SNO+ experiment: Search for $0\nu\beta\beta$

Ziping Ye
University of Pennsylvania
2023-12-05 @ TAU2023

Content

- $0\nu\beta\beta$
- SNO+ experiment

What is $0\nu\beta\beta$?

Double beta decay

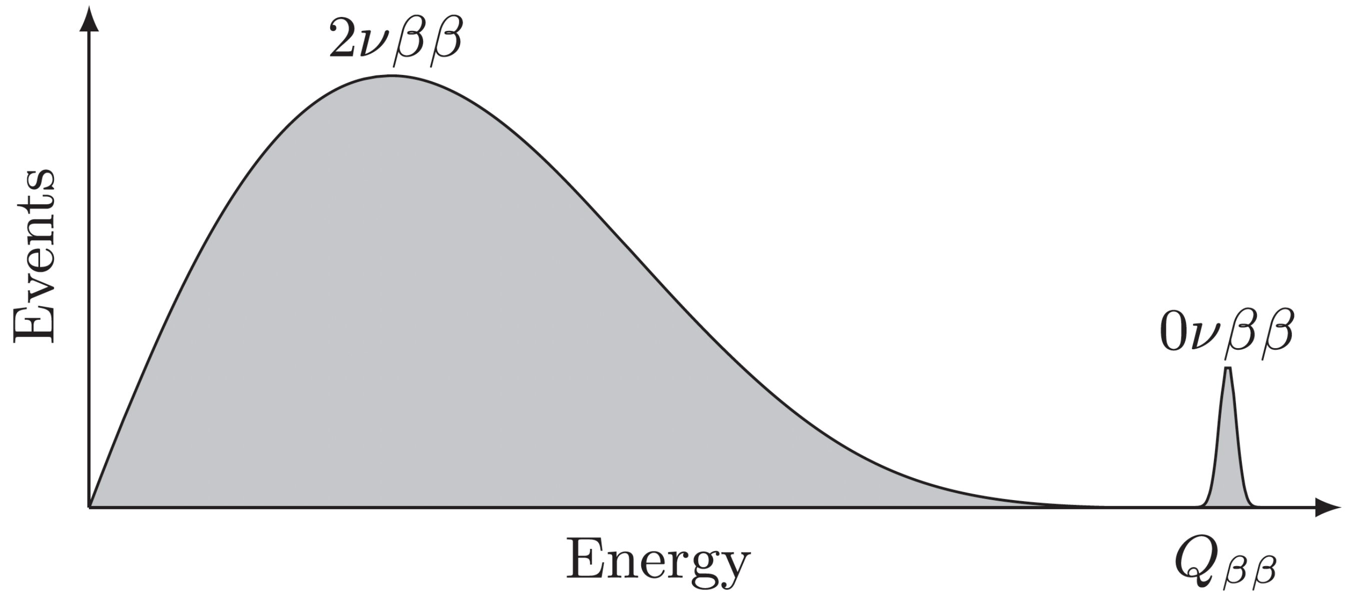
Some isotopes can $2\nu\beta\beta$ decay :

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\overline{\nu_e}$$

If neutrinos are Majorana particles, these isotopes can $0\nu\beta\beta$ decay :

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-}$$

Search for $0\nu\beta\beta$ by checking if there is a monoenergetic peak at $Q_{\beta\beta}$.



Why search for $0\nu\beta\beta$?

- L violation

  Leptogenesis: Lepton imbalance can be converted to baryon imbalance, creating matter-antimatter imbalance in the Universe.

- $B - L$ violation

  Physics beyond the Standard Model

- Neutrino mass

  Measure effective Majorana neutrino mass
  Determine/constrain masses of all neutrino mass eigenstates
  Probe the physics (energy scale and mechanism) for neutrino mass generation

- Majorana neutrinos : a bridge between matter and antimatter

$0\nu\beta\beta$ isotope half-life

The half-life of $0\nu\beta\beta$ isotopes can be given (light neutrino exchange model) by

$$T_{1/2}^{0\nu} = \left(G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2\right)^{-1} \approx 10^{27-29}\left(\frac{0.01\ eV}{\langle m_{\beta\beta}\rangle}\right)^2\ years$$

Phase-space factor : $G^{0\nu} \propto Q_{\beta\beta}^5$

Nuclear matrix element (NME) : $|M^{0\nu}|^2$

Effective Majorana neutrino mass : $\langle m_{\beta\beta}\rangle = \left|\sum_j |U_{ej}^2| e^{i\varphi_j} m_j\right|$

Choosing an isotope with higher $Q_{\beta\beta}$ is beneficial:

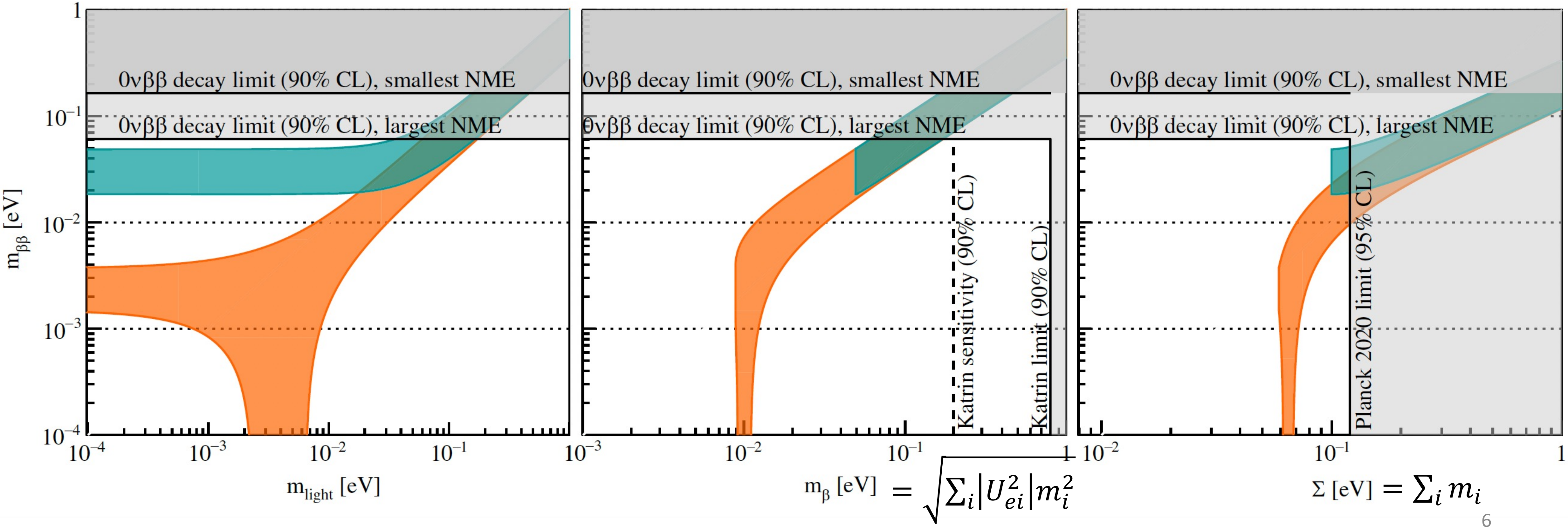
(1) Larger decay rate; (2) Less backgrounds.

Though the isotope abundance and feasible detector technology need to be considered.

