SNO+

Ton-scale Search for Double Beta Decay

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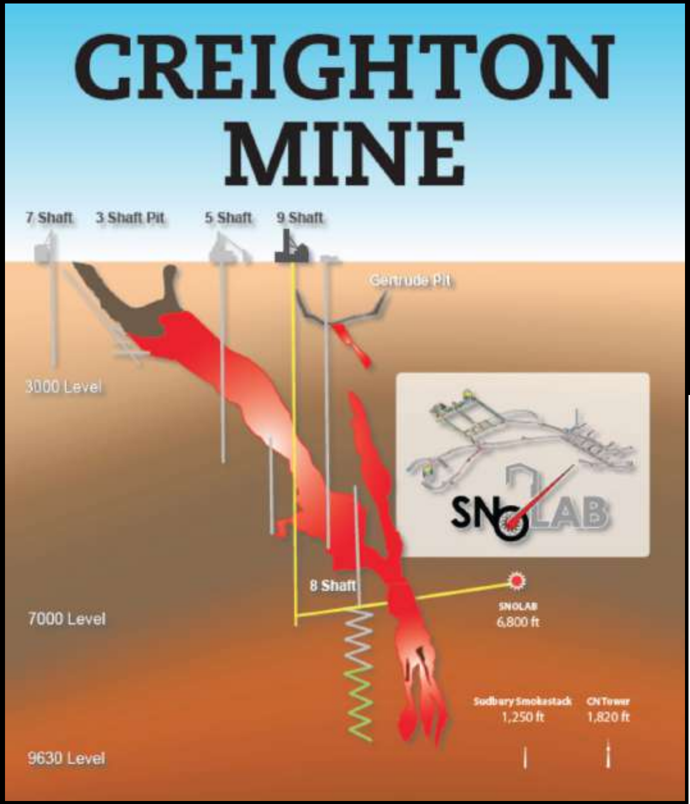
King's College London - 29th March 2021

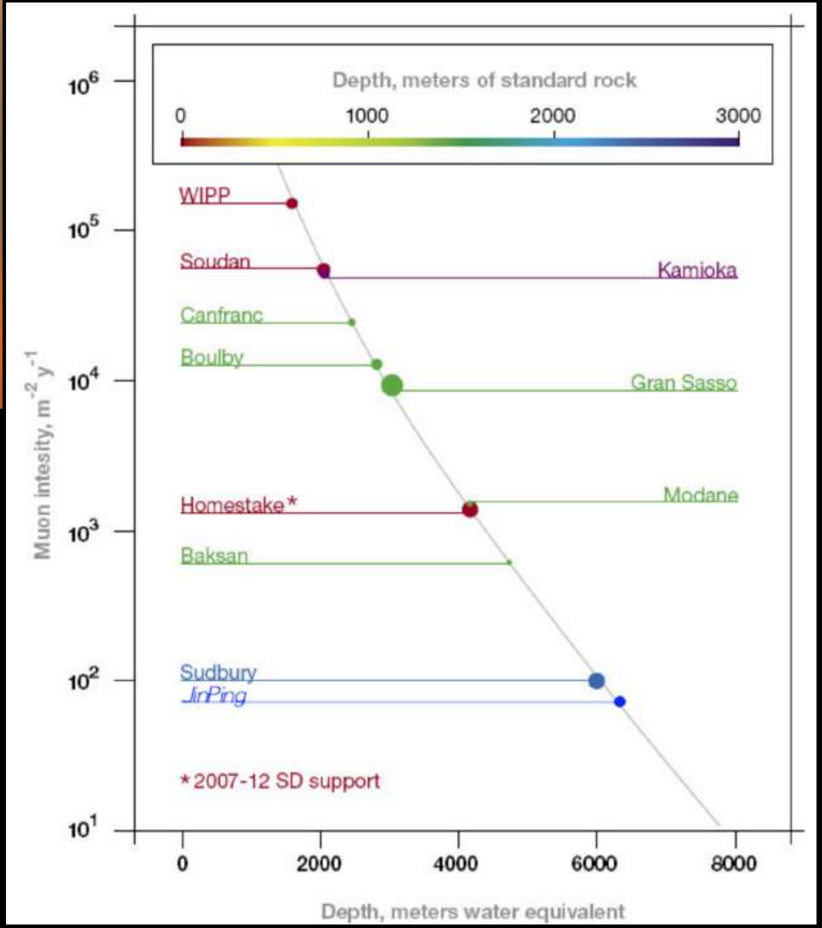
Overview

- The SNO+ Detector
- Physics program
- Water Phase Results
- Current Status
- Prospects for the future

SNOLAB

Sudbury, Ontario, Canada

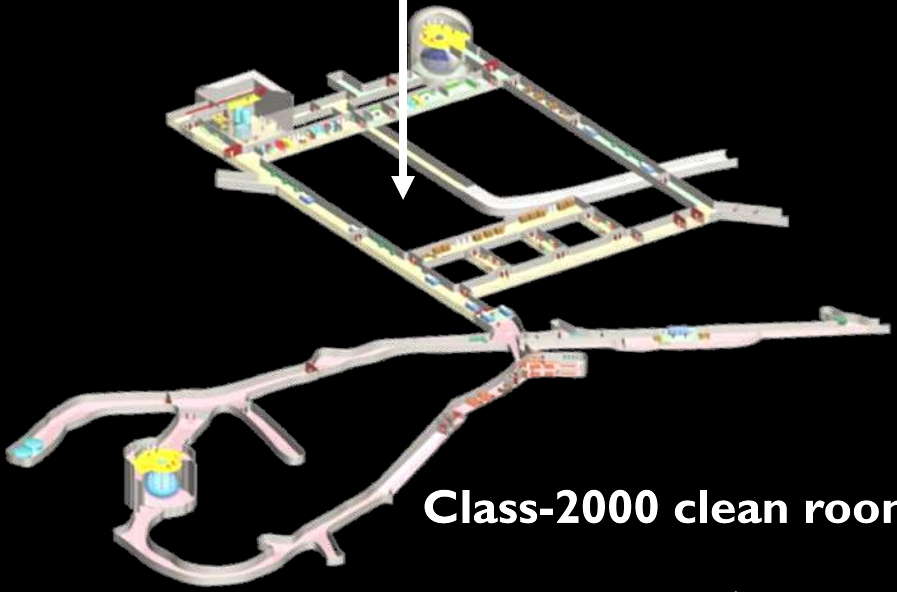




SNOLAB

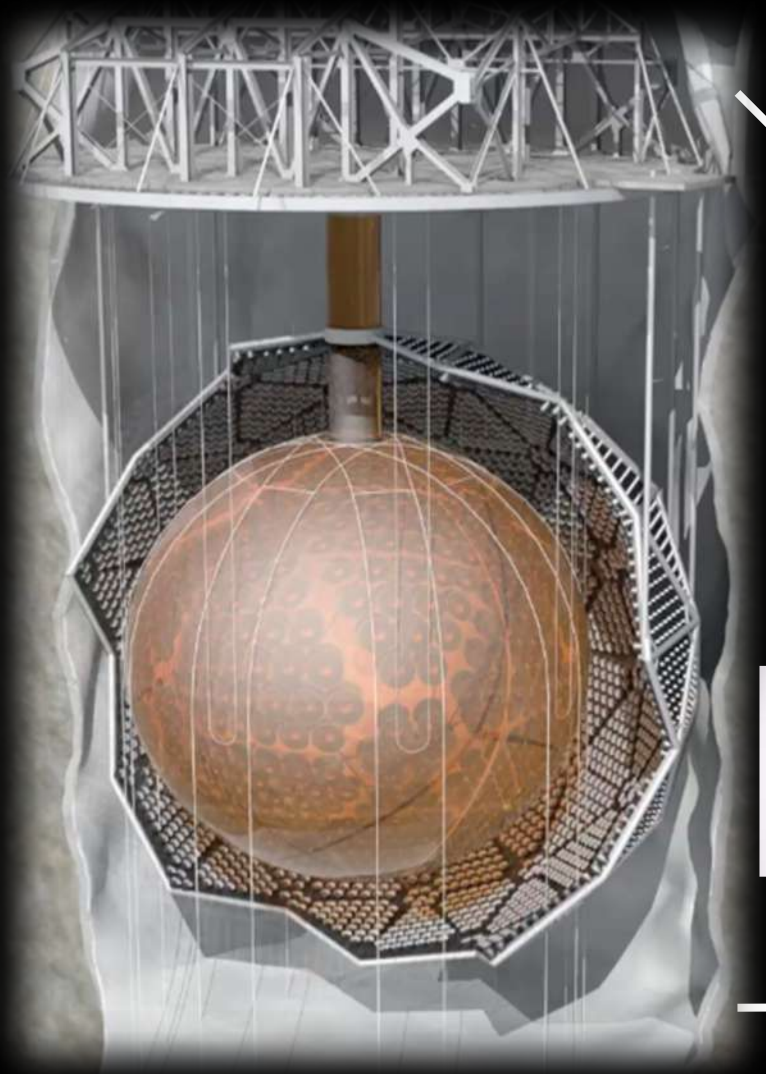
2070m (6000m w.e.)

