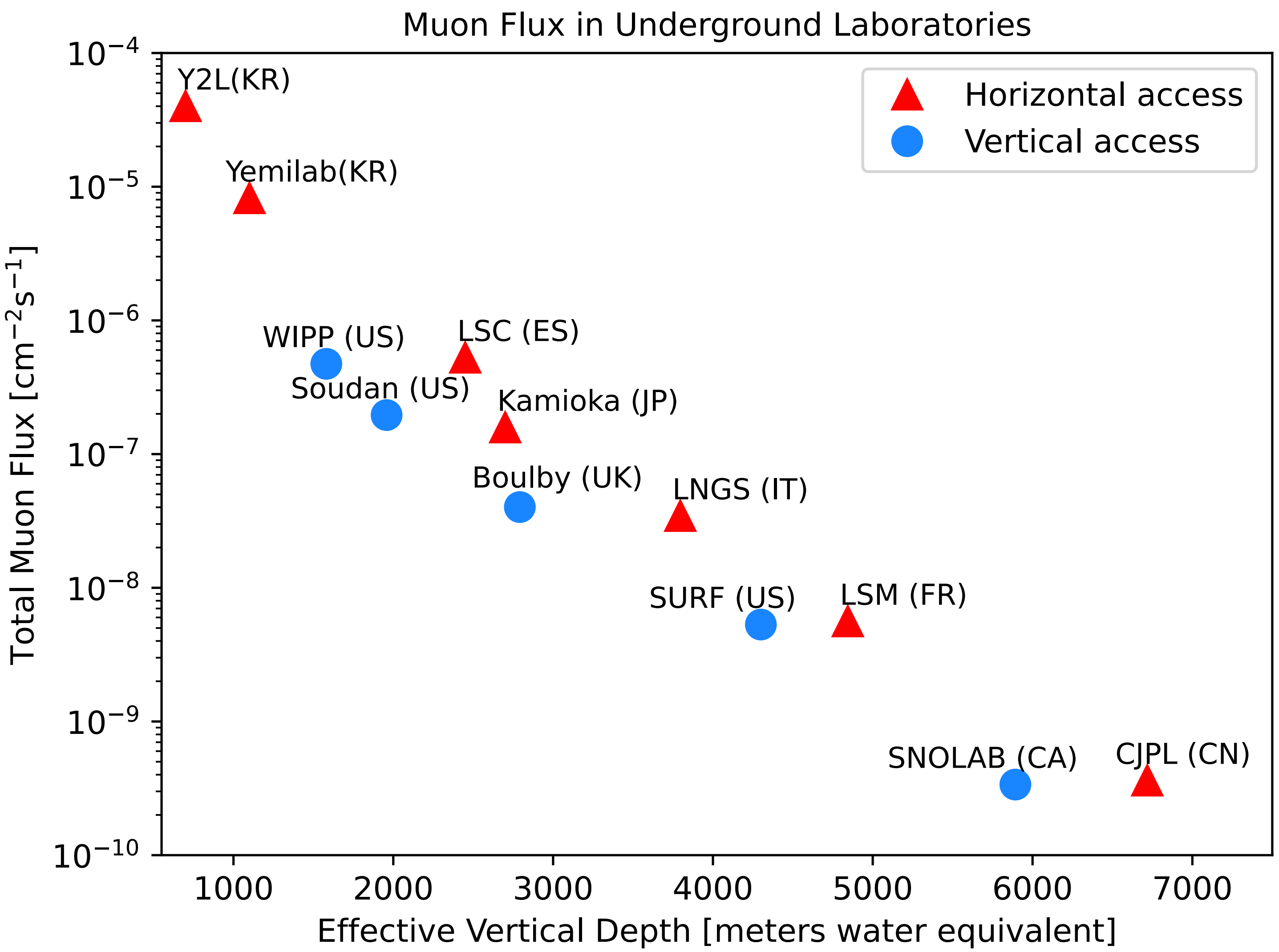
Boston University
BNL
University of California Berkeley
LBNL
University of Chicago
University of Pennsylvania
UC Davis

Oxford University
Kings College London
University of Liverpool
University of Sussex
University of Lancaster

Shandong University

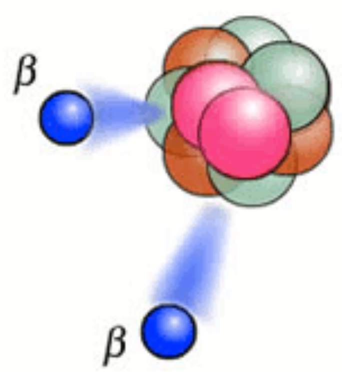
Back up

@SNOLAB, Sudbury, Canada



SNO+ Physics
(water, LS, TeLS)

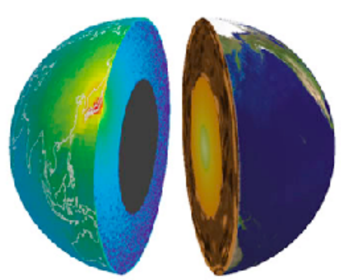
0/1 = not doable/doable in water, LS, TeLS phase



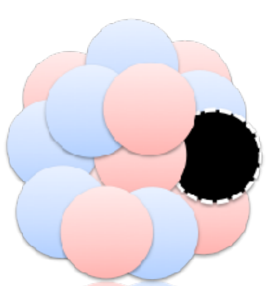
Neutrinoless double-beta decay of ^{130}Te (0,0,1)

Solar neutrinos (1,1,1)

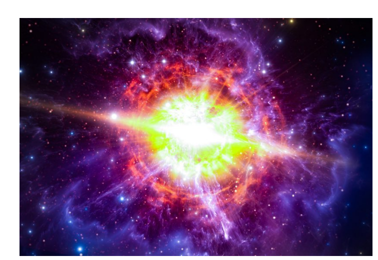
Reactor antineutrinos (1,1,1)



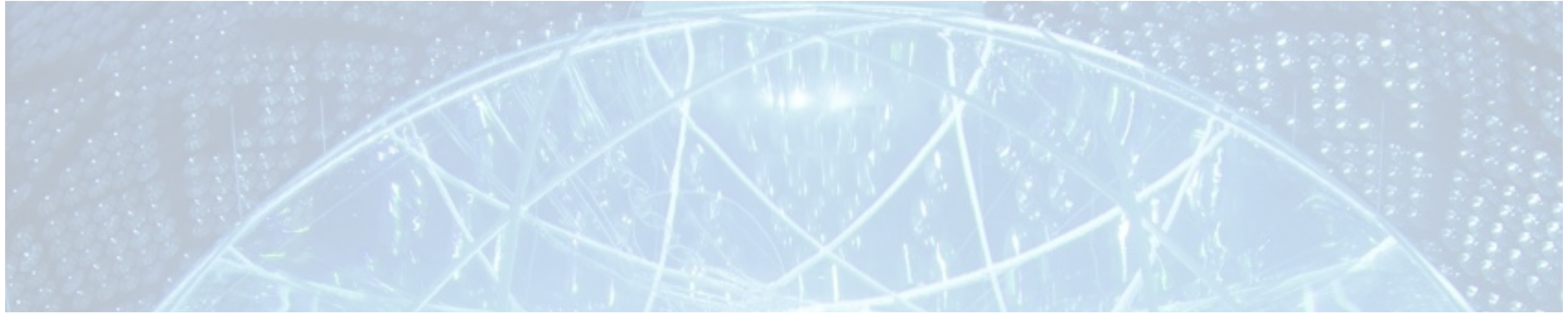
Geo anti-neutrinos (0,1,1)