Effective Majorana neutrino mass

A sensitivity of $\langle m_{\beta\beta} \rangle \sim 18\ meV$ ($1\ meV$) is needed to probe the entire (most) parameter space allowed by inverted (normal) mass ordering, corresponding to $T^{0\nu}_{1/2} \sim 10^{27}\ years$ ($10^{29}\ years$).

Most next-gen $0\nu\beta\beta$ experiments aim at probing the inverted ordering parameter space.



M. Agostini, G. Benato, J. A. Detwiler, J. Menendez, F. Vissani. Rev. Mod. Phys. 2023.

Experiment sensitivity

The number of observed $0\nu\beta\beta$ events is $N_s = \frac{Ma}{m} \cdot t \cdot \frac{ln2}{T_{1/2}^{0\nu}} \cdot \varepsilon$

M : total mass of the element

m : atomic mass of the $0\nu\beta\beta$ isotope

$T_{1/2}^{0\nu}$: $0\nu\beta\beta$ isotope half-life

a : abundance of the $0\nu\beta\beta$ isotope

t : experiment time

ε : detection efficiency

For experiments with background, of level ~ $B\ events/(ton \cdot year \cdot keV)$, the number of background events is $N_b \sim B \cdot M \cdot t \cdot \Delta E$, and it requires $N_s \geq 3\sqrt{N_b}$ to claim a 3σ discovery, so the discovery sensitivity is $T_{1/2}^{0\nu} \sim \frac{ln2}{3} \frac{a\ \varepsilon}{m} \sqrt{\frac{M\ t}{B\ \Delta E}}$.

SNO+ experiment design strategy

- Large mass
  SNO+ : ~ 780 tons liquid scintillator detector

- High abundance
  SNO+ : Te130 abundance ~ 34.1%

- High Q-value
  SNO+ : Te130 Q-value ~ 2.53 MeV

- Low background
  SNO+ : Deep underground, radiopure LS, shielding, background reduction methods, etc.

- Good energy resolution
  SNO+ : Bright liquid scintillator (LS), ~ 400 PE / MeV

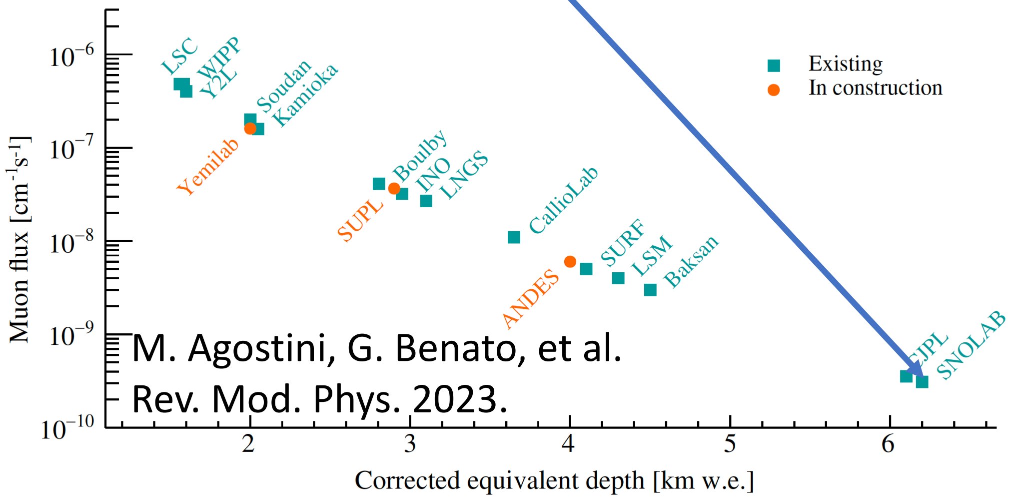
- Good detection efficiency
  SNO+ : Efficiency lost mainly due to fiducial volume cut and energy ROI cut.
  Reject external backgrounds with higher efficiency to get a larger fiducial volume.

SNO+ detector

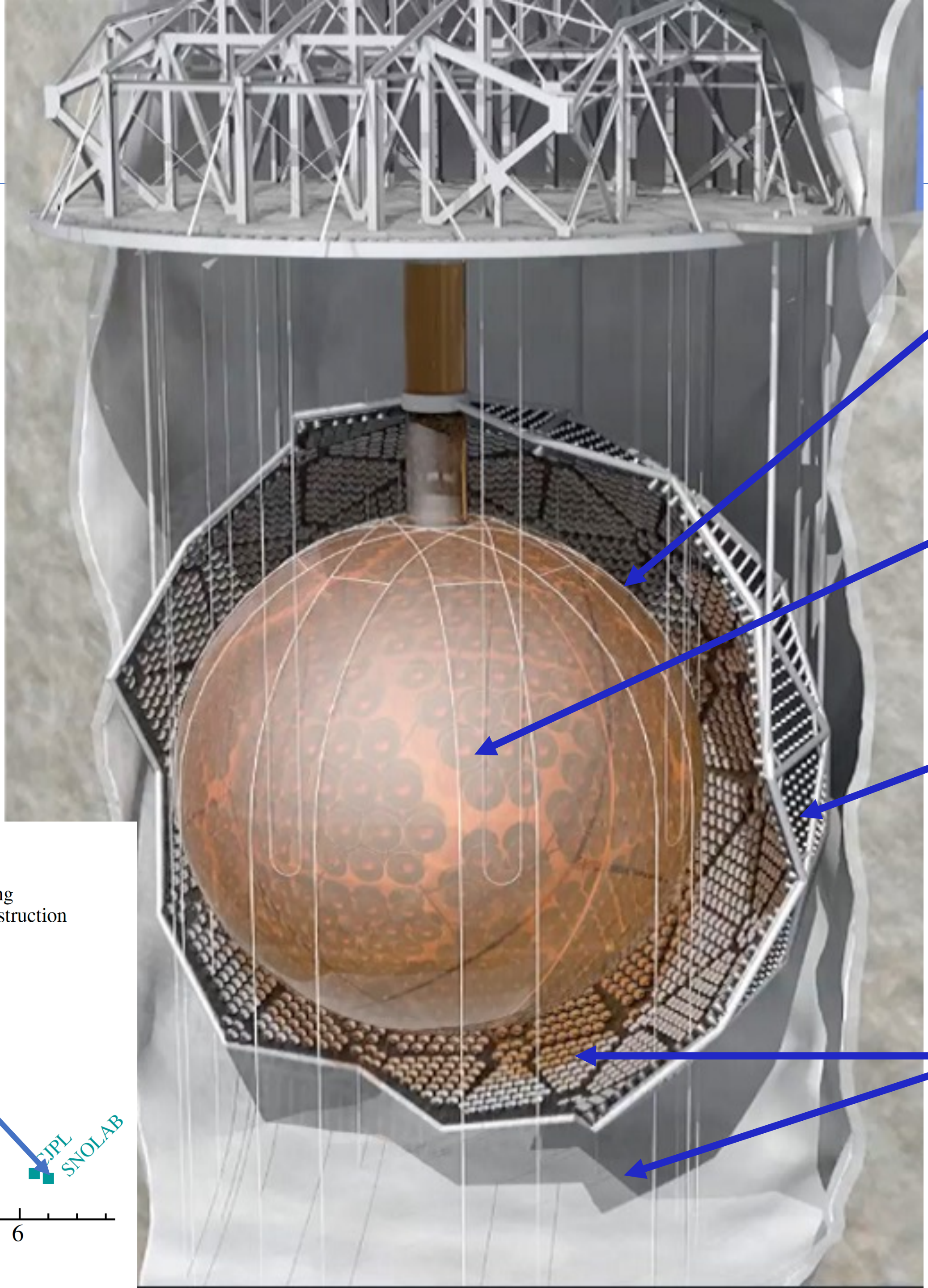
~ 2100 m underground
at SNOLAB, Canada

Deepest underground lab
~ 6000 m.w.e. overburden

Muon rate ~ $0.27\ \mu\ /\ m^2\ /\ day$



M. Agostini, G. Benato, et al.
Rev. Mod. Phys. 2023.



12 m diameter
acrylic sphere

780 tonnes LAB-based
liquid scintillator

9400 PMTs at R ~ 9 m

90 PMTs facing
outward for muon veto

7000 tonnes
ultrapure water

SNO+ water phase

SNO+ water phase (2017 – 2019)