~ 63 cosmic muons/day



Class-2000 clean room

The SNO+ Detector



Successor of the
SNO Experiment

SNOLAB

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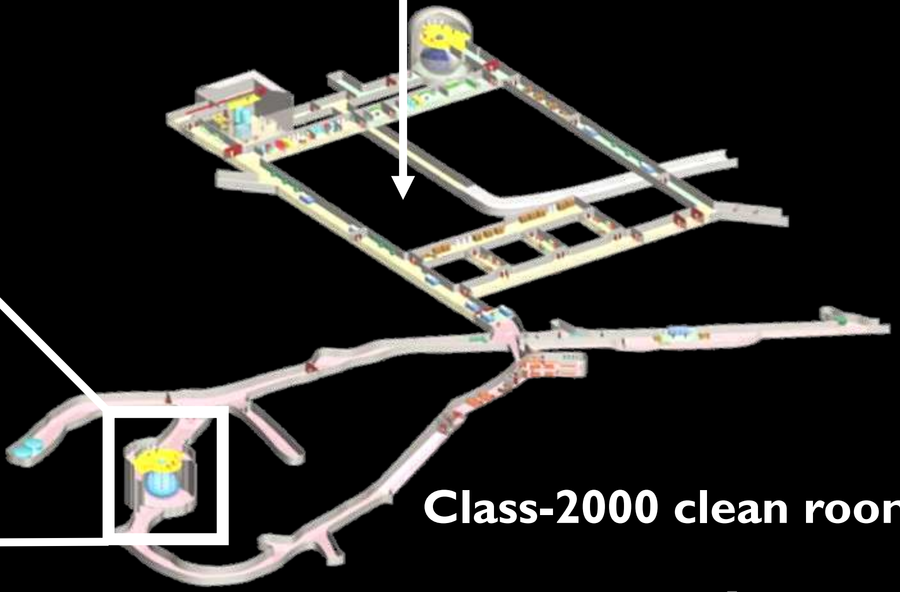

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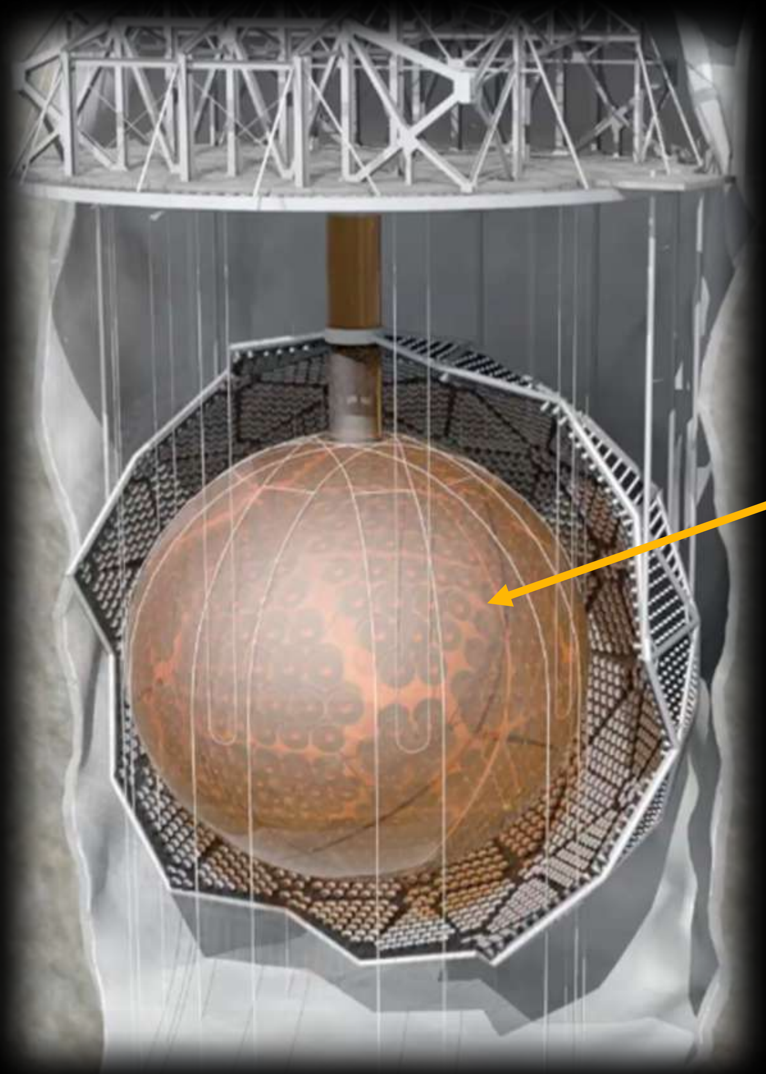
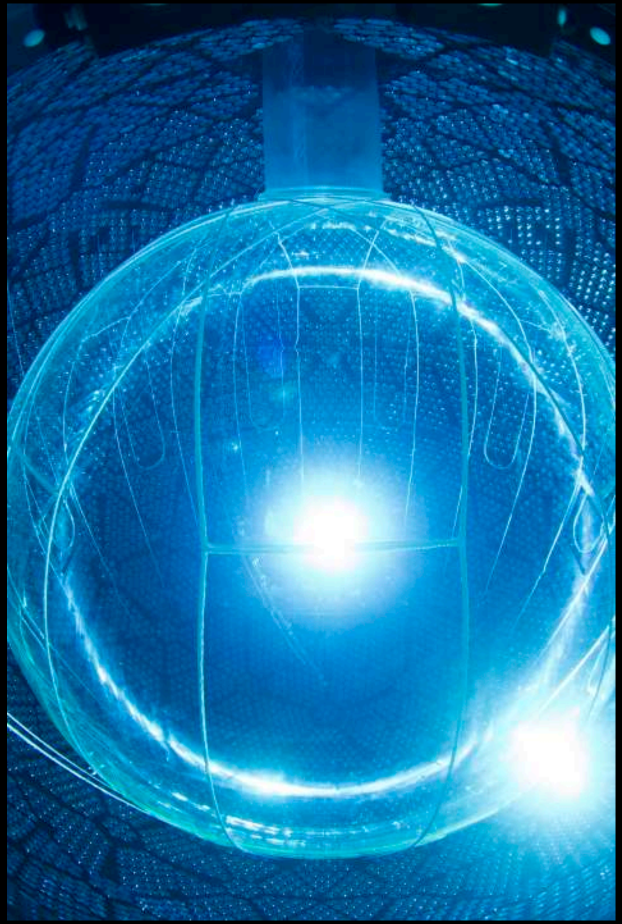


Acrylic vessel (AV)
UV-transparent
6m radius
5cm thickness

1. 905 tonnes of UPW
2. 780 tonnes of LAB+PPO
3. LAB+PPO + Tellurium cocktail



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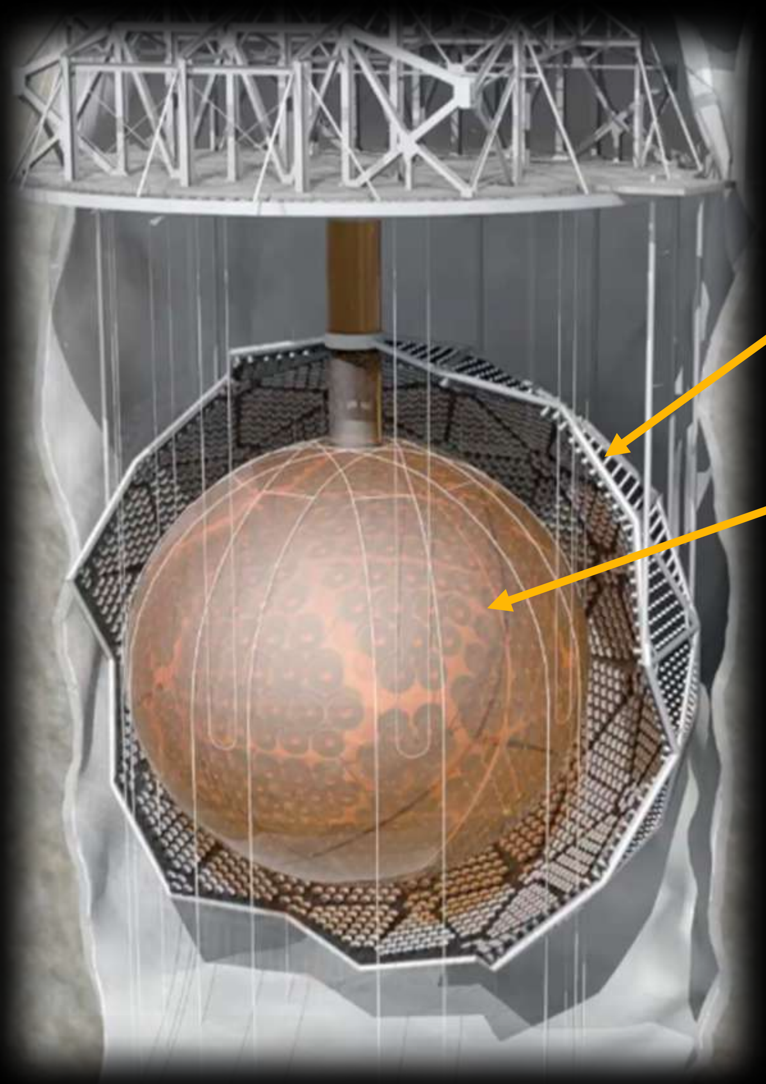
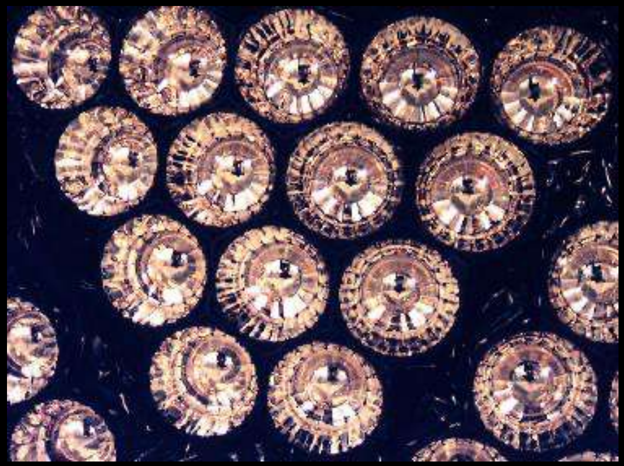