Rare decays and interactions (1,1,1)



Supernovae neutrinos (1,1,1)

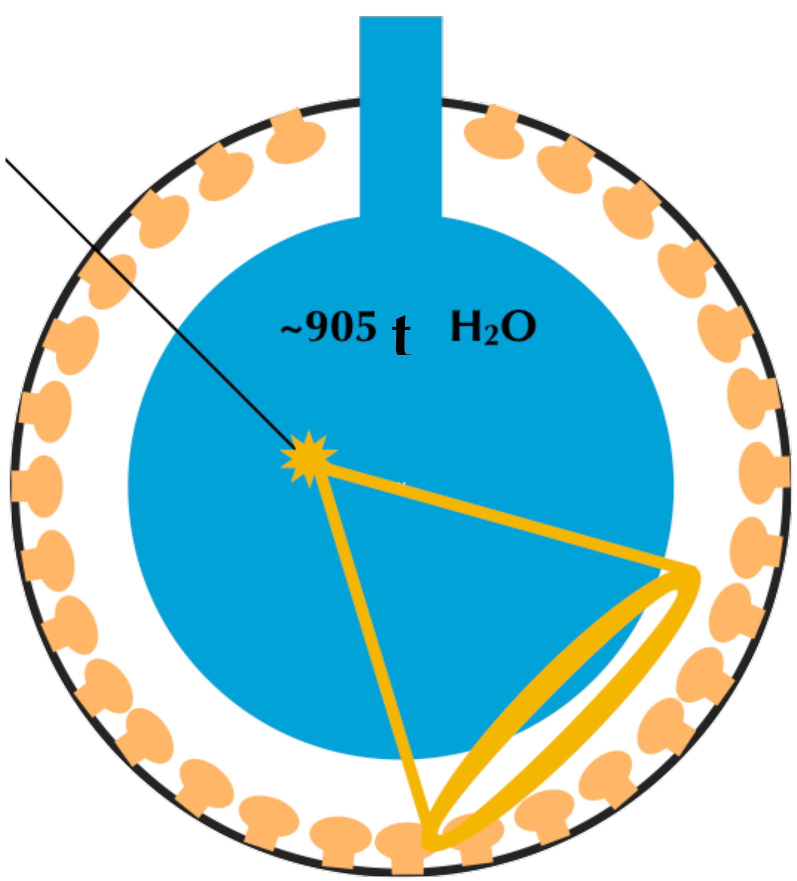


2017 — **2018** — **2019**

May - December 2017
(~115 gold physics days)
First SNO+ water phase
Phys.Rev.D 99, 032008

October 2018 - June 2019
(~185 gold physics days)
Second SNO+ water phase
Phys.Rev.D 105, 112012

Additional Cover gas shielding to reduce Rn ingresses in water

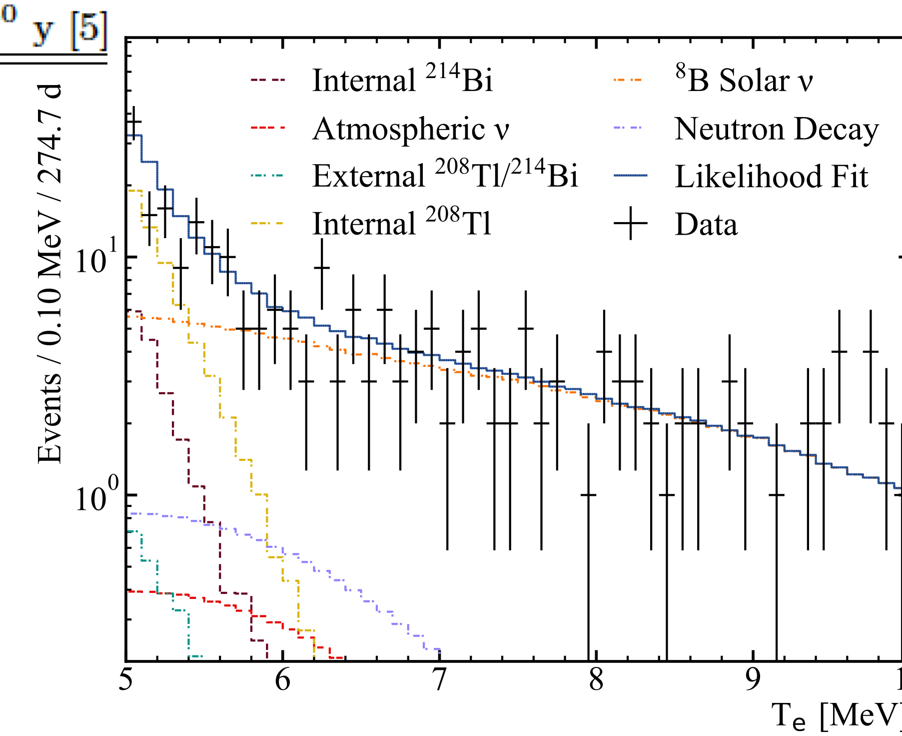


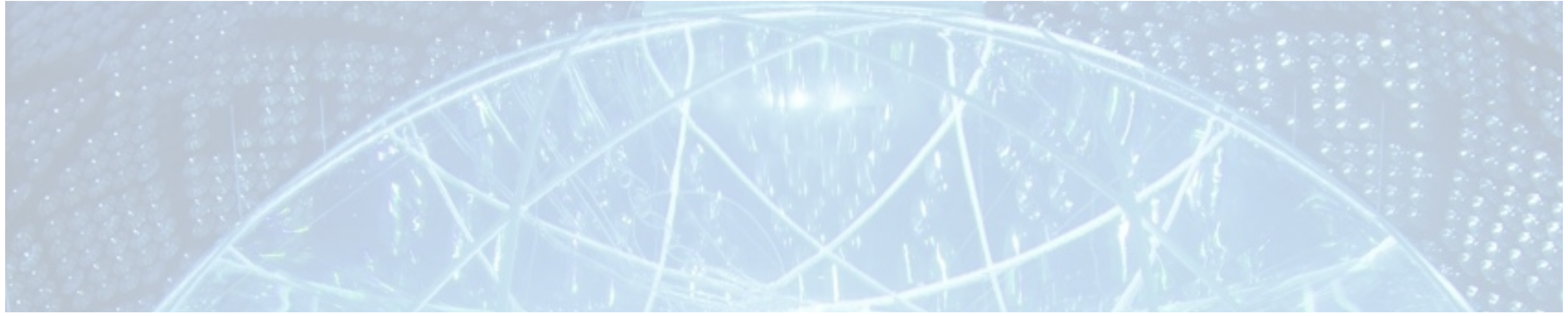
Major Outcomes

- Nucleon decay modes into invisible channels

Decay Mode	Partial Lifetime Limit	Existing Limits
n	9.0×10^{29} y	5.8×10^{29} y [5]
p	9.6×10^{29} y	3.6×10^{29} y [6]
pp	1.1×10^{29} y	4.7×10^{28} y [6]
np	6.0×10^{28} y	2.6×10^{28} y [6]
nn	1.5×10^{28} y	1.4×10^{30} y [5]

Best limit for all channels!