1. PMTs calibration
   (2015 *JINST* **10** P03002)

2. Detector optics calibration
   (2021 JINST 16 P10021)

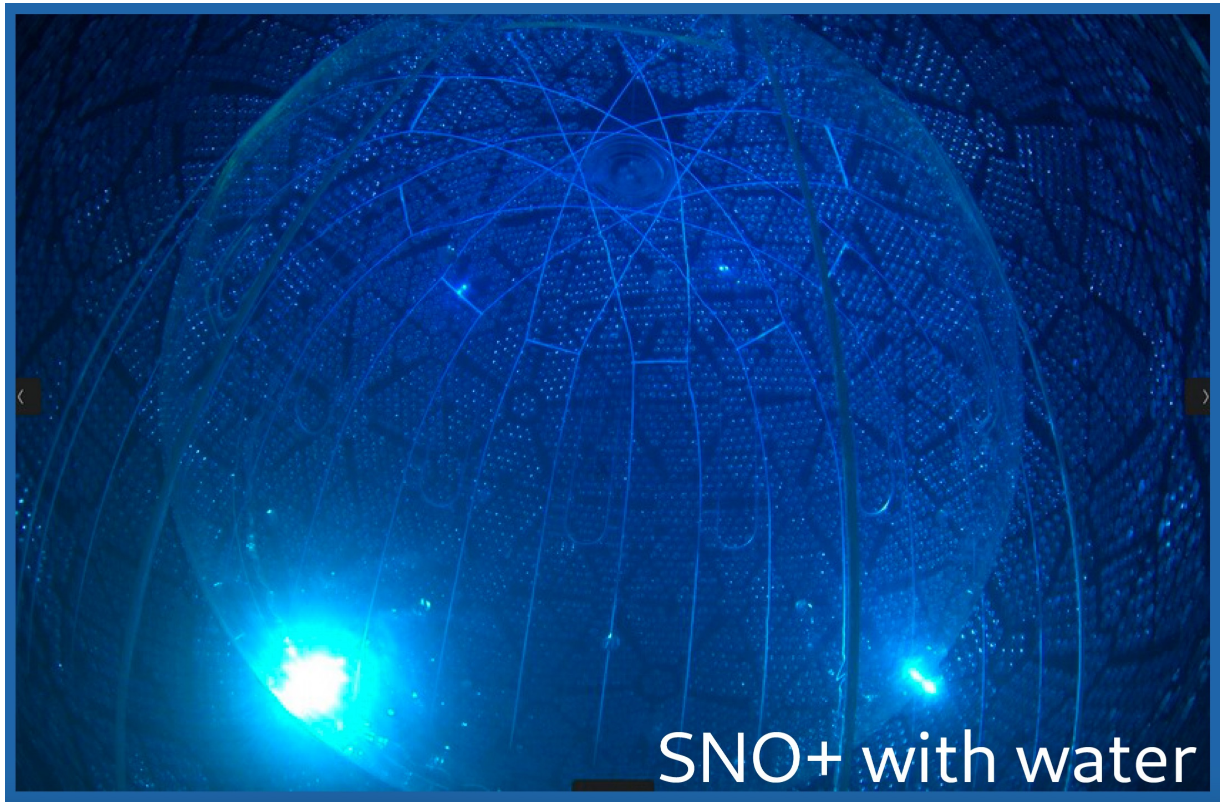
3. Measure external backgrounds
   Identify sources with directionality

4. First detection of reactor neutrinos in water
   (2023 Phys. Rev. Lett. **130**, 091801)

5. World-leading limits on invisible nucleon decay
   (2022 Phys. Rev. D **105**, 112012)

6. Measurement of solar B8 neutrinos
   (2019 Phys. Rev. D **99**, 012012)

7. Highest efficiency measurement of neutron capture on proton in water detector
   (2020 Phys. Rev. C **102**, 014002)



SNO+ partial fill

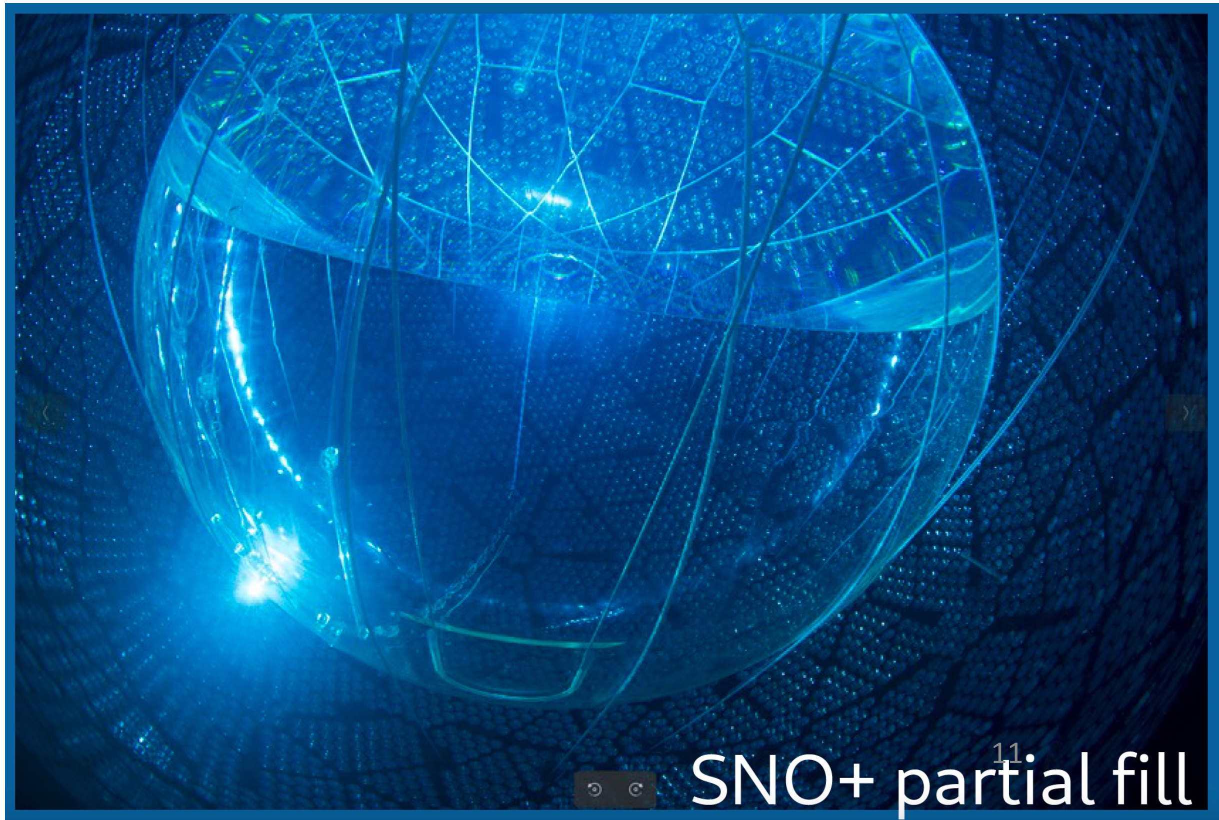
SNO+ was partially filled with LS (LAB + 0.6 g/L PPO) for ~ 2 years (2019 – 2021) due to the pandemic