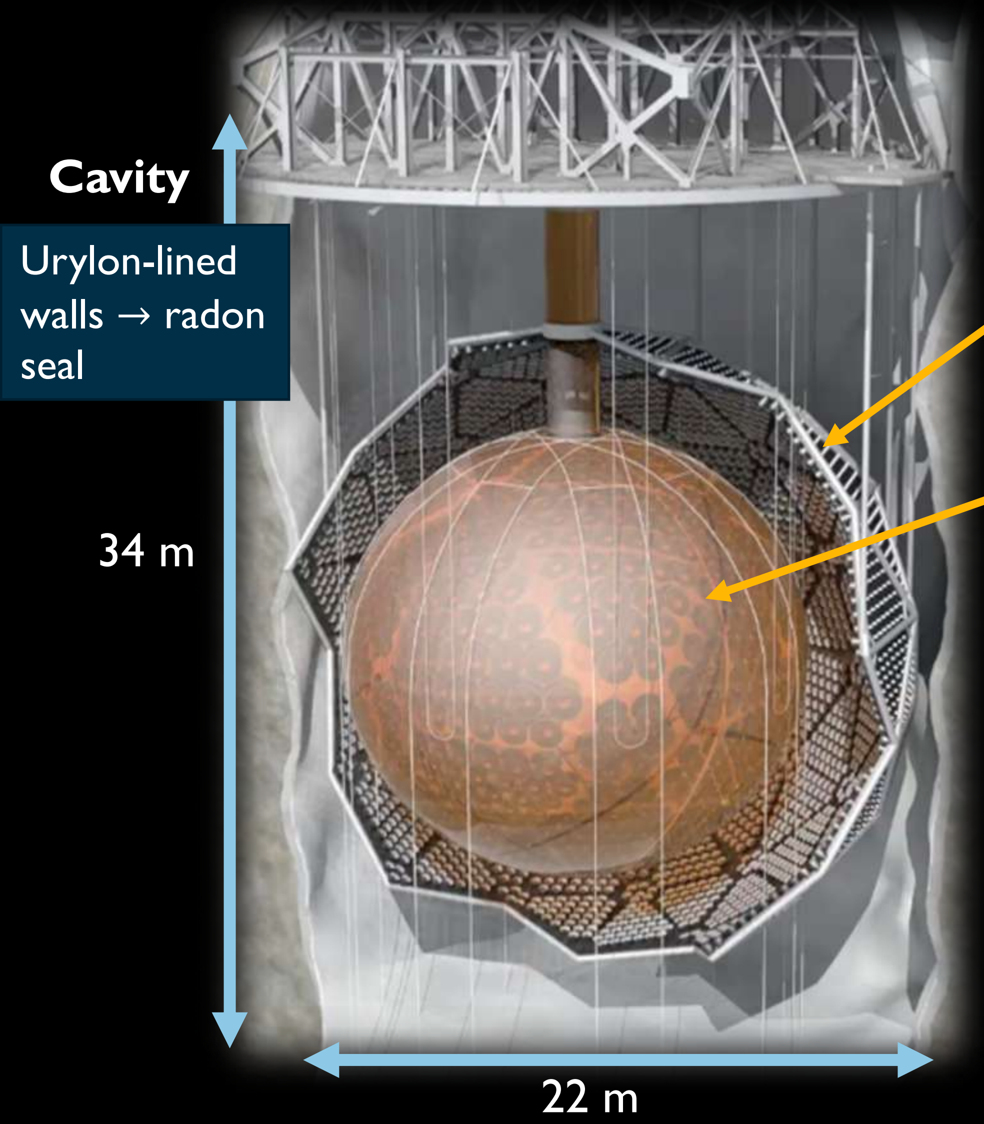


~9400 photomultiplier tubes (PMTs)
54% effective photocoverage
~90 outward looking PMTs for tagging cosmic rays

Acrylic vessel (AV)
UV-transparent
6m radius
5cm thickness

8” Hamamatsu R1408 PMTs
+
27-cm diameter concentrator

The SNO+ Detector



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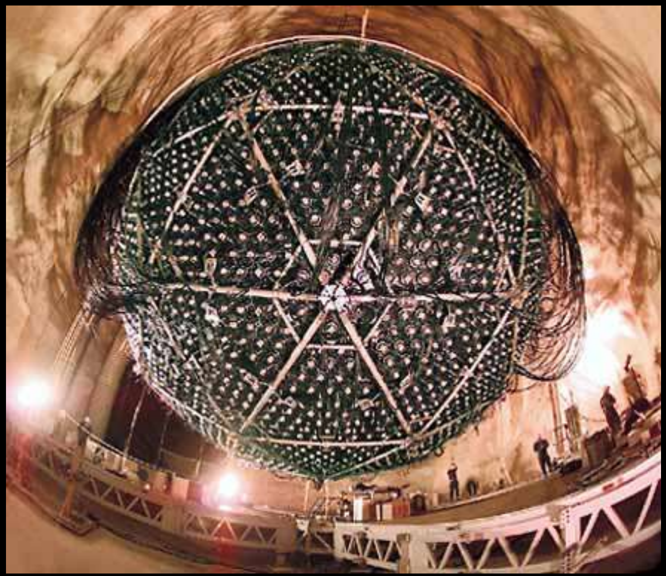

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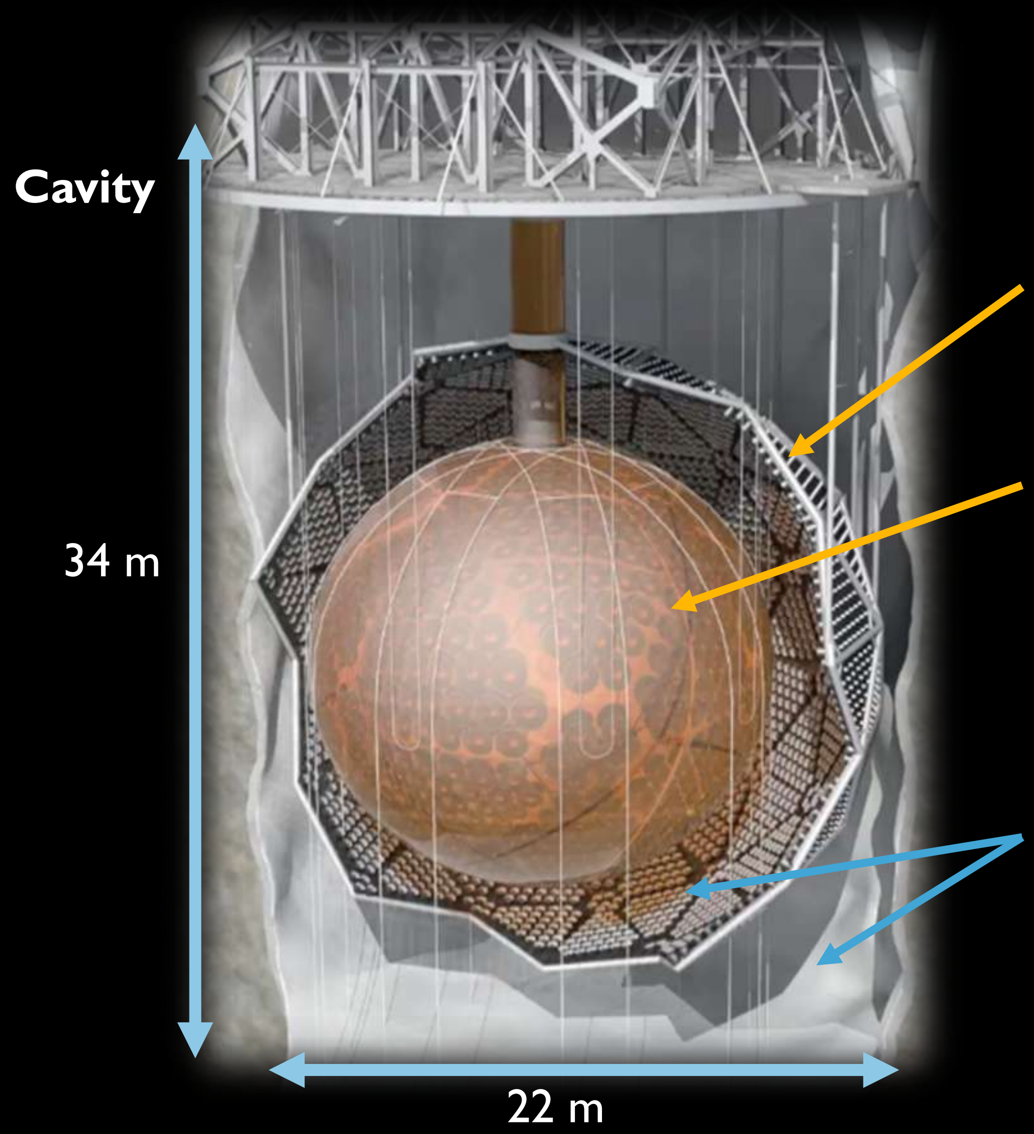

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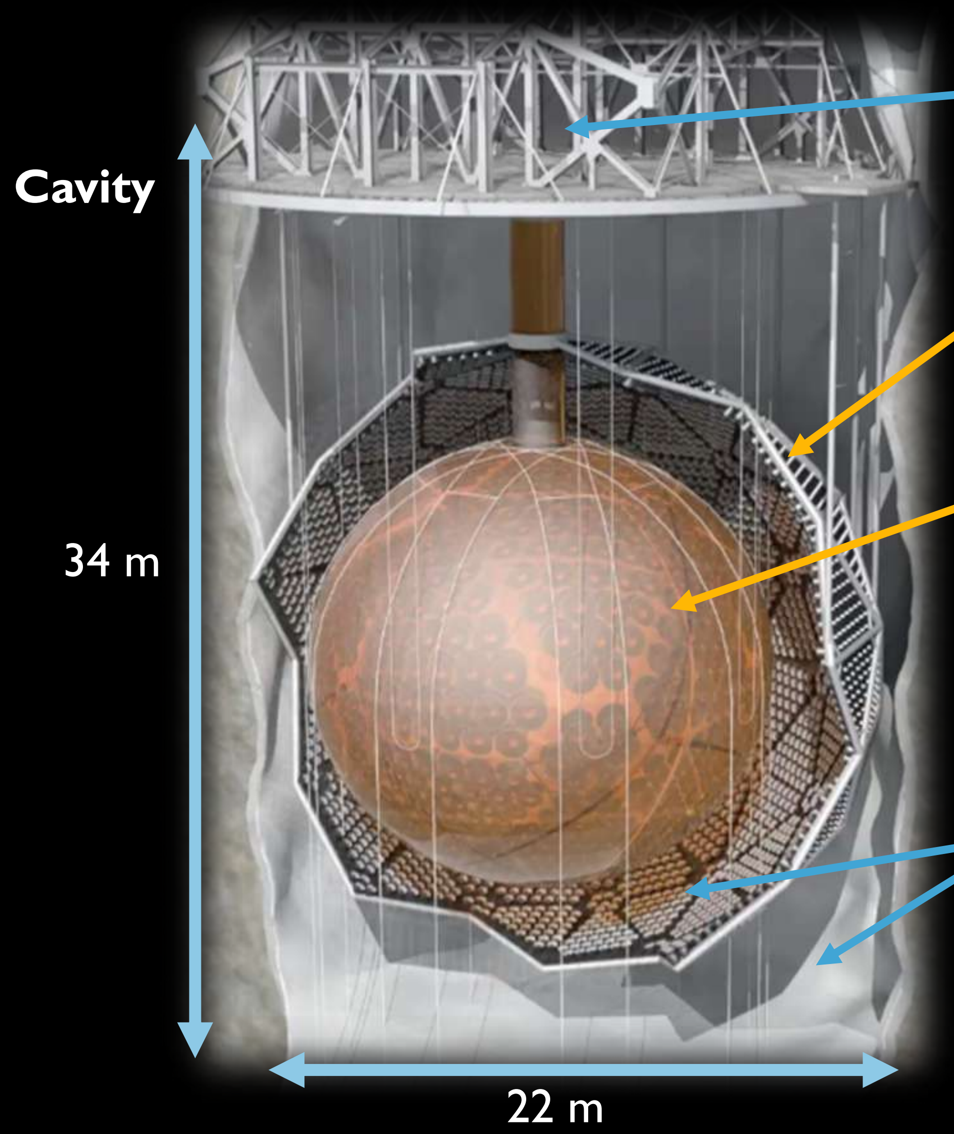
Acrylic vessel (AV)
UV-transparent
6m radius
5cm thickness