2017 2018 2019

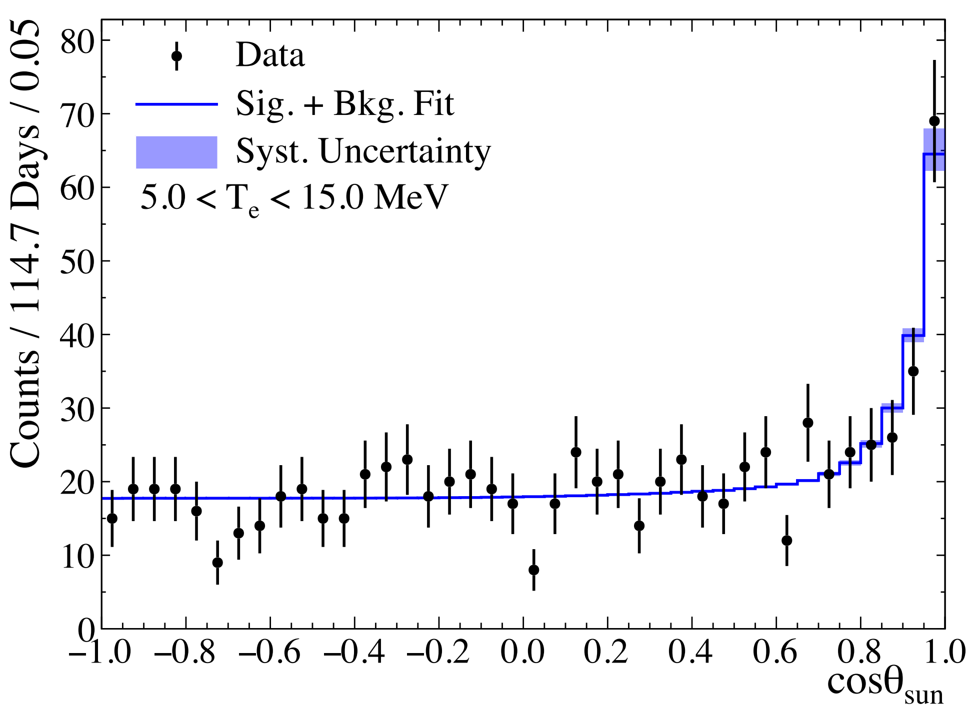
May - December 2017
(~115 gold physics days)
First SNO+ water phase
Phys.Rev.D 99, 012012

October 2018 - June 2019
(~185 gold physics days)
Second SNO+ water phase
In preparation

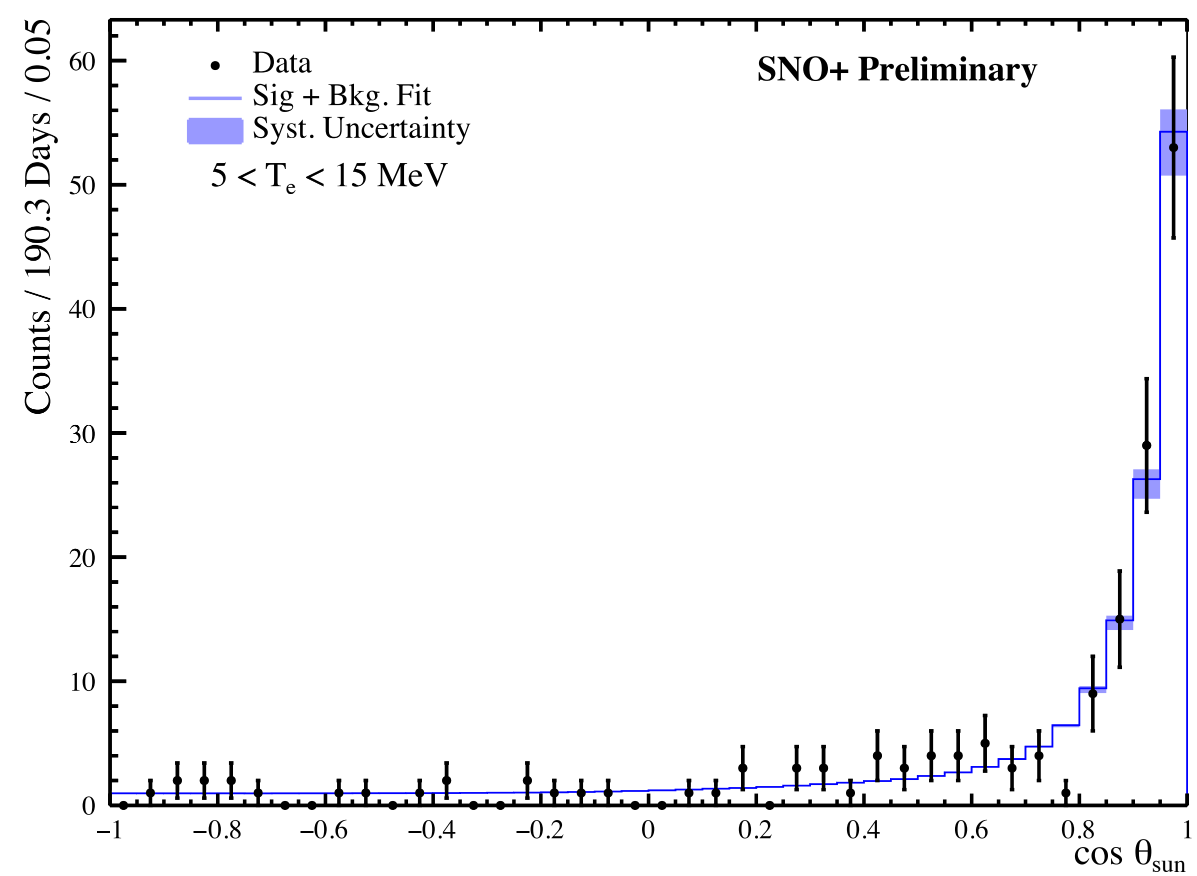
Additional Cover gas shielding to reduce Rn ingresses in water

