LIP Lisbon Seminar
Lisbon, 14 December 2023

The liquid scintillator phase of SNO+:
current status and future prospects

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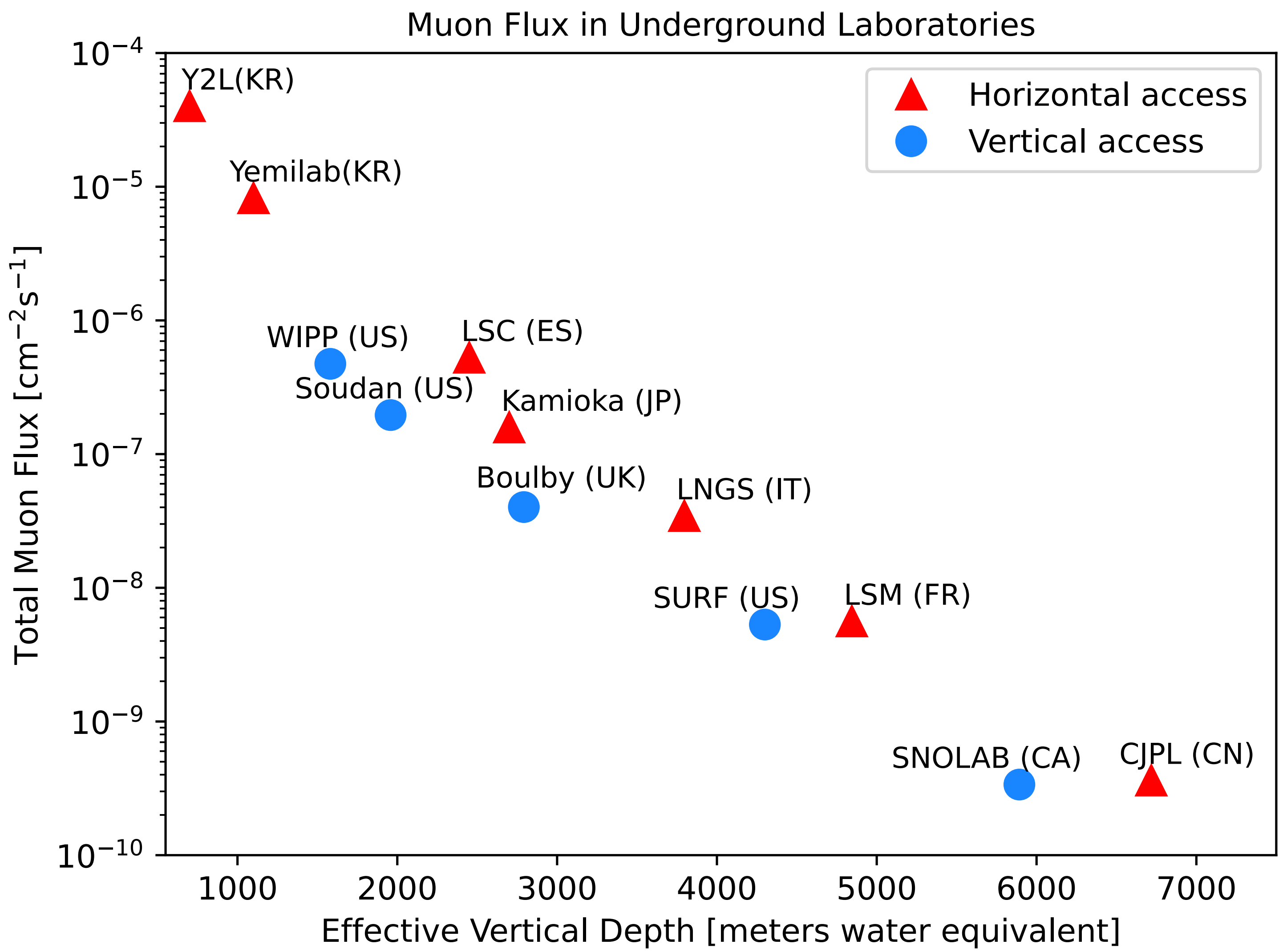
FCT Fundação para a Ciência e a Tecnologia

LIP Lisbon

SNO+ DETECTOR

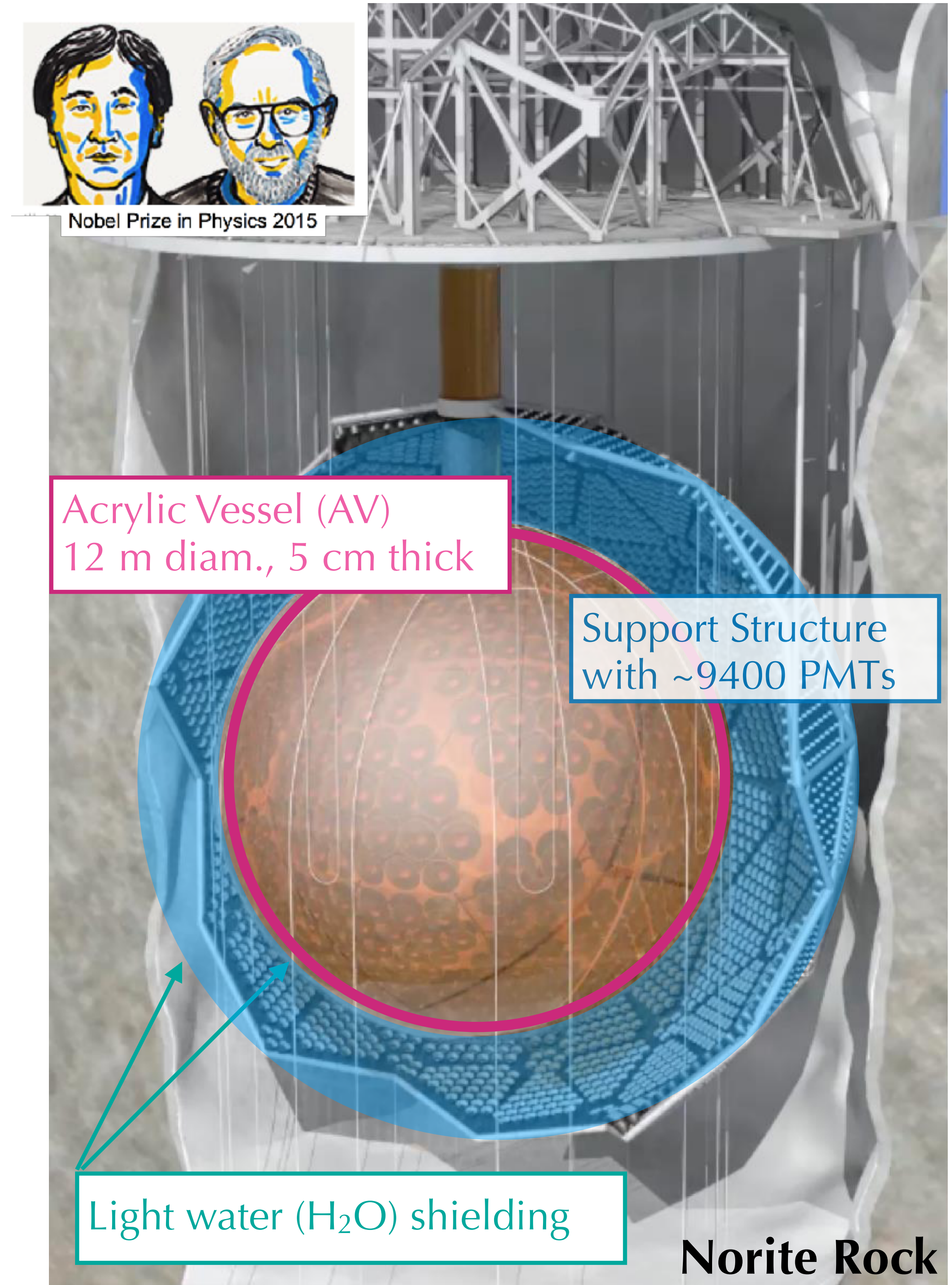
@SNOLAB, Sudbury, Canada



SNO+ DETECTOR

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

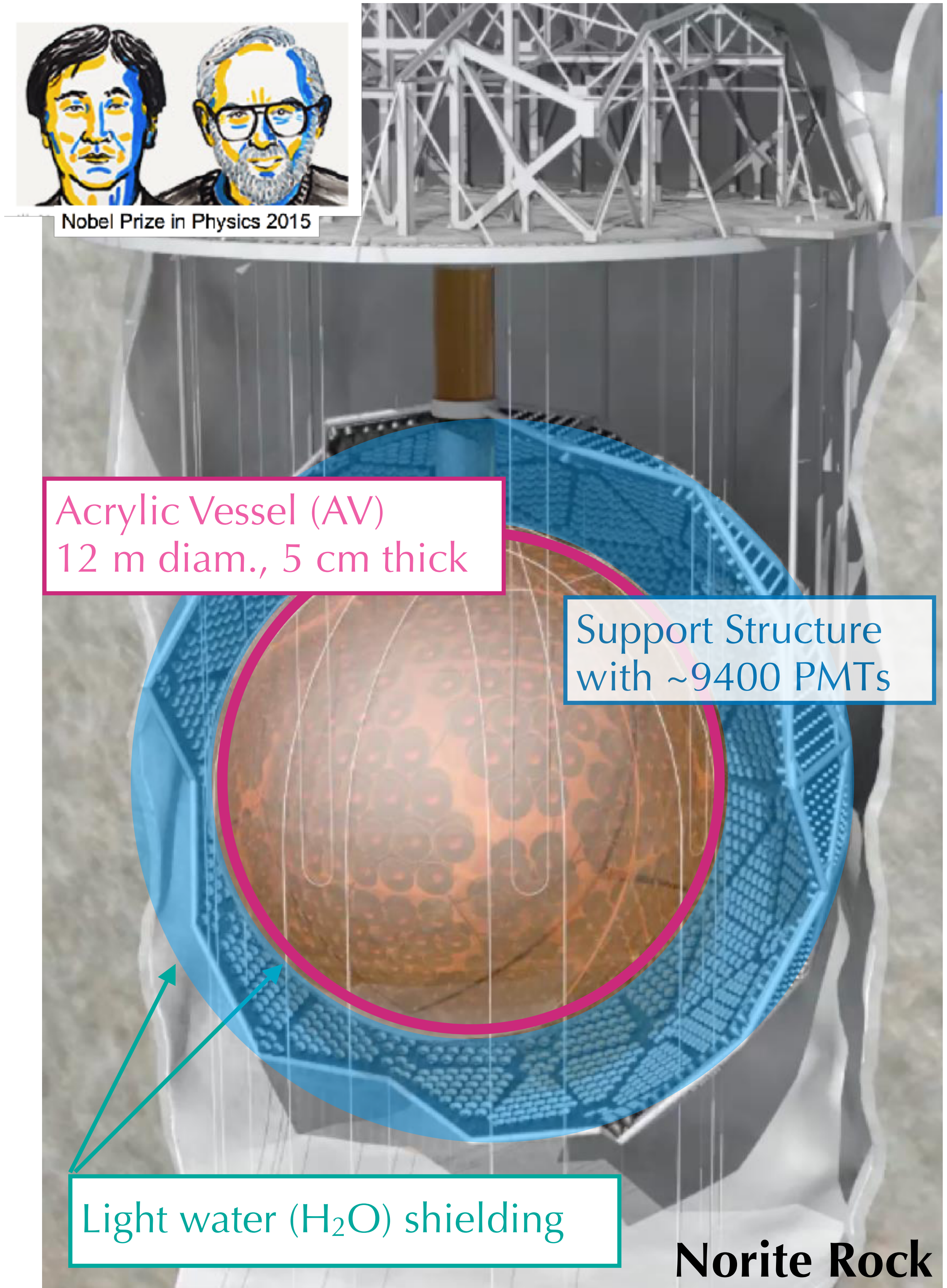
JINST **16 (2021) 08, P08059**



SNO+ DETECTOR

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

- Three target's materials:
  - 905 t of *ultra-pure water* (2017-2019);
  - ~780 t of *high purity liquid scintillator* + 2.2 g/L PPO +bisMSB (2022-2024);
  - 3.9 t ^{nat}*Te-loaded scintillator* (2024 -).



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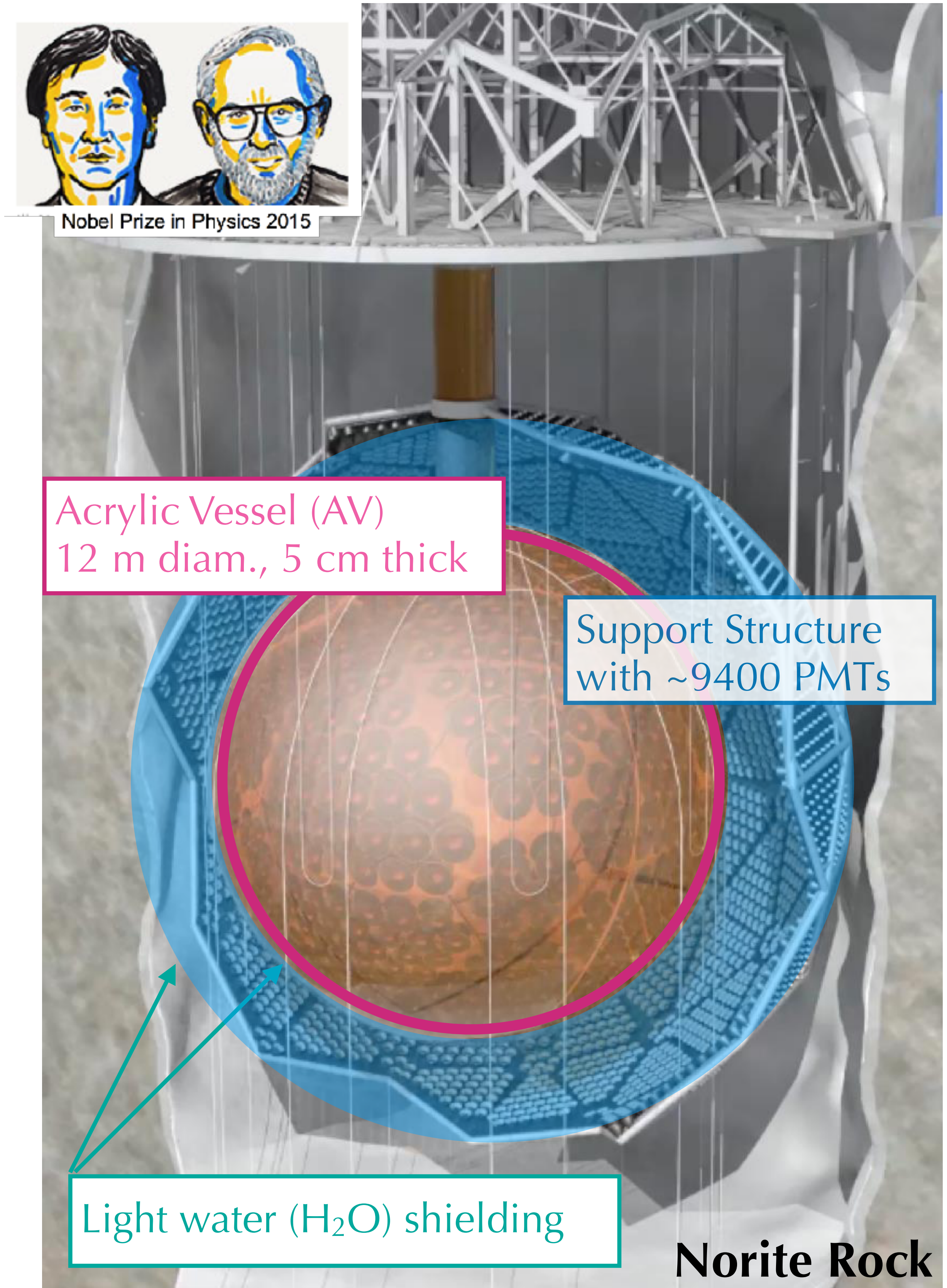
- Several background reduction layers:
  - 7 kt of high-purity water shield;
  - N_2 Cover Gas blanket across the entire detector;
  - Radon-impermeable plastic covering the cavity walls.



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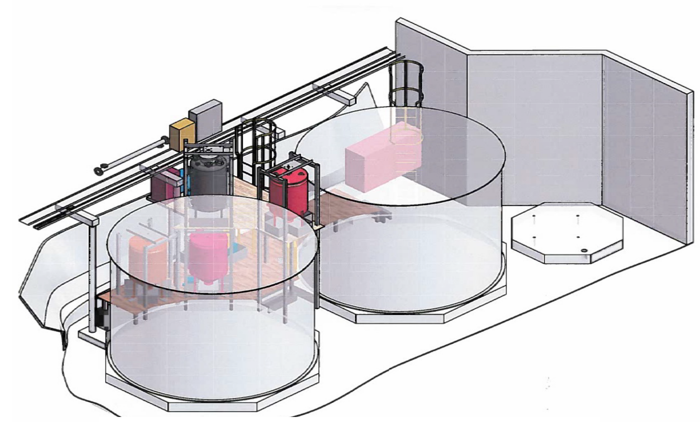
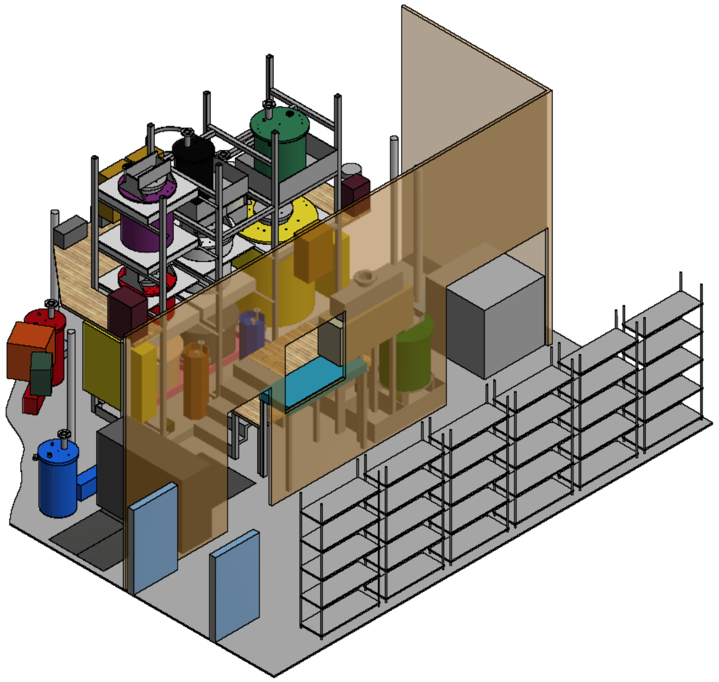
  - 3.9 t ^{nat}*Te-loaded scintillator* (2024 -).
- Material purification:
  - 4 purification plants UG for water, scintillator and Te;
  - Possibility to recirculate and repurify water and scintillator;
  - Extensive QA campaigns before, during and after filling/loading.



TeDiol purification plant

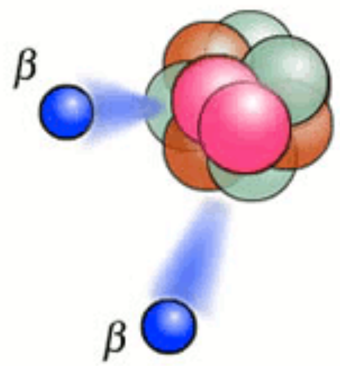
LS purification plant



TeA purification plant

SNO+ Physics
(water, LS, TeLS)

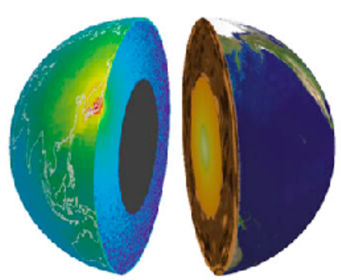
0/1 = not doable/doable in water, LS, TeLS phase



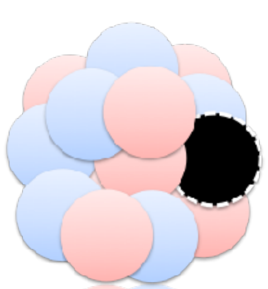
Neutrinoless double-beta decay of ^{130}Te
(0,0,1)

Solar neutrinos (1,1,1)

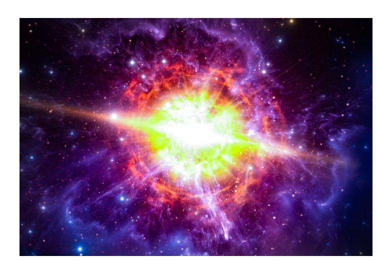
Reactor anti-neutrinos
(1,1,1)



Geo anti-neutrinos
(0,1,1)

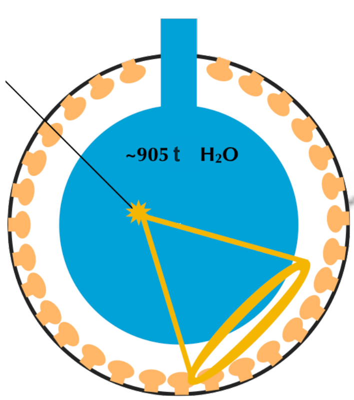


Rare decays and interactions
(1,1,1)



Supernovae neutrinos
(1,1,1)

Towards the scintillator phase



SNO+ WATER

2017 2018 2019

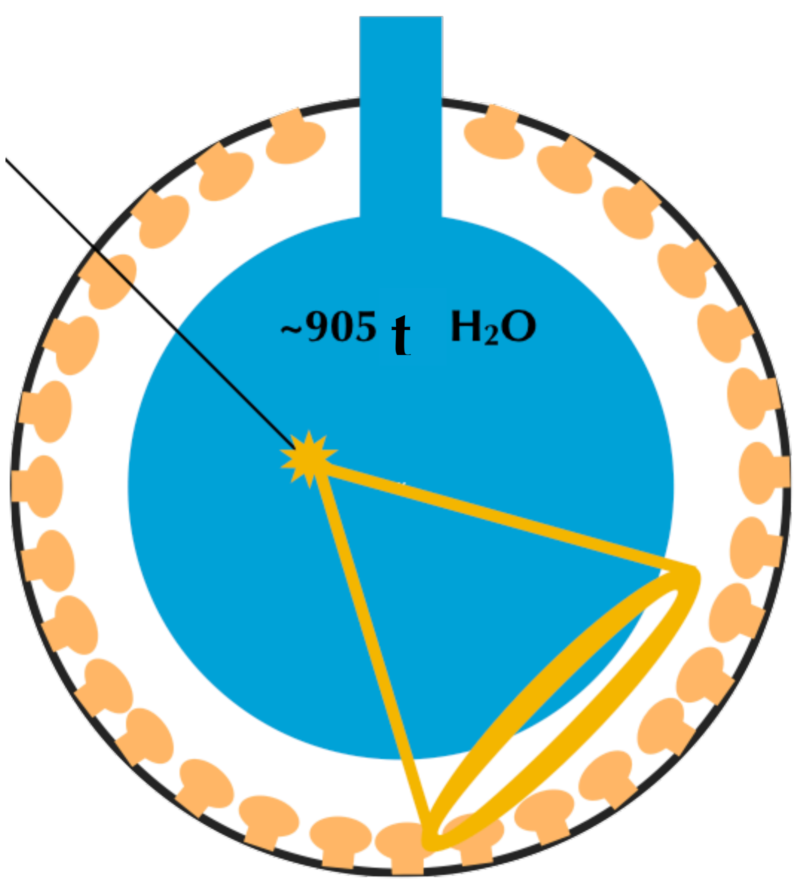
May - December 2017
(~115 gold physics days)
First SNO+ water phase
Phys.Rev.D 99, 032008

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

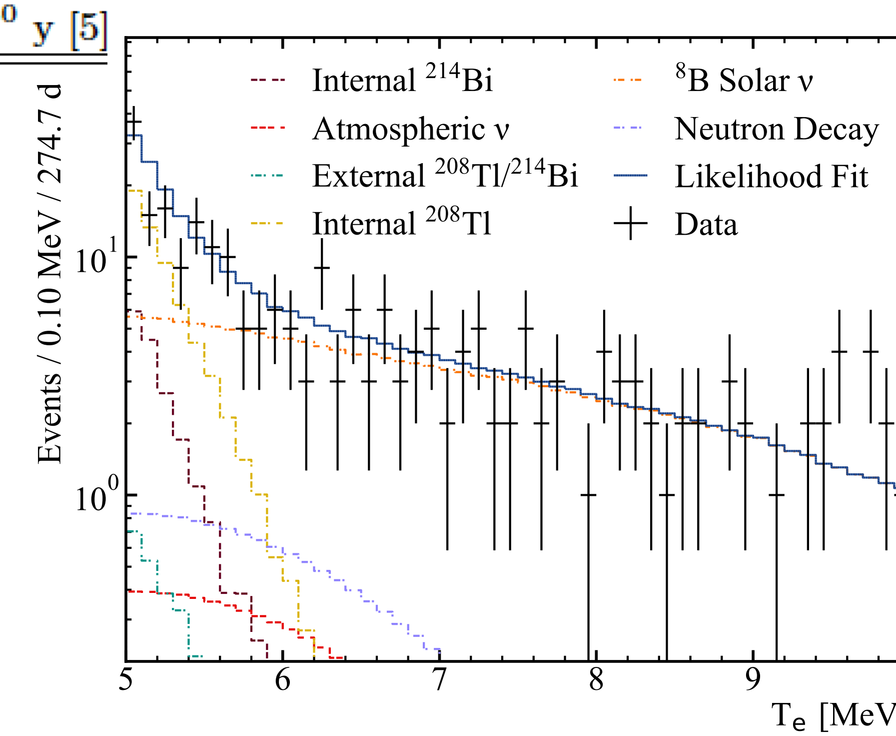
Major Outcomes

✤ 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!