Water shielding
1.7 kt between AV and PMT support structure to reduce backgrounds from PMT materials
5.3 kt between PMT support structure and cavity, reduce background from rock wall

The SNO+ Detector



Upgraded DAQ/electronics system, calibration hardware

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~90 outward looking PMTs for tagging cosmic rays

Acrylic vessel (AV)
UV-transparent
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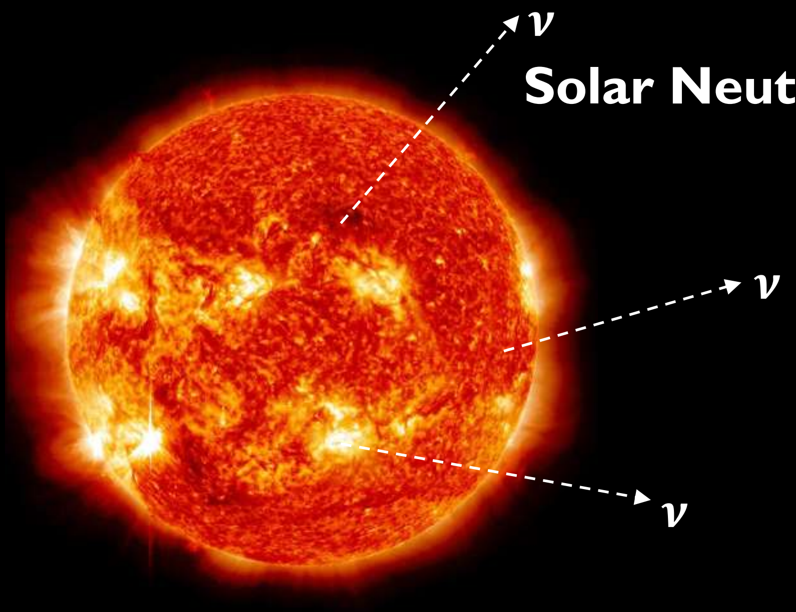
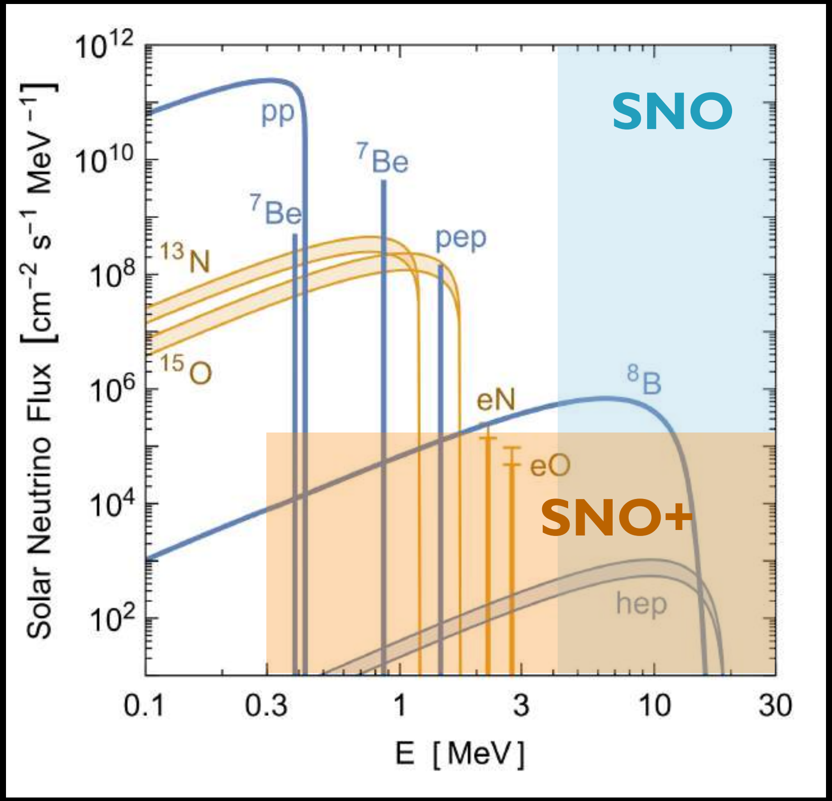
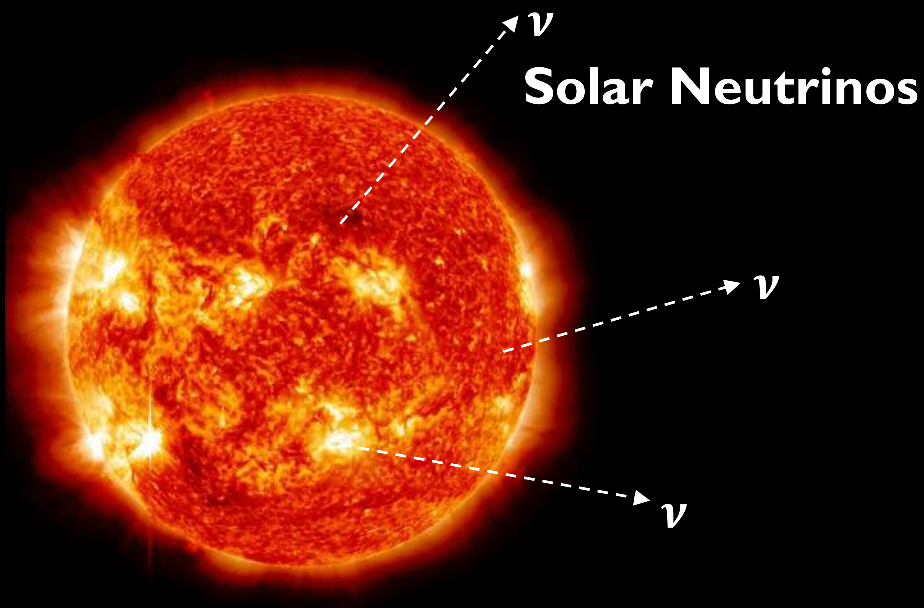
Physics Programme

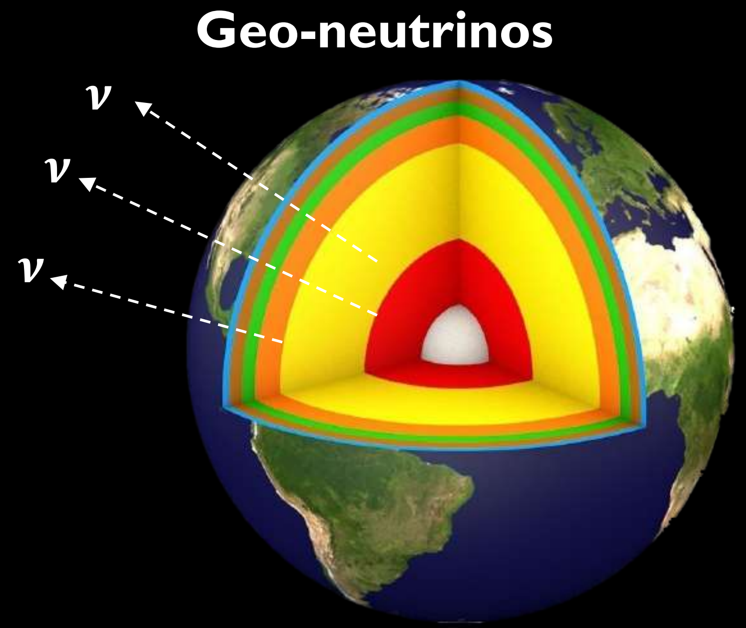




Adapted from E.Vitagliano *et al,* Rev. Mod. Phys. **92**, 45006 (2020)