Major Outcomes

- Nucleon decay modes into invisible channels
- Solar neutrinos

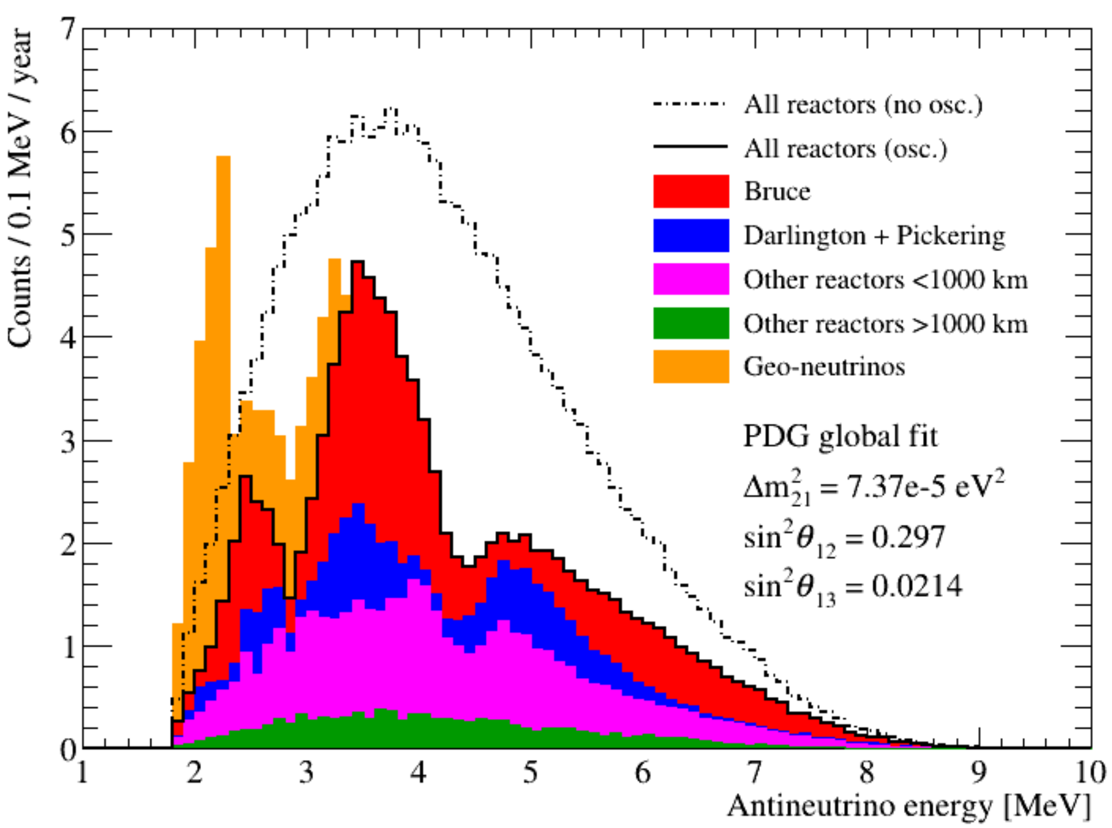


Improved background reduction



Detection mode = Inverse beta decay

Reactor anti-neutrinos = total flux about 20% of KamLAND, but baseline between reactors and SNO+ gives a unique spectral shape distortion



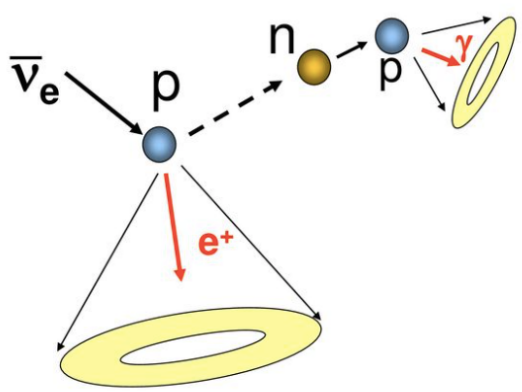
Dashed line: nonoscillated reactor spectrum
Solid line: geoneutrino spectrum
Red: Bruce reactor at 240km
Blue: Darlington & Pickering reactors at 350km
Green+**Magenta**: Other reactors

2017 2018 2019

May - December 2017
(~115 gold physics days)
First SNO+ water phase

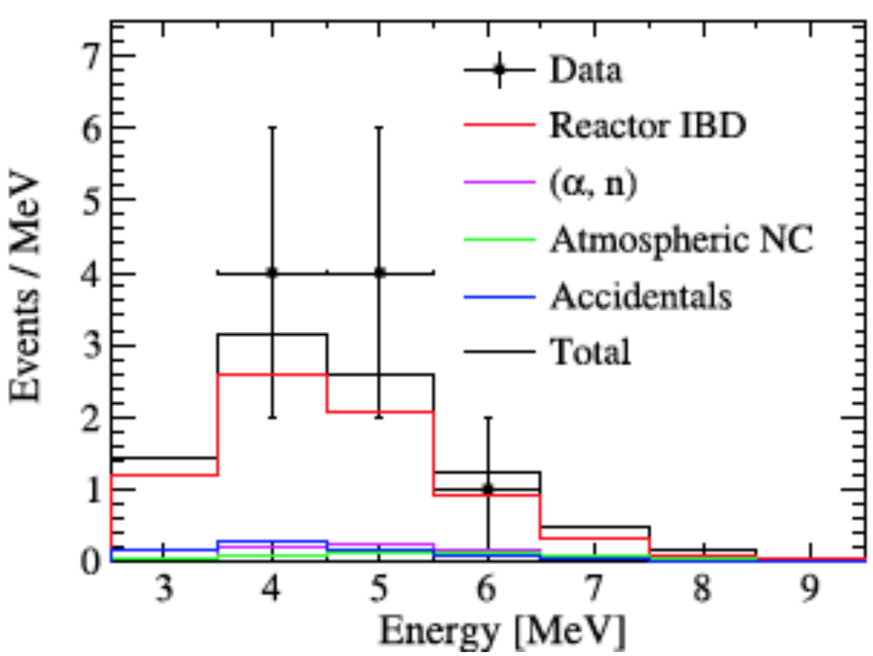
October 2018 - June 2019
(~185 gold physics days)
Second SNO+ water phase

Additional Cover gas shielding to reduce Rn ingresses in water



Major Outcomes

- Nucleon decay modes into invisible channels
- Solar neutrinos
- Reactor antineutrinos
  - Efficiency for triggering on a neutron: **(49.08 ± 0.39)%** at center ***Phys.Rev.C 102, 014002***
  - **First measurement** of reactor antineutrinos using pure water ***Phys.Rev.Lett 130, 091801***
    PRL Editor's Choice
    APS Physics Magazine Highlight