1. Directionality of solar B8 neutrinos in LS detector
   Separation of Cherenkov light from scintillation light
   (2023 arXiv:2309.06341)

2. Detection of reactor neutrinos
   (paper in preparation)

3. Measurement of solar neutrinos

4. Measure detector backgrounds



SNO+ liquid scintillator phase

SNO+ fully filled with LS (2021 - now)

(1) LAB + 0.6 g/L PPO
(2) LAB + 2.2 g/L PPO
(3) LAB + 2.2 g/L PPO + bisMSB

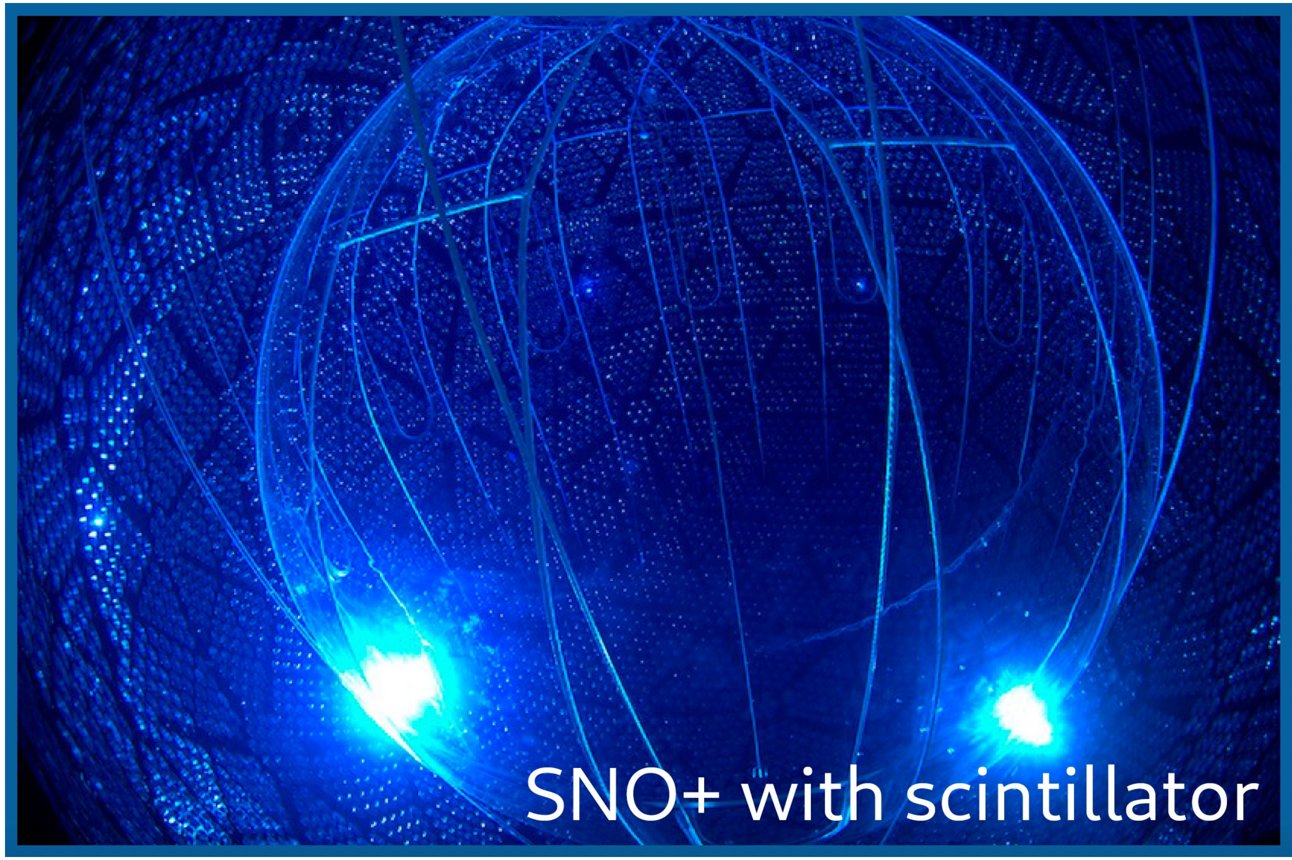
1. Constrain backgrounds for $0\nu\beta\beta$ search
   (1) internal radioactivity of non-Te
   (2) external radioactivity
   (3) cosmogenic backgrounds of non-Te
   (4) solar neutrino backgrounds

2. Characterization of LS energy & optics

3. Reactor neutrinos

4. Geo-neutrinos

5. Solar neutrinos



Bis-MSB was added to the LS recently, and the light yield has increased by $\gtrsim$ 60% .

SNO+ Te phase

Te will be loaded into SNO+ LS in 2025.

The Te has been stored underground since 2015
to reduce the backgrounds due to neutron activation.

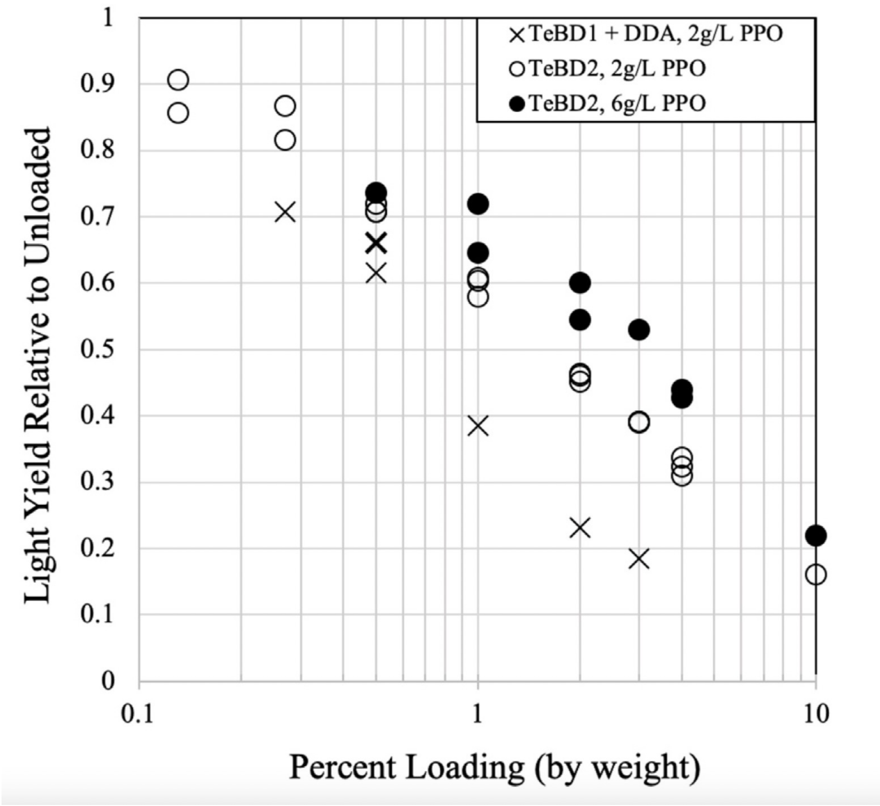
Scintillator, TeA, TeBD purification plants underground

$0\nu\beta\beta$ signals

The sensitivity is $T_{1/2}^{0\nu} \propto \frac{a\,\varepsilon}{m}\sqrt{\frac{M\,t}{B\,\Delta E}}$.