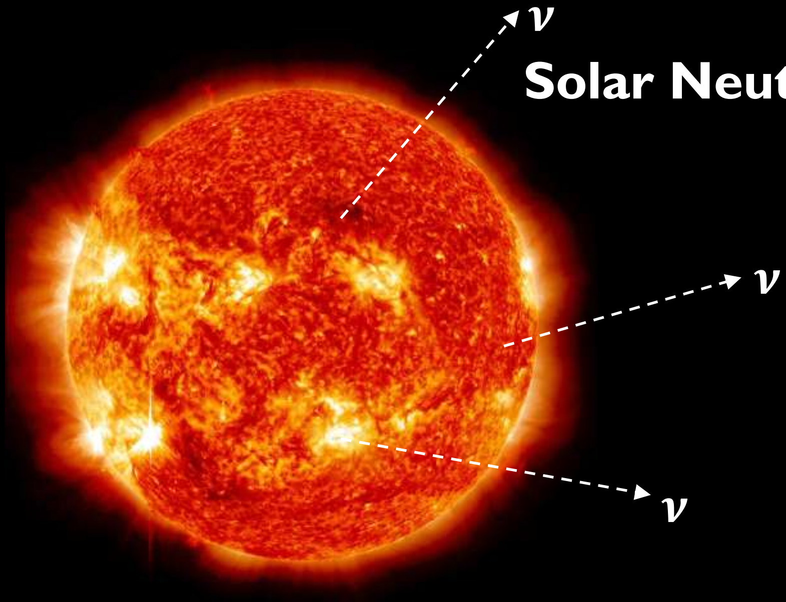
Physics Programme

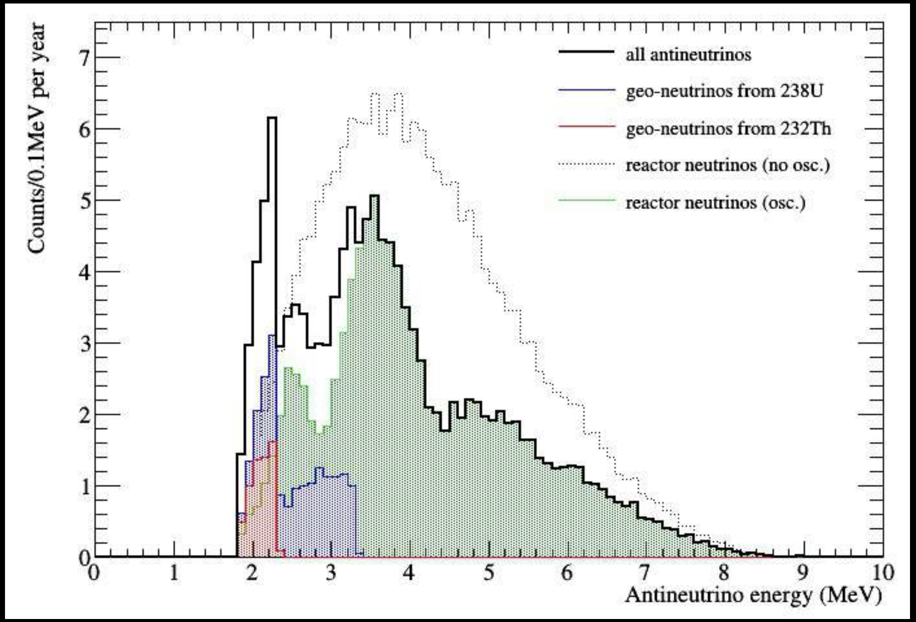




Physics Programme

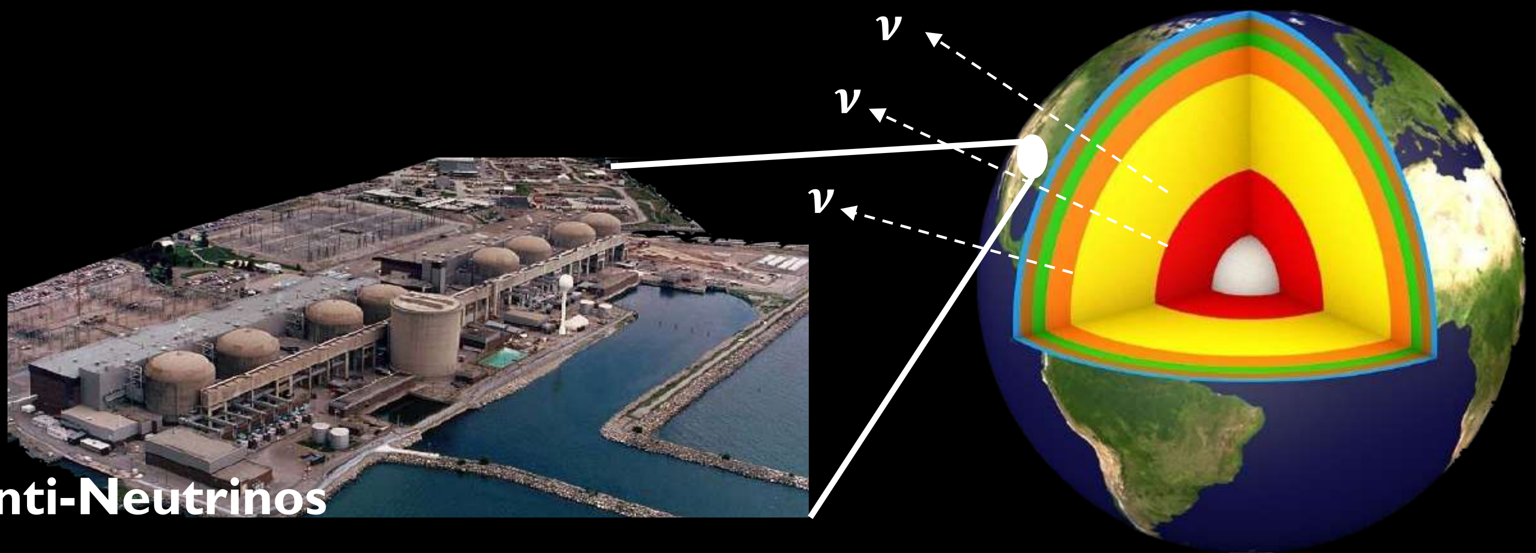
Solar Neutrinos





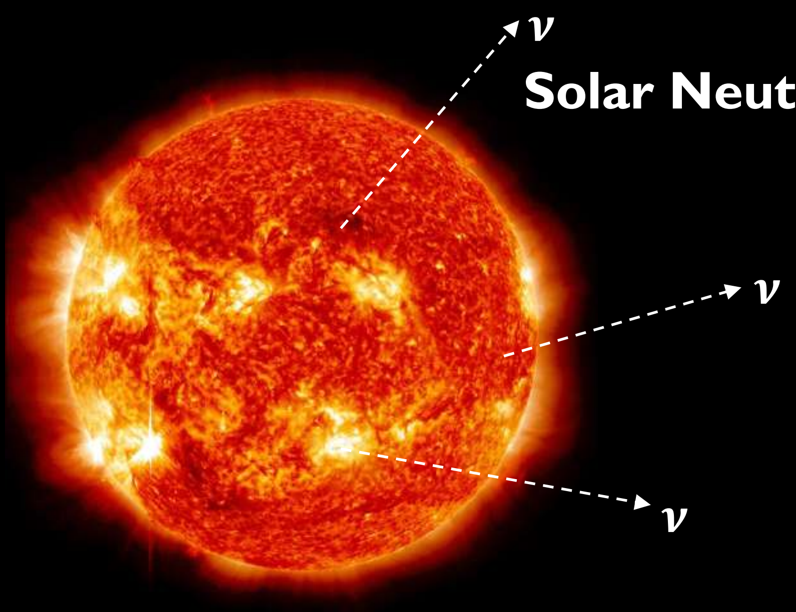
Expected $\bar{\nu}_e$ energy spectrum in SNO+ (solid). Geo-neutrinos from ^{238}U (blue) and ^{232}Th (red) decays in the Earth. Contribution from nuclear reactors is in green.