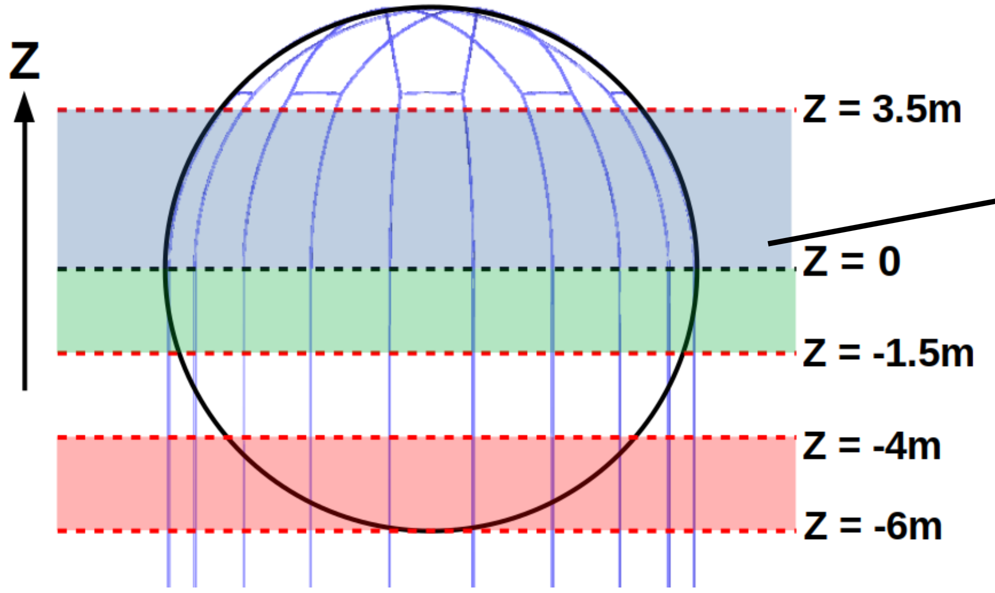


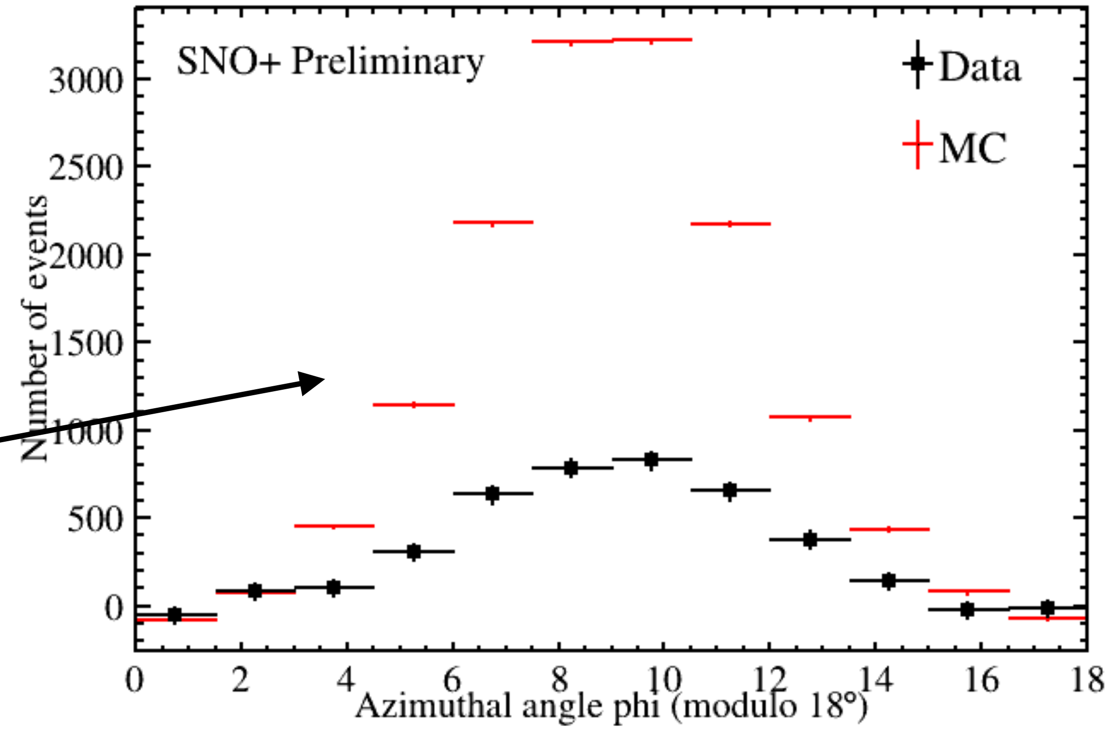
See talk
T. Kaptanoglu
Aug 31, 2023, 3:15PM
Hörsaal 21 lecture hall

- Measure of the rope's radioactivity.

Event Selection:

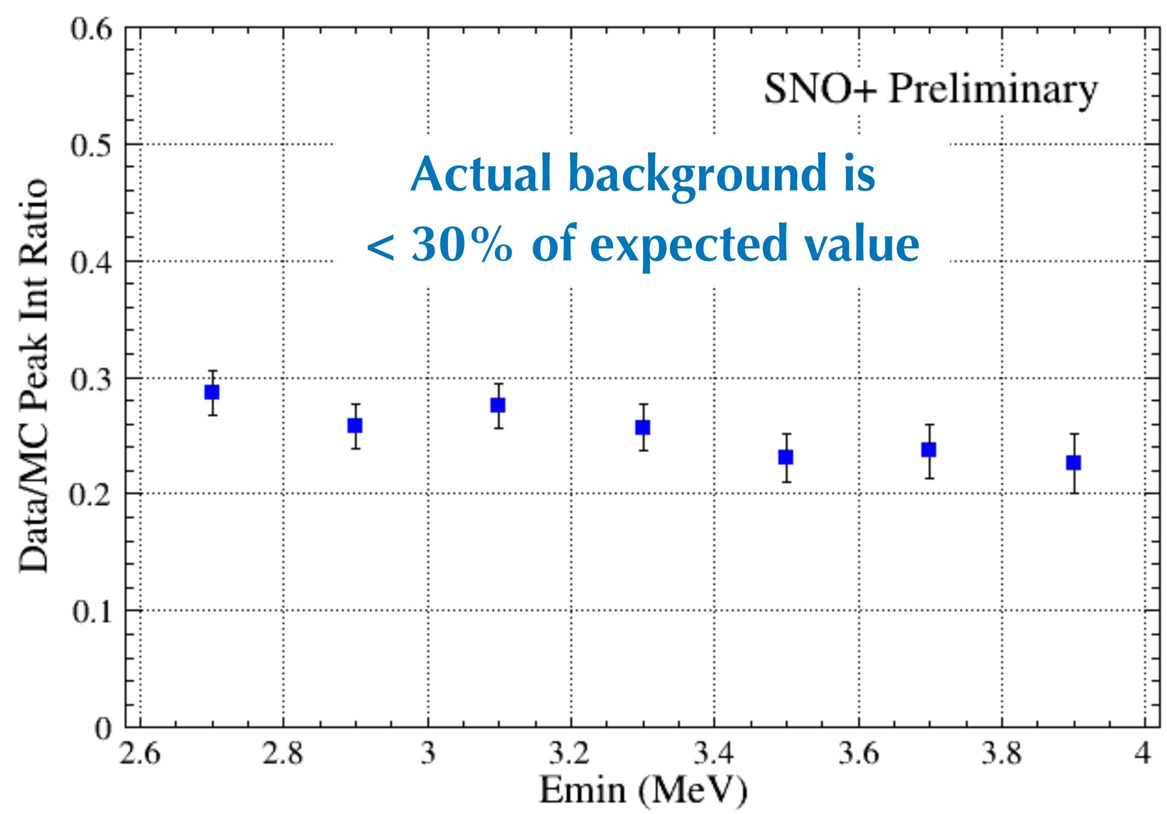
- *Box Analysis*



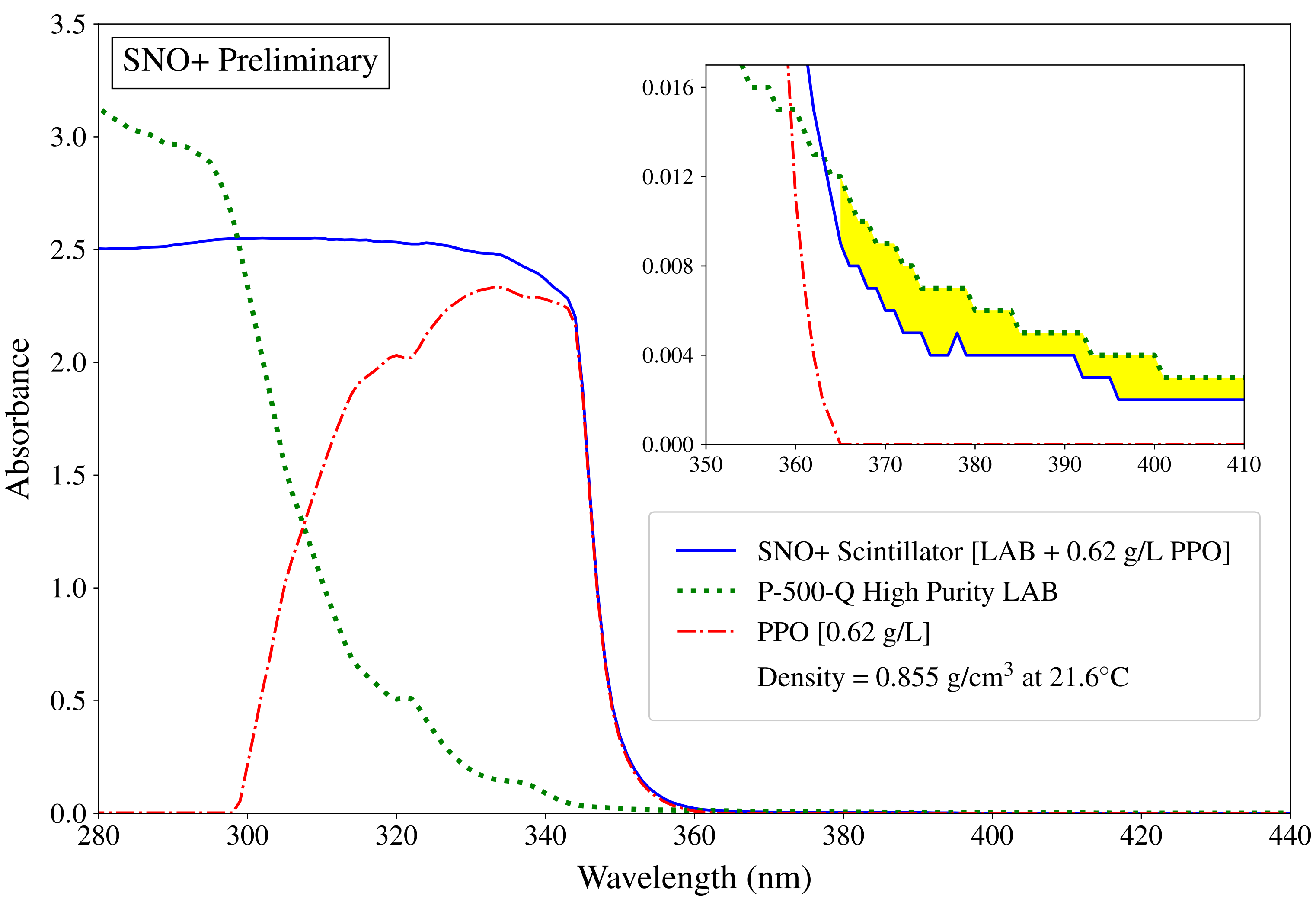


Use the azimuthal dependence (phi) of the ropes
Other backgrounds are flat in phi

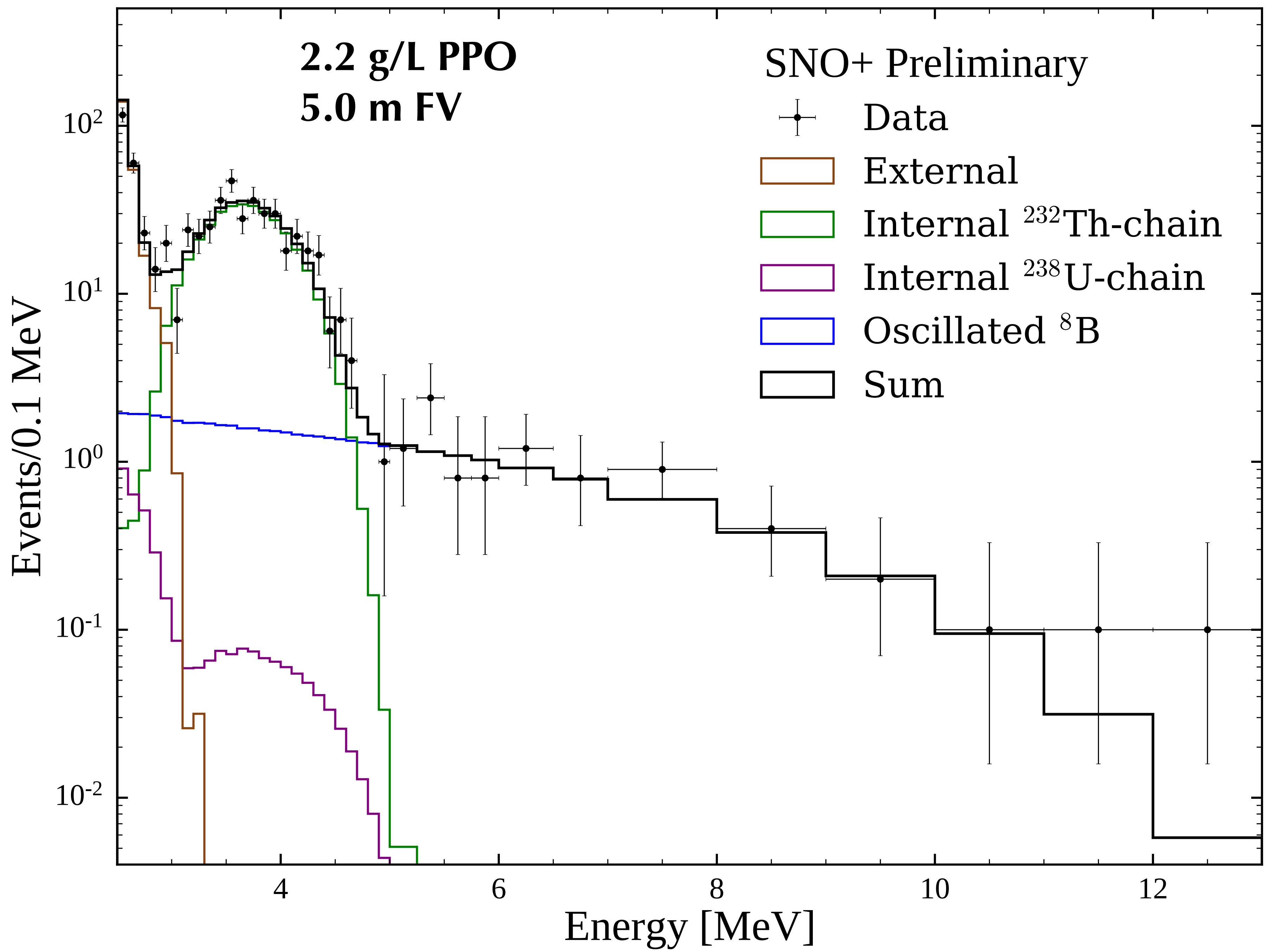
Data/MC Peak Integral vs Emin (MeV)