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Phys.Rev.D 99, 012012

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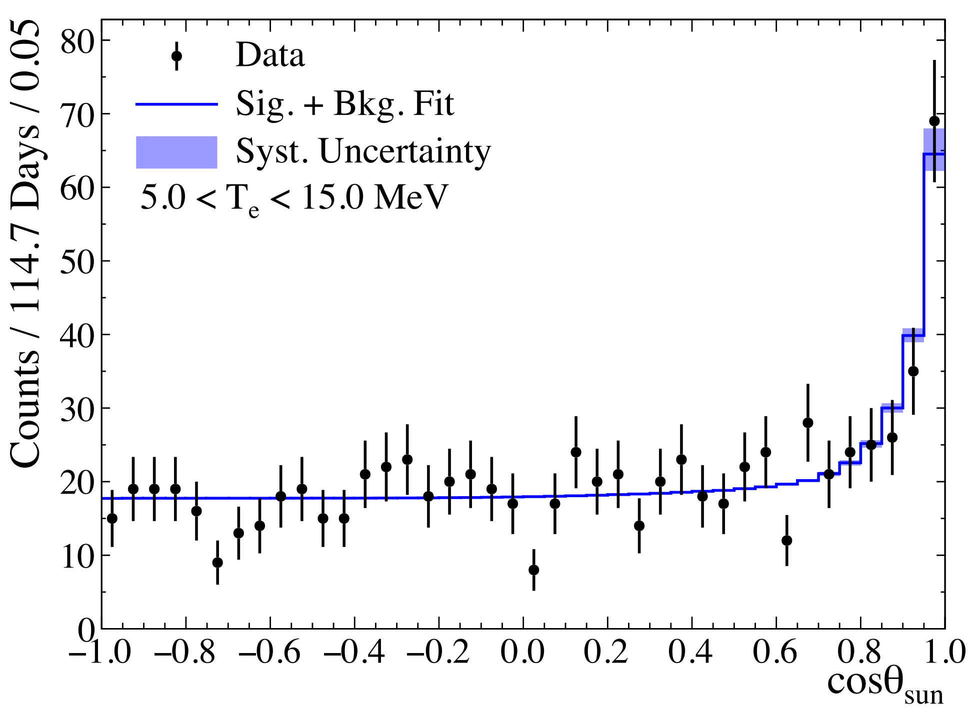
In preparation

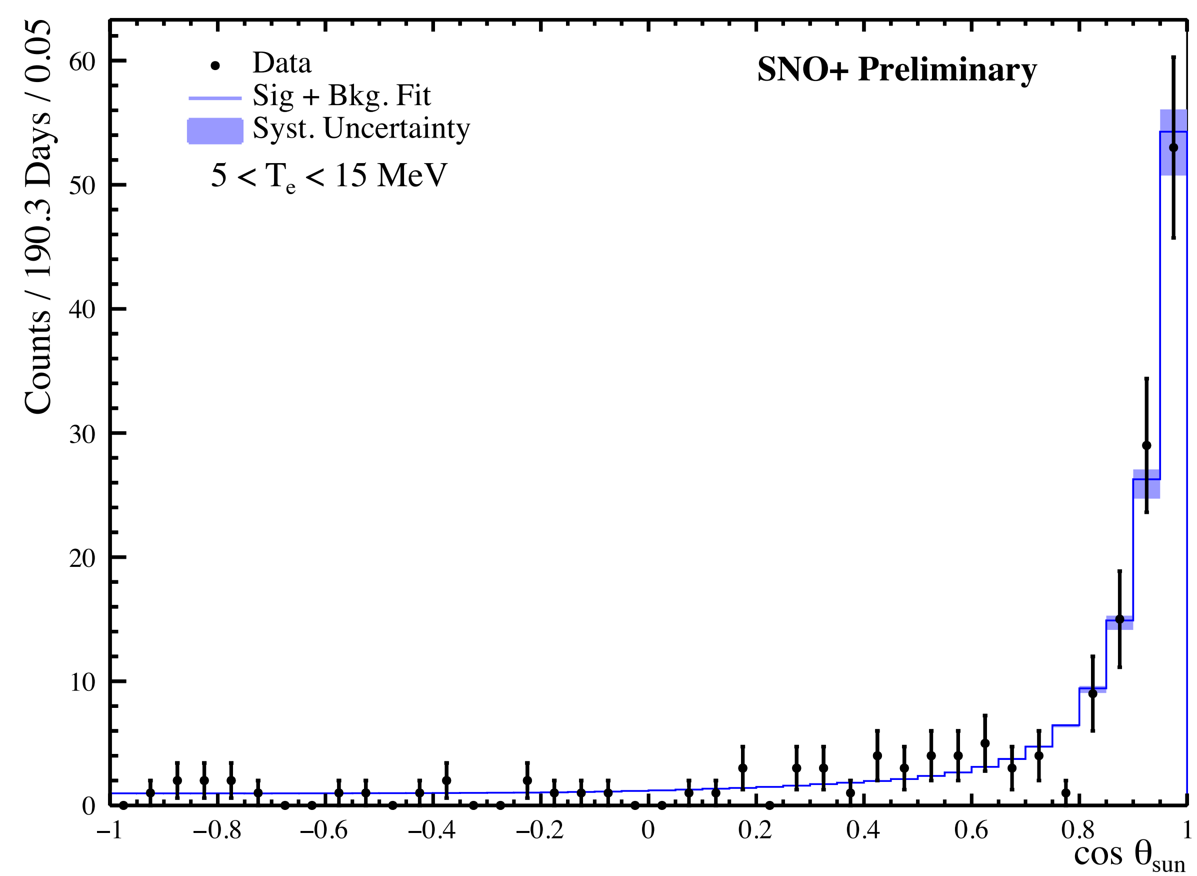
Additional Cover gas shielding to reduce Rn ingresses in water

Major Outcomes

- Nucleon decay modes into invisible channels
- Solar neutrinos



Improved background reduction



$$\Phi_{8B} = 5.95{+}0.75(\text{stat.}){+}0.28(\text{syst.}) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$

$\Phi_{8B}=(5.25 \pm 0.20)\times10^6\ \text{cm}^{-2}\text{s}^{-1}$ (SNO)

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- Nucleon decay modes into invisible channels
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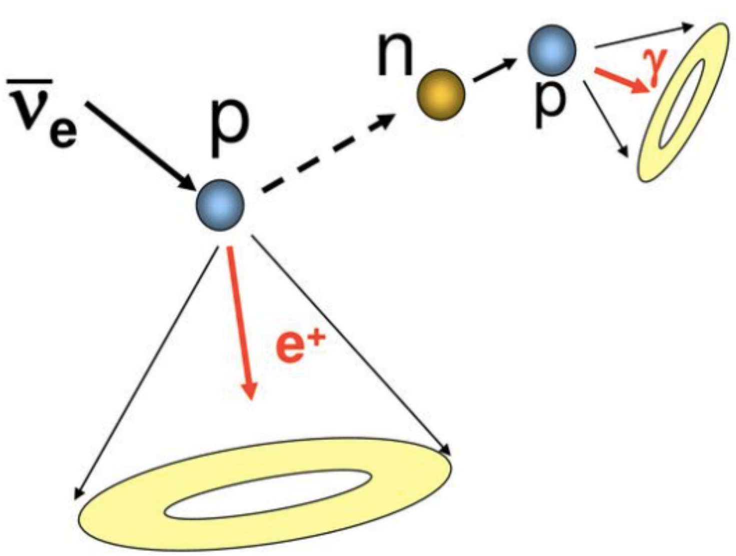
- Reactor anti-neutrinos
  - Efficiency for triggering on a neutron: **(49.08 ± 0.39)%** at center ***Phys.Rev.C 102, 014002***



Inverse Beta Decay (IBD) reaction

SNO+ WATER

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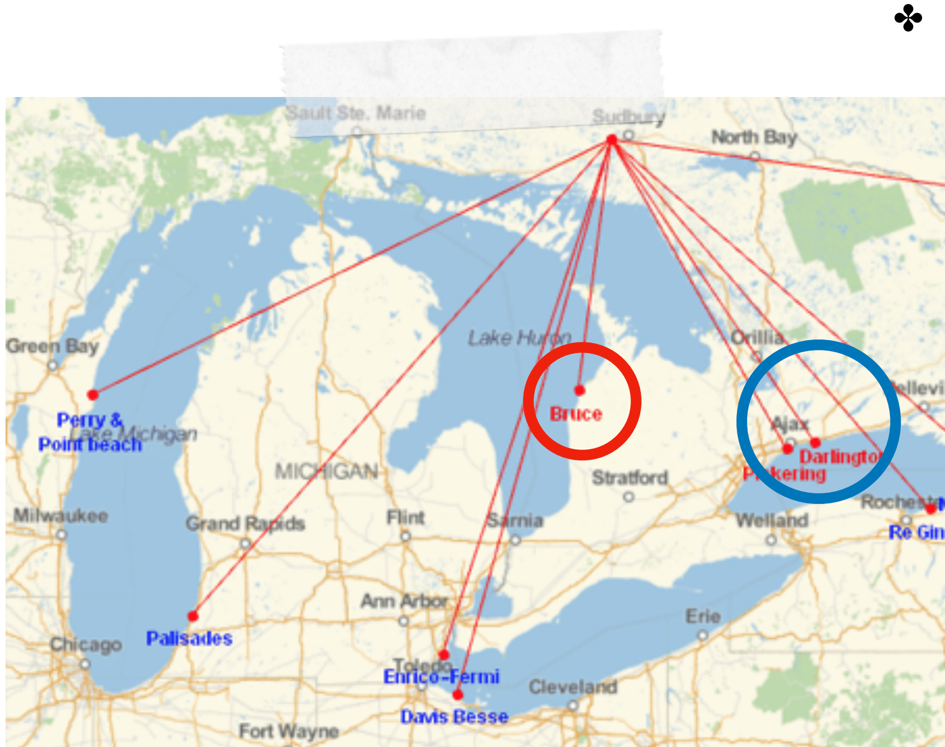
  - **First measurement** of reactor anti-neutrinos using pure water ***Phys.Rev.Lett 130, 091801***
    PRL Editor's Choice
    APS Physics Magazine Highlight



Flux ~ 20% of KamLAND, but baseline between reactors and SNO+ gives a unique spectral shape distortion

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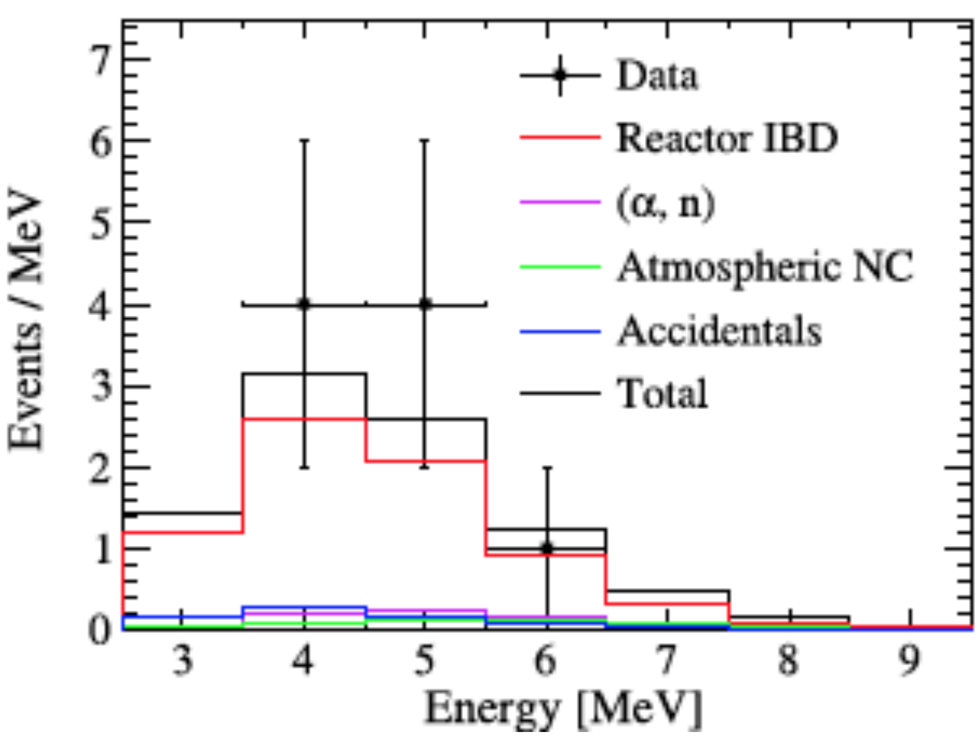


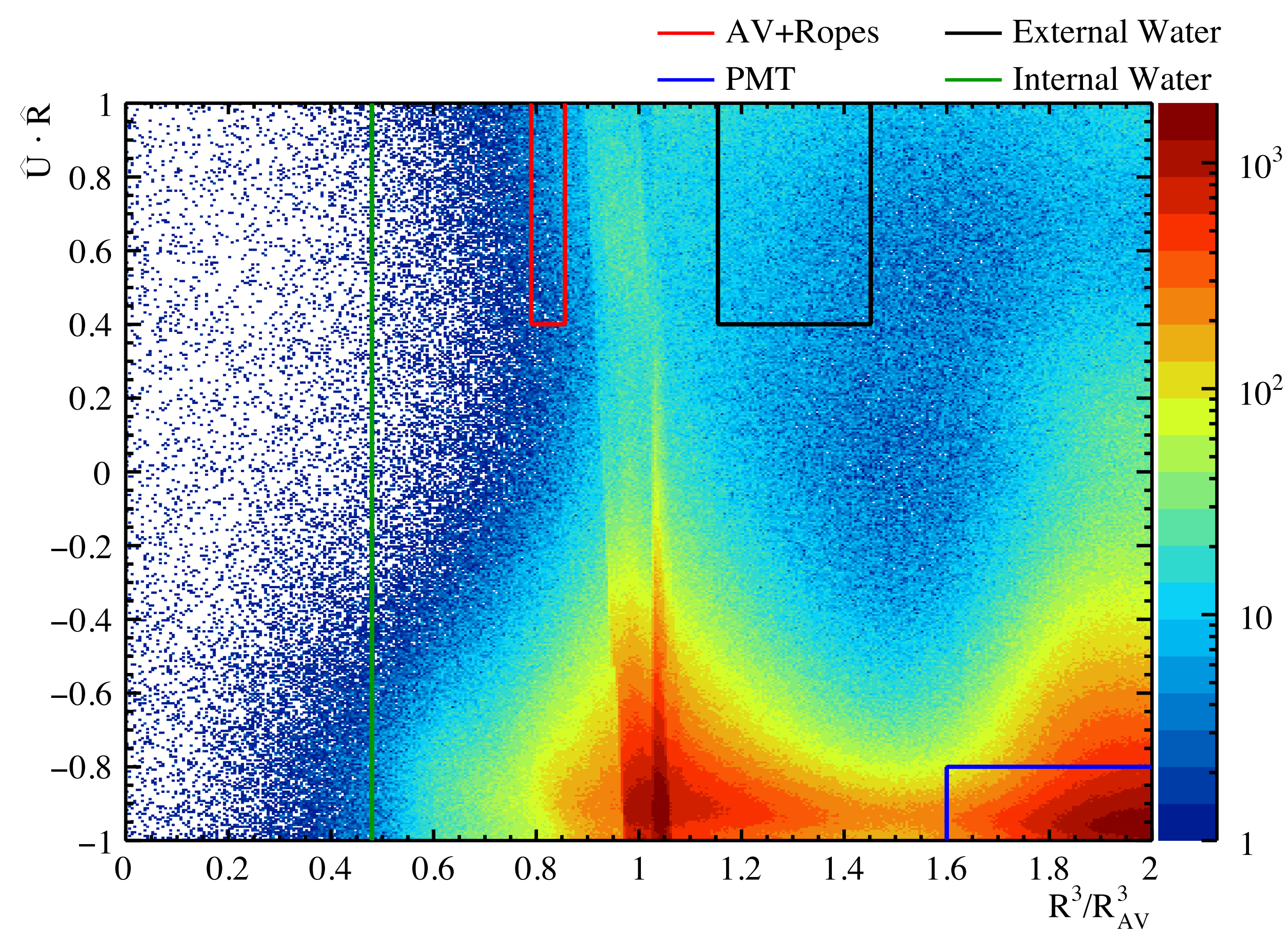
SNO+ External Backgrounds

Input for future phases

- Gammas from ^{232}Th and ^{238}U from detector components such as the acrylic vessel, the support ropes, the PMTs.
- An early measurement during the water phase allows to use a directional cut (**u**.**R**) and separate the various components
  - With the exception of potential Rn ingresses in the water shield, these background sources are not expected to change towards SNO+ phases

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

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	$1.48 \pm 0.002^{+1.65}_{-0.60}$



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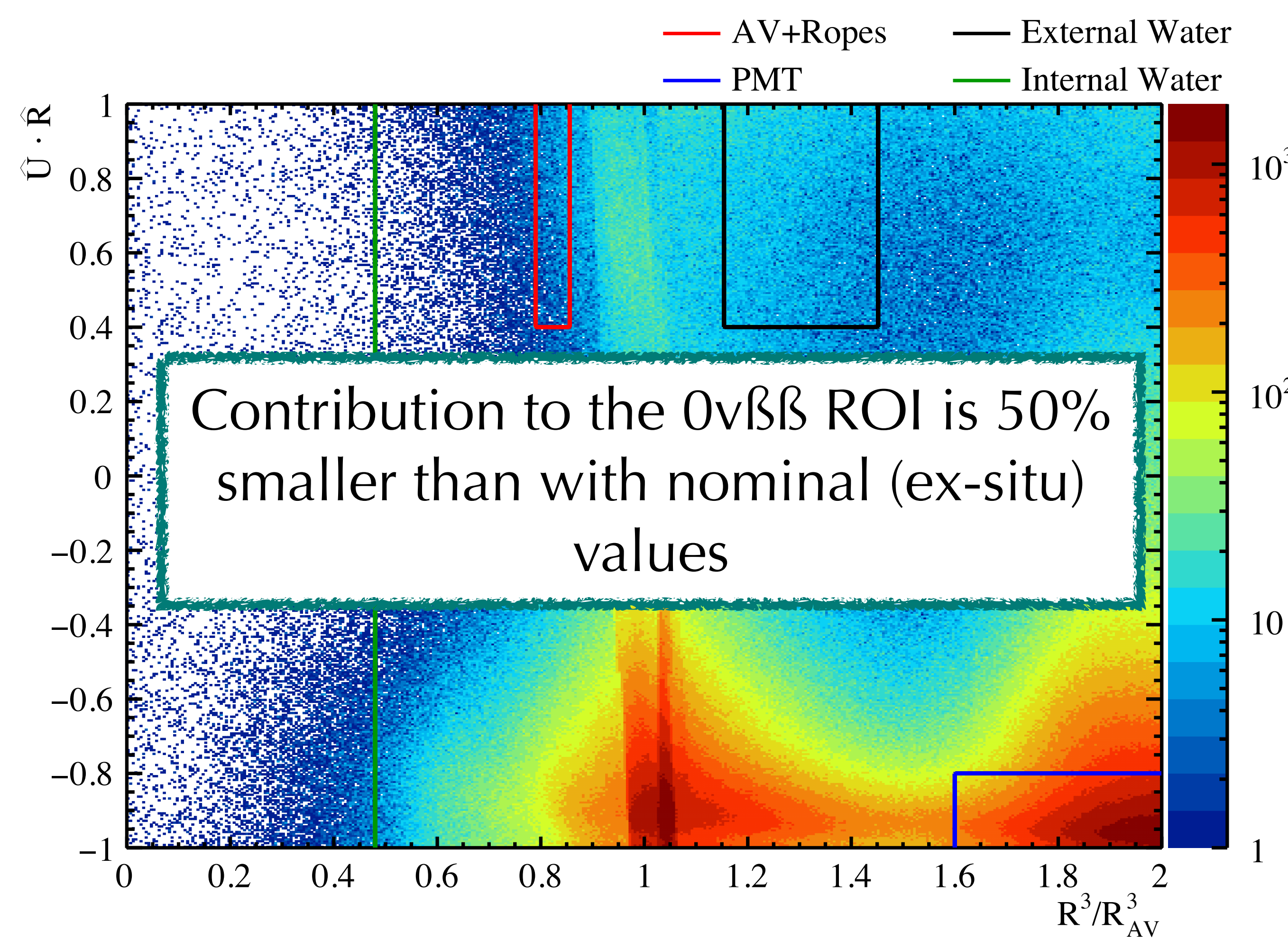
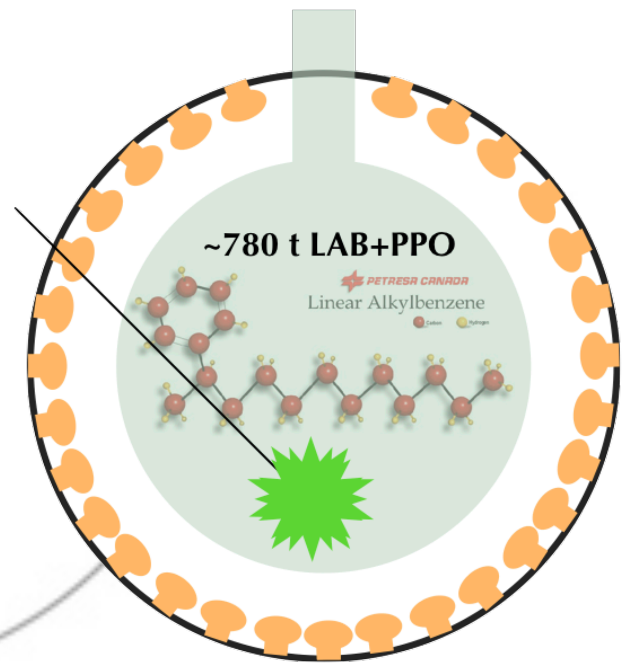
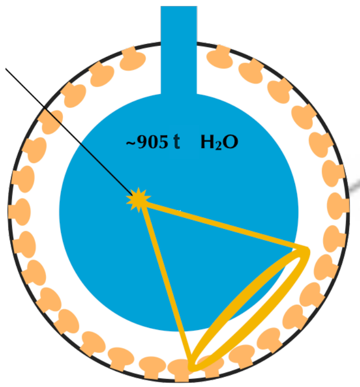




THE SCINTILLATOR PHASE

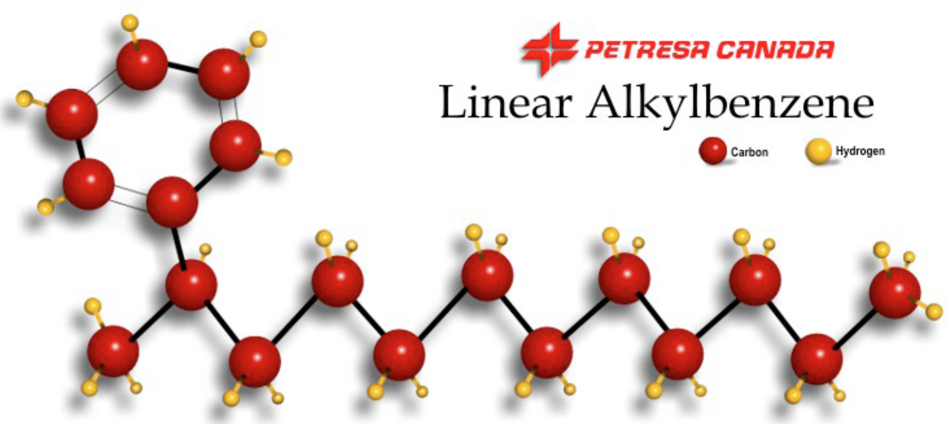


SNO+ Scintillator

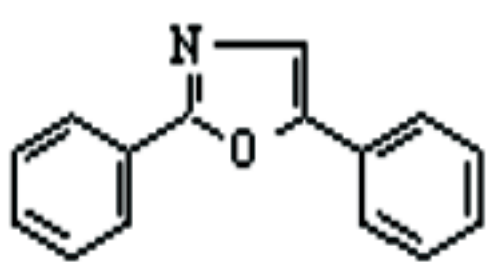
2017 2018 2019 2020 2021

Filling the detector with liquid scintillator
JINST 16 P05009

April - October 2020
(92 gold physics days)
Bonus phase: half-filled detector with scintillator
0.6 g/L PPO

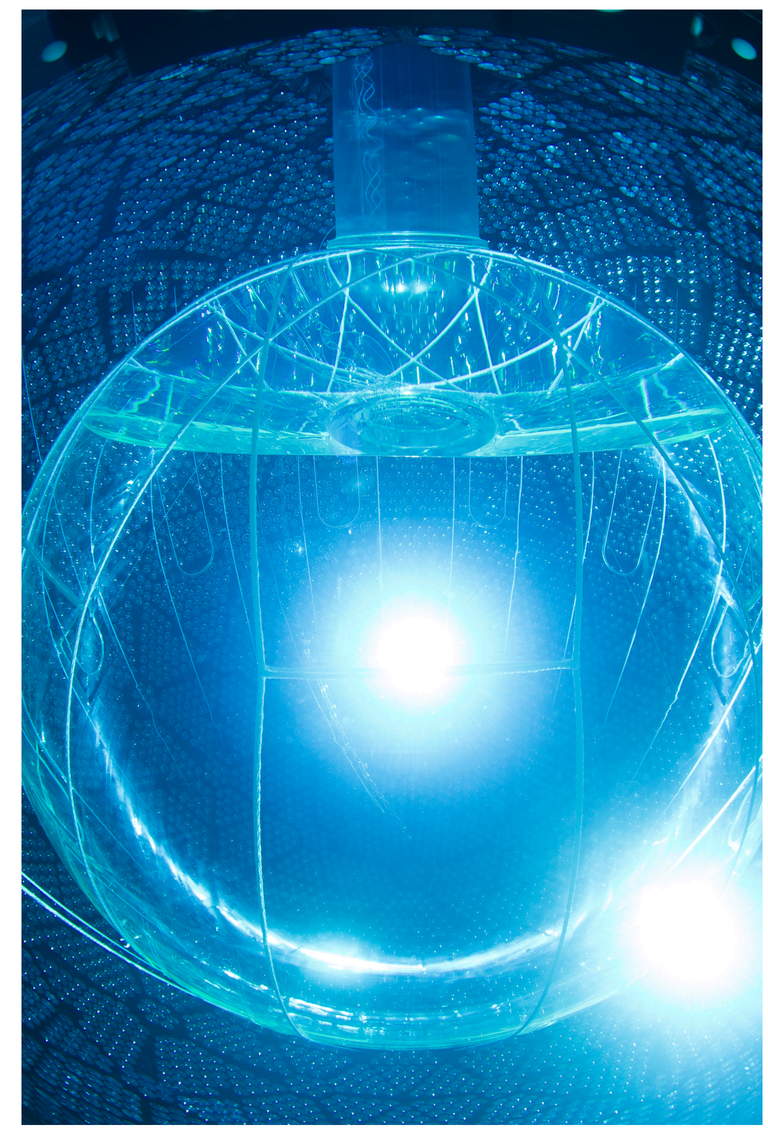


+



PPO

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



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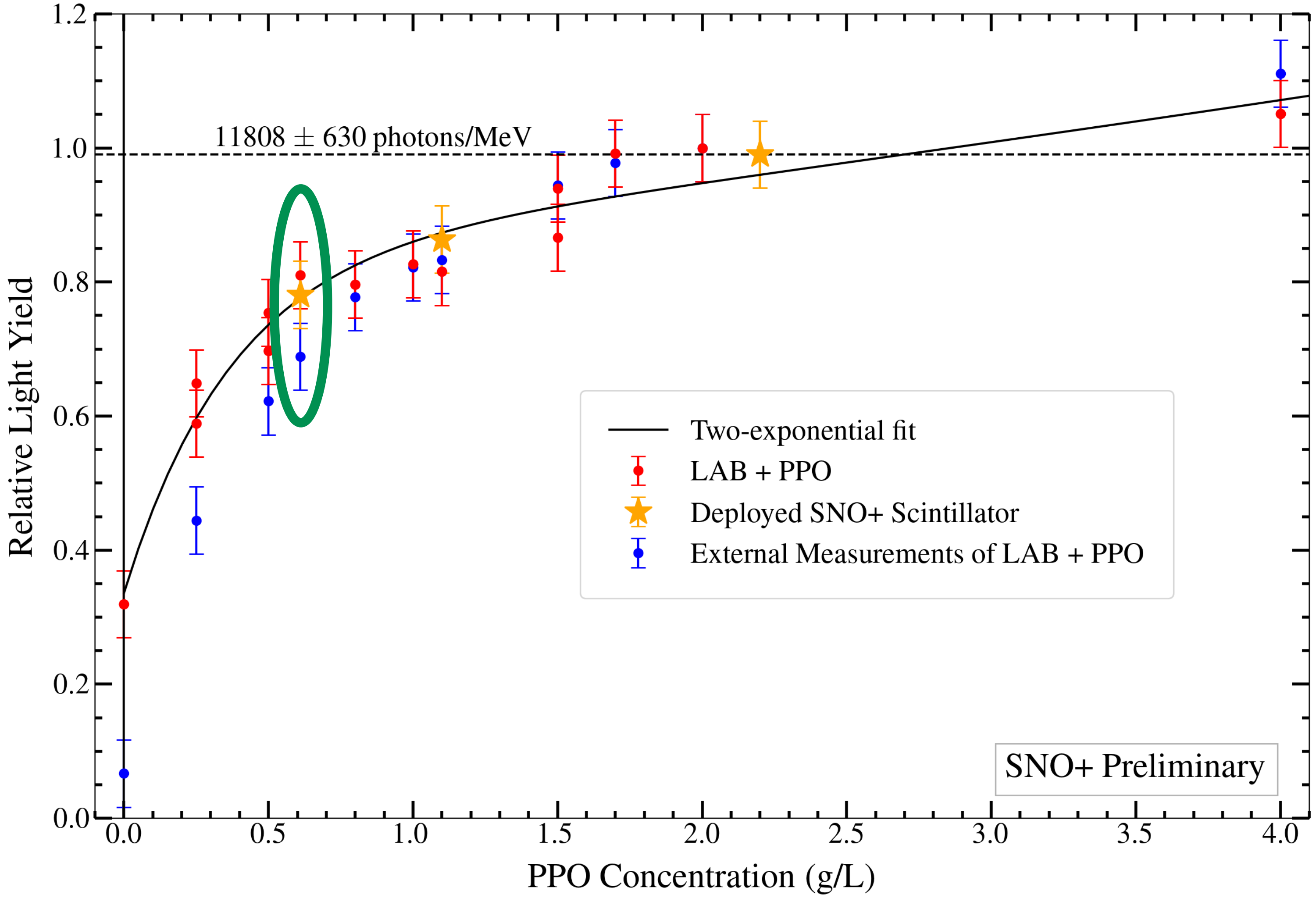
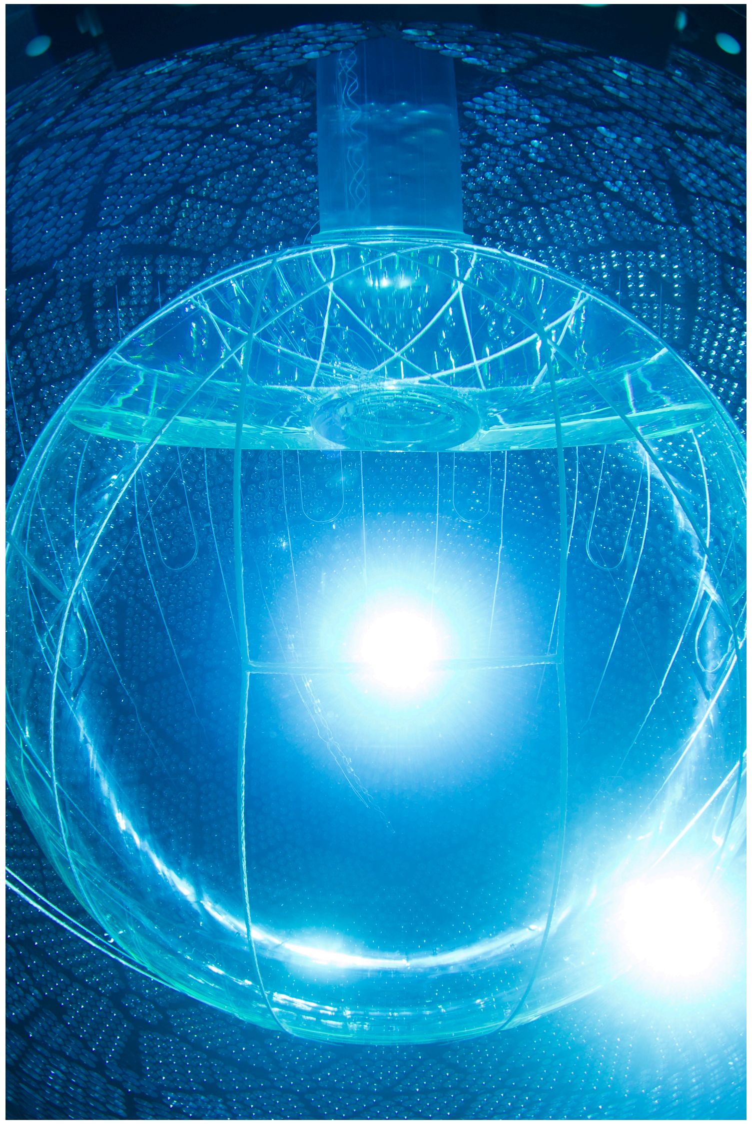