A method of loading Te into LS at several percent level is developed.

Loading percentage	Te mass [ton]	Te130 mass [ton]
0.5%	3.9	1.33
1.5%	11.7	3.99
2.5%	19.5	6.65



D.J. Auty, D. Bartlett, S.D. Biller, et al. 2023 NIMA.

The light yield of 2.5% loading is ~ 50% of that of unloaded.

(1) Low radioactive backgrounds thanks to distillable chemicals
(2) Good light yield
(3) Small optical absorption
(4) Chemical stability

Backgrounds

Backgrounds:

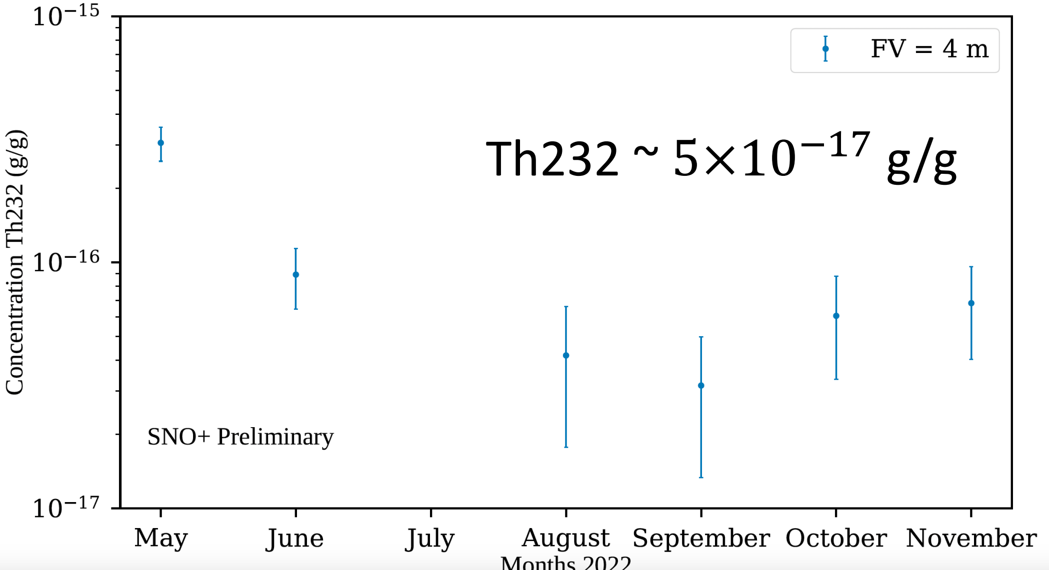
1. Internal radioactivity
2. External radioactivity
3. Cosmogenic backgrounds
4. Te impurity
5. Cosmic activation isotopes
6. Solar neutrinos
7. $2\nu\beta\beta$

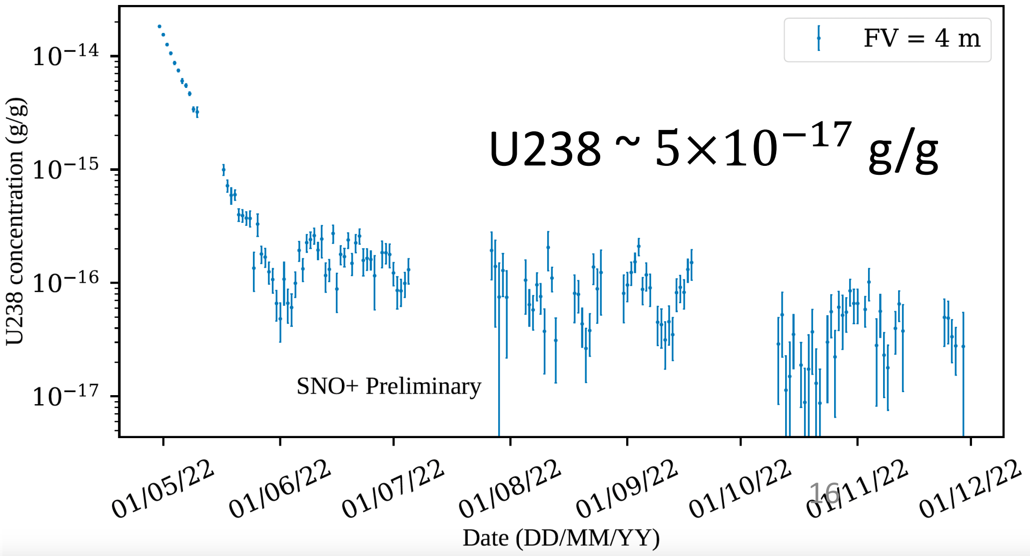
Backgrounds

Backgrounds:

1. Internal radioactivity
2. External radioactivity
3. Cosmogenic backgrounds
4. Te impurity
5. Cosmic acti
6. Solar neutri
7. $2\nu\beta\beta$

- LS purification
- Suppress Rn ingress
- Measure U/Th activities in LS phase, constrained background levels for $0\nu\beta\beta$ analysis
- Coincidence tagging and pile-up classifier to reject BiPos
- Multi-sites classifier to reject γ backgrounds



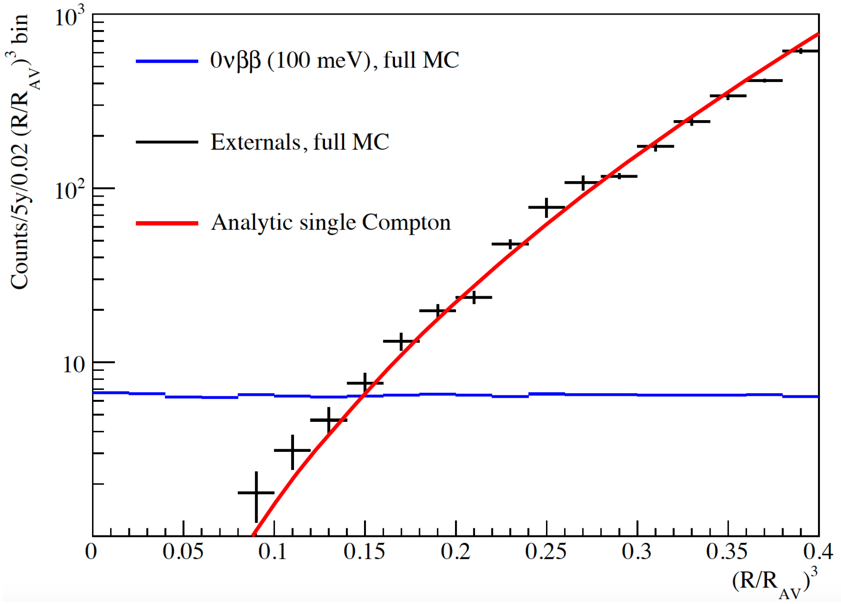


Backgrounds

Backgrounds:

1. Internal radioactivity
2. External radioactivity
3. Cosmogenic backgrounds
4. Te impurity
5. Cosmic activation isotopes
6. Solar neutrinos
7. $2\nu\beta\beta$

- Pure water shielding
- Fiducial cut
- Reject γ backgrounds with multi-sites classifier
- Reject neutrons by coincidence and energy
- Measure external backgrounds in water & LS phase



Backgrounds

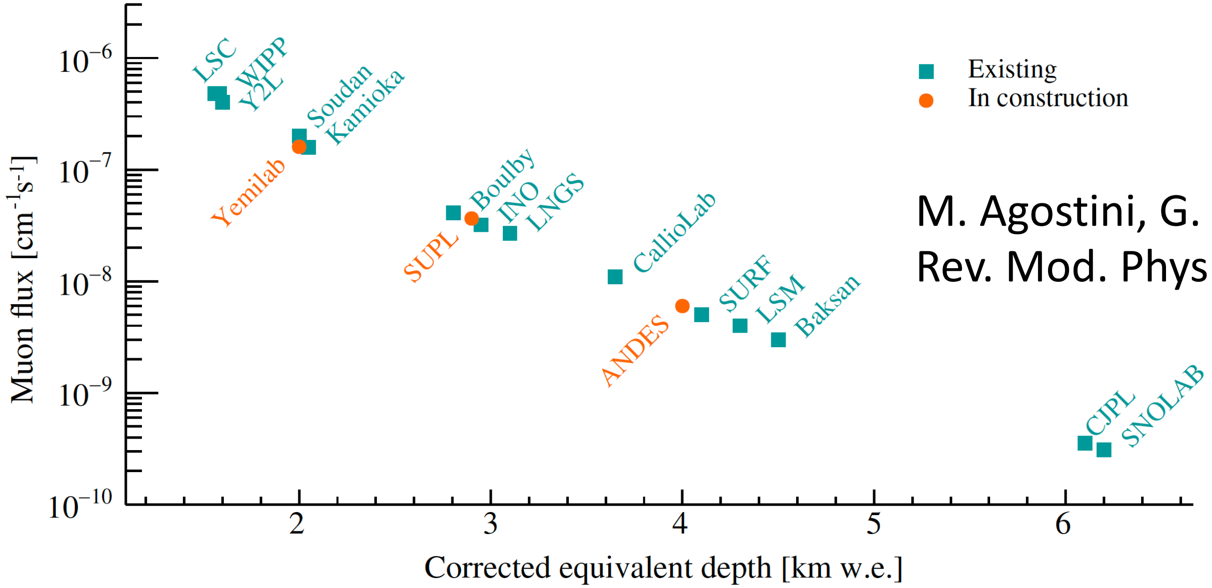
Backgrounds:

1. Internal radioactivity
2. External radioactivity
3. **Cosmogenic backgrounds**
4. Te impurity
5. Cosmic activation isotopes
6. Solar neutrinos
7. $2\nu\beta\beta$

Deep underground

Muon veto

Only ~ 3.0 μ / hour through a 18 m diameter circular area covering the detector: Reject ~ 1 min data after muons removes basically all cosmogenic backgrounds.



M. Agostini, G. Benato, et al. Rev. Mod. Phys. 2023.

Backgrounds

Backgrounds:

1. Internal radioactivity
2. External radioactivity
3. Cosmogenic backgrounds
4. Te impurity
5. Cosmic activation isotopes
6. Solar neutrinos
7. $2\nu\beta\beta$

Distillable chemicals are used to load Te in LS, allows purification.

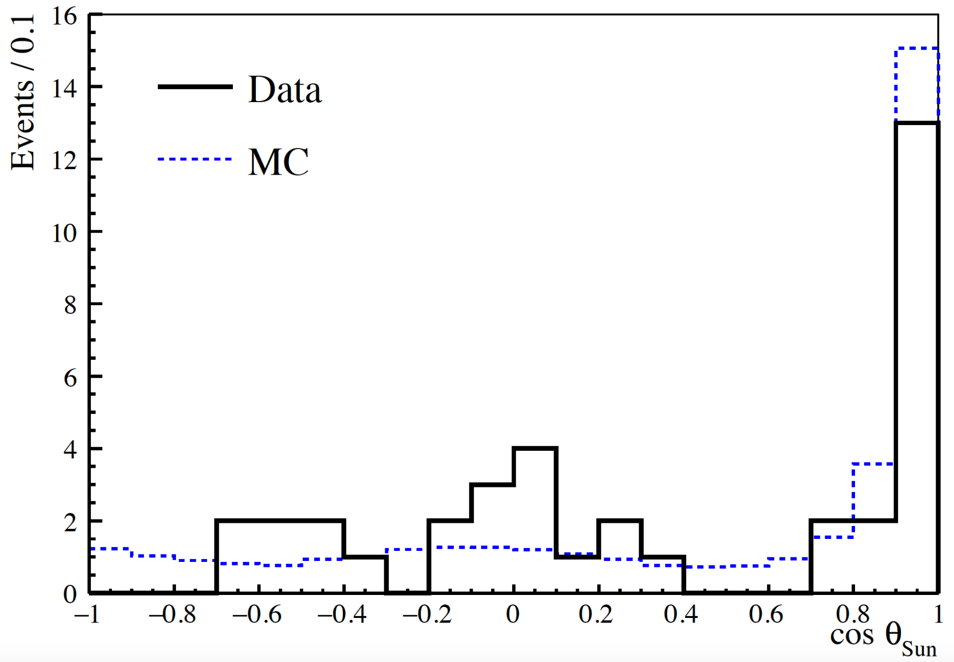
Te stored underground since 2015, to reduce activation backgrounds.

All techniques of rejecting internal radioactivity apply as well.

Backgrounds

Backgrounds:

1. Internal radioactivity
2. External radioactivity
3. Cosmogenic backgrounds
4. Te impurity
5. Cosmic activation isotopes
6. Solar neutrinos → Directionality ?
7. $2\nu\beta\beta$



Directionality of solar B8 neutrinos in SNO+ with LAB + 0.6 g/L PPO is achieved.

For LAB + 2.2 g/L PPO + bisMSB , still need to study.

Backgrounds

Backgrounds:

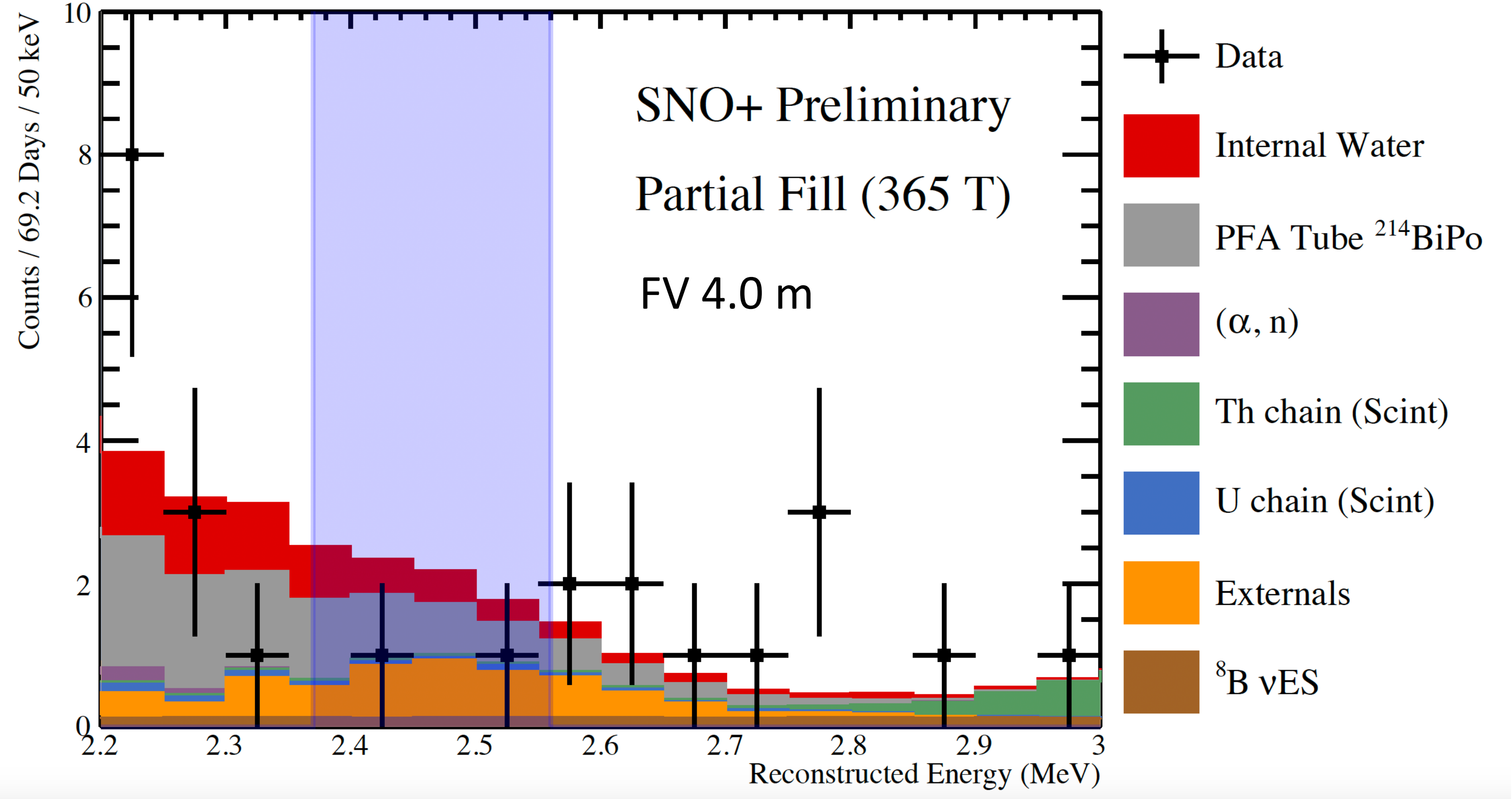
1. Internal radioactivity
2. External radioactivity
3. Cosmogenic backgrounds
4. Te impurity
5. Cosmic activation isotopes
6. Solar neutrinos
7. $2\nu\beta\beta$ → Irreducible

Ratio of $0\nu\beta\beta$ signal to $2\nu\beta\beta$ background

$$\frac{S_{0\nu}}{B_{2\nu}} \propto \left(\frac{Q_{\beta\beta}}{\Delta E}\right)^6 \cdot \frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$

Energy resolution is important.