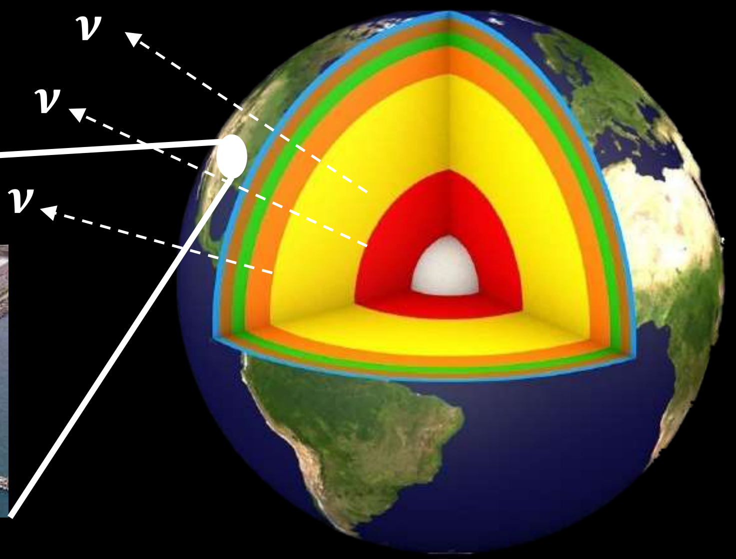
Geo-neutrinos



Reactor Anti-Neutrinos

Physics Programme

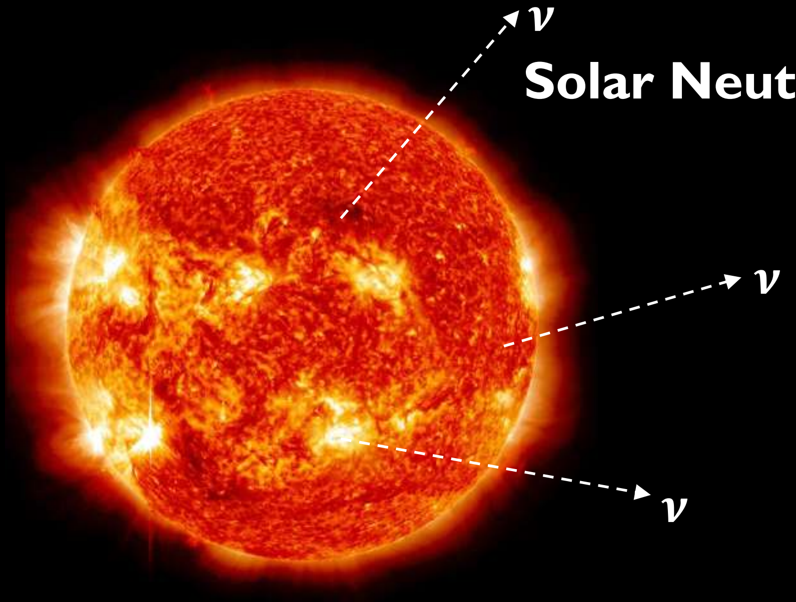




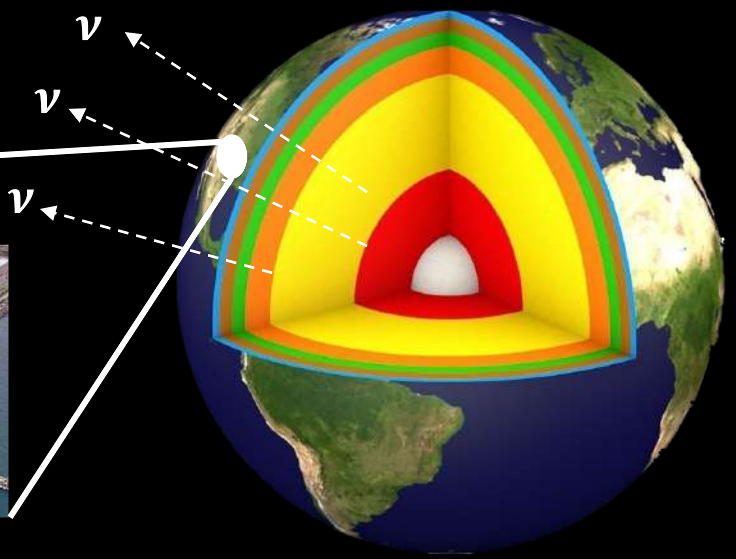
Physics Programme

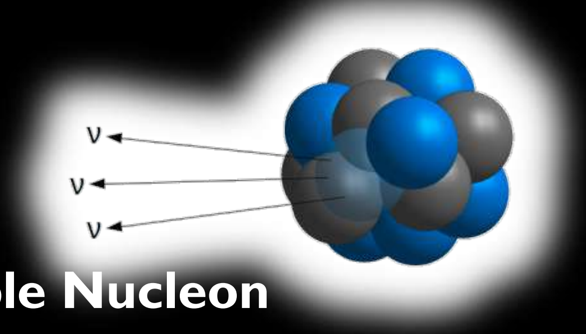
Supernova
Neutrinos

Solar Neutrinos



Geo-neutrinos

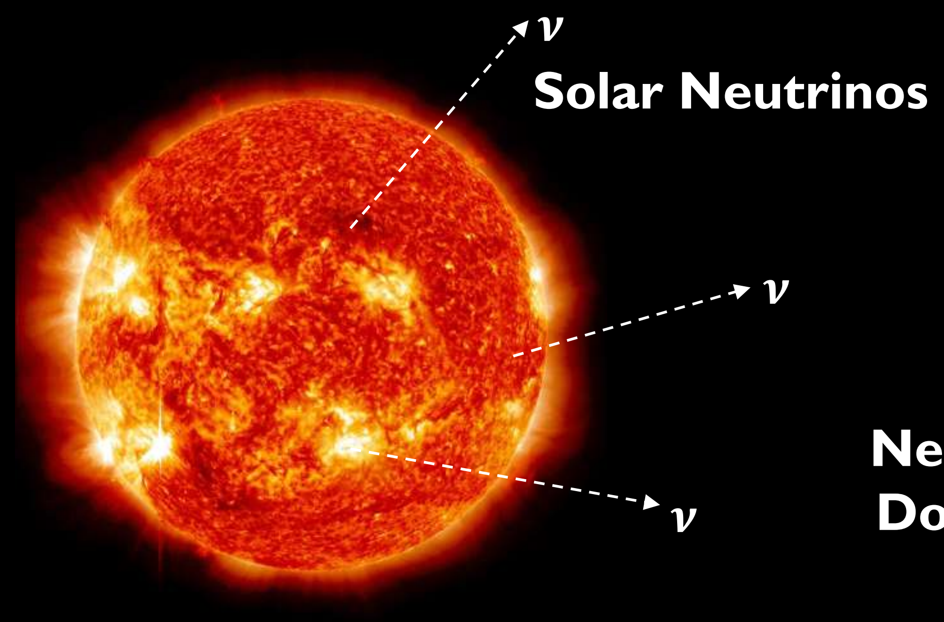


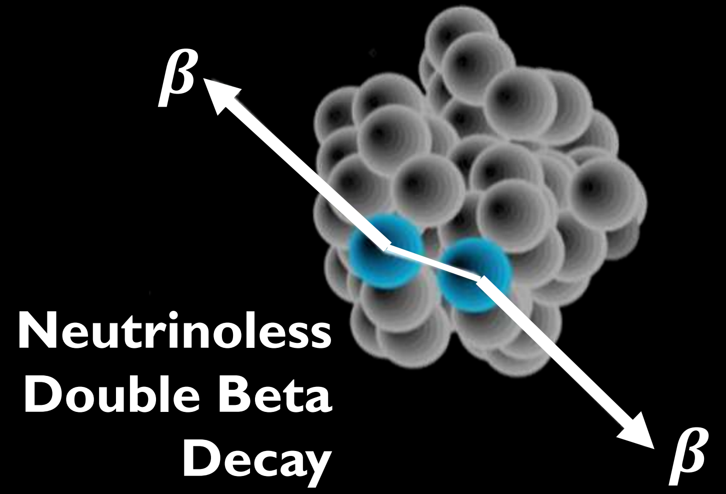


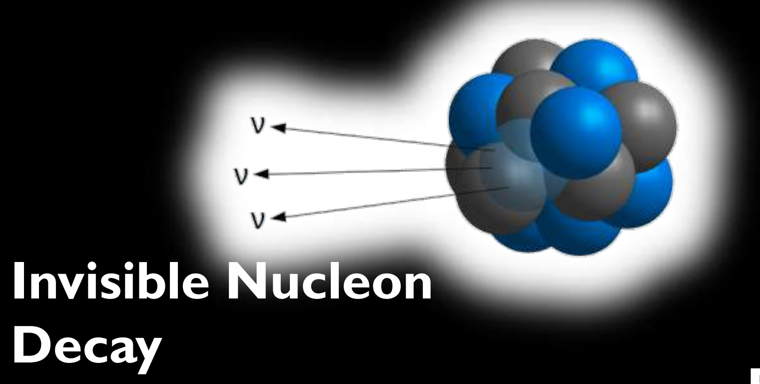
Invisible Nucleon
Decay

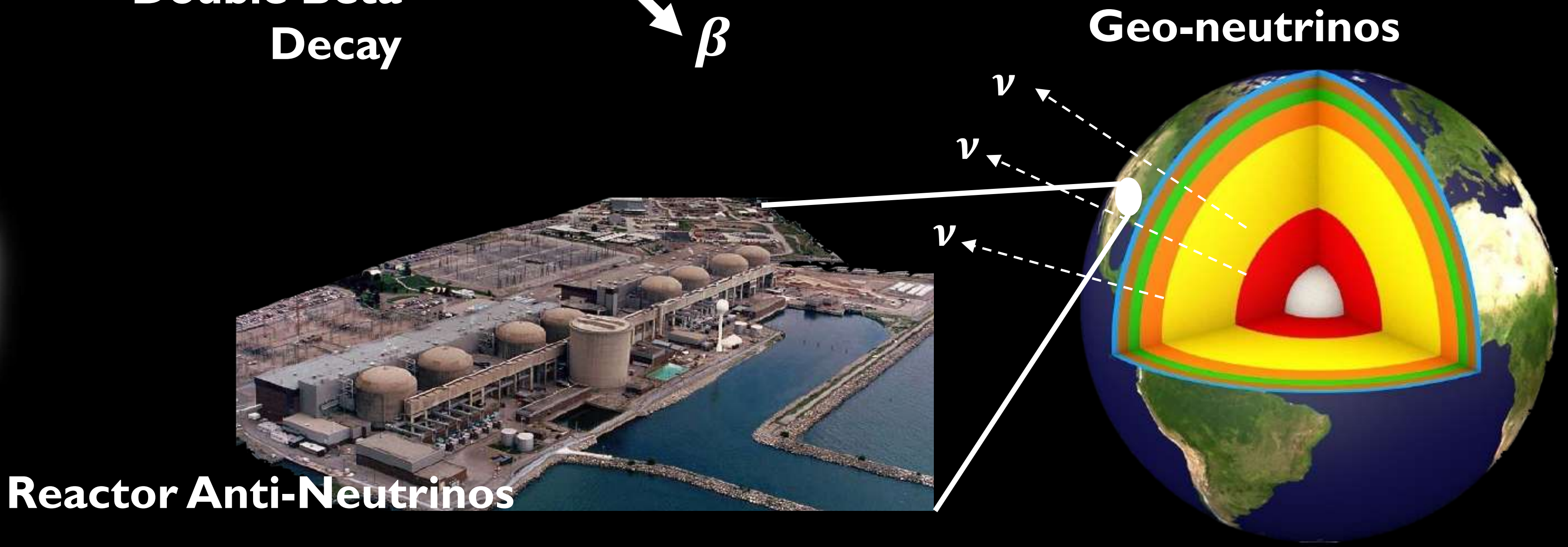
Reactor Anti-Neutrinos

Physics Programme









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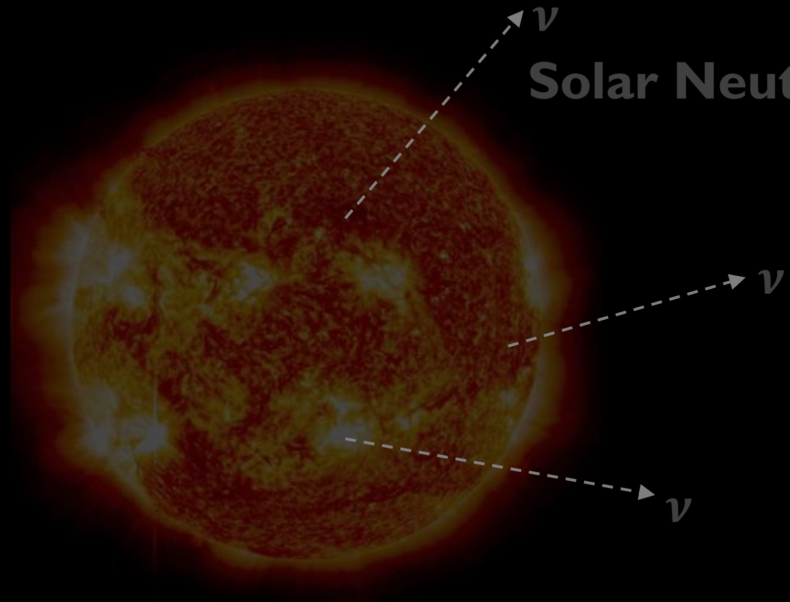
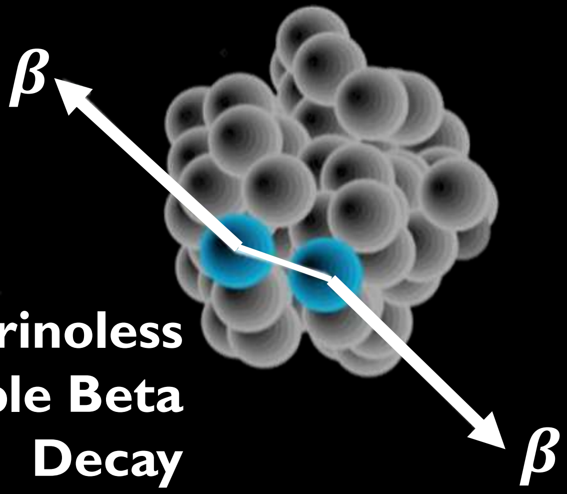
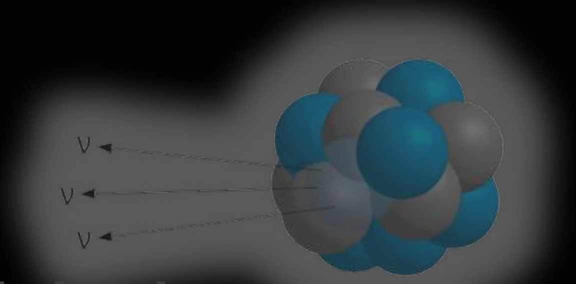