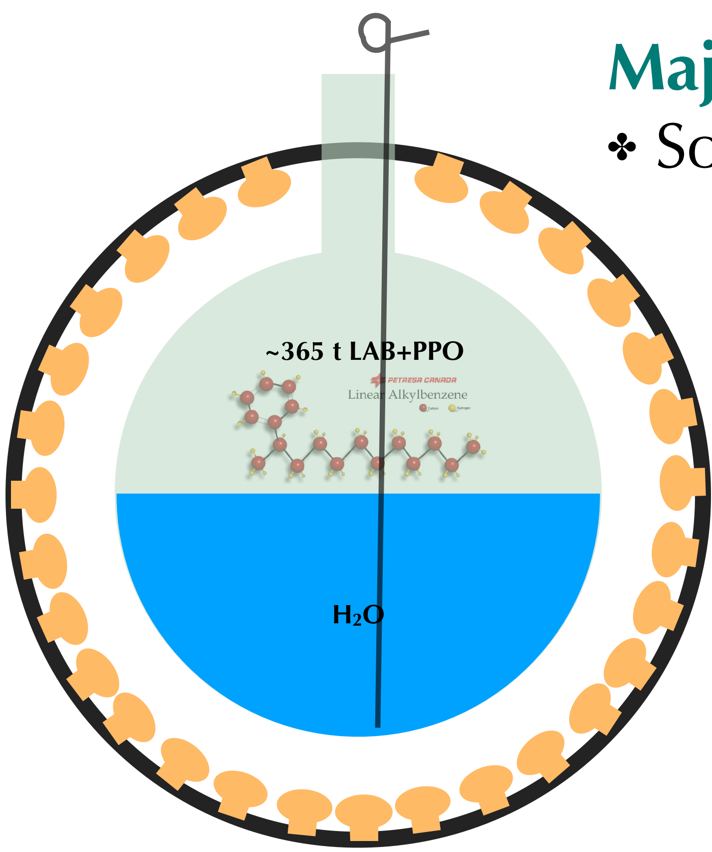


SNO+ Partial-Fill

2017 2018 2019 2020 2021

April - October 2020
(92 gold physics days)
Bonus phase: half-filled detector with scintillator 0.6 g/L PPO

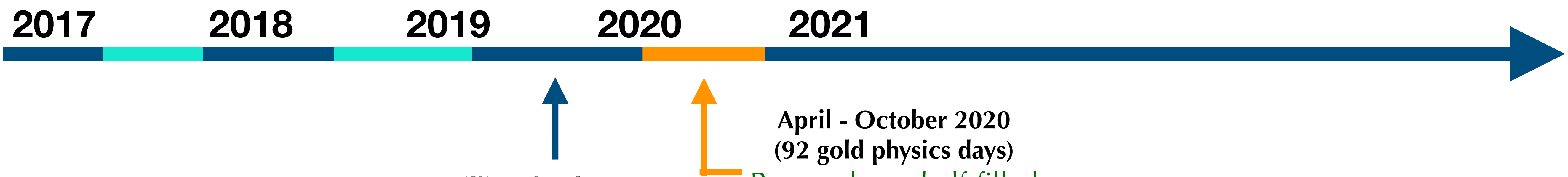
Filling the detector with liquid scintillator
JINST 16 P05009



Major Outcomes

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

SNO+ Partial-Fill

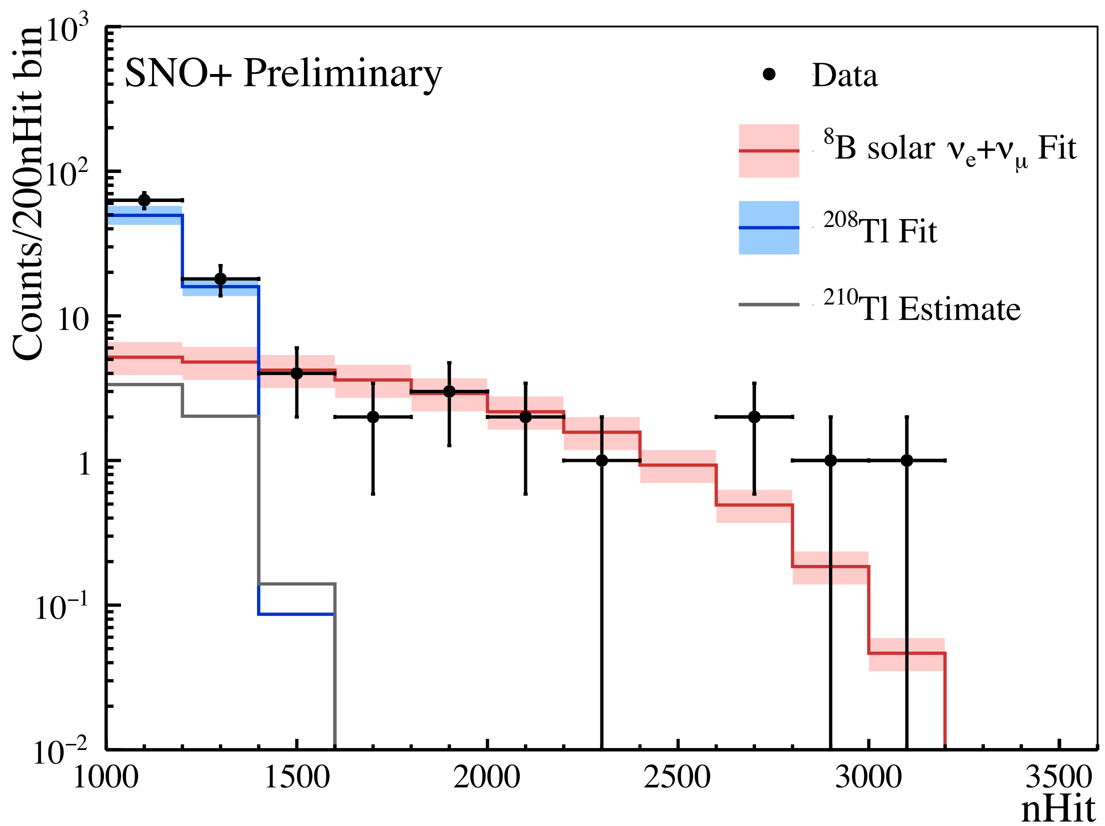


April - October 2020
(92 gold physics days)
Bonus phase: half-filled detector with scintillator
0.6 g/L PPO

Filling the detector with liquid scintillator
JINST 16 P05009

Major Outcomes

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



	$\Phi_{^8B}$
R = 4.5 m	$6.45\times10^{6}\ ^{+26.2\%}_{-22.4\%}(stat.)\ ^{+8.8\%}_{-11.5\%}(syst.)\ cm^{-2}\ s^{-1}$

Φ_{8B} = 5.95+0.75(stat.)+0.28(syst.) × $10^{6} cm^{-2} s^{-1}$
(SNO+ water Phase I)

SNO+ Partial-Fill

2017 2018 2019 2020 2021

Filling the detector with liquid scintillator
JINST 16 P05009

April - October 2020
(92 gold physics days)
Bonus phase: half-filled detector with scintillator
0.6 g/L PPO

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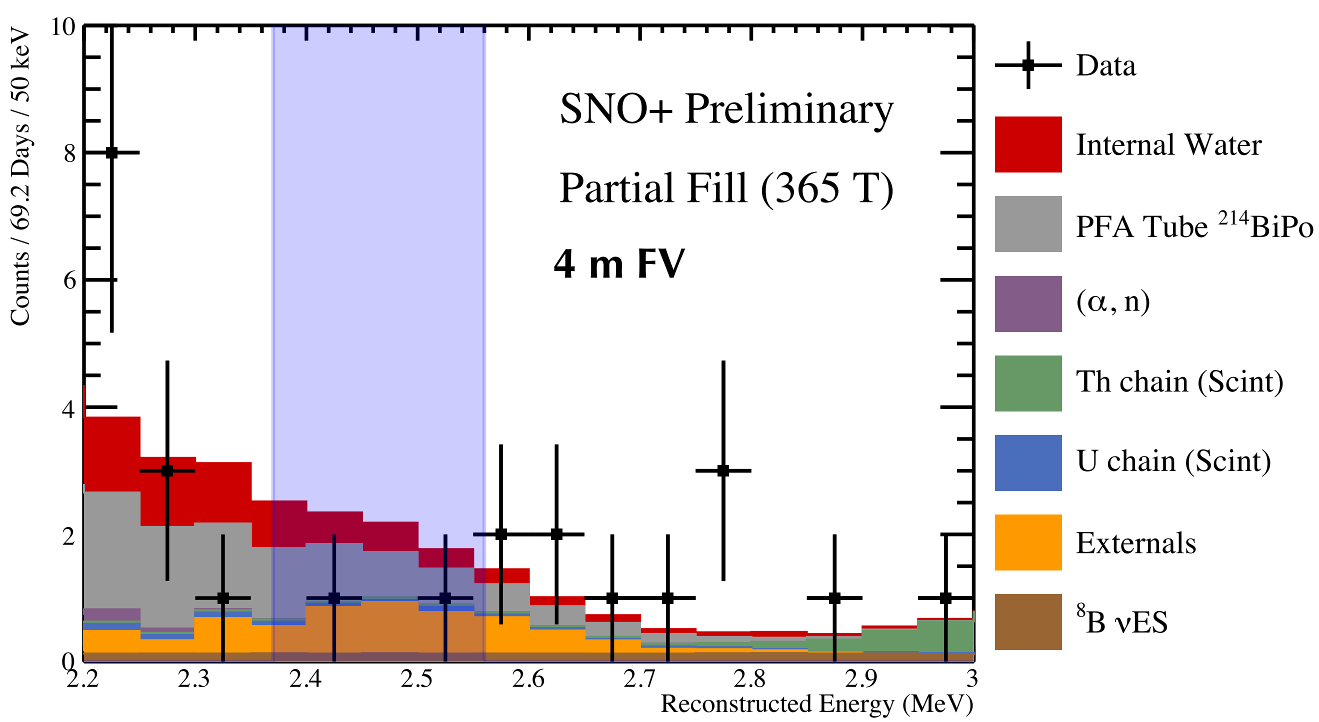
- Preparation for the double-beta decay phase: target-out measurement



~69 gold physics days

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

SNO+ Partial-Fill

2017 2018 2019 2020 2021

Filling the detector with liquid scintillator
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April - October 2020
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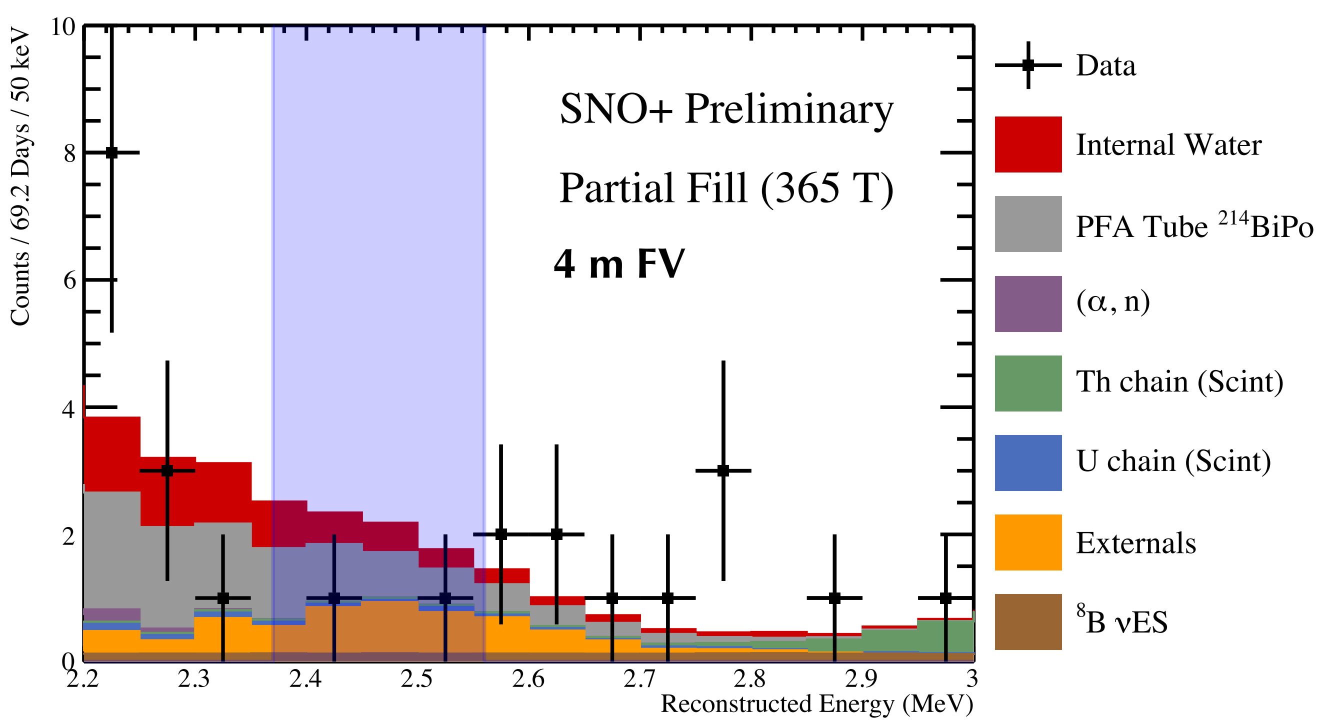


~69 gold physics days

Partial fill:

- Expected 8 events, seen 2

SNO+ Inter-Phases

2017 2018 2019 2020 2021 2022 2023

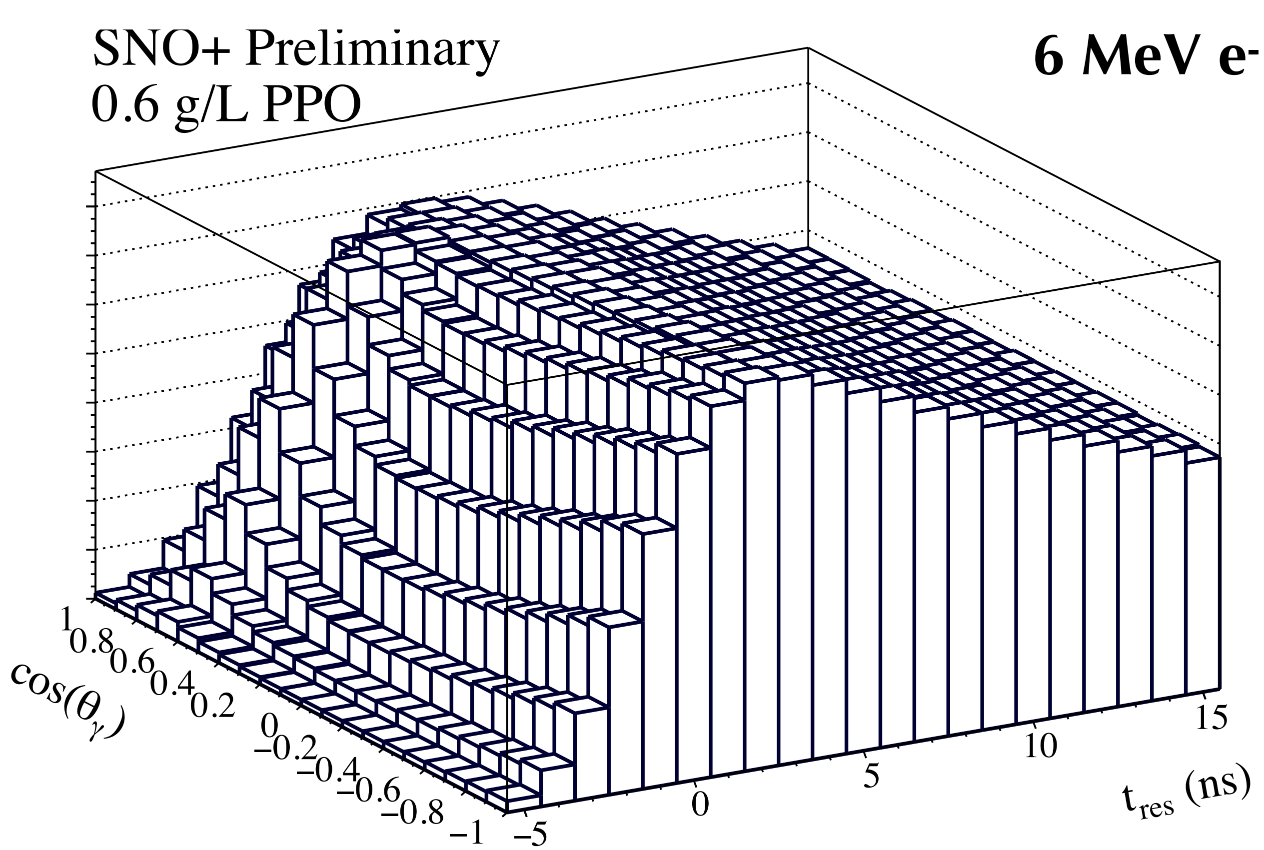
April - October 2020
(92 gold physics days)
Bonus phase: half-filled detector with scintillator
0.6 g/L PPO

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

https://arxiv.org/abs/2309.06341

Major Outcomes

- 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



SNO+ INTER-PHASES

2017 2018 2019 2020 2021 2022 2023

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Bonus phase: half-filled detector with scintillator
0.6 g/L PPO

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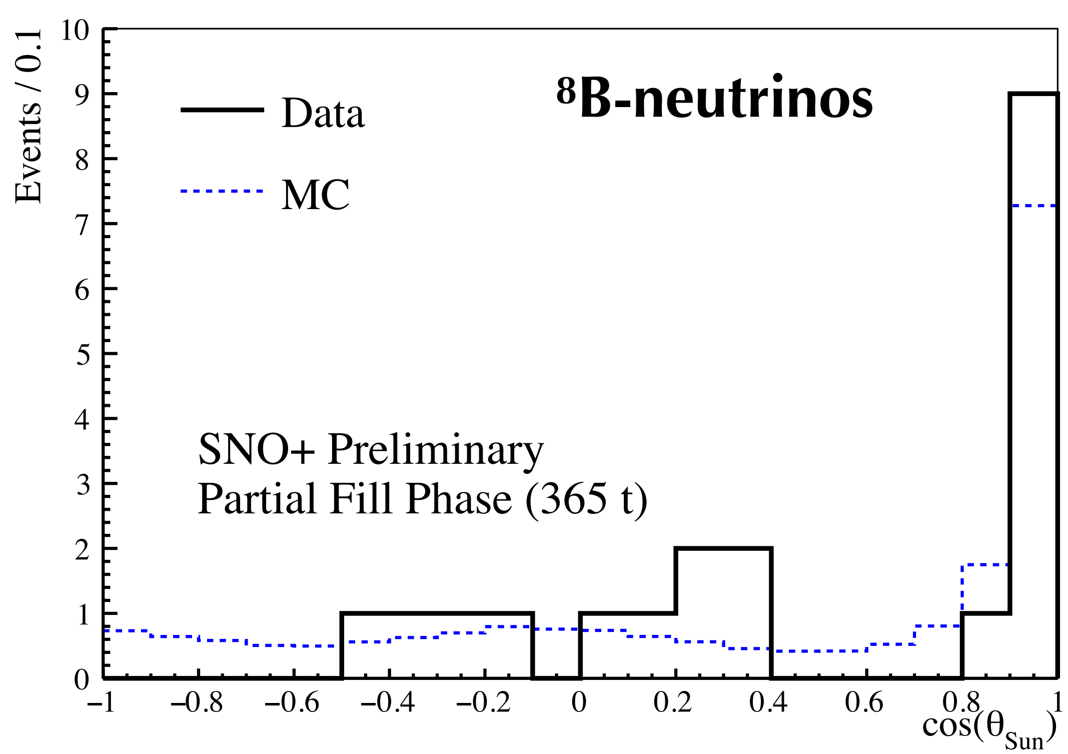
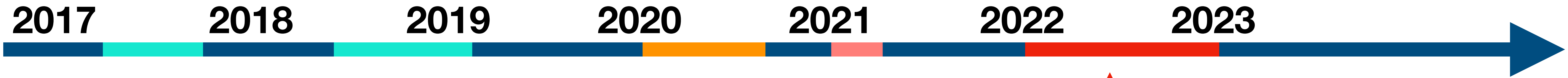
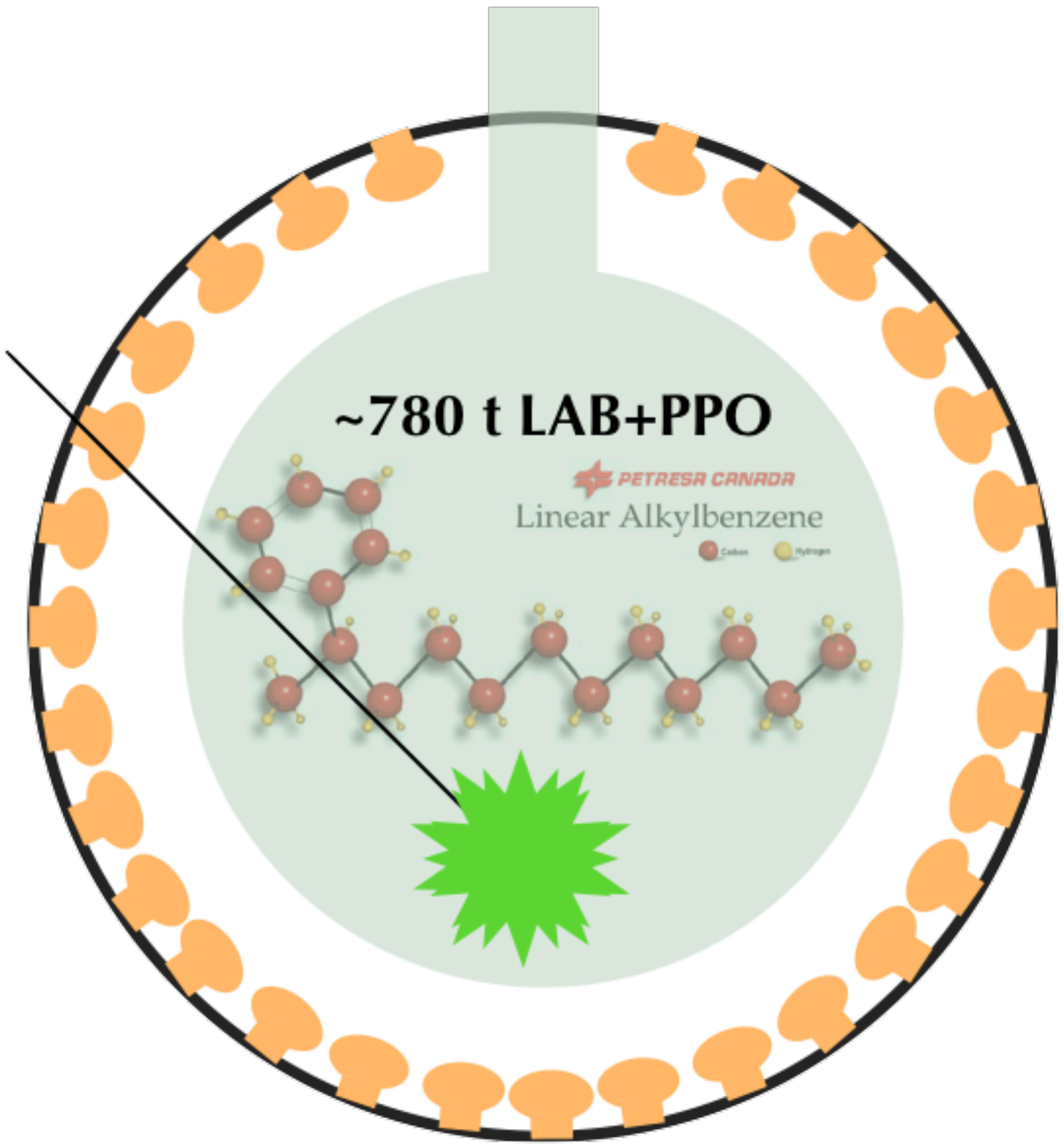
- Very promising results for the 0.6 g/L PPO scintillator:
  - Determined by fitting prompt timing profiles to combined Cherenkov-scintillation 2D PDFs
  - Event-by-event direction reconstruction compared to Borexino Correlated and Integrated Directionality
    - **first time in liquid scintillation experiment**