Backgrounds

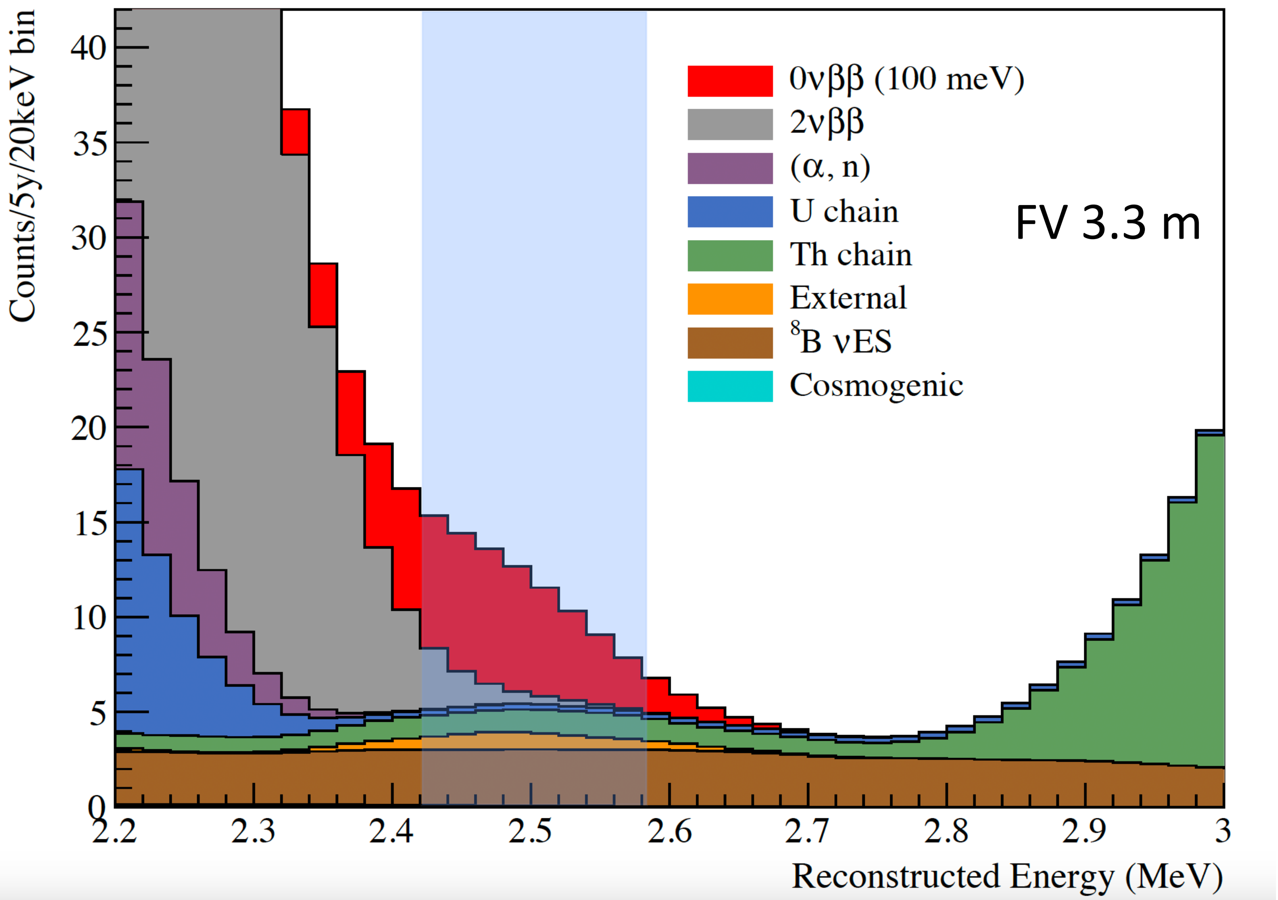


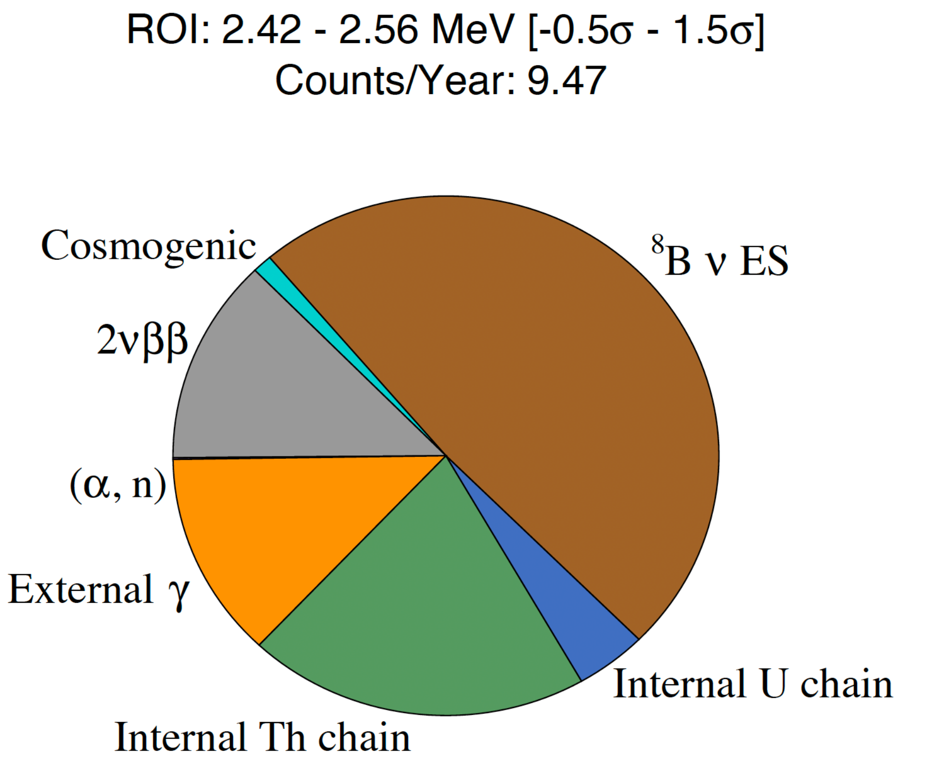
Measurement of backgrounds in partial fill

8 expected, 2 observed in $0\nu\beta\beta$ ROI

Measurement of backgrounds in full fill LS is ongoing

Backgrounds





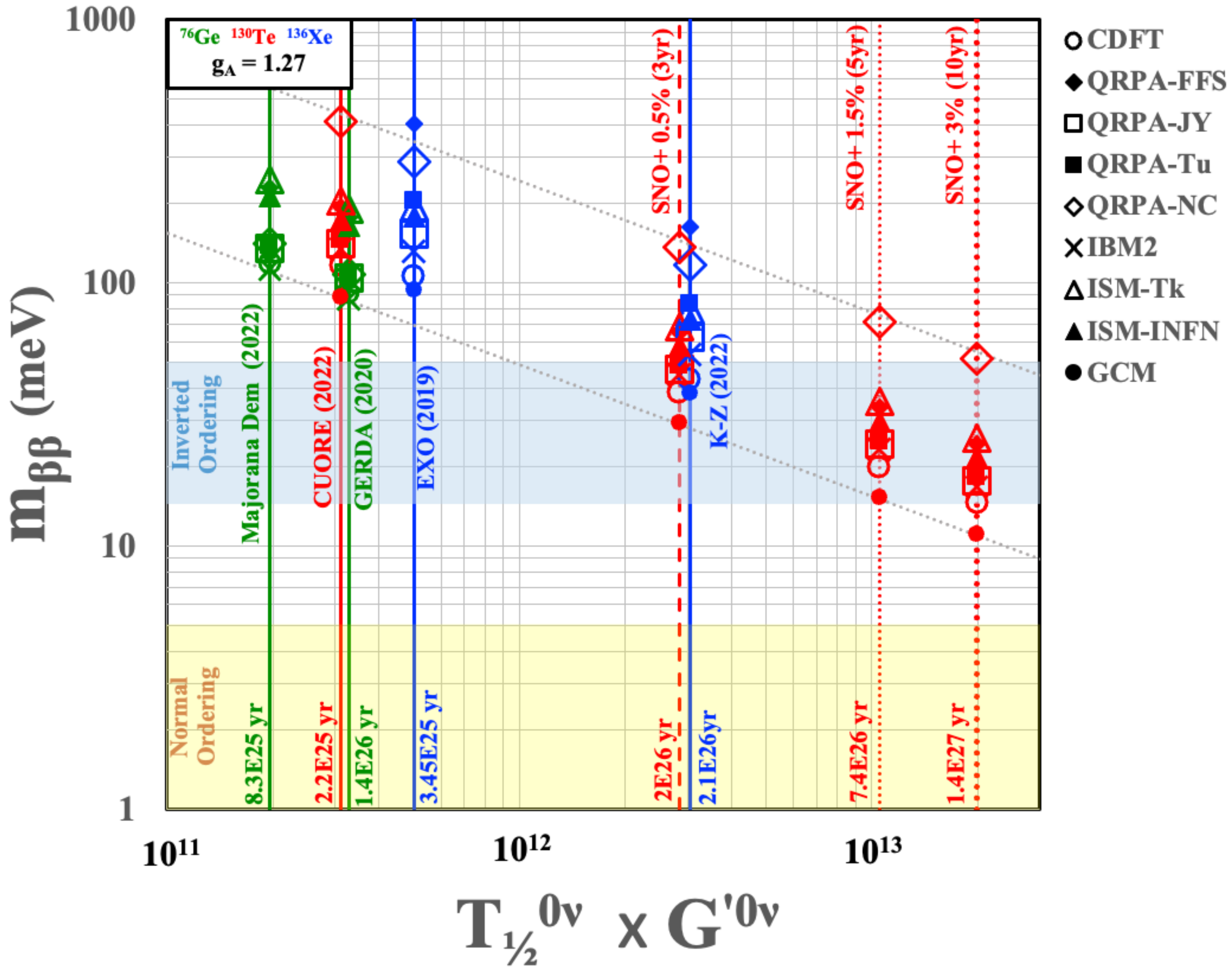
SNO+ preliminary estimate of backgrounds

$0\nu\beta\beta$ sensitivity

With 0.5% Te running for 3 years, SNO+ can reach a sensitivity of $T_{1/2}^{0\nu} \sim 2.0{\times}10^{26}$ years , $\langle m_{\beta\beta} \rangle \sim 37 - 89\ meV$.

With 1.5% Te running for 5 years, SNO+ can reach a sensitivity of $T_{1/2}^{0\nu} \sim 7.4{\times}10^{26}$ years , $\langle m_{\beta\beta} \rangle \sim 20 - 47\ meV$.

With 3.0% Te running for 10 years, SNO+ can reach a sensitivity of $T_{1/2}^{0\nu} \sim 1.4{\times}10^{27}$ years , $\langle m_{\beta\beta} \rangle \sim 14 - 34\ meV$.



Summary

- Detection of $0\nu\beta\beta$ would have profound impacts on physics :
  Help understand the origin of matter in the Universe ;
  Probe physics beyond the Standard Model .

- SNO+ will load a large mass of Te130 to search for $0\nu\beta\beta$,
  state-of-the-art techniques are developed to reduce backgrounds .

  $0\nu\beta\beta$ data taking will begin in 2025 ,
  $\langle m_{\beta\beta} \rangle$ sensitivity deep into the inverted mass ordering parameter space is expected.

Thank you for your attention!

SNO+ 2023