Main Goal





Invisible Nucleon
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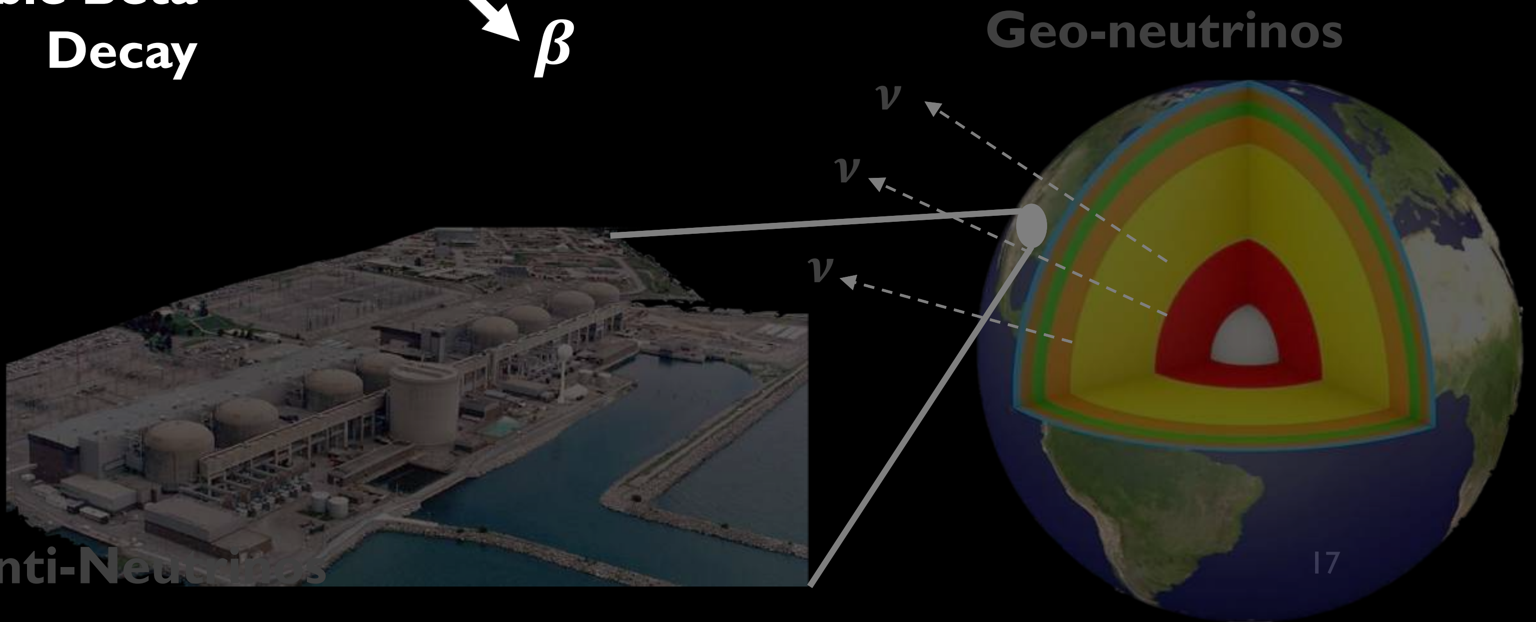
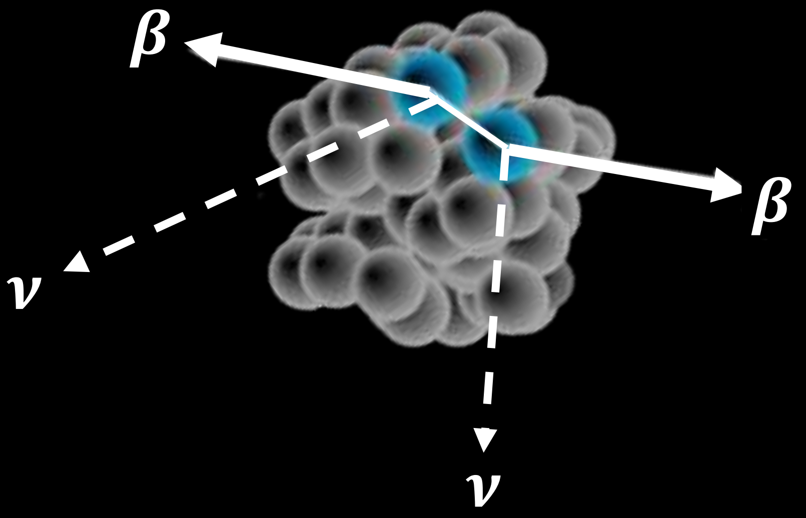


Double Beta Decay

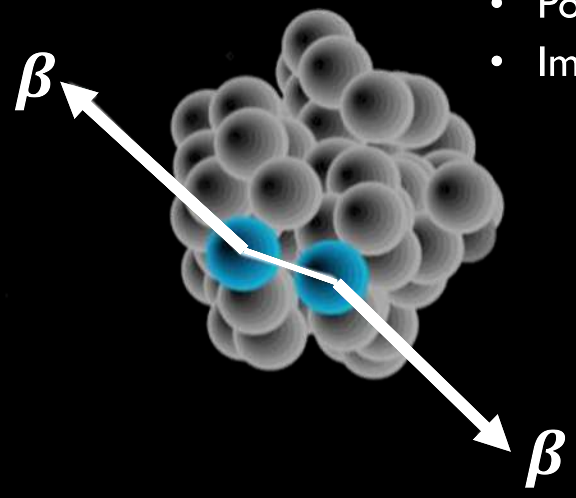


Two neutrino double beta decay

- Allowed by the Standard Model (conserves lepton number).
- Occurs in nuclei where single beta decay is energetically forbidden.
- 35 naturally-occurring isotopes, observed in 11: ^{48}Ca, ^{76}Ge, ^{130}Te, ^{136}Xe…
- Long half-lives between 10^{19} and 10^{24} years.

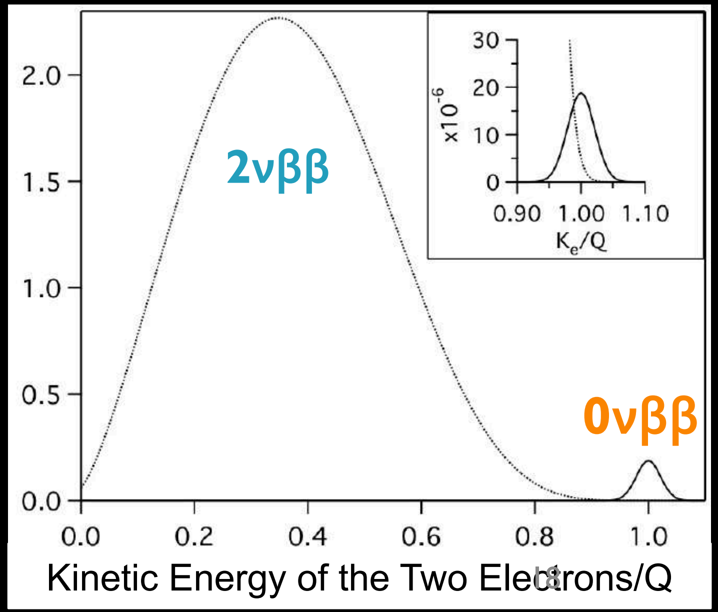
Neutrinoless double beta decay

- Possible if neutrinos are Majorana particles.
- Implies lepton number violation.