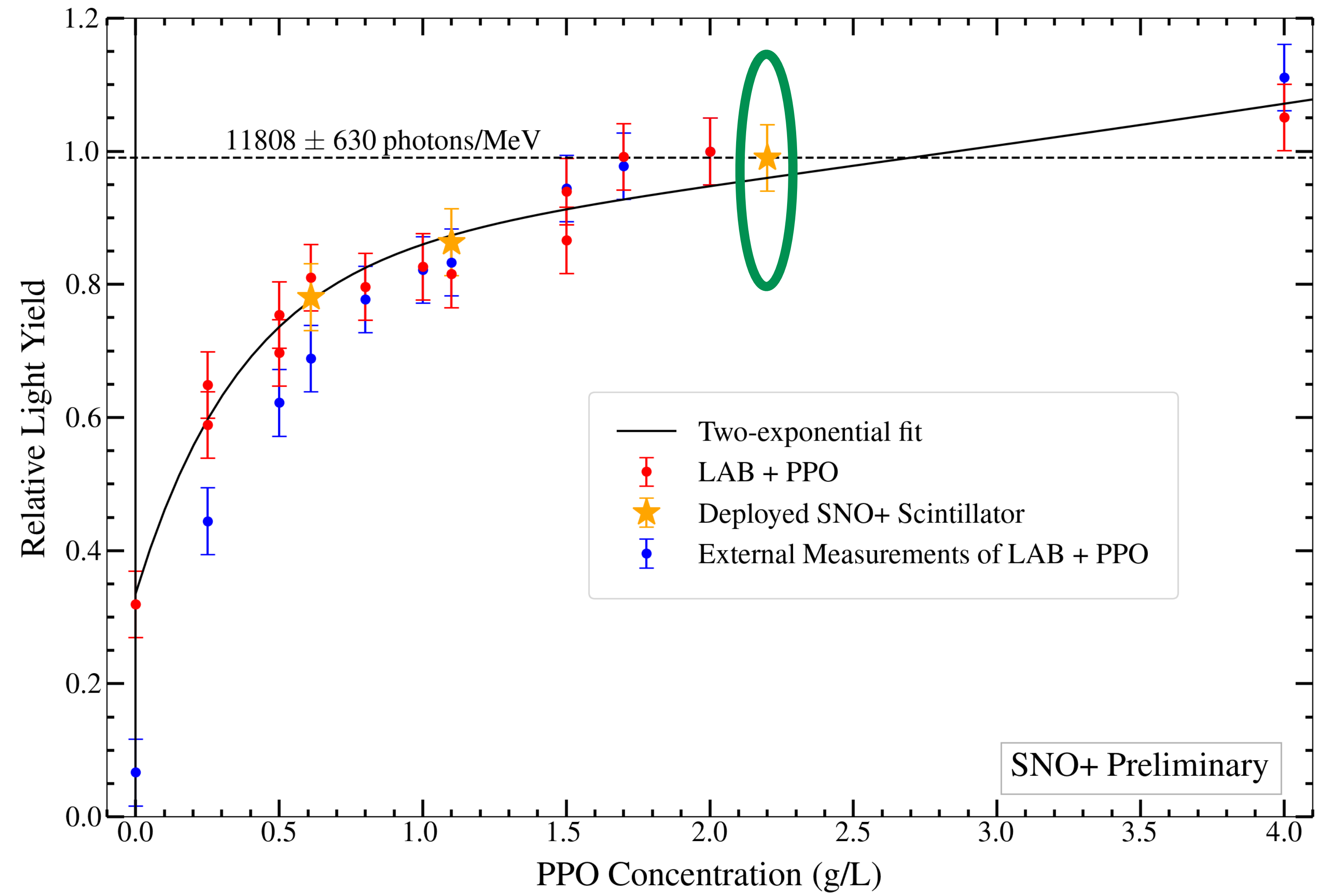


SNO+ Full-Fill



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

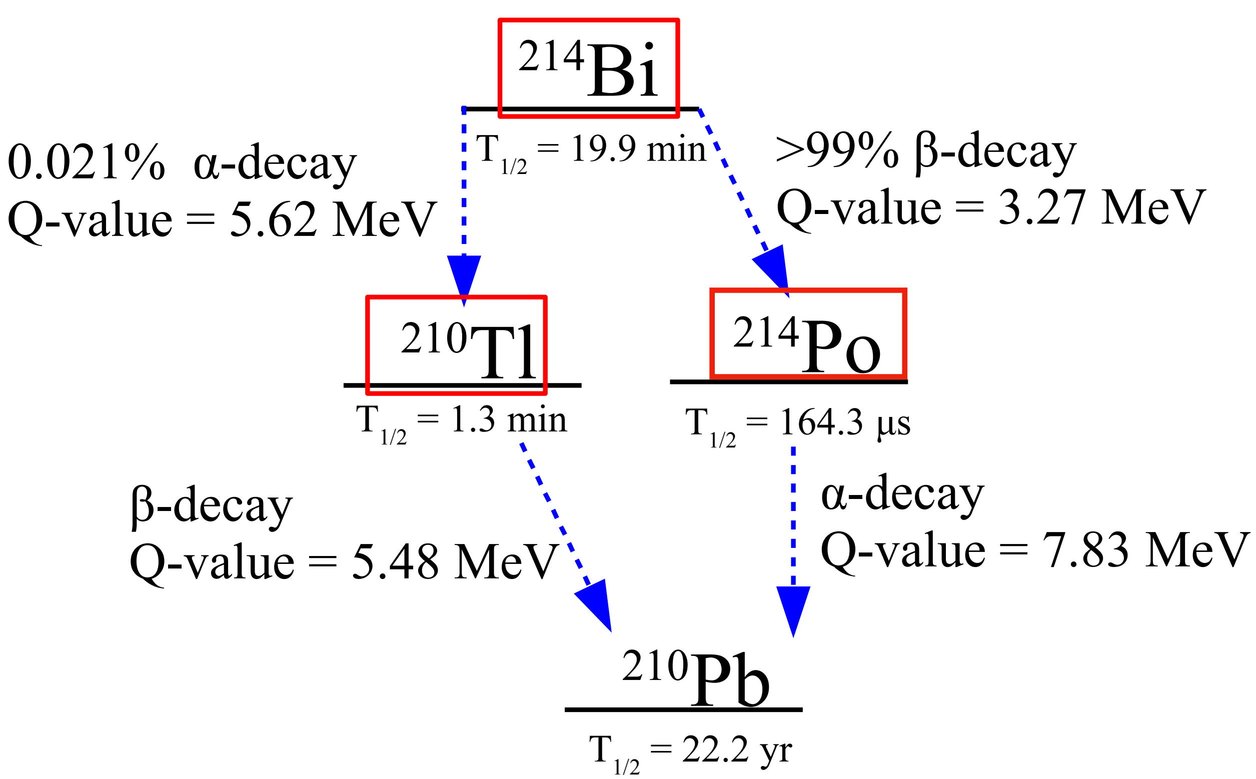




Major Outcomes

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

^{238}U via ^{214}BiPo



Coincidence analysis in space and time

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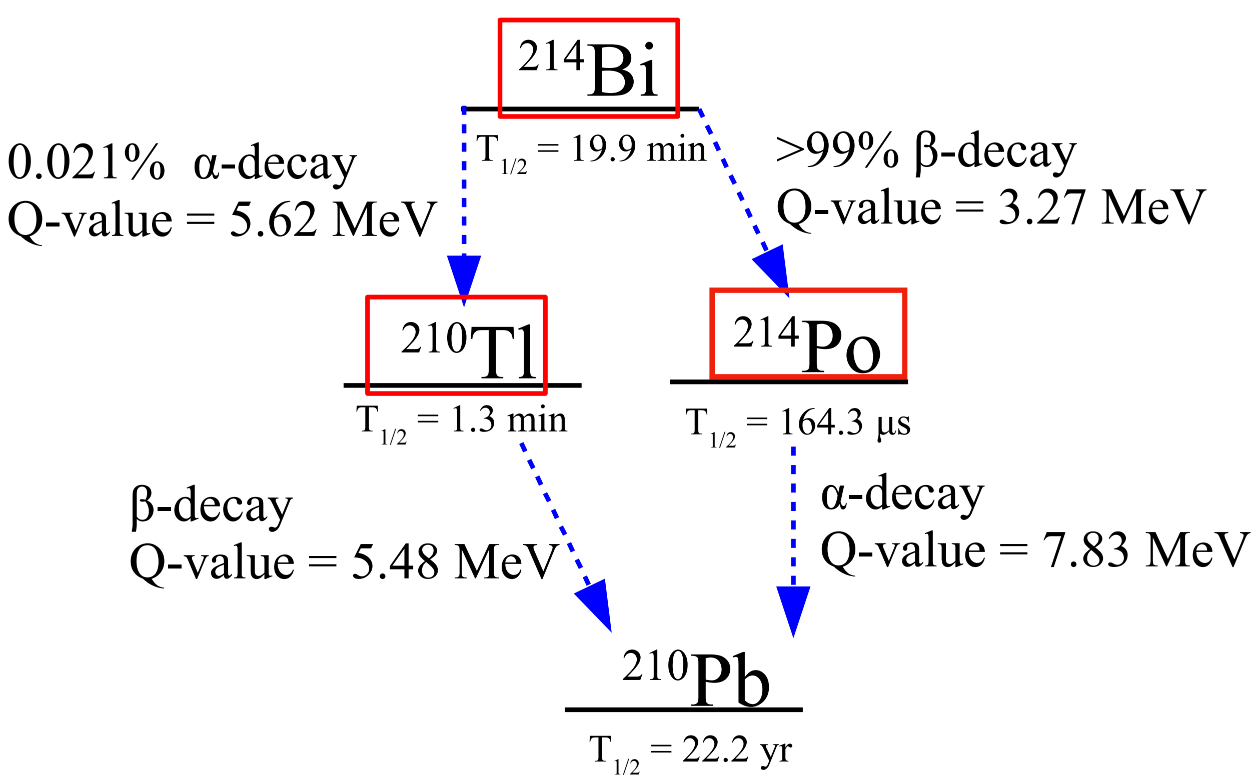

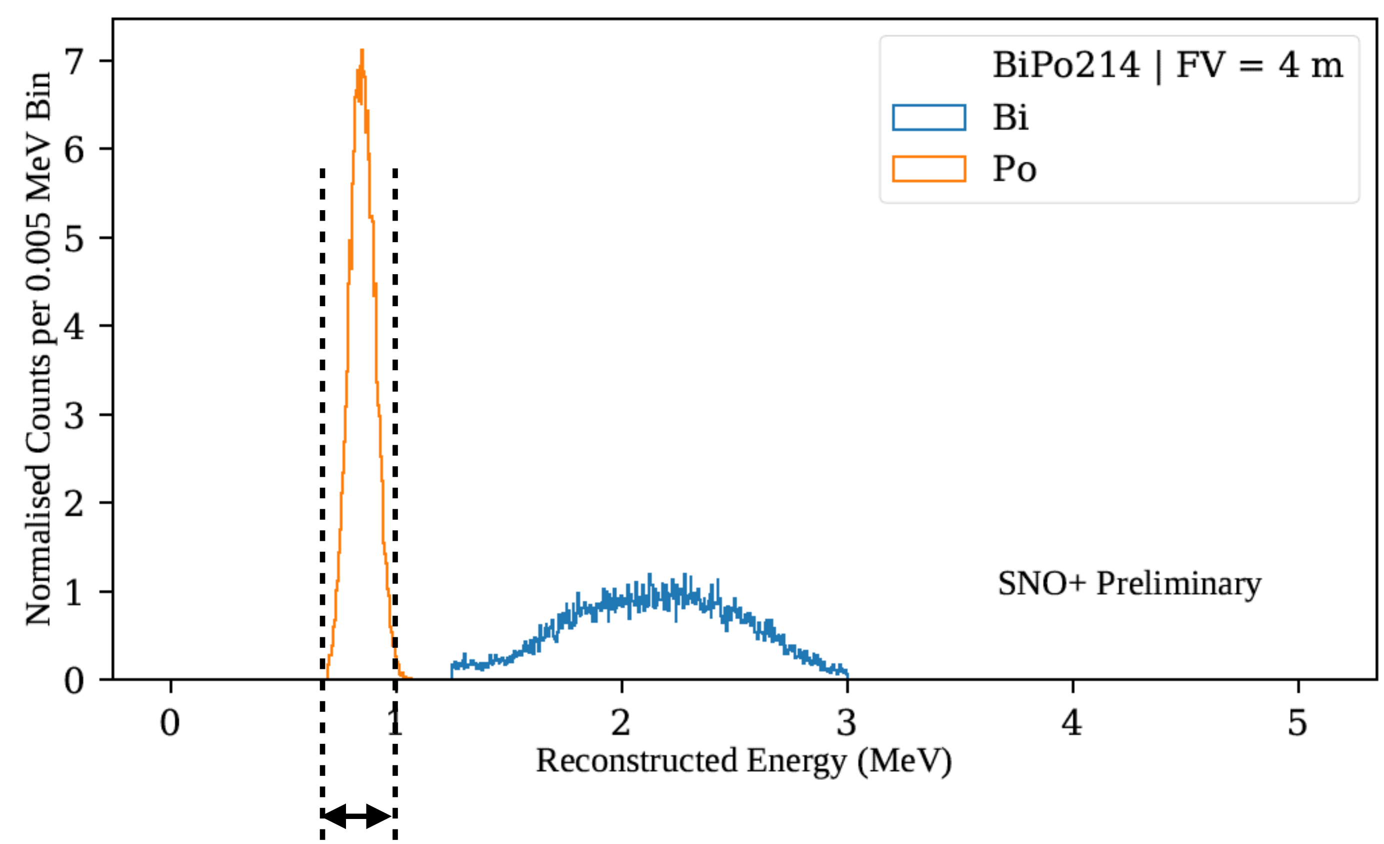

1. Po En. window

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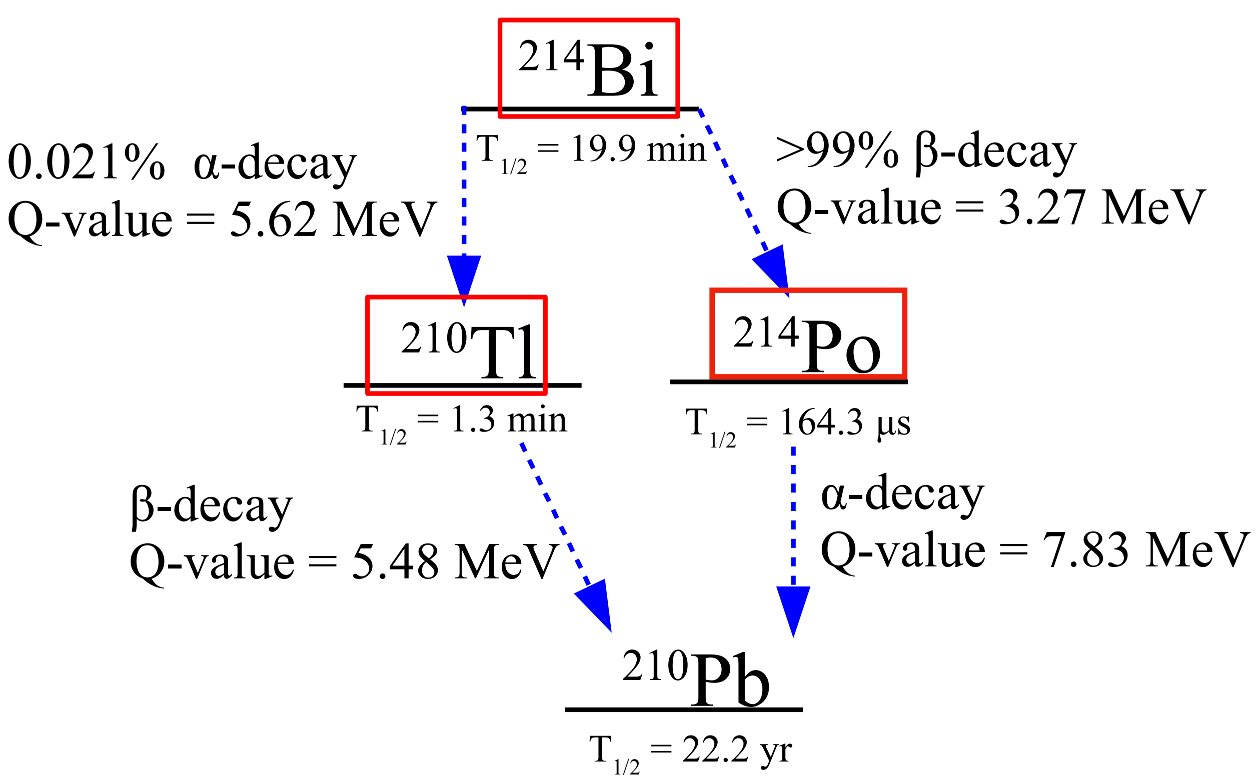
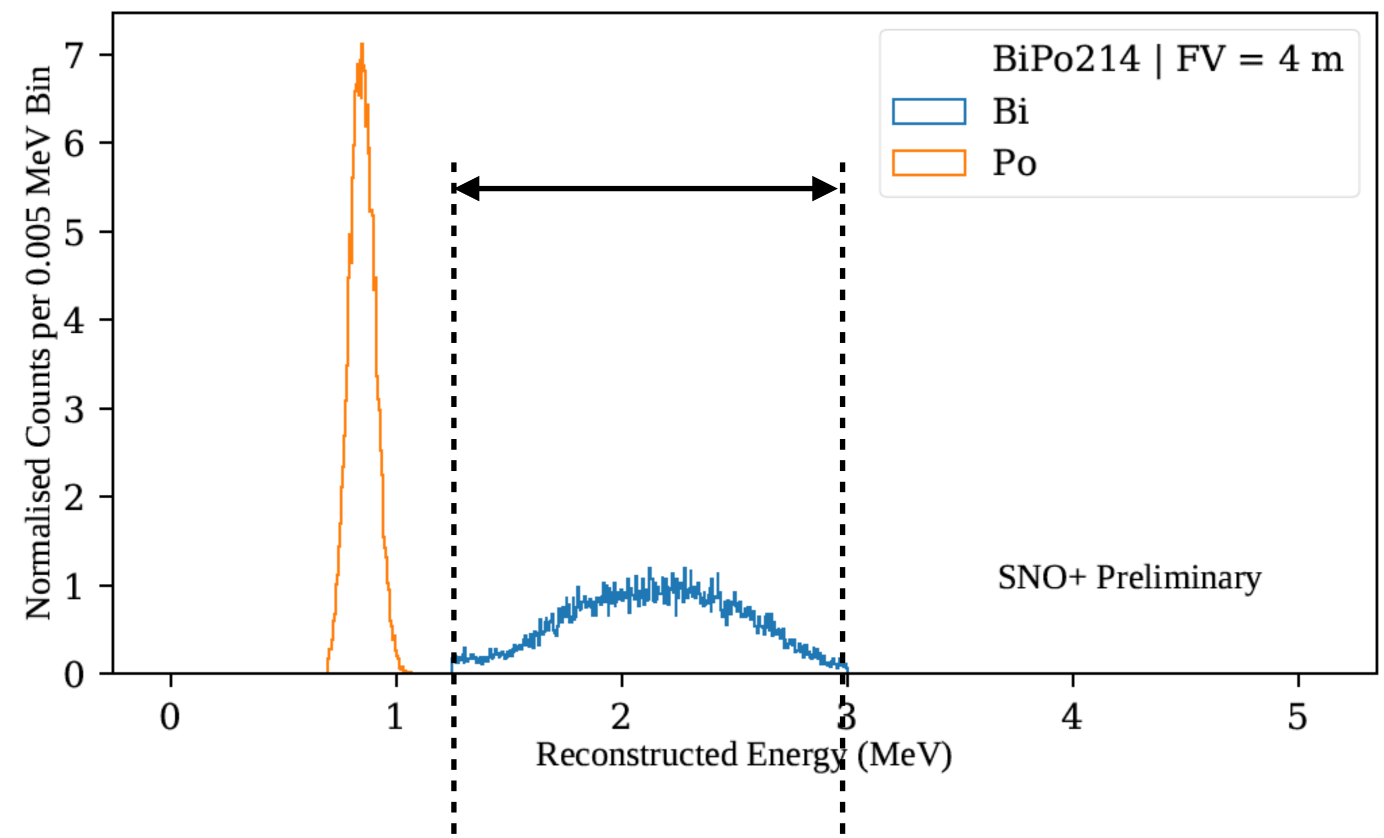
^{238}U via $^{214}BiPo$