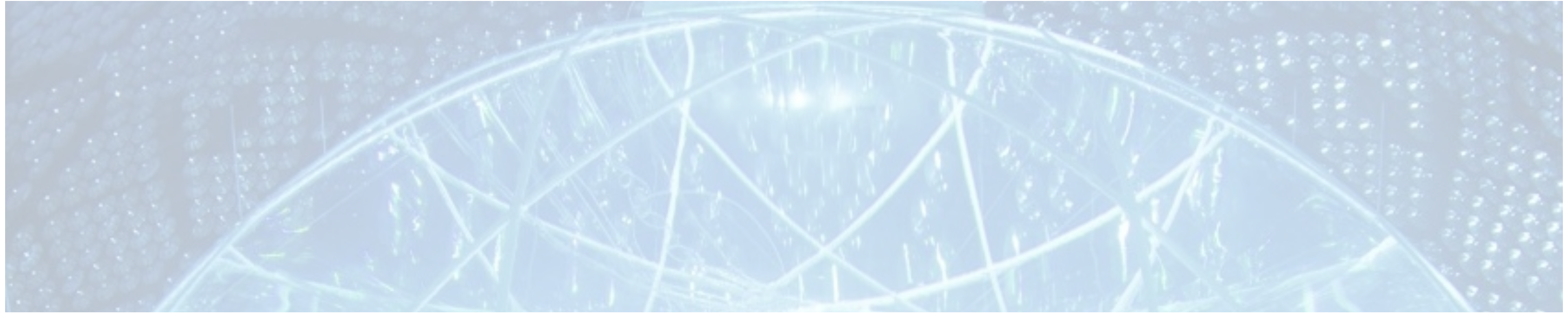


- LAB, Master Solution, and final scintillator assessed for quality hourly during purification plant operation and detector filling
    - Observe excellent clarity above PPO absorption (UV-Vis spectroscopy)



- Cross-checked via ^{208}Tl peak fit = major background for solar ^{8}B analysis



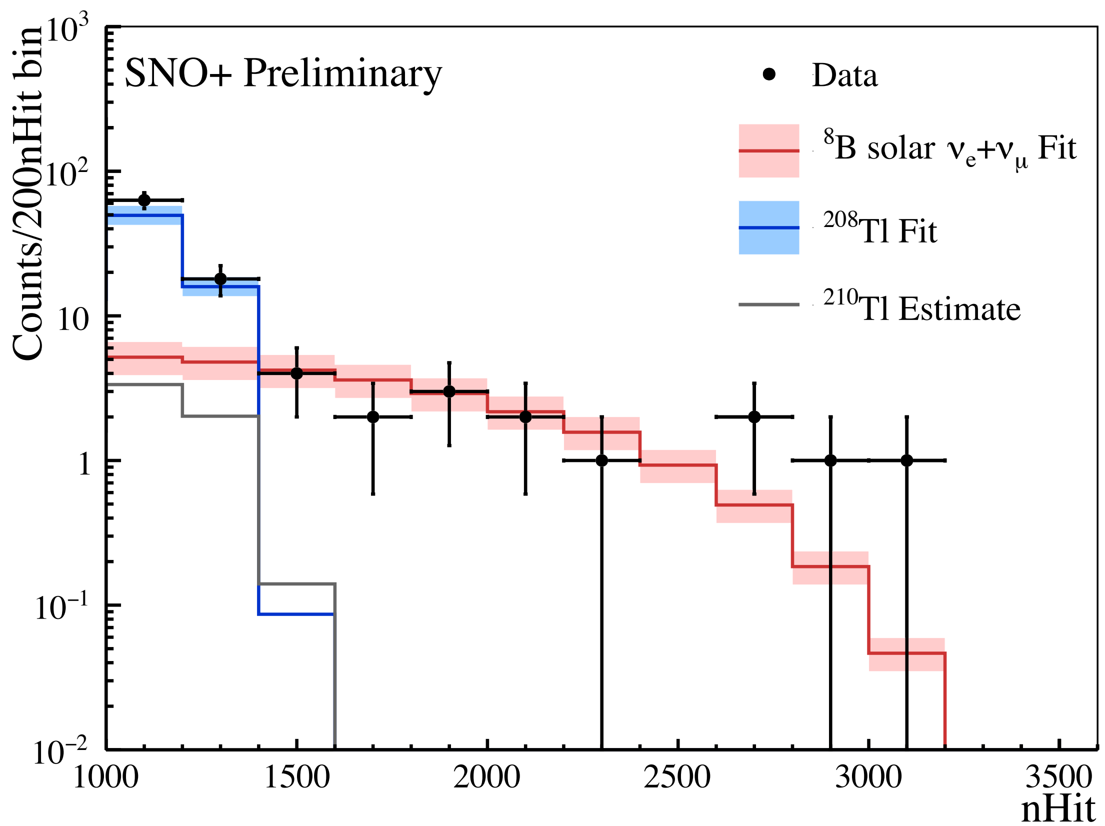


2017 2018 2019 2020 2021 2022 2023

April - October 2020
(92 gold physics days)
Bonus phase:
partial fill
0.6 g/L PPO