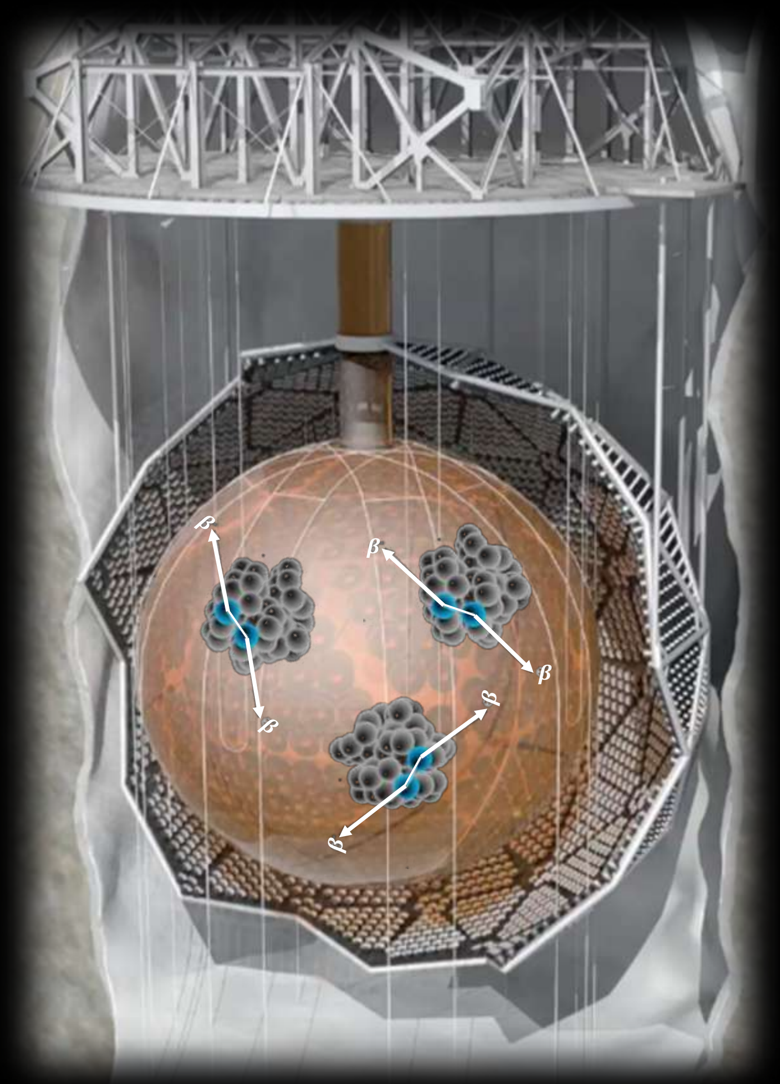
$$\left[T_{0\nu}^{1/2}\right]^{-1} = G_{0\nu}|\mathcal{M}_{0\nu}|^2\left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

$$m_{\beta\beta} = \left|\sum_{i=1,2,3} e^{i\xi_i}|U_{ei}^2|m_i\right|$$



Neutrinoless Double Beta Decay Search in SNO+

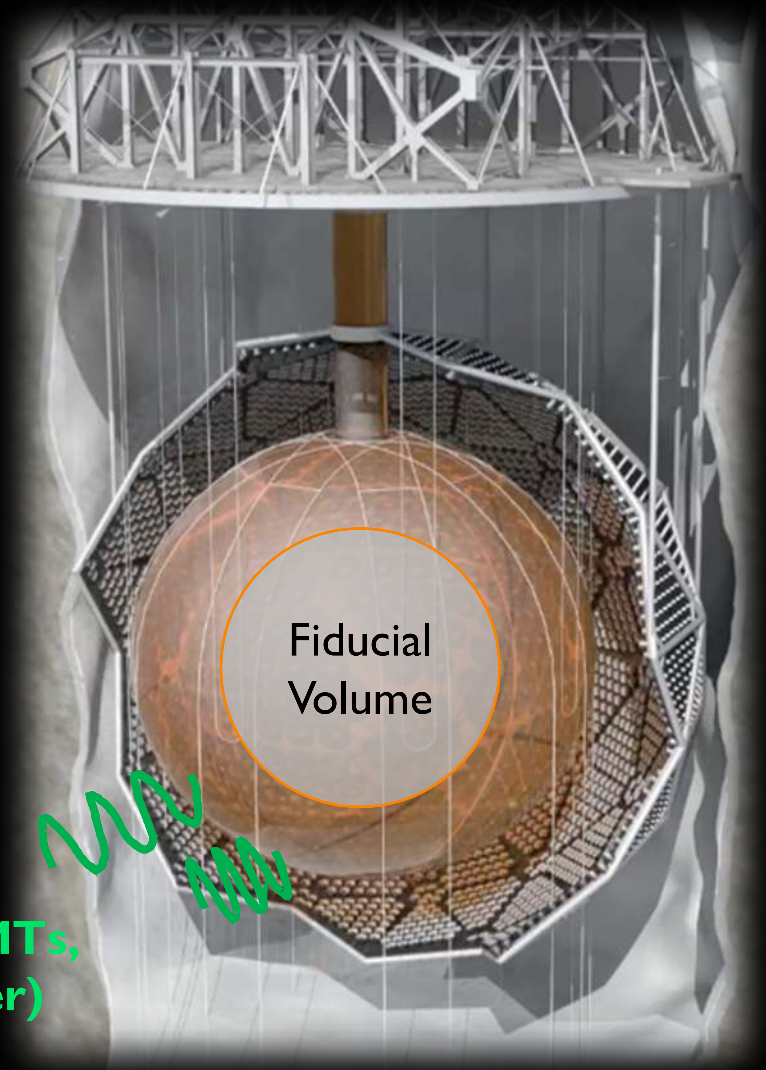
What are the advantages?



Neutrinoless Double Beta Decay Search in SNO+

What are the advantages?

1. Massive detector
   - High statistics
   - Self-shielding from external backgrounds through fiducialization.



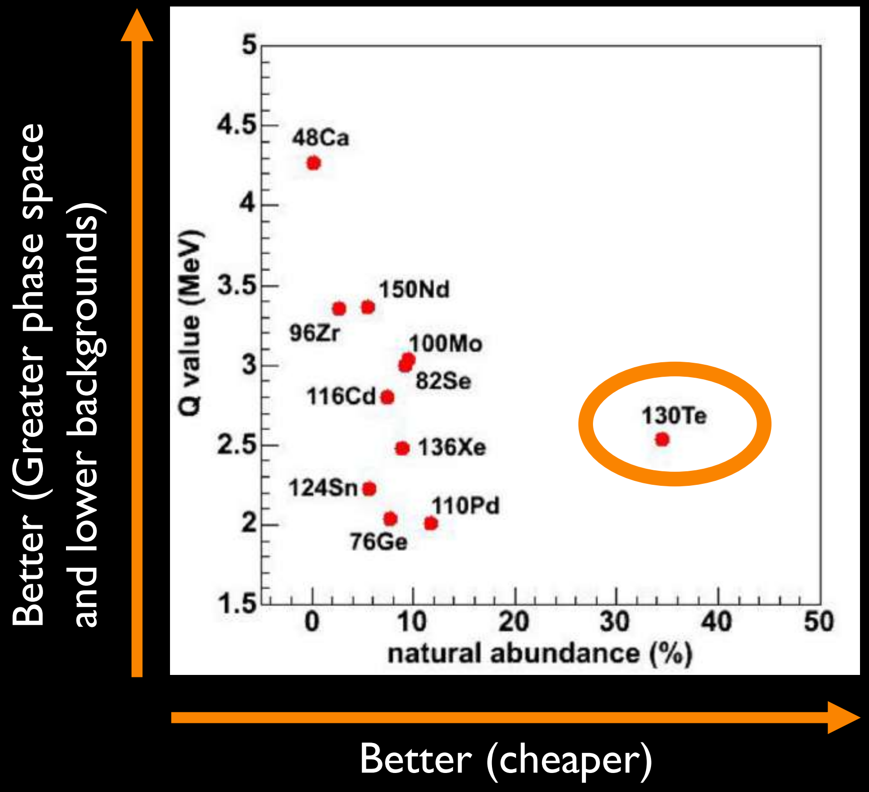
Neutrinoless Double Beta Decay Search in SNO+

What are the advantages?

1. Massive detector
   - High statistics
   - Self-shielding from external backgrounds through fiducialization.
2. $0\nu\beta\beta$ decay candidate: **^{130}Te**
   - Highest natural abundance (34%), no enrichment needed – easily scalable at low cost.
   - Q-value at 2.527 MeV – less background from natural radioactivity
   - Initial phase loading: 0.5% natural Te by weight

     = 1333 kg of ^{130}Te.

Ton-scale!



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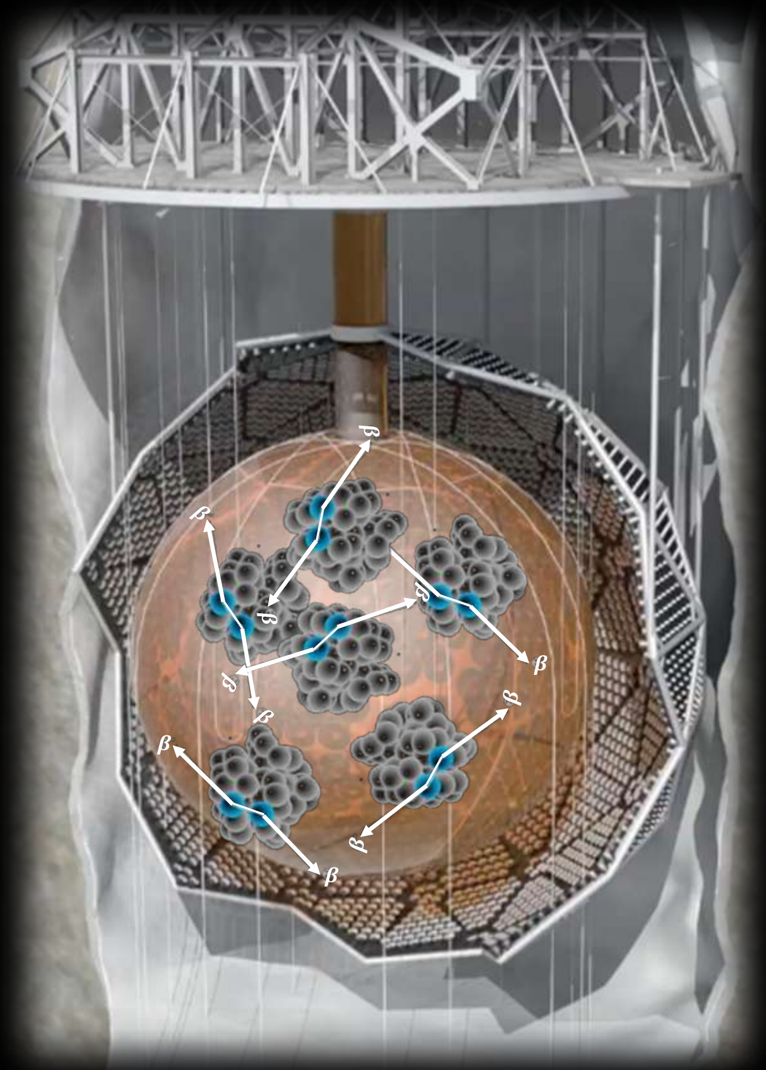

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