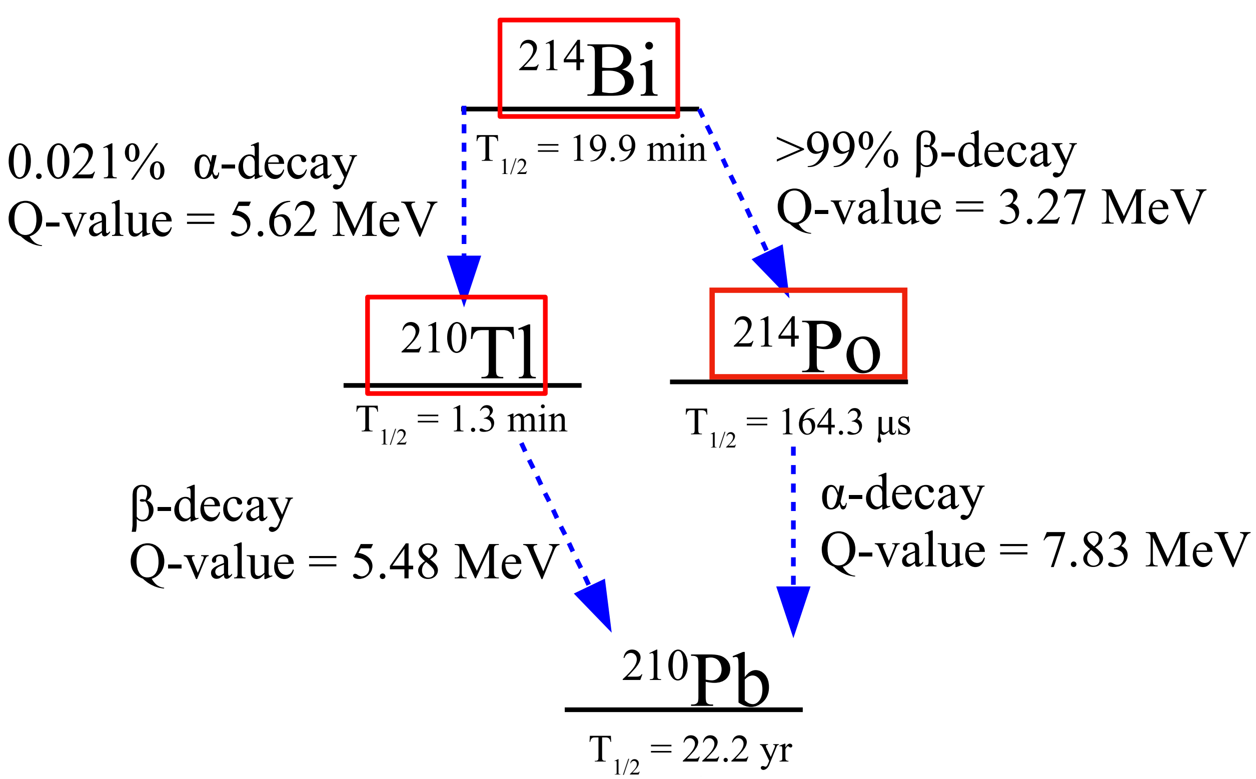


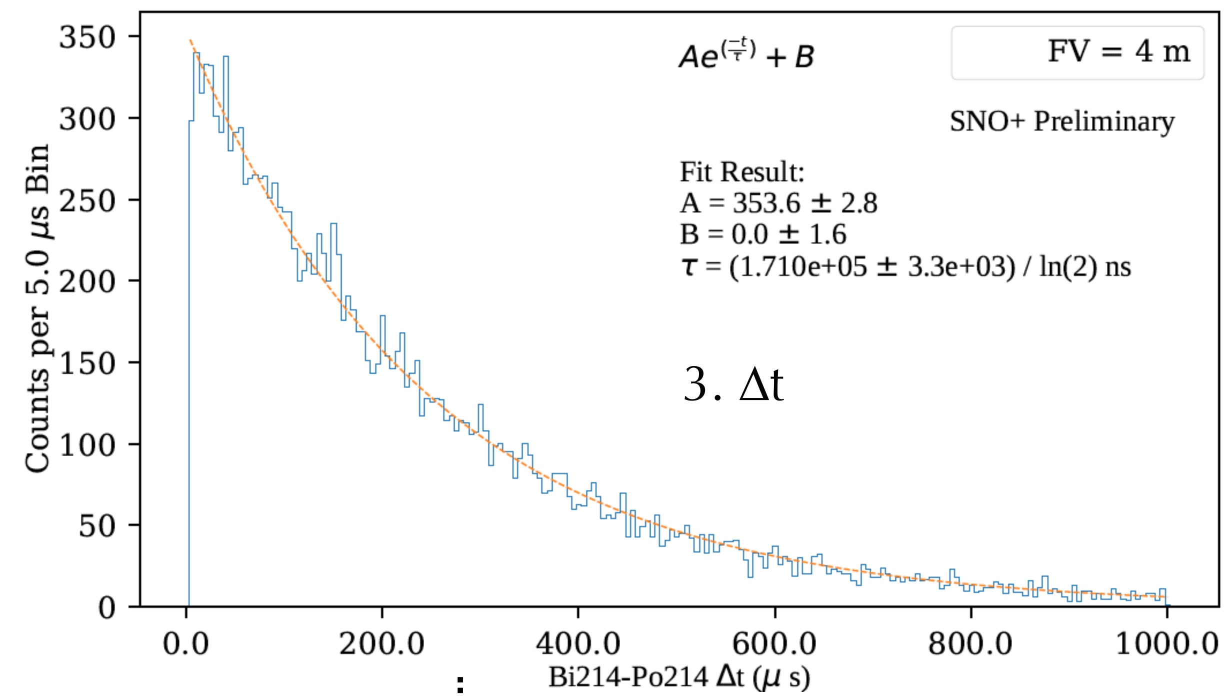
2. Bi En. window

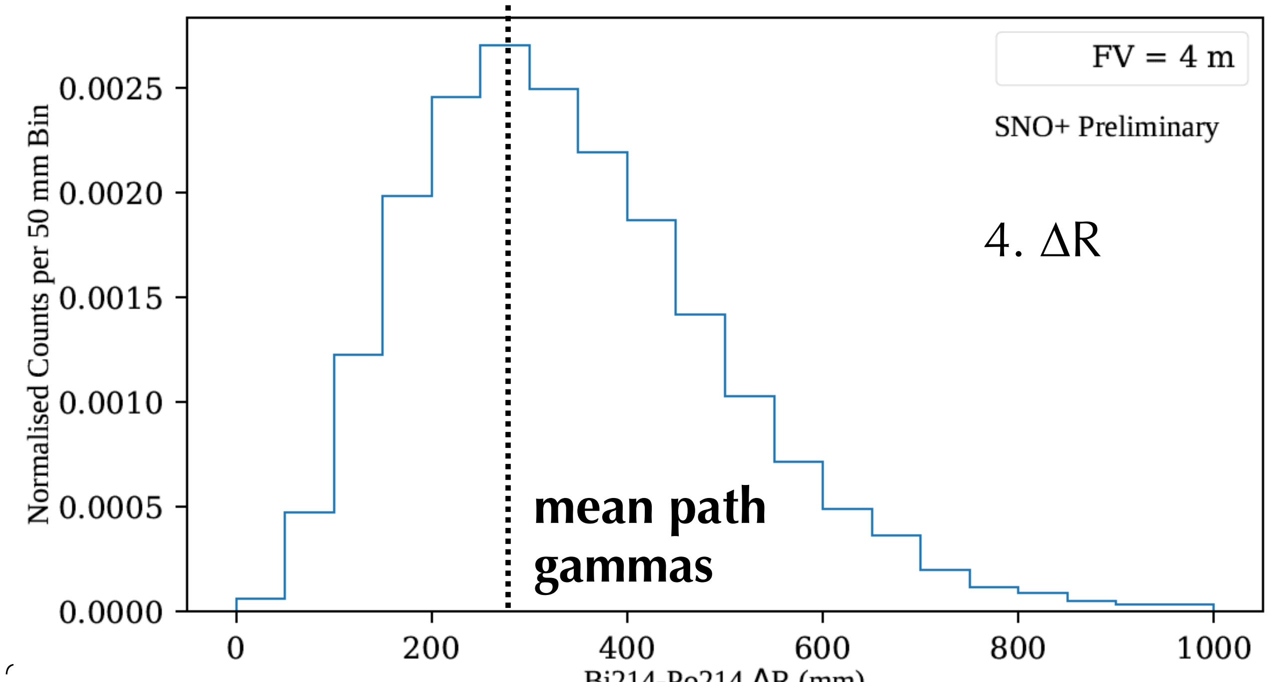
Major Outcomes

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

^{238}U via ^{214}BiPo





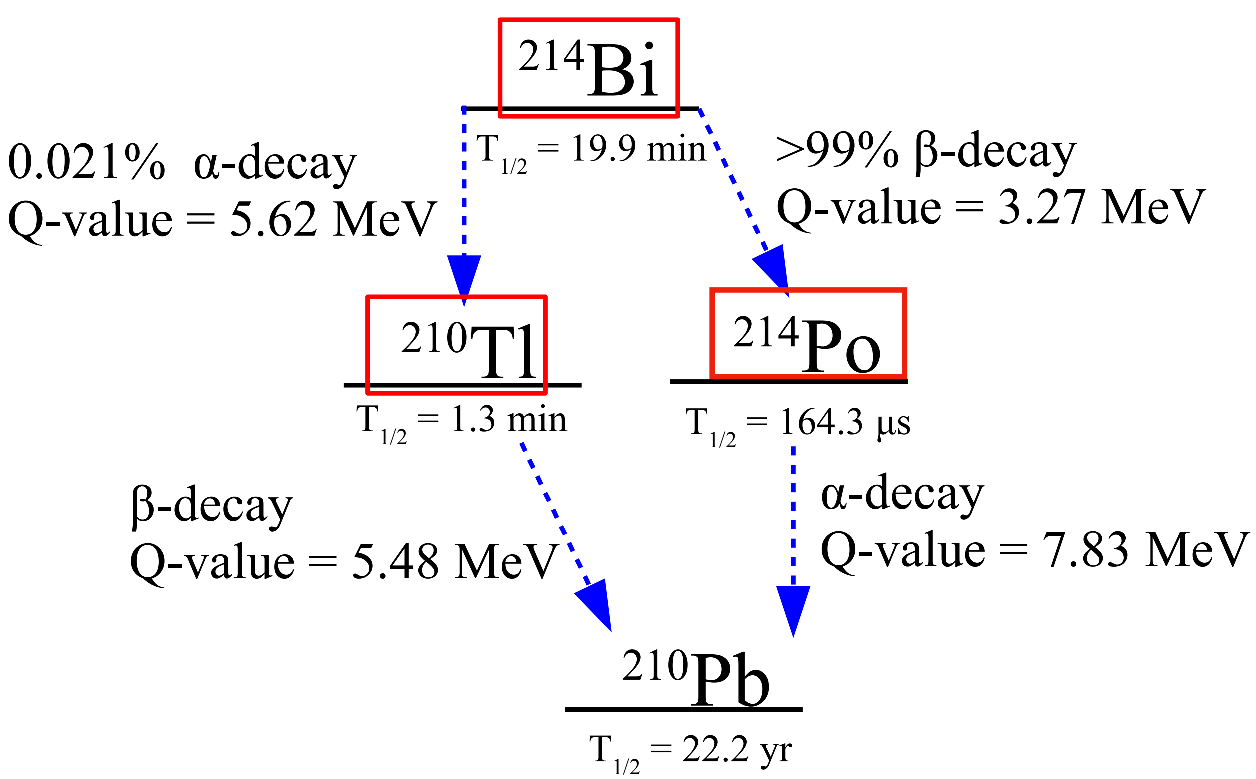


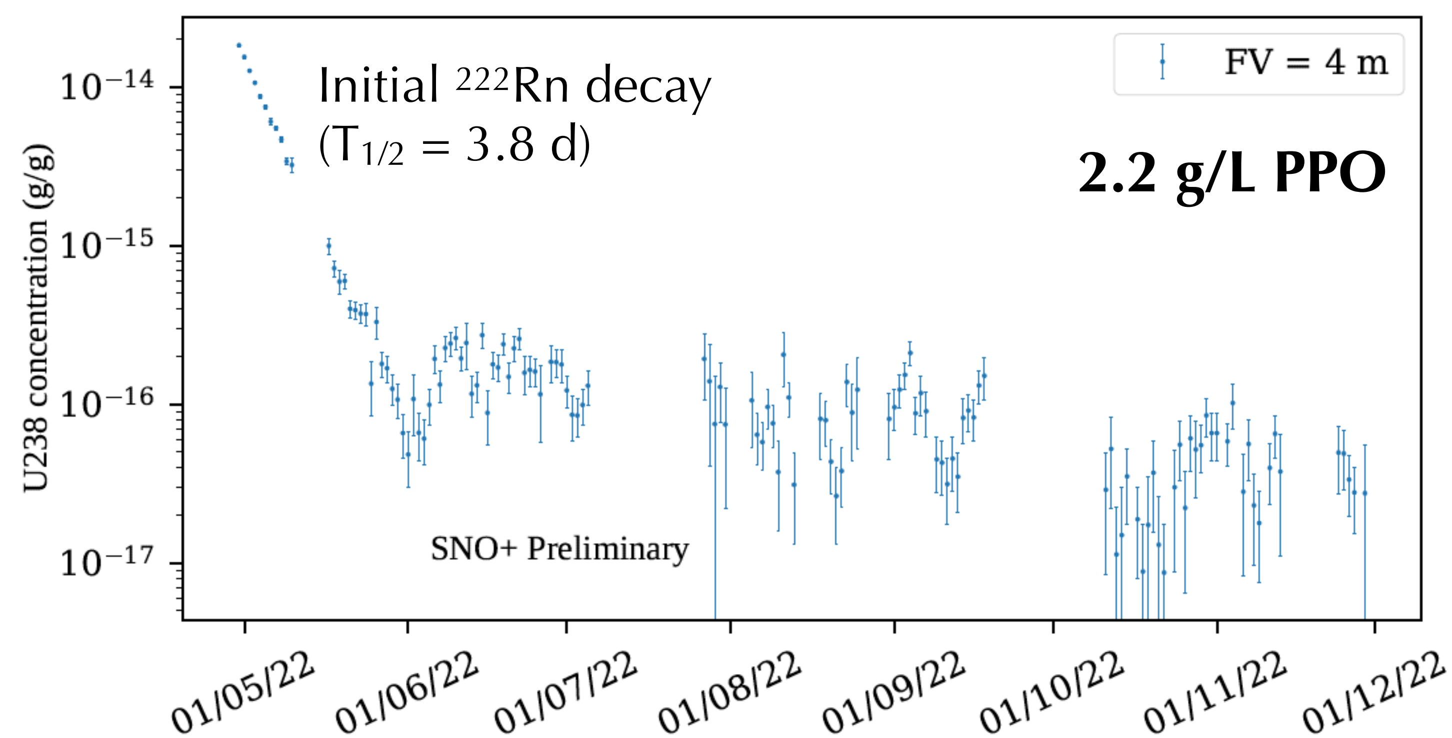
SNO+ Backgrounds

Major Outcomes

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

^{238}U via ^{214}BiPo





^{238}U = (5.3±0.1)10^{-17} g/g

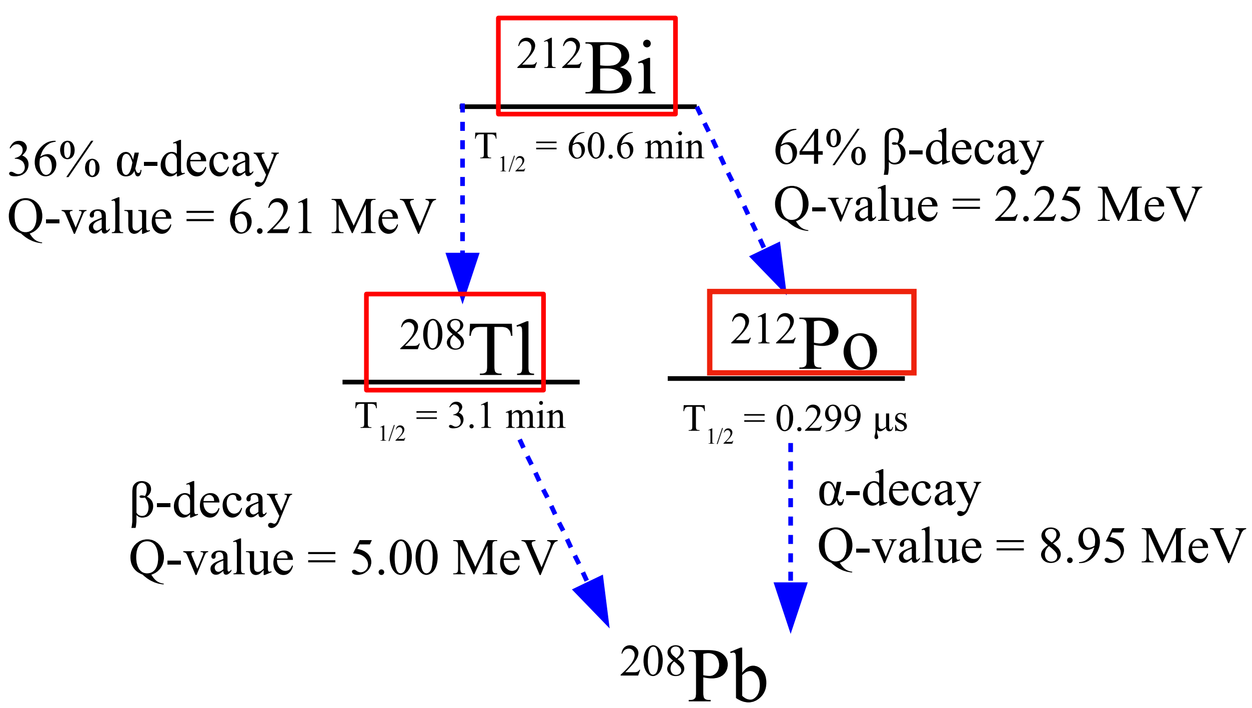
Below DBD-phase requirements!

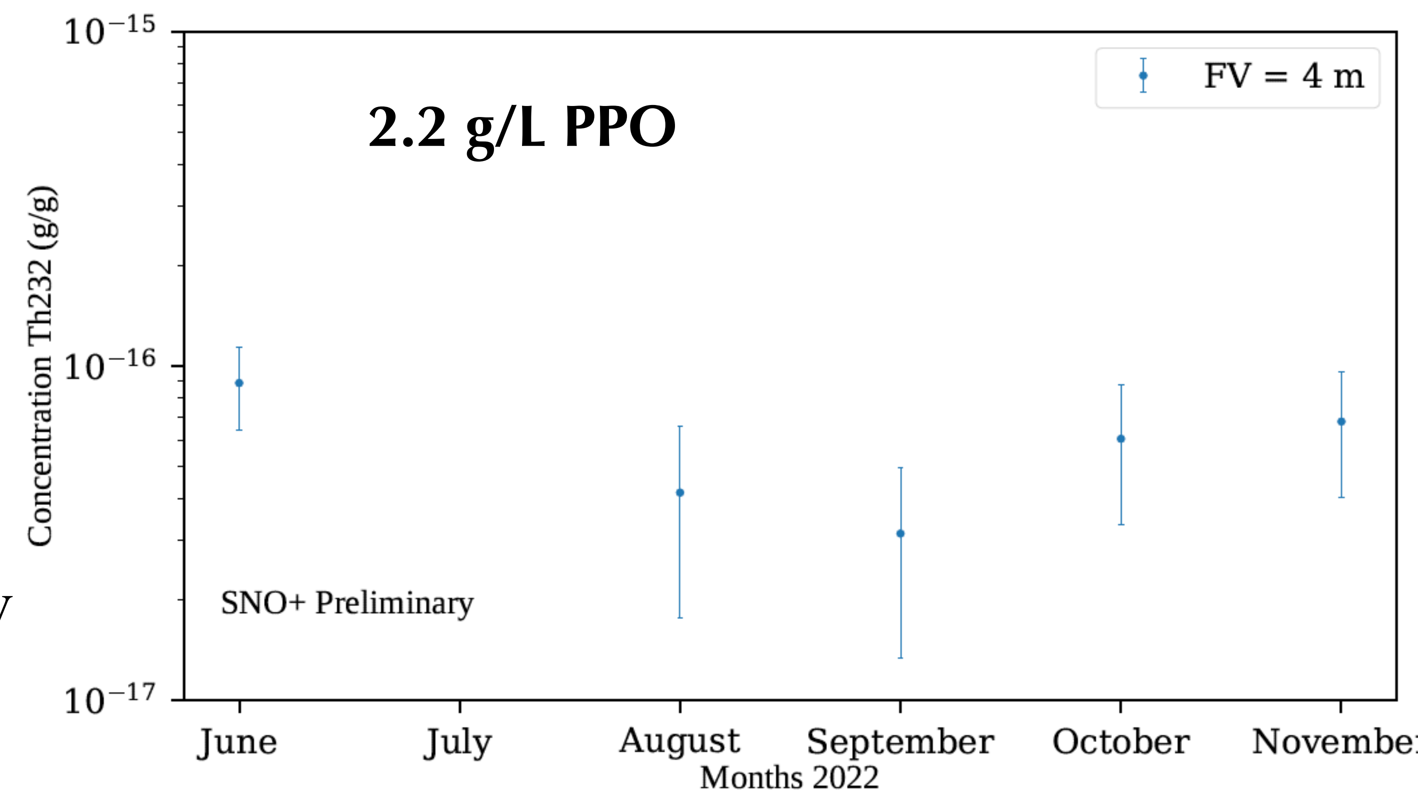
SNO+ Backgrounds

Major Outcomes

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

^{232}Th via ^{212}BiPo



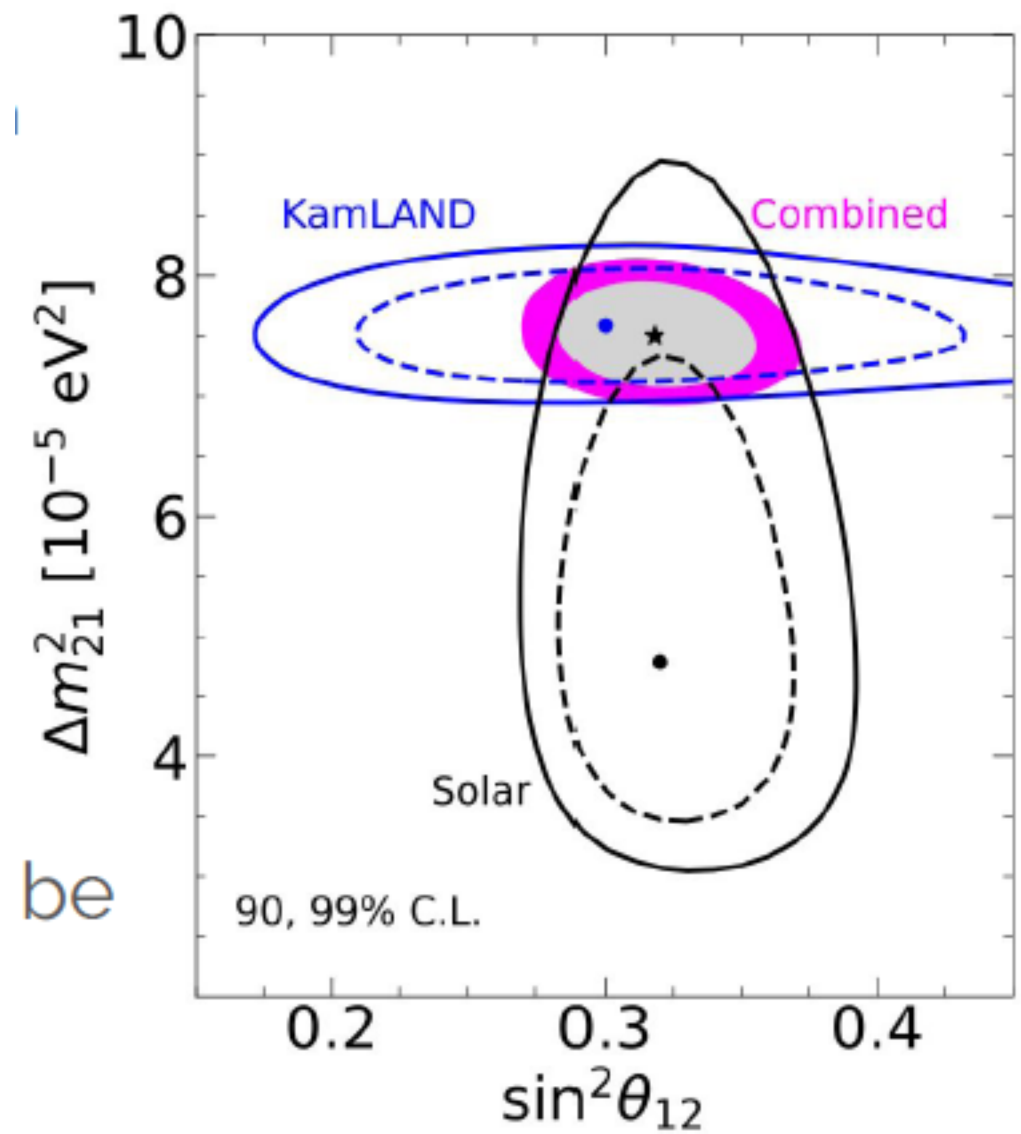


^{232}Th = $(5.7\pm0.3)10^{-17}$ g/g

Below DBD-phase requirements!

Why?

- Tension between the two types of experiments that have measured Δm^2_{21}
  - KamLAND = $\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\ \mathrm{eV}^2$
  - Solar = $\Delta m^2_{21} = 4.8^{+1.3}_{-0.6} \times 10^{-5}\ \mathrm{eV}^2$
- Another reactor anti-neutrinos oscillation measurement would help

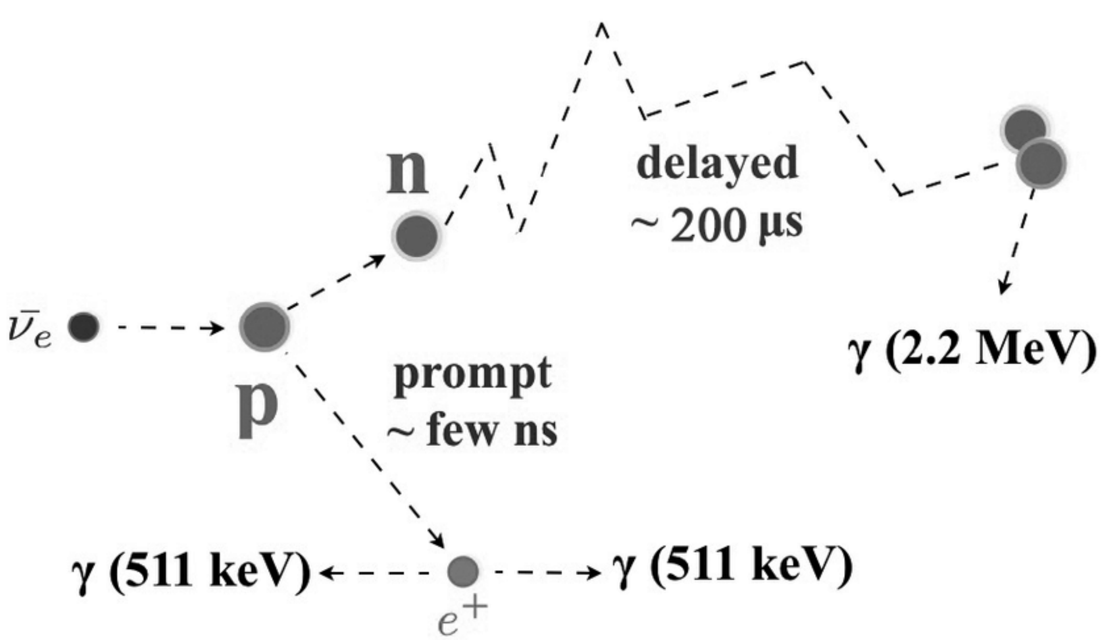


de Salas, et. al.
J. High Energy Phys. 2021, 71 (2021)

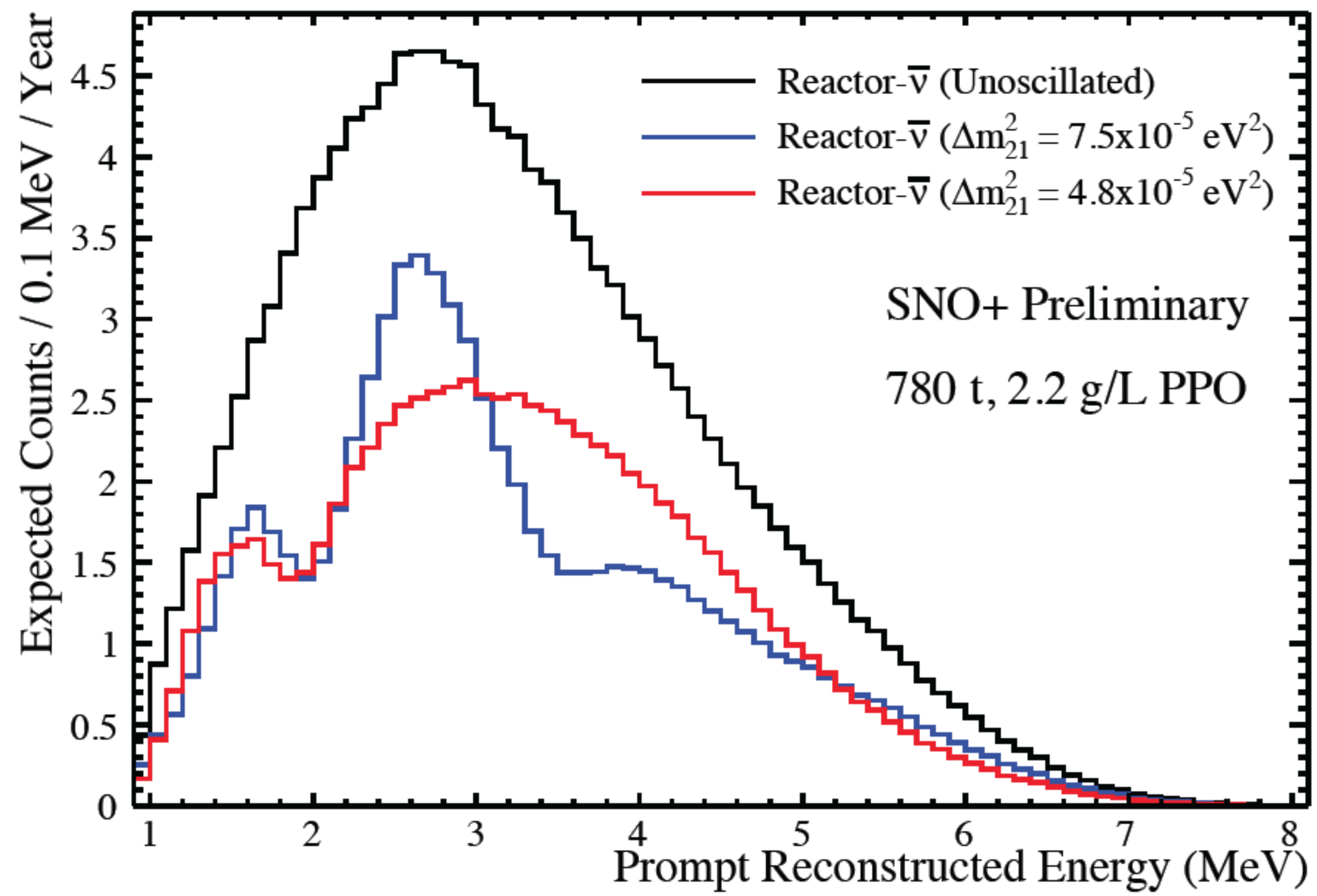
SNO+
Reactor Anti-neutrinos

Major Outcomes

- Expect ~100 reactor anti-neutrino interactions per year
  - ~60% of reactor anti-neutrino flux comes from 3 Canadian reactors
    - characteristic structure of the oscillated spectrum

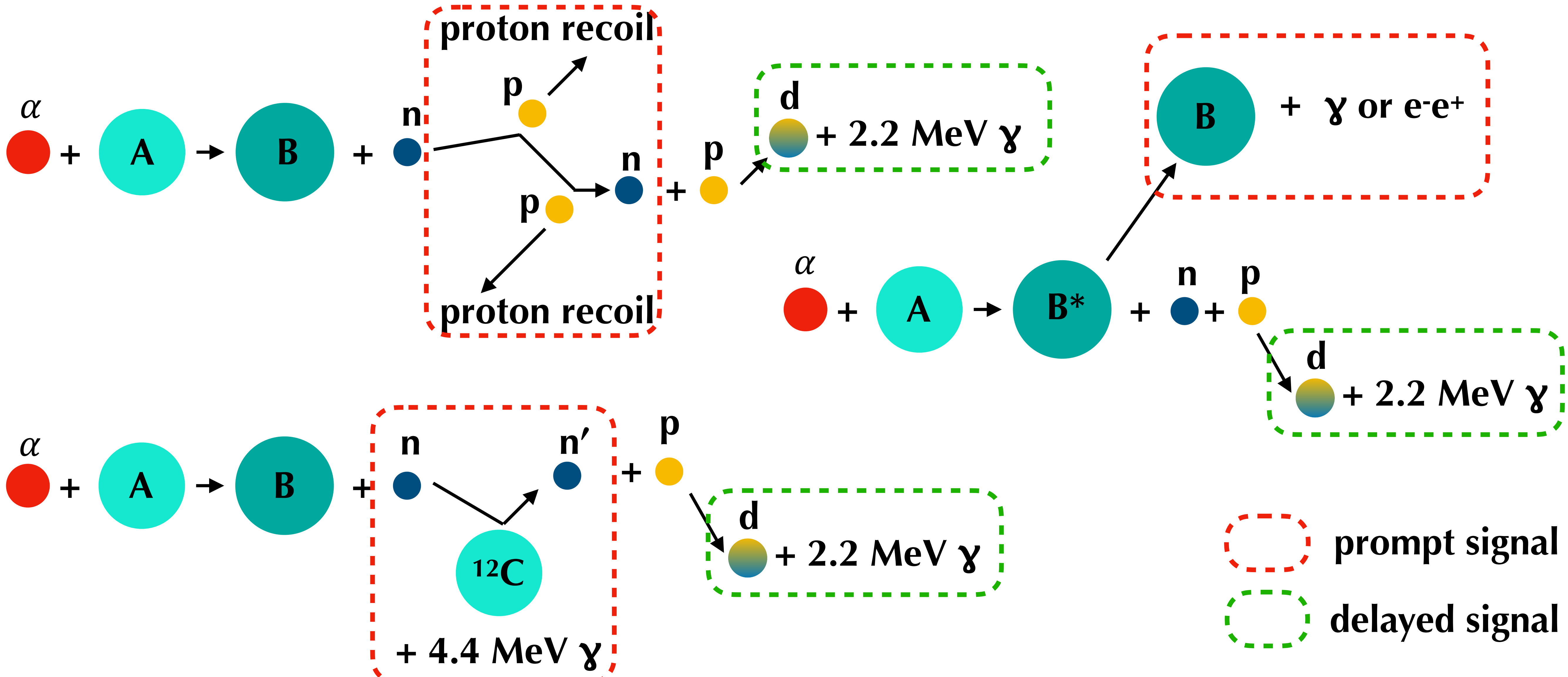


Inverse Beta Decay (IBD) reaction



Major Outcomes

- Expect ~100 reactor anti-neutrino interactions per year
  - ~60% of reactor anti-neutrino flux comes from 3 Canadian reactors
- Major source of alphas is ^{210}Po
  - Highly reduced (~3x) ^{210}Po background from partial fill to the 2.2 g/L full fill phase