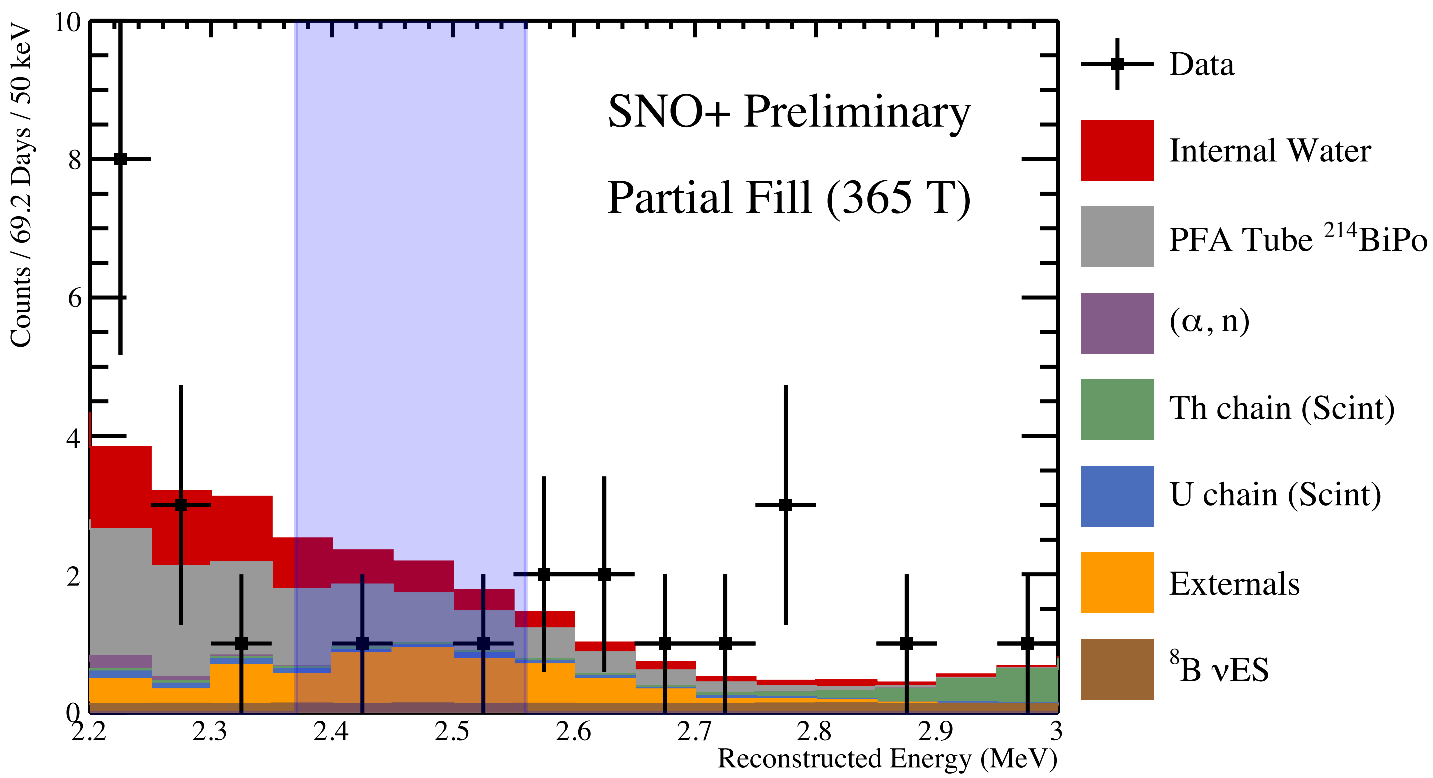
Major Outcomes

- Solar neutrinos with 11.2 kt-day during partial fill = PoS-PANIC2021-274



	$\Phi_{^8B}$
R = 4.5 m	$6.45\text{x}10^6\ ^{+26.2\%}_{-22.4\%}(stat.)\ ^{+8.8\%}_{-11.5\%}(syst.)\ \text{cm}^{-2}\ \text{s}^{-1}$

✤ Preparation for the double-beta decay phase: background and target-out measurement



Background	Expected Counts in Partial Fill ROI
Internal Water	1.8 §
* PFA Tube ^{214}BiPo	2.9 §
Externals	2.5
(α, n)	0
Th Chain (Scint)	0.1
U Chain (Scint)	0.3
^{8}B νES	0.5
Total Backgrounds	8.0

* tube used to remove water from the detector
§ not relevant for the full fill phase

June - October 2020
(~69 gold physics days)

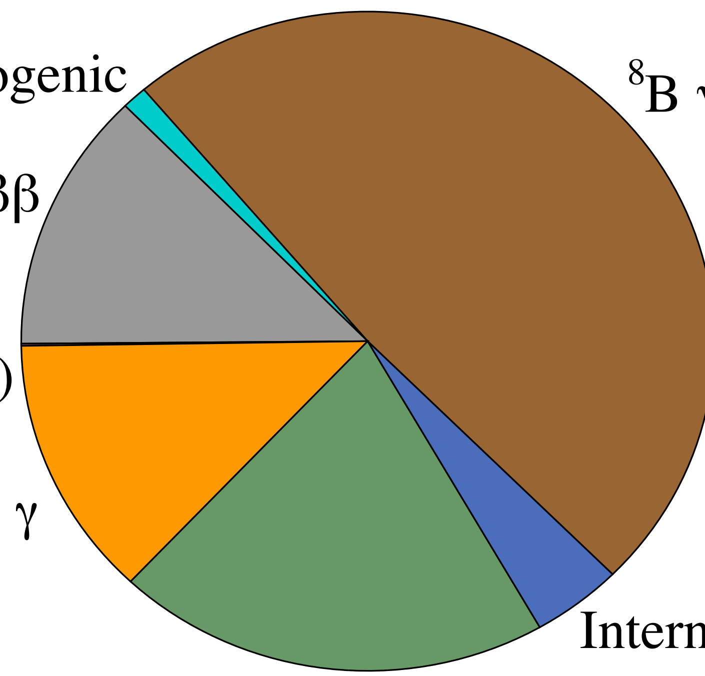
Bonus phase:
partial fill
0.6 g/L PPO

Background breakdown in $0\nu\beta\beta$ ROI

See Poster
T. Kroupova
Event Reconstruction in the SNO+ Experiment

Cosmogenic:
- ^{60}Co, ^{110m}Ag, ^{88}Y, ^{22}Na
- mitigation: purification + "cool-down" UG
- First Te UG since 2015
- multi-site classifier

(a,n):
- alpha-capture on $^{13}C/^{18}O$
- **Measure the contribution from LS components before Te loading**
- delayed coincidence tagging



^{8}B solar neutrinos:
- **constrained by SNO/SK data**
- Directionality?

External gammas:
- from AV, ropes, water, PMTs
- **Measured in water phase, below expectation**
- Fiducialization to minimize the leak in ROI

Internal U/Th chain:
- $^{214}BiPo$, $^{212}BiPo$, ^{210}Tl
- **LAB components below target for the TeLS phase**
- **Constantly monitoring the contribution from the scintillator before adding Te**
- $\beta - \alpha$ delayed coincidence tagging + in-window rejection

Optimised FV and ROI	$T_{1/2}$ [yr]	$m_{0\nu\beta\beta}$ [meV]
0.5% Te, 5 yr	2.1×10^{26}	37 - 89

- Increasing the amount of isotope increases the signal
  - ^{8}B-nu solar background (main) remains the same
  - Improved loading scheme maintains acceptable light yield despite increased absorption
  - Samples with several % loading have been stable on timescales of years.
  - Incremental cost ~$2M / tonne Te