Major Outcomes

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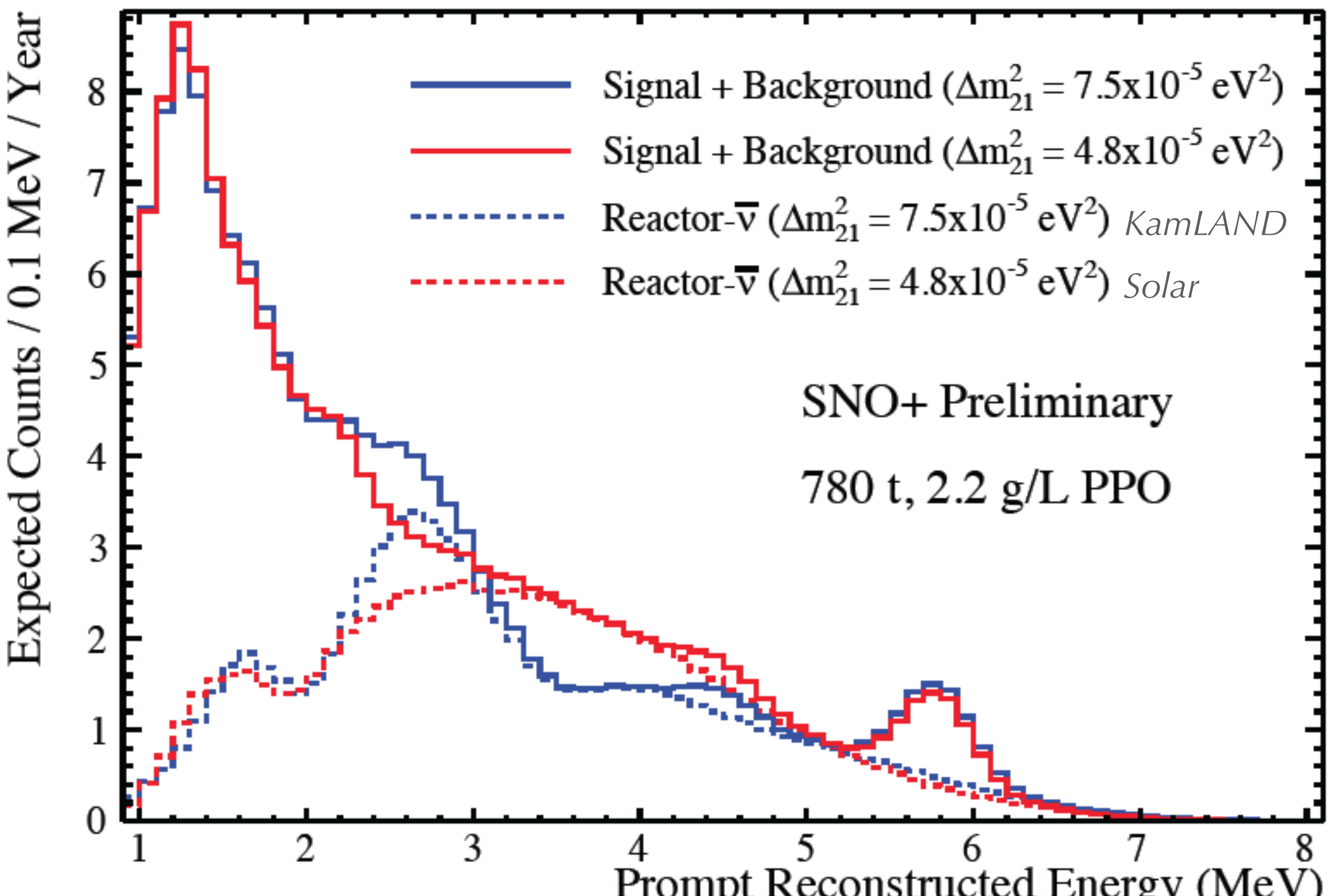
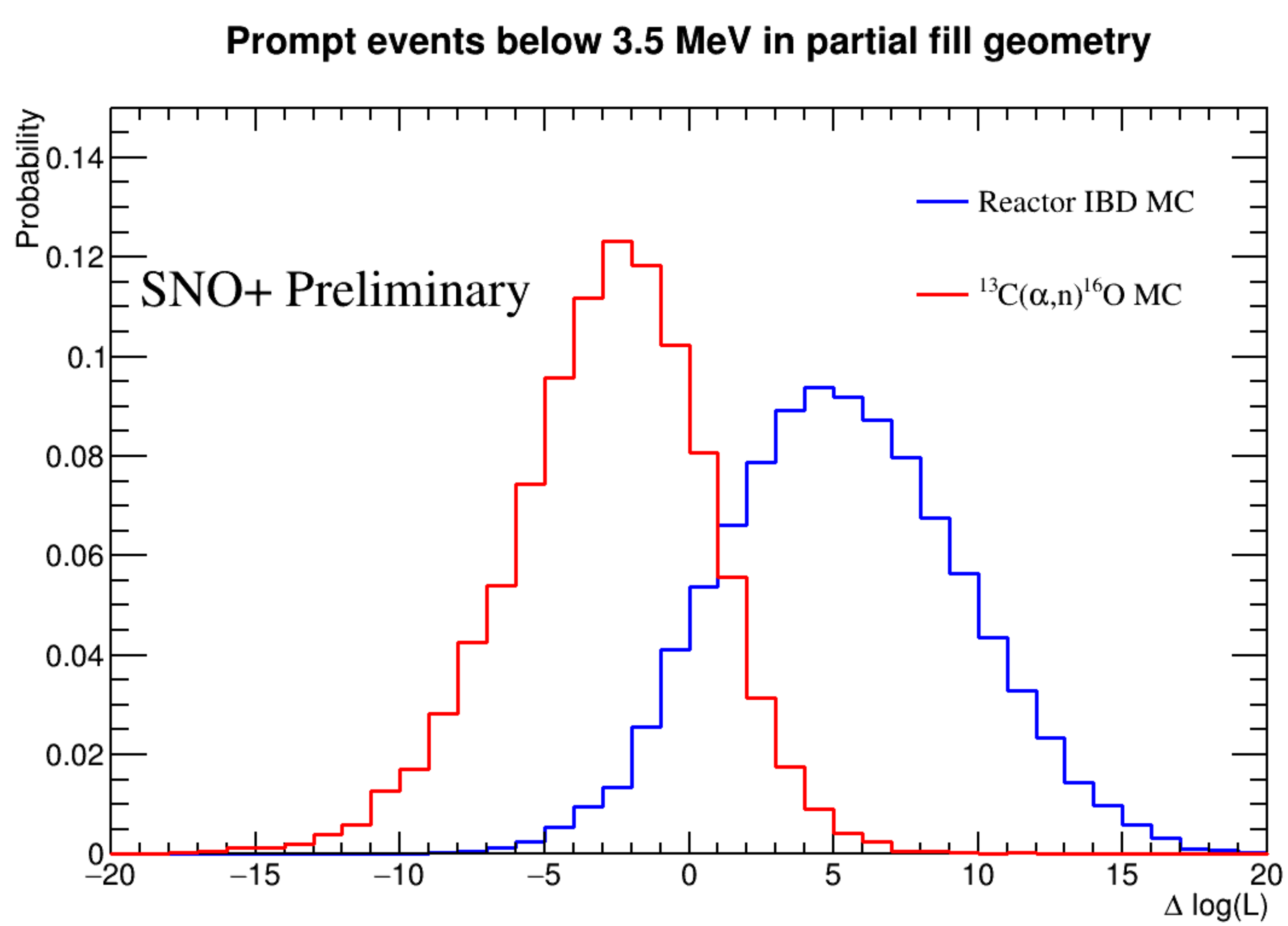


Distinguishable features under different oscillation scenarios

Major Outcomes

- Expect ~100 reactor anti-neutrino interactions per year
  - ~60% of reactor anti-neutrino flux comes from 3 Canadian reactors
- Major source of alphas is ^{210}Po
  - Highly reduced (~3x) ^{210}Po background from partial fill to the 2.2 g/L full fill phase
- Classifiers are being developed to separate signal from background
  - Good outcome in the partial fill phase

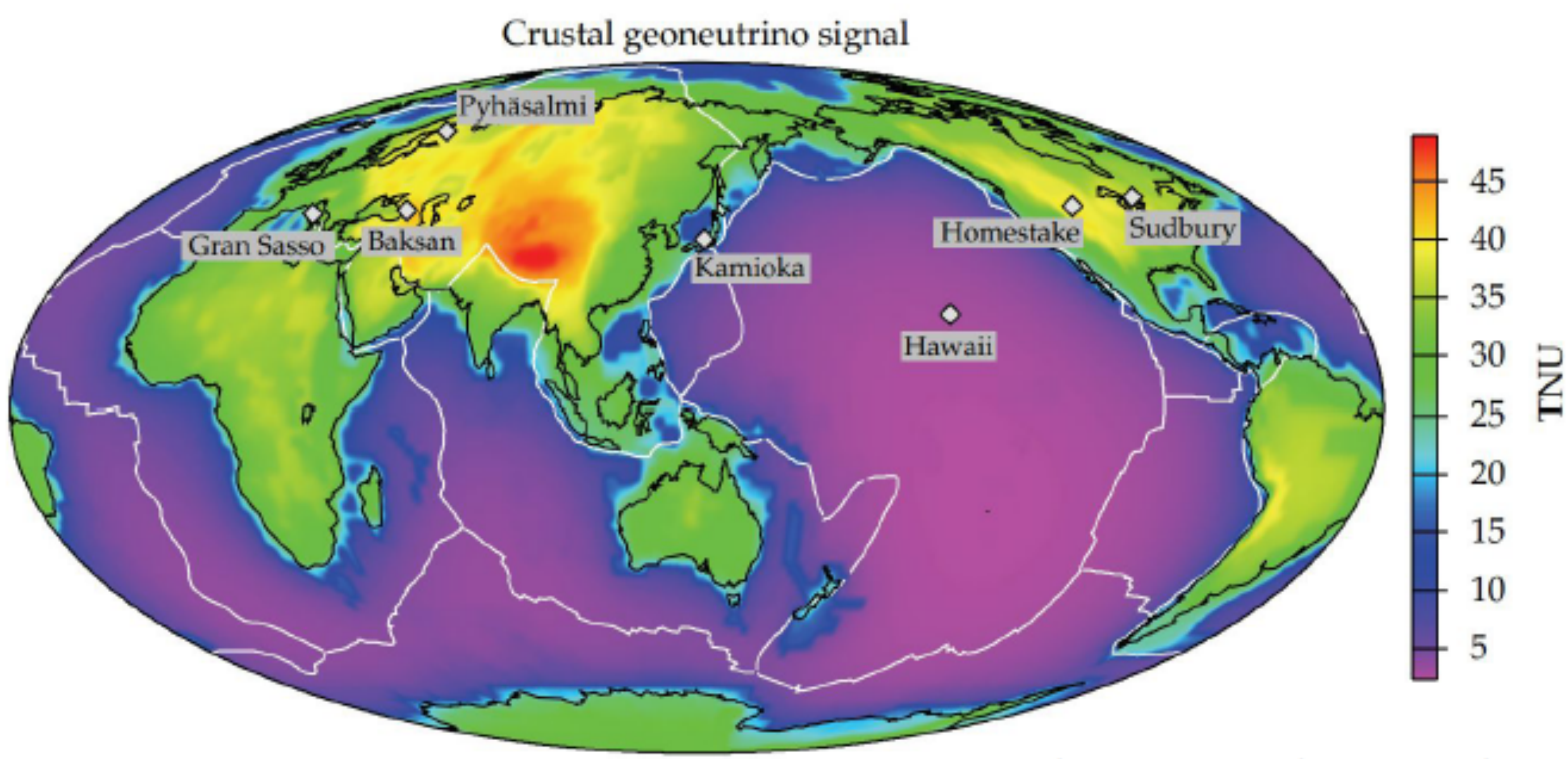


0.6 g/L PPO
Partial fill

SNO+
Geo anti-neutrinos

Why?

- Expect ~25 geo anti-neutrino interactions per year
- SNO+ will make **first measurement** of geo anti-neutrinos in North America
  - Constrain geological models

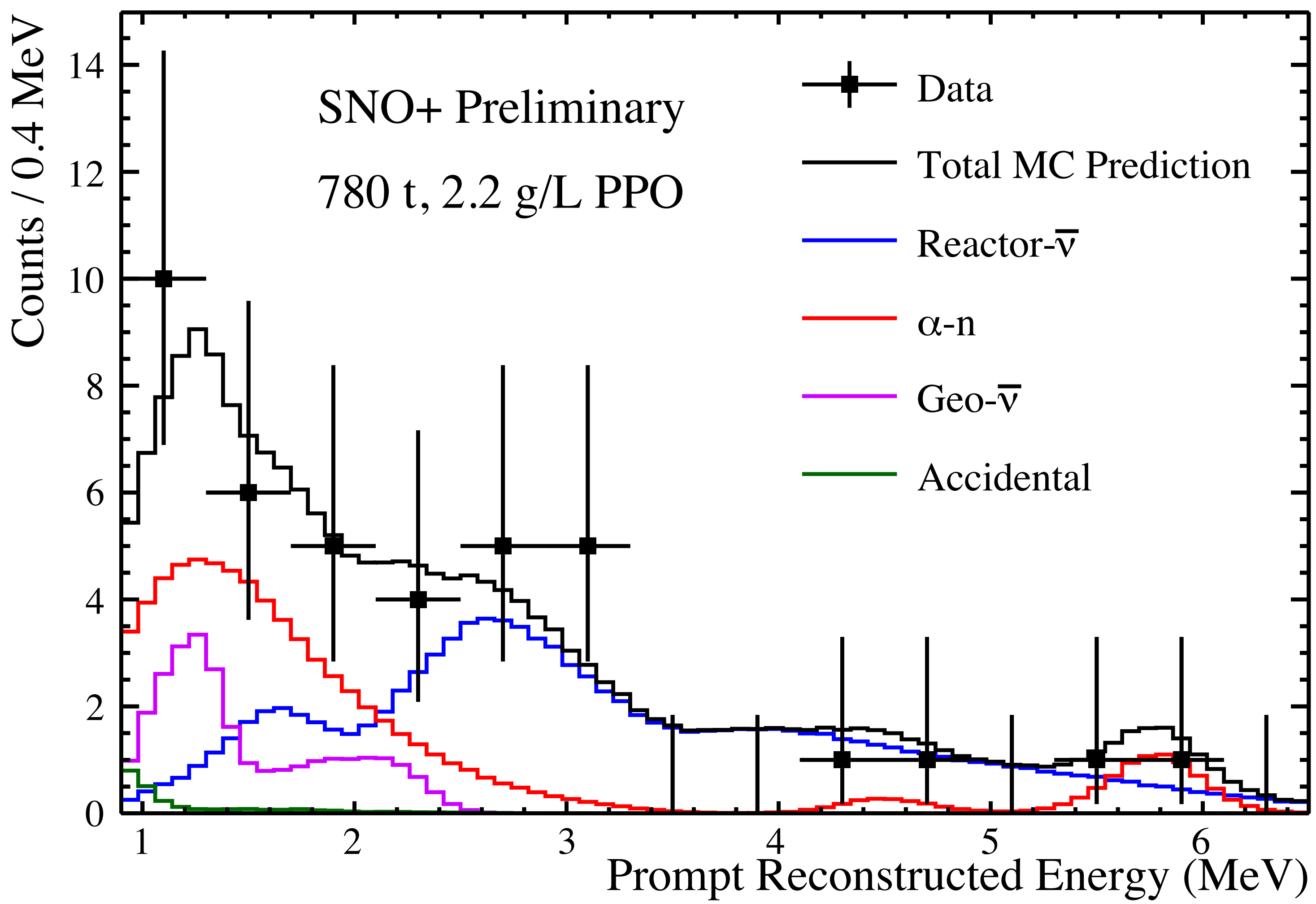


Sramek, McDonough, Learned
Adv. High Energy Phys. 2012 (2012) 235686

SNO+ Anti-neutrinos

Major Outcomes

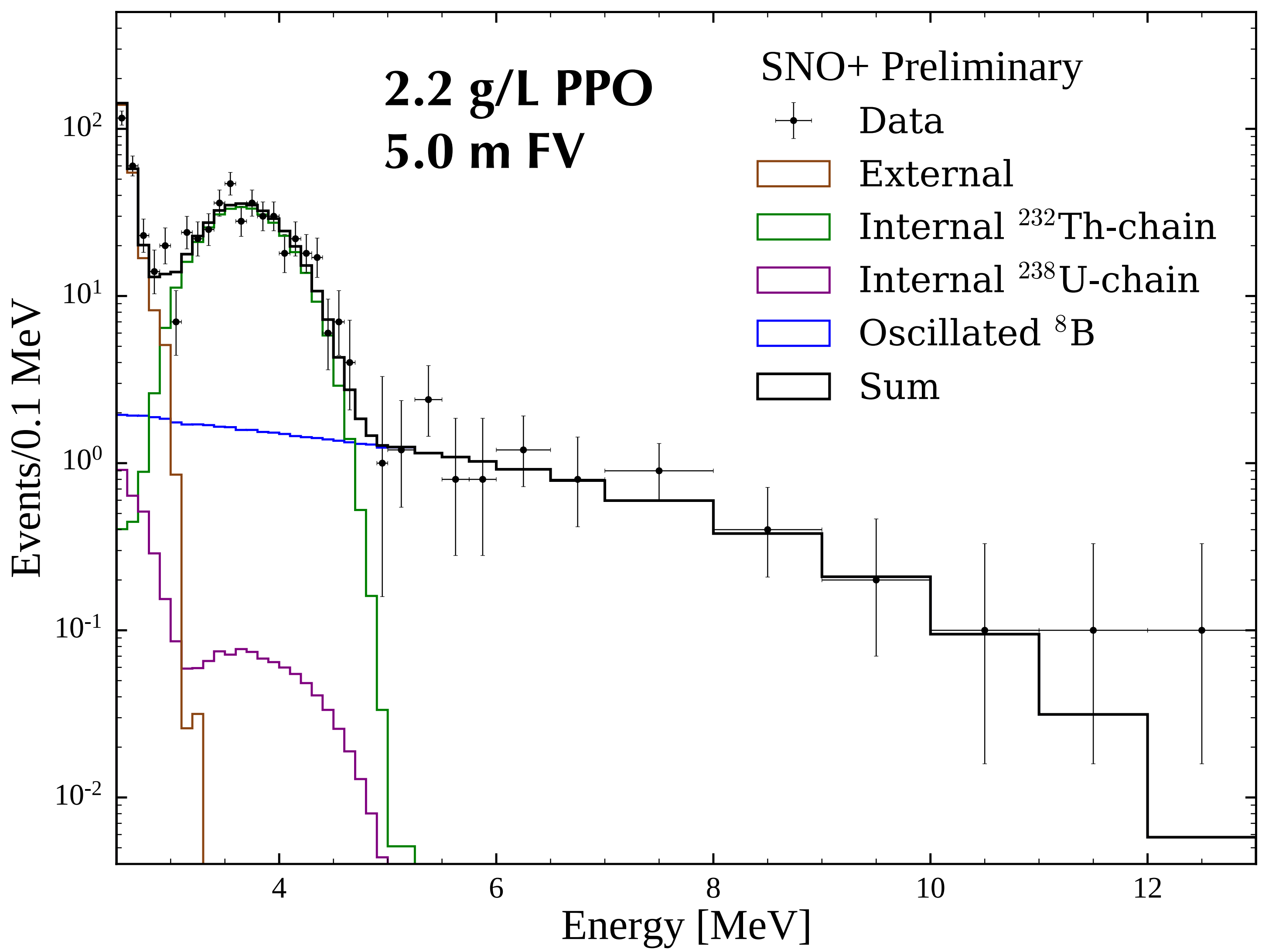
- Preliminary study in SNO+ within a 5.7 m Fiducial Volume
  - Finalising optics and classifiers
- Sensitivity similar to KamLand (±0.18 10^{-5} eV^2) expected within few years
  - not affected by Te loading



Reactor IBD oscillated using:
- $\Delta m^2_{21} = 7.53 \times 10^{-5}$ eV^2
- $\sin^2(\theta_{12}) = 0.307$

Major Outcomes

- Preliminary study in SNO+ within 80.9 days of data
  - Expected to double the statistics
- Major background for high energy neutrinos is ^{208}Tl (^{232}Th-chain).
  - Multi-site analysis under development for signal/background discrimination



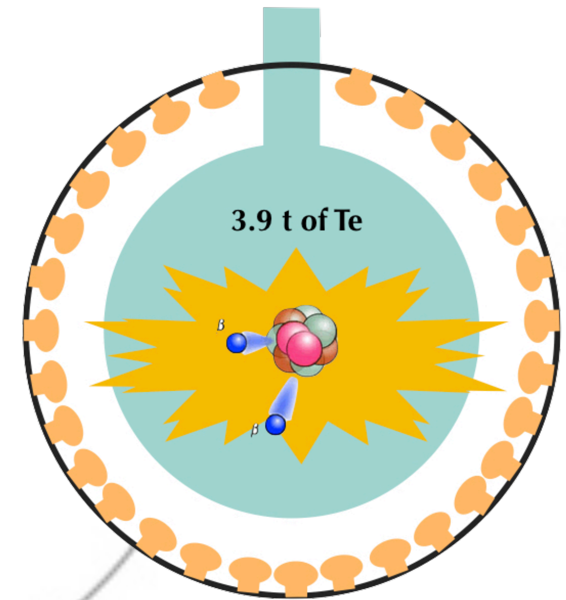
Bayesian 1σ Credible Interval:

$$\theta_{12} = 36.4^{\circ}{}^{+8.0^{\circ}}_{-7.9^{\circ}}$$

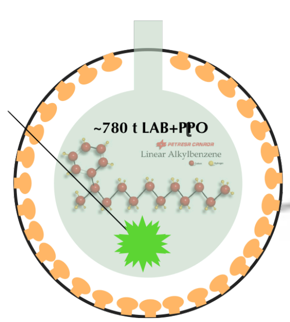
Current global fit value by NuFit 5.2 [3]:

$$\theta_{12} = 33.41^{\circ}{}^{+0.75^{\circ}}_{-0.72^{\circ}}$$

Results statistically-limited.

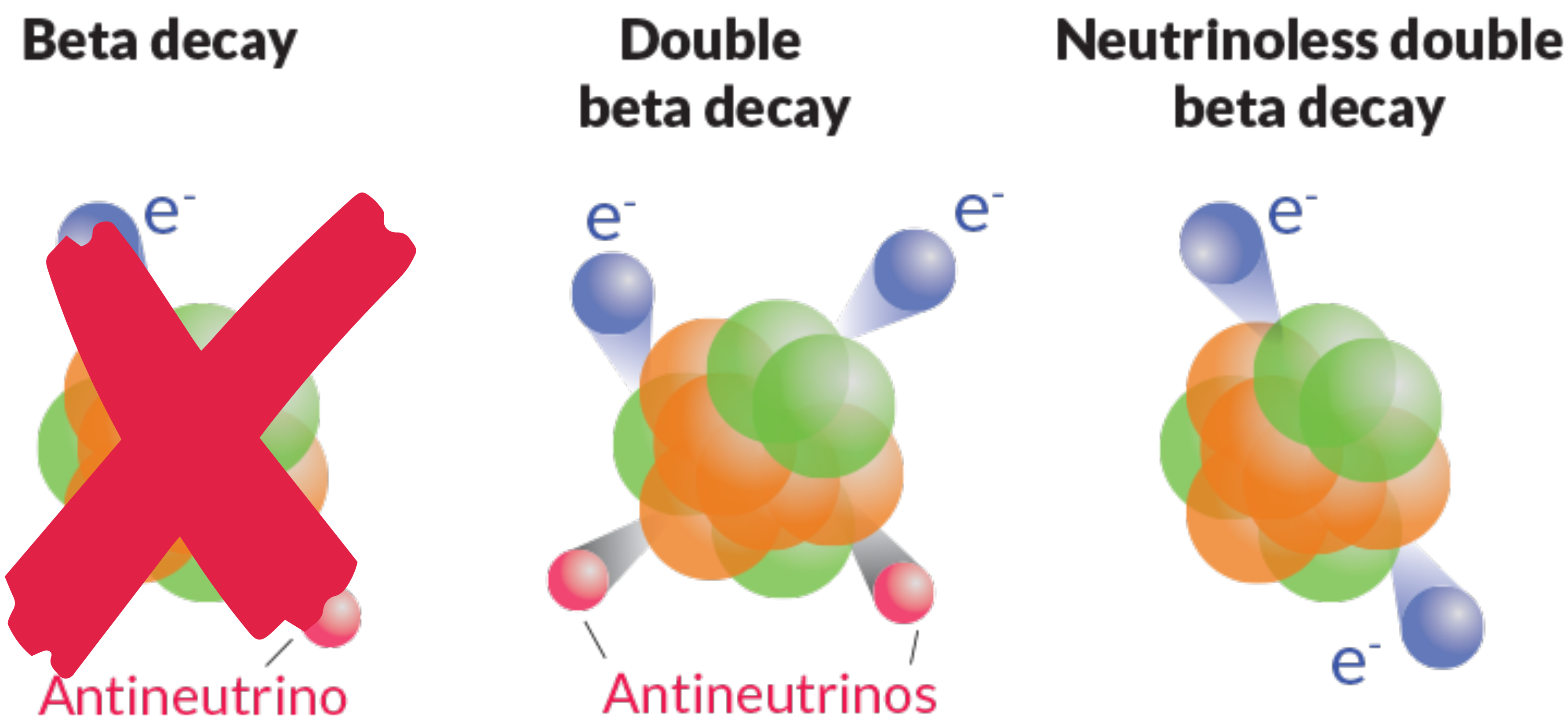


Beyond the scintillator phase



0νββ

Quick overview:



Energetically forbidden

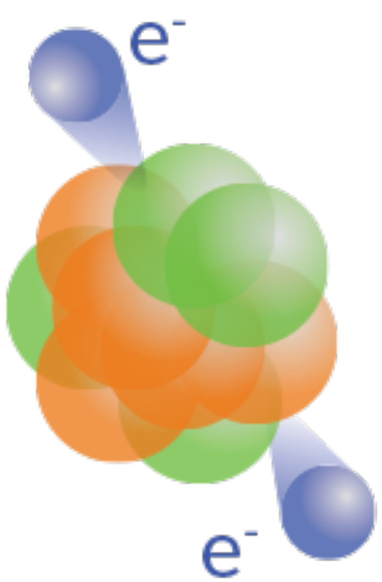
Only happens if neutrinos are Majorana

Happens in ~35 isotopes
Decay scale is of the order of 10^{20} yrs

0νββ Theory

Quick overview:

Neutrinoless double beta decay



Phase-space factor $\sim Q_{\beta\beta}^5$

Nuclear Matrix Element, depends on the nuclear level distribution of the initial and final state
<u>Largest theoretical uncertainty</u>

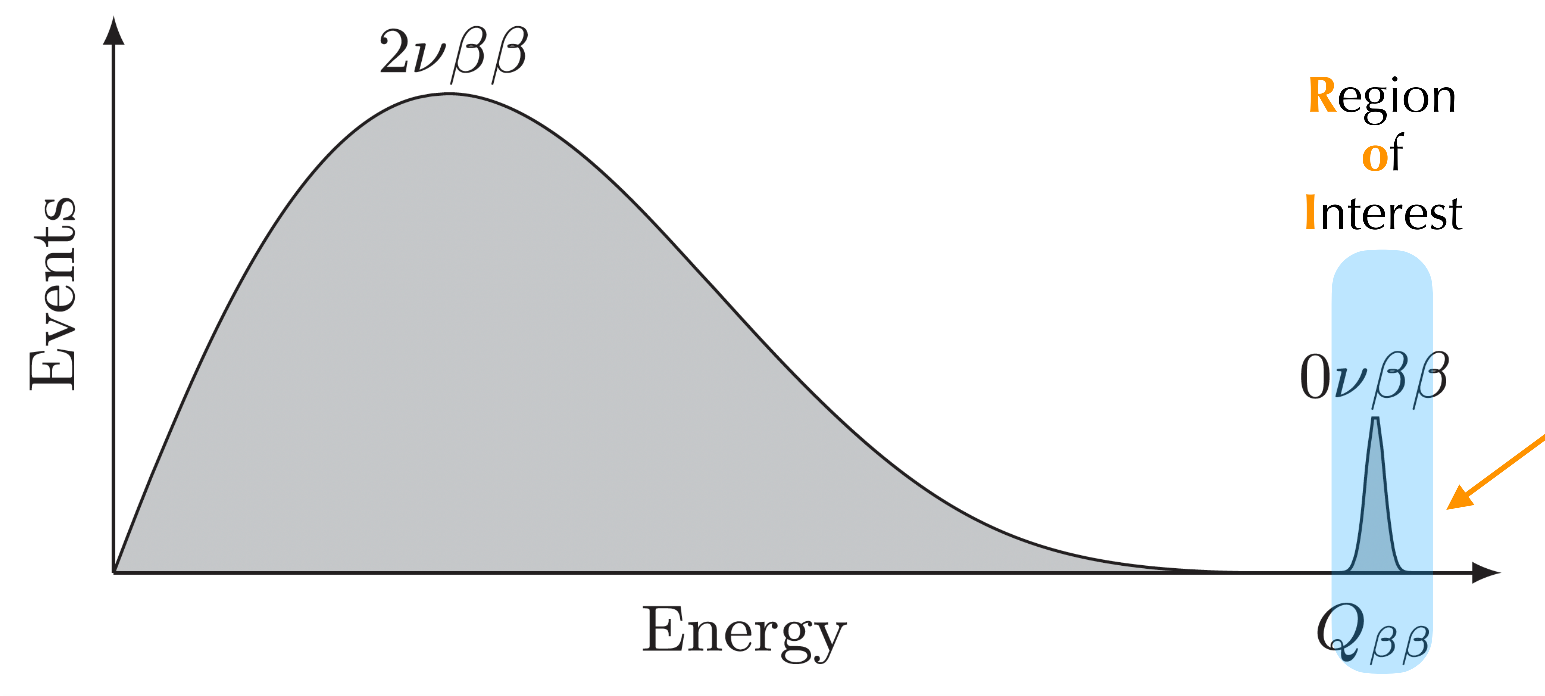
$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu} \left|\mathcal{M}\right|^2 \left|\frac{m^{\nu}_{ee}}{m_e}\right|^2$$

Half-life of the decay

Effective Majorana neutrino mass
Depends on m_1, m_2, m_3 and the mixing angles

$$m^{\nu}_{ee} = m_1 c^2_{12} c^2_{13} + m_2 s^2_{12} c^2_{13} e^{2i\alpha_2} + m_3 s^2_{13} e^{2i(\alpha_3+\delta)}$$

Quick overview:



Count the number of events at the Q-value of the reaction

0v efficiency

mass within the fiducial volume

$$T^{0\nu}_{1/2} \propto \frac{\epsilon}{A} \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

Background index
events/keV/kg/yr
SNO+ (expected) = 2.9e-4
GERDA = 5.4e-4
CUORE = 1.5e-2
KamLAND-Zen = 1.3e-4

To improve the current sensitivity by a factor **2**, it is necessary an experimental improvement of a factor **16**

Large mass
High radiopurity
Good energy resolution

0νββ
why

Are neutrinos their own antiparticles?

Is lepton number is violated?

What is the absolute value of the mass of neutrinos?

Why the Universe contains more matter than antimatter?

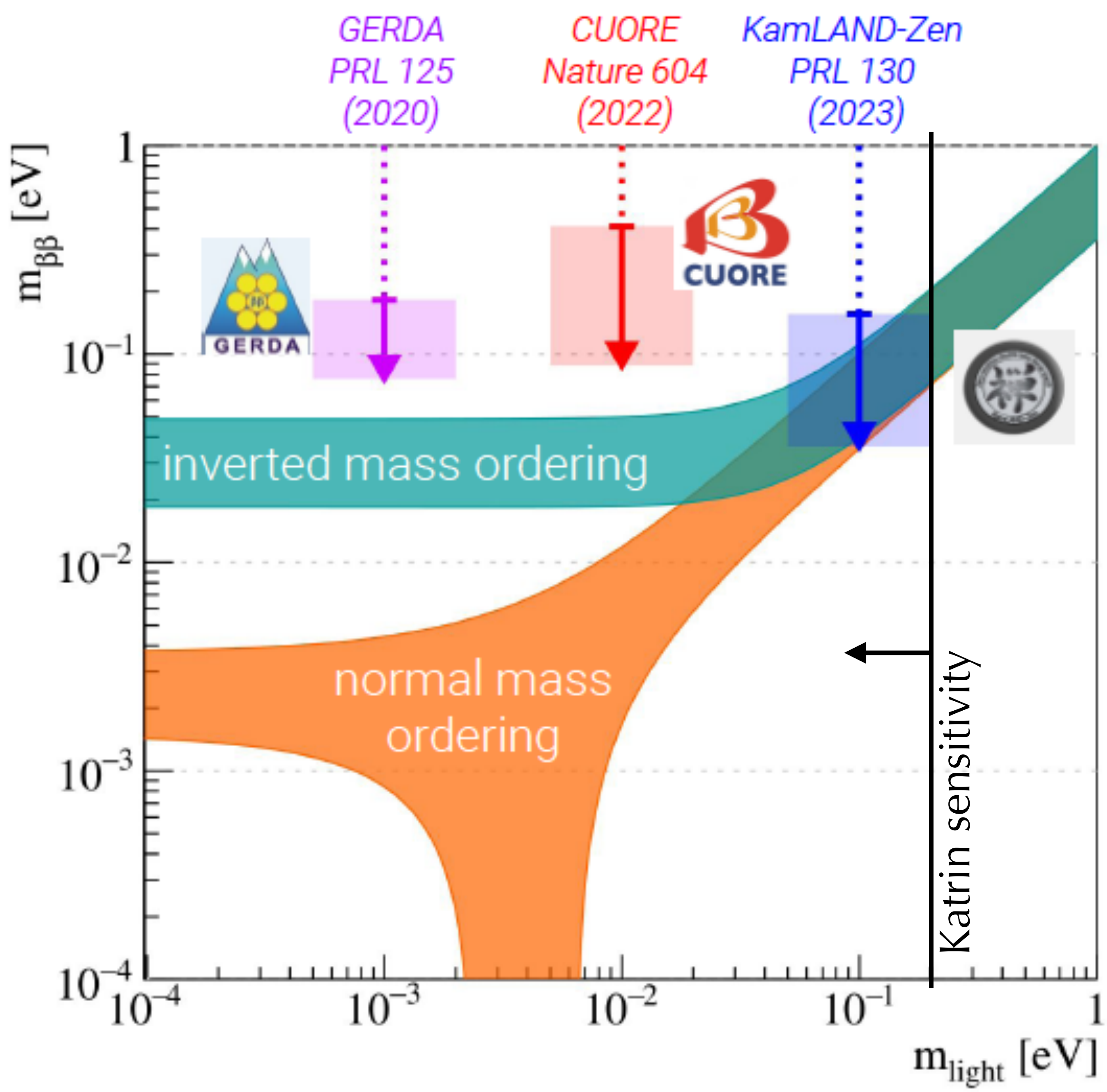
Results have impact across research areas

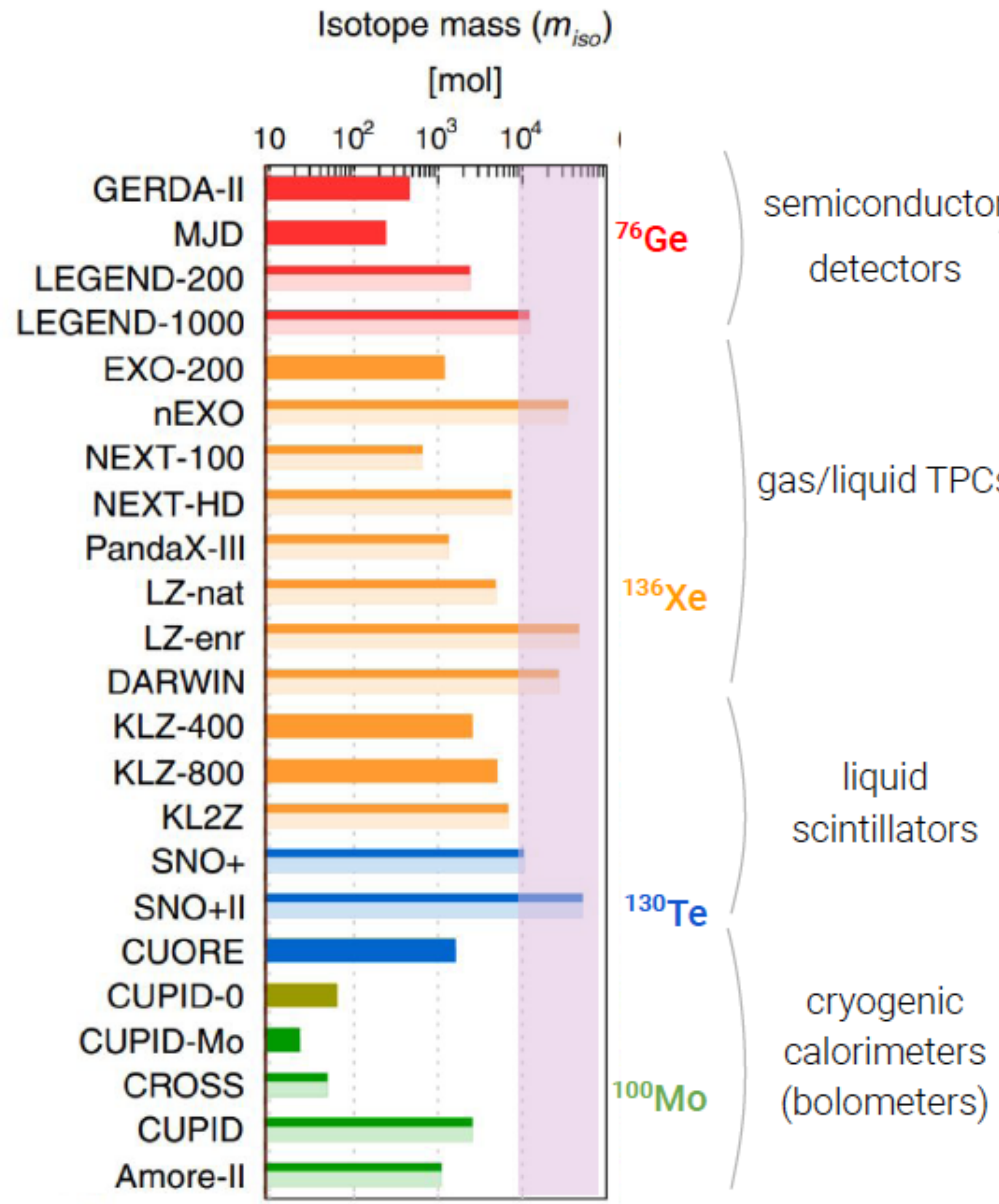
Neutrino physics

Standard Model of particle physics

Cosmology

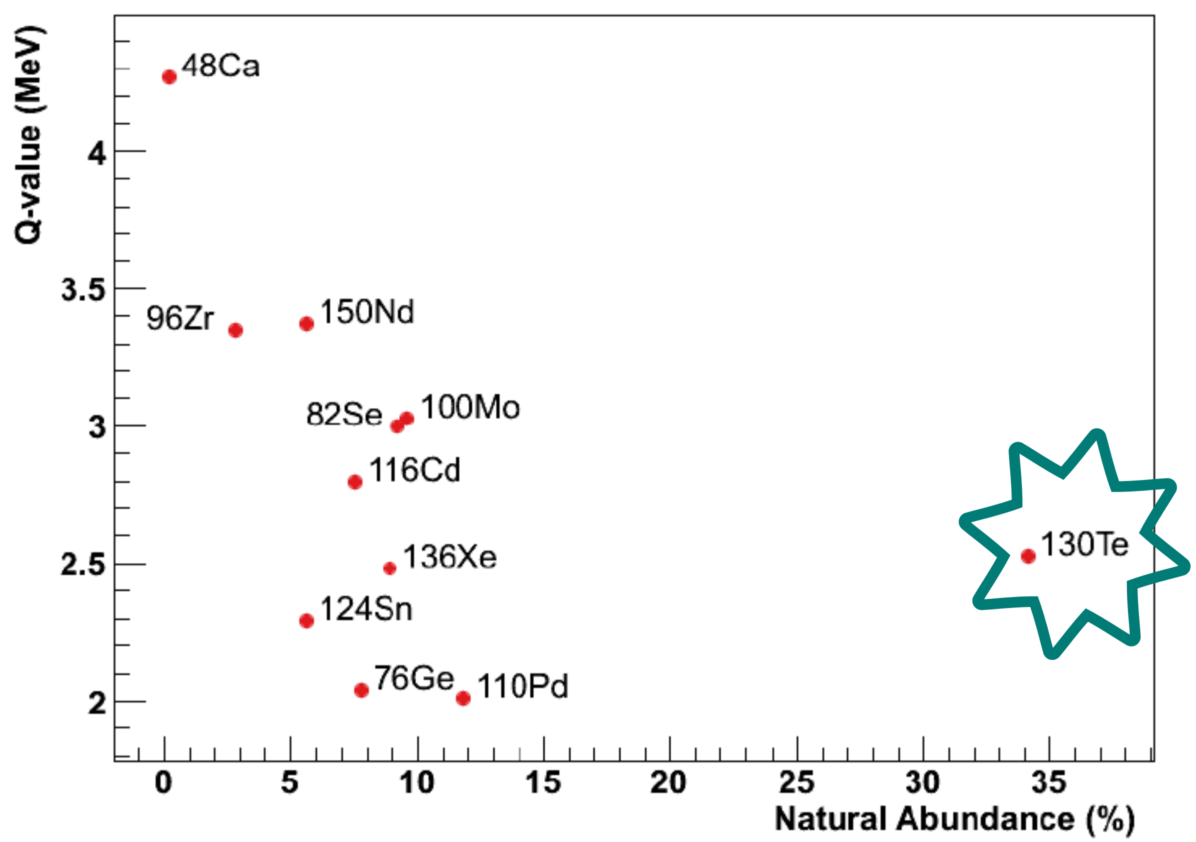
0νββ State of the Art





M. Agostini, Neutrinoless $\beta\beta$ Decay - Status & Prospects
XX International Workshop on Neutrino Telescopes, Venice

0νββ with SNO+



Major Advantages of Te

- No need for enrichment
- Long 2νßß half-life (7.9×10^{20} yrs)
- High Q-value of 2.5 MeV

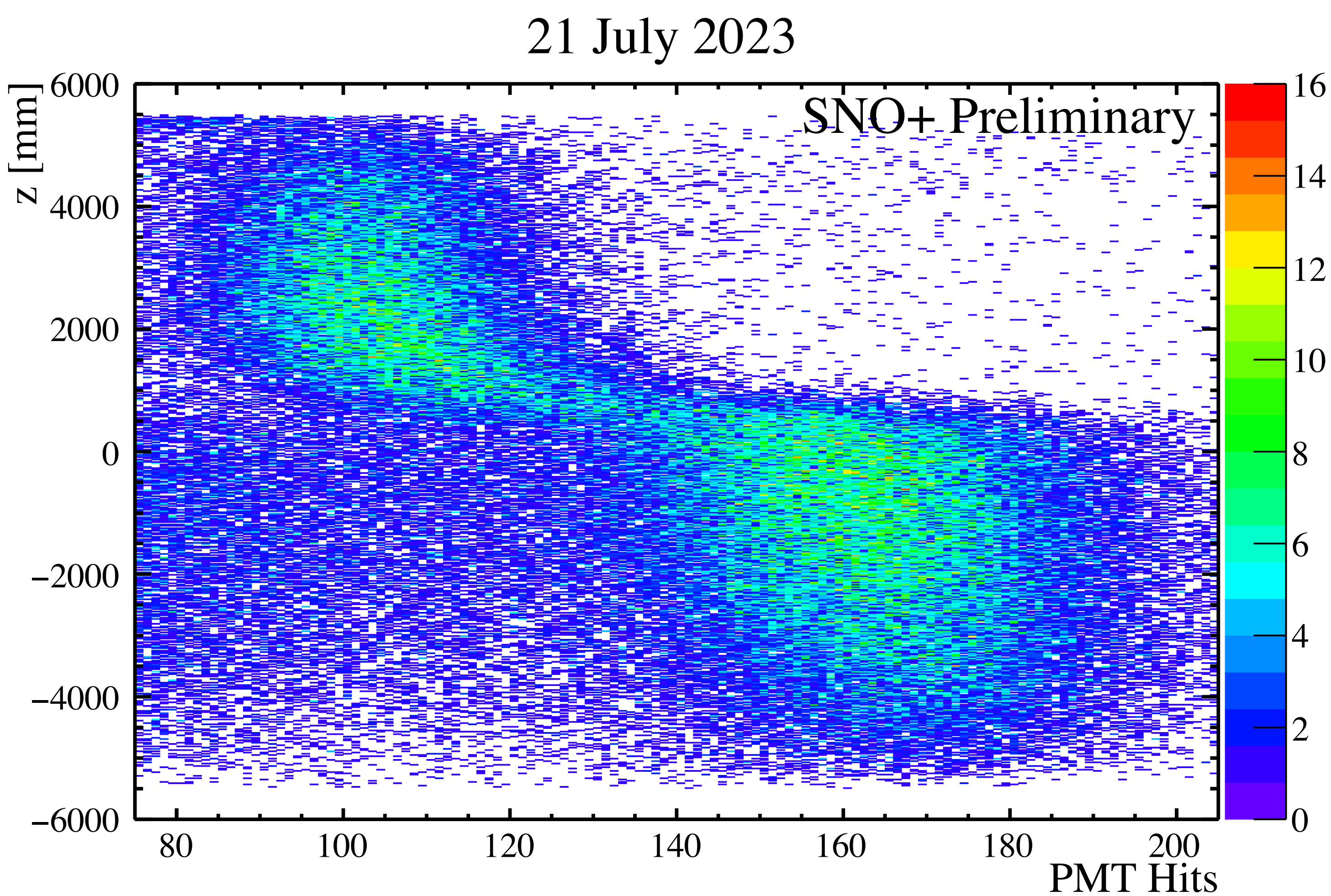
Major Advantages of SNO+

- 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+ BisMSB

2017 2018 2019 2020 2021 2022 2023 2024

July 2023
Started to add bisMSB to the detector

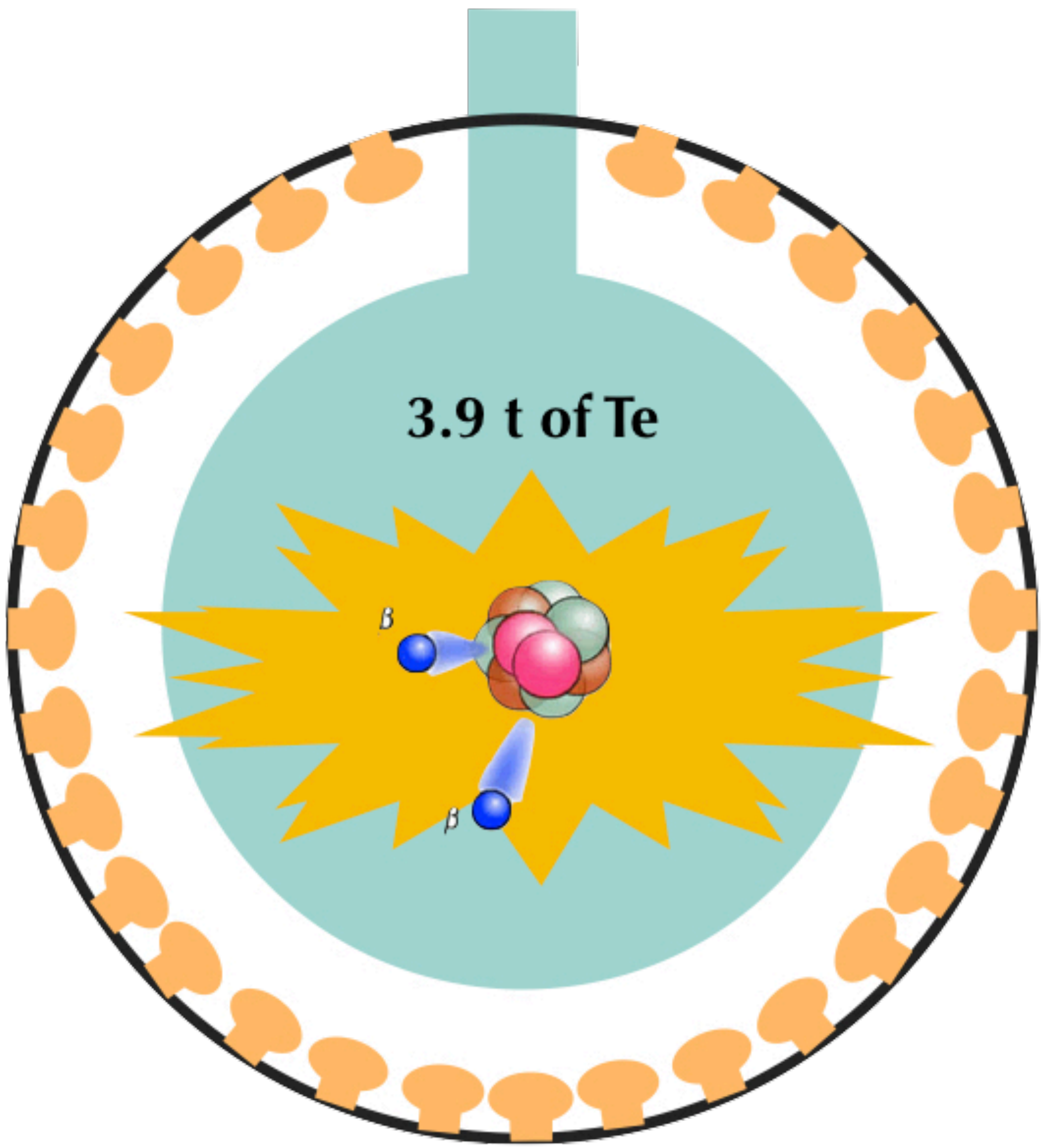


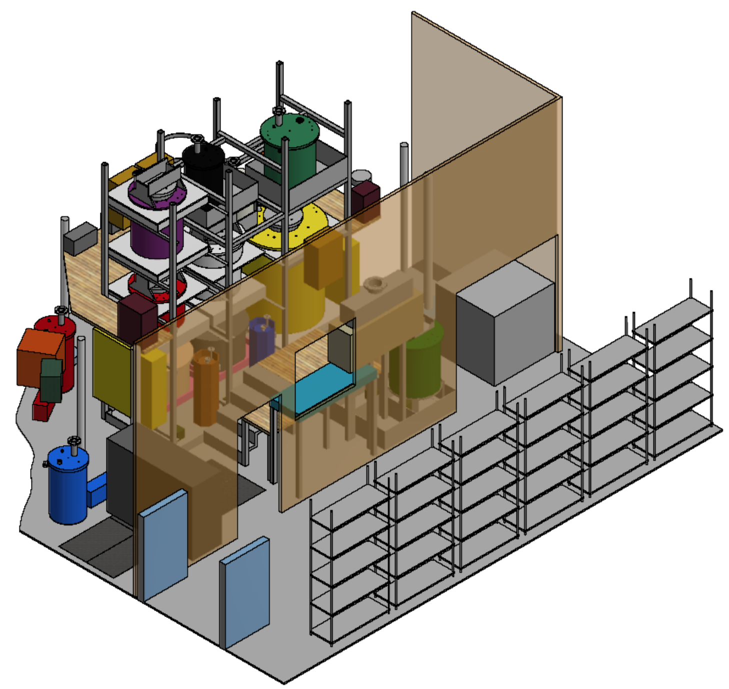
- Tracking ^{210}Po decays
- BisMSB added at the bottom of the detector (0.5 kg) and started to mix
- **Clear improvement (~1.5x) in light output**

SNO+ TeLS

2017 2018 2019 2020 2021 2022 2023 2024

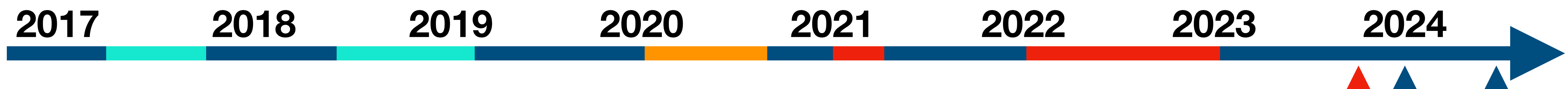
Early 2024
Test batch (~200 kg) of the TeA purification plant





- **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)

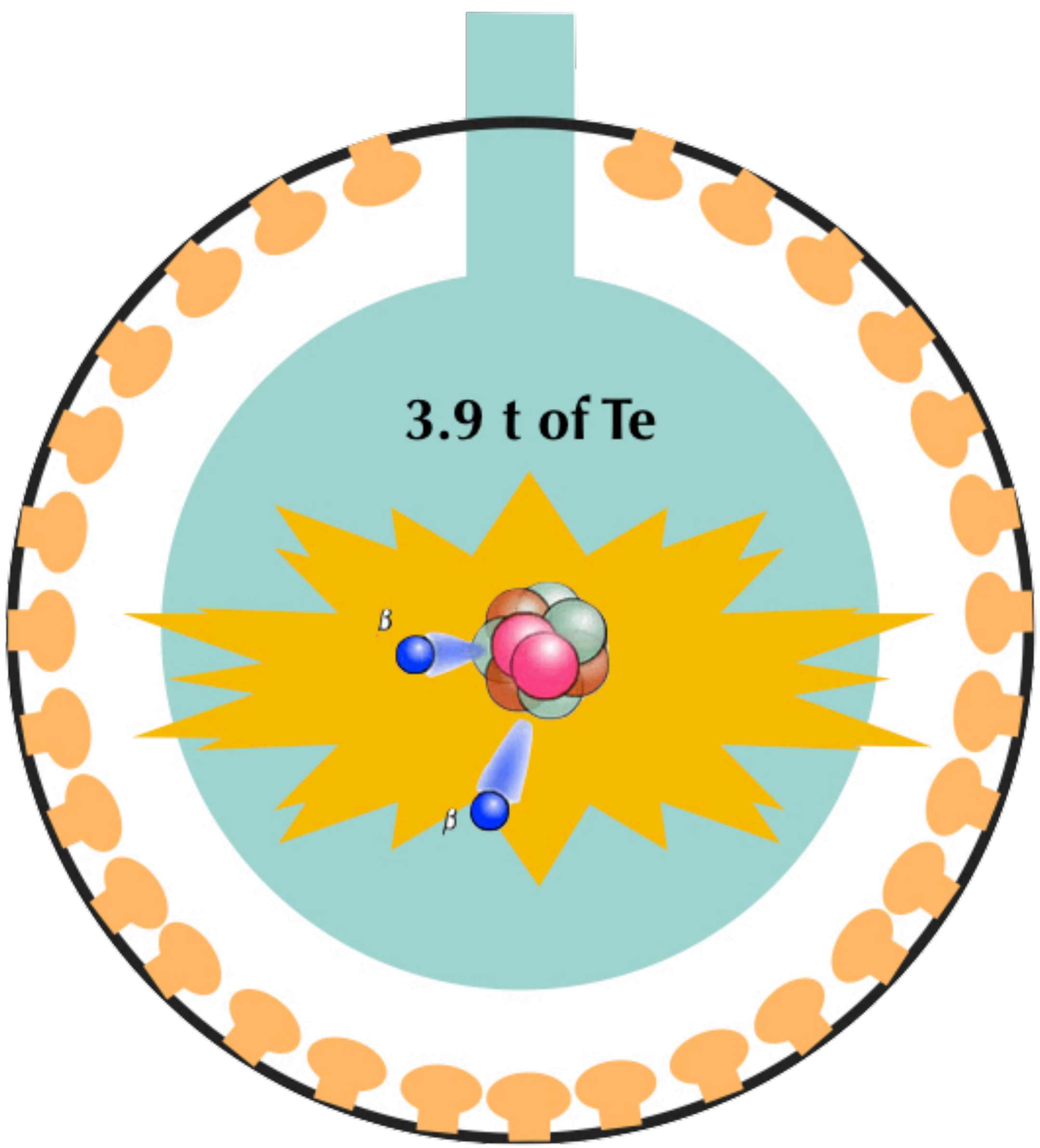
SNO+ TeLS

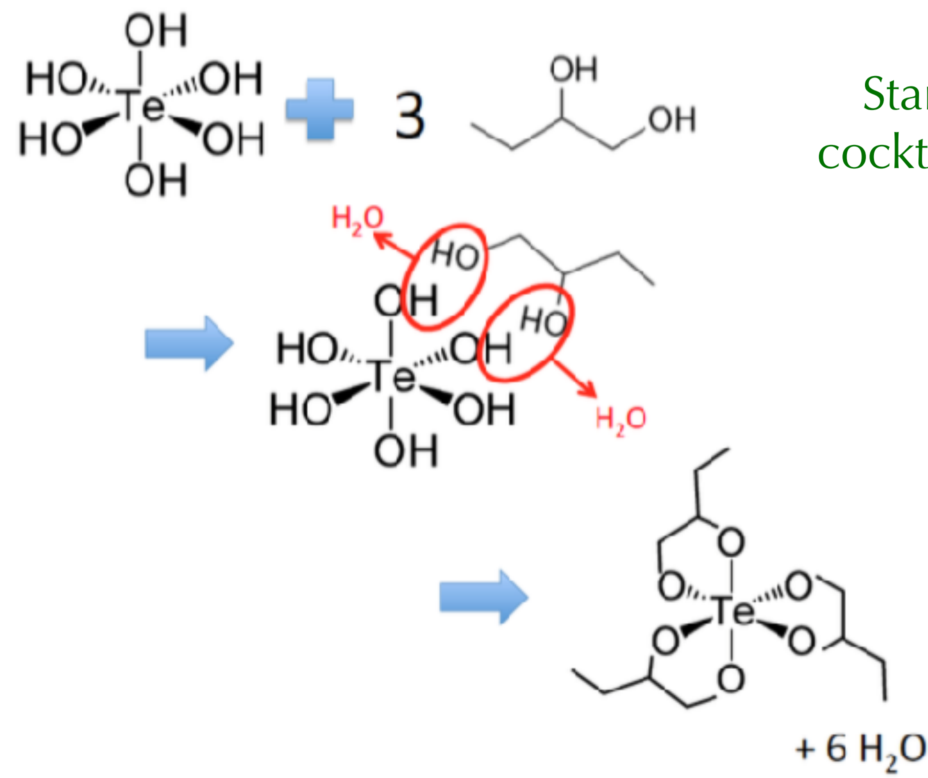


Early 2024
Test batch (~200 kg) of the TeA purification plant

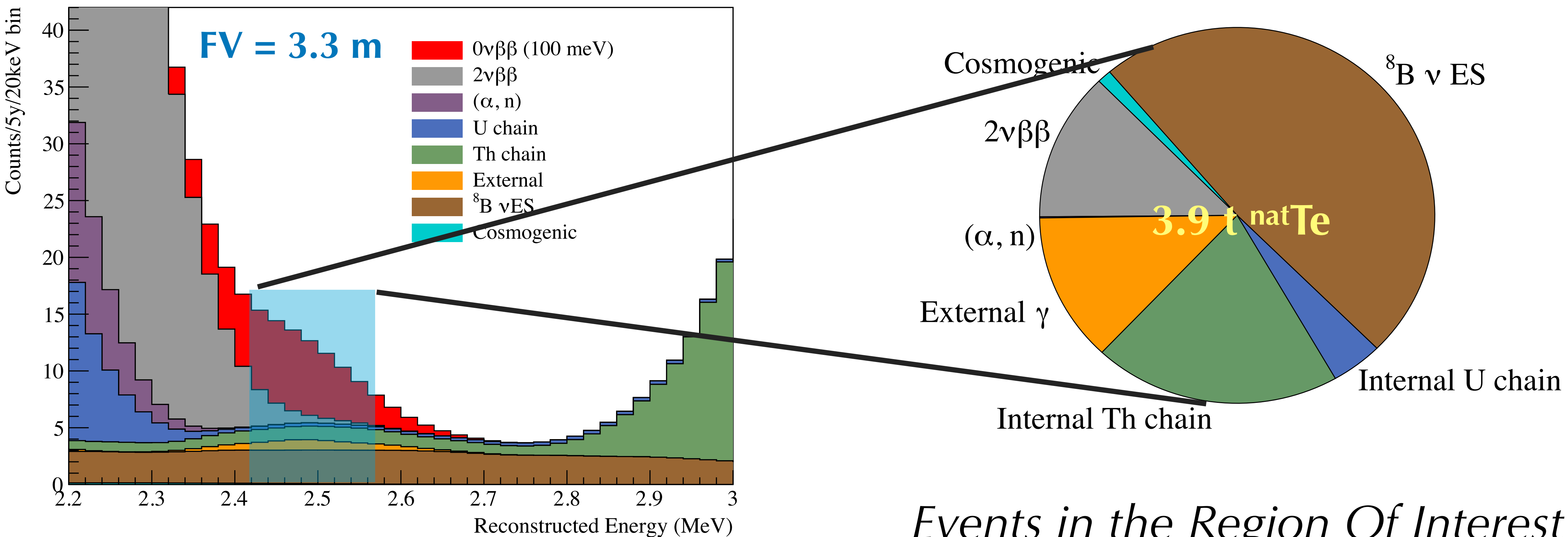
From 2024
Start to add TeLS cocktail components

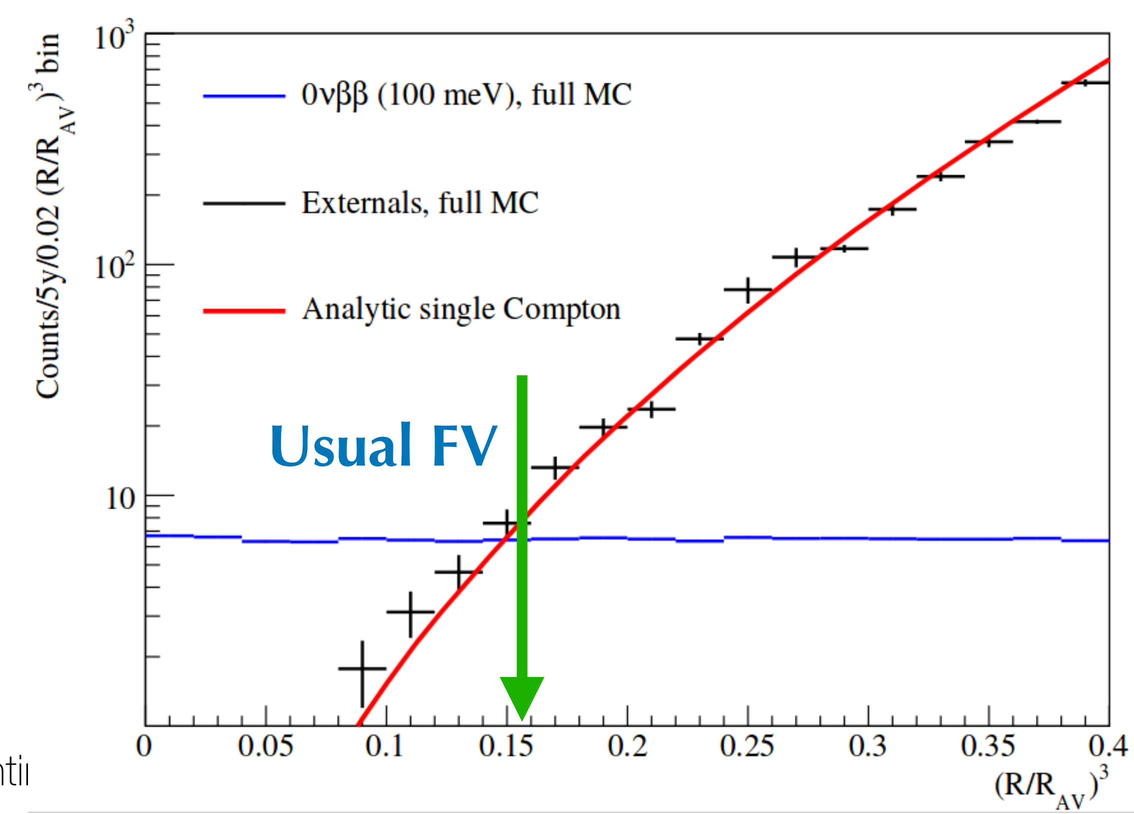
From 2025
Start count with Te





Expected Signal/Background



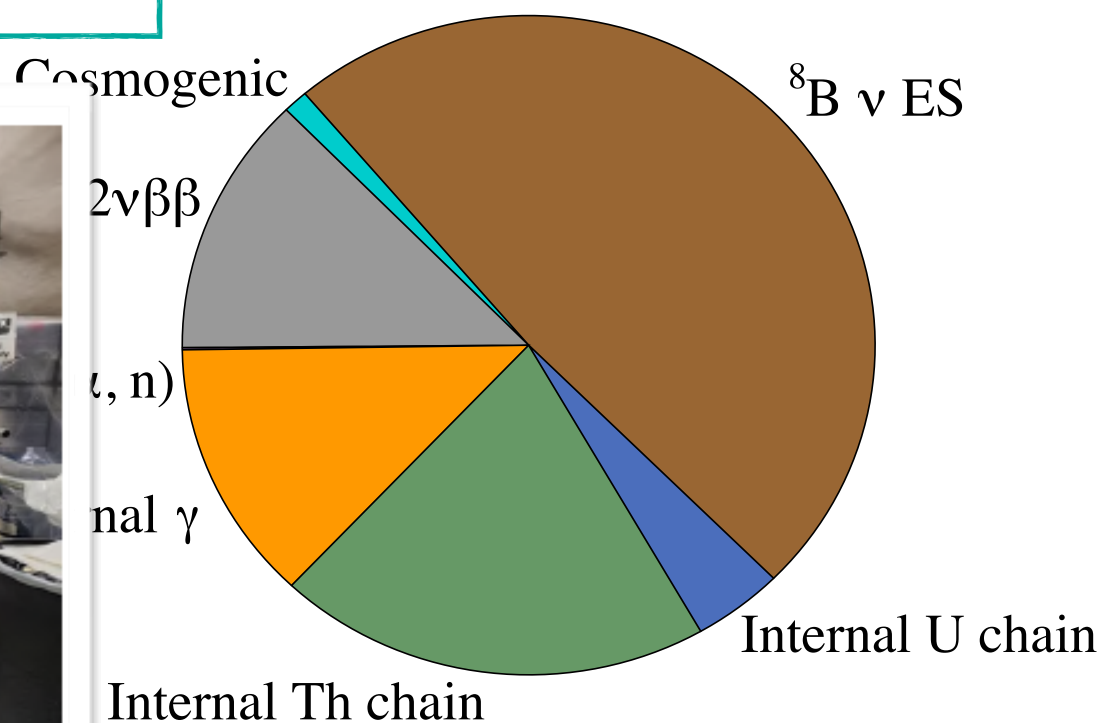


Events in the Region Of Interest + Fiducial Volume

9.47 events/yr (at nominal backgrounds)

Cosmogenic + solar-ν induced:
- ^{60}Co, ^{110m}Ag, ^{88}Y, ^{22}Na, ^{130}I
- mitigation: purification + "cool-down" UG
- First Te UG since 2015
- multi-site classifier

Background breakdown in 0νββ ROI



TeA cooling UG since 2015

Mitigation Strategies

Cosmogenic + solar-ν induced:
- ^{60}Co, ^{110m}Ag, ^{88}Y, ^{22}Na. ^{130}I
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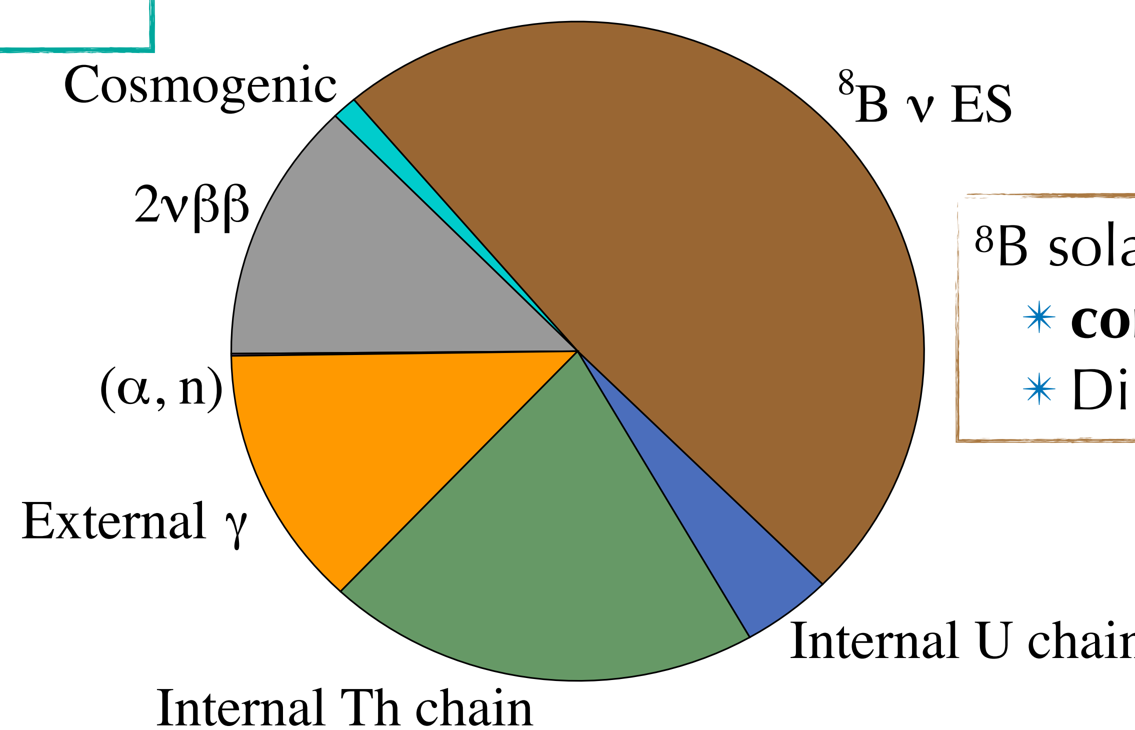

^{8}B solar neutrinos:
- **constrained by SNO/SK data**
- Directionality?

Mitigation Strategies

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- ^{60}Co, ^{110m}Ag, ^{88}Y, ^{22}Na. ^{130}I
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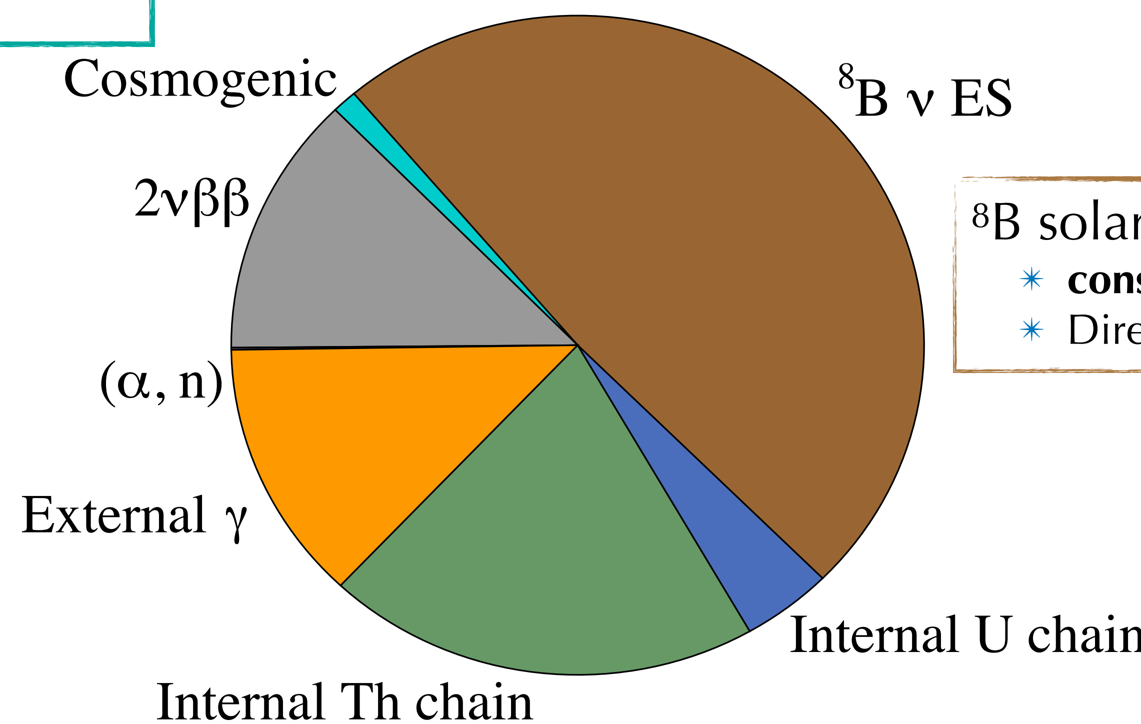

^{8}B solar neutrinos:
- **constrained by SNO/SK data**
- Directionality?

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

Cosmogenic + solar-ν induced:
- ^{60}Co, ^{110m}Ag, ^{88}Y, ^{22}Na. ^{130}I
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- First Te UG since 2015
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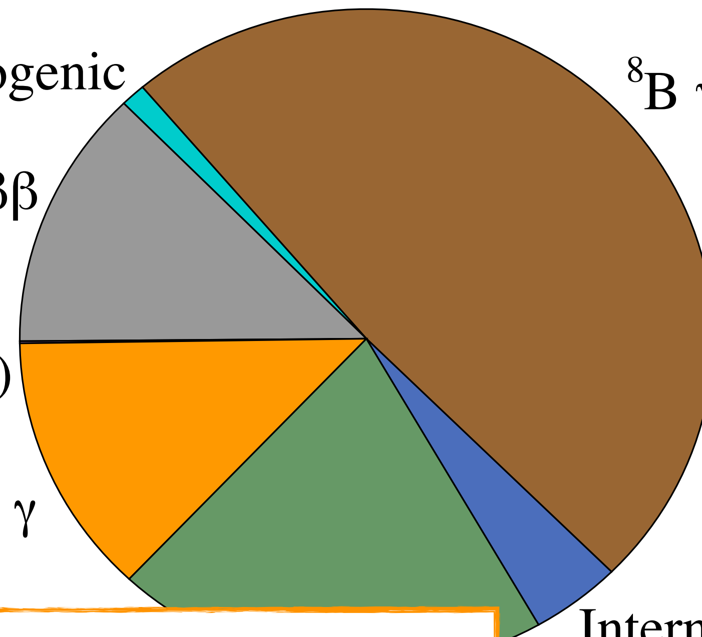

^{8}B solar neutrinos:
- **constrained by SNO/SK data**
- Directionality?

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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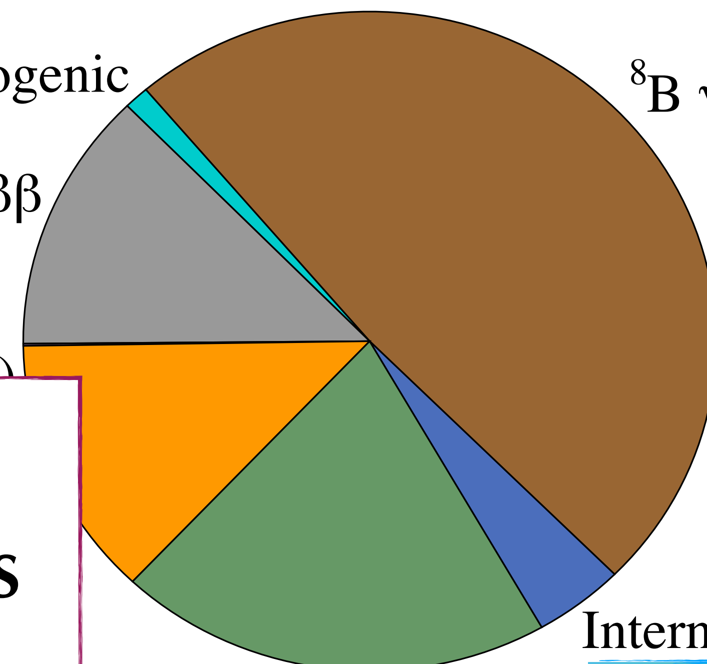
- First Te UG since 2015
- multi-site classifier

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



^{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

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

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

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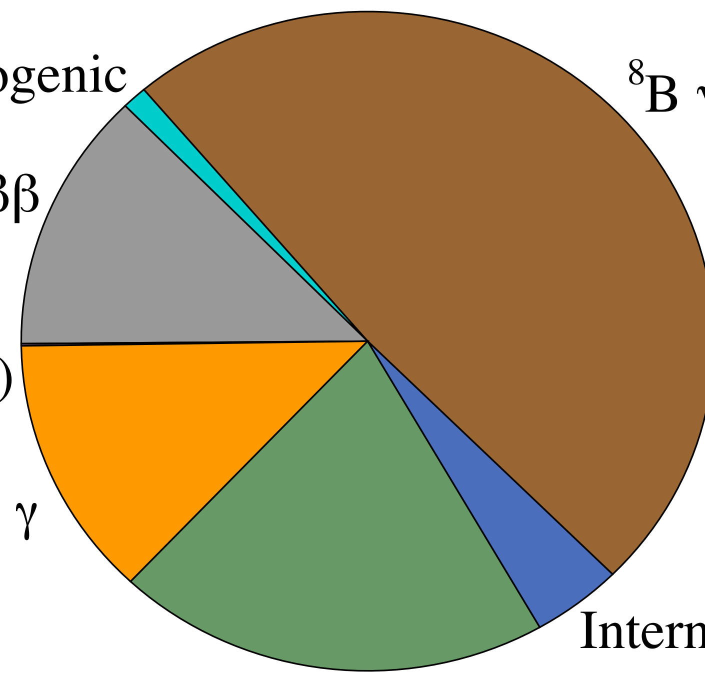

(a,n):
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- delayed coincidence tagging

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

External gammas:
- from AV, ropes, water, PMTs
- **Measured in water phase, below expectation**
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Internal U/Th chain:
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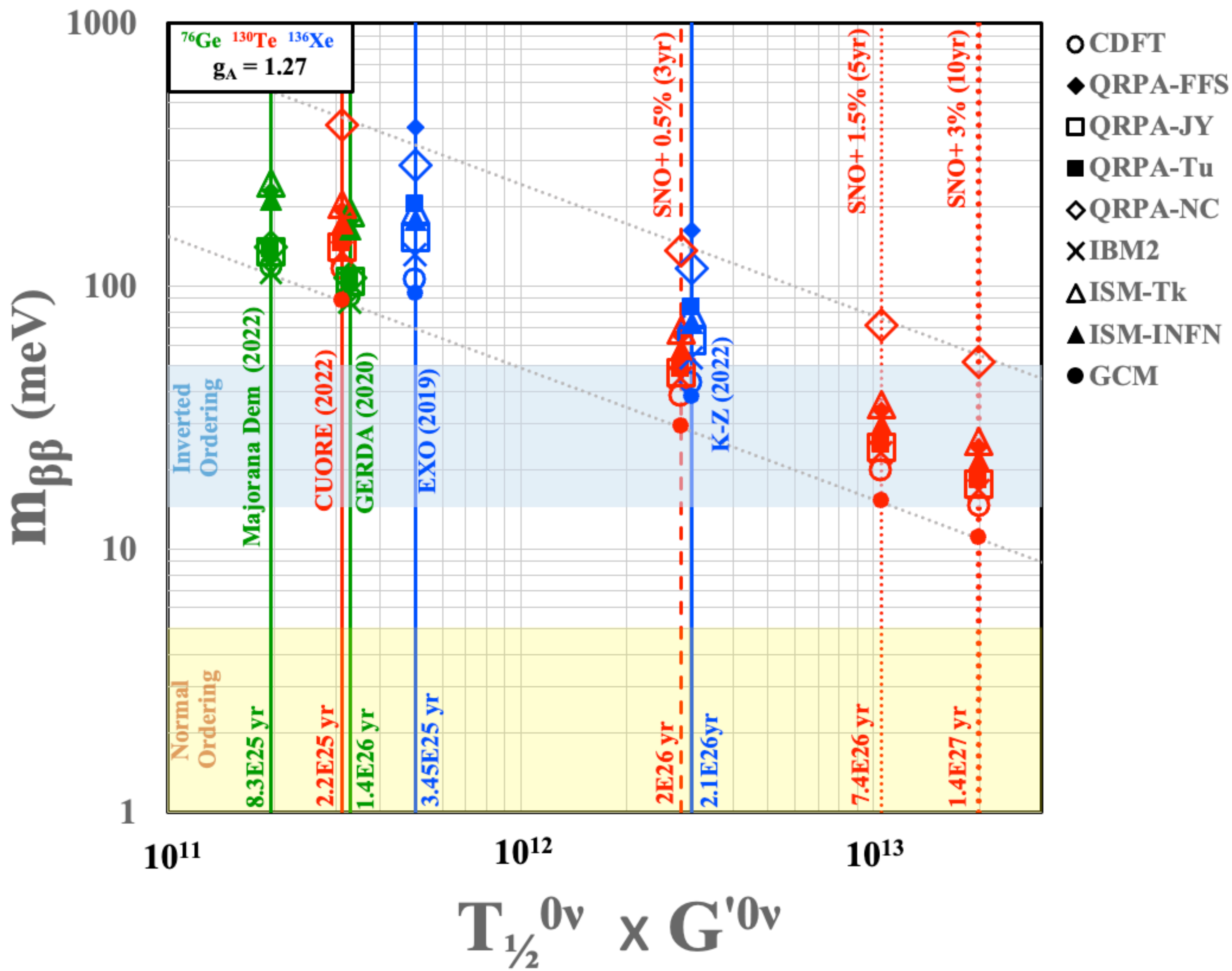
- **LAB components below target for the TeLS phase**
- **Constantly monitoring the contribution from the scintillator before adding Te**
- ß – α delayed coincidence tagging + in-window rejection

Optimised FV and ROI	$T_{1/2}$ [yr]	$m_{0\nu\beta\beta}$ [meV]
0.5% Te, 3 yr	2×10^{26}	37 - 89



^{76}Ge ^{130}Te ^{136}Xe
g_A = 1.27
1000
100
10
1
$m_{\beta\beta}$ (meV)
10^{11}
10^{12}
10^{13}
$T_{1/2}^{0\nu}$ x $G'^{0\nu}$
Inverted Ordering
Normal Ordering
Majorana Dem (2022)
CUORE (2022)
GERDA (2020)
EXO (2019)
SNO+ 0.5% (3yr)
K-Z (2022)
SNO+ 1.5% (5yr)
SNO+ 3% (10yr)
8.3E25 yr
2.2E25 yr
1.4E26 yr
3.45E25 yr
2E26 yr
2.1E26yr
7.4E26 yr
1.4E27 yr
CDFT
QRPA-FFS
QRPA-JY
QRPA-Tu
QRPA-NC
IBM2
ISM-Tk
ISM-INFN
GCM

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

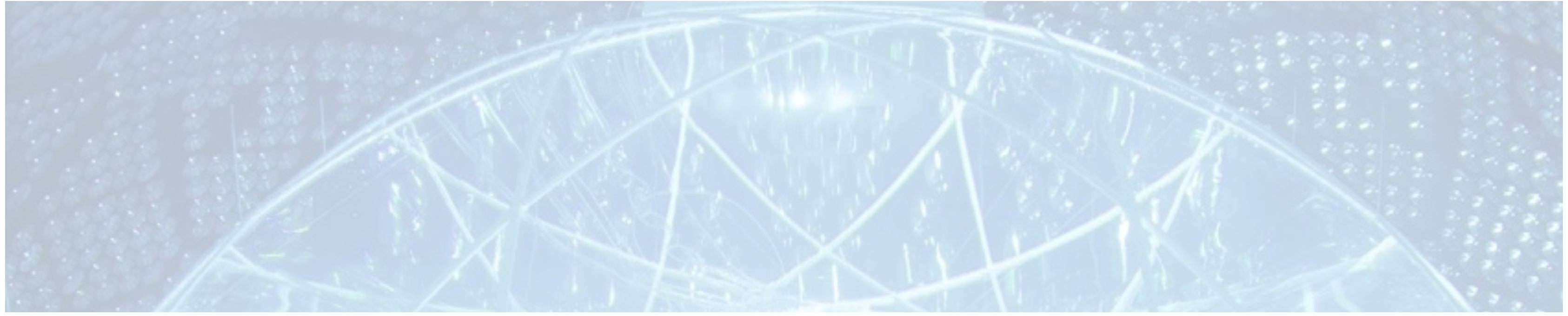
TU Dresden

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

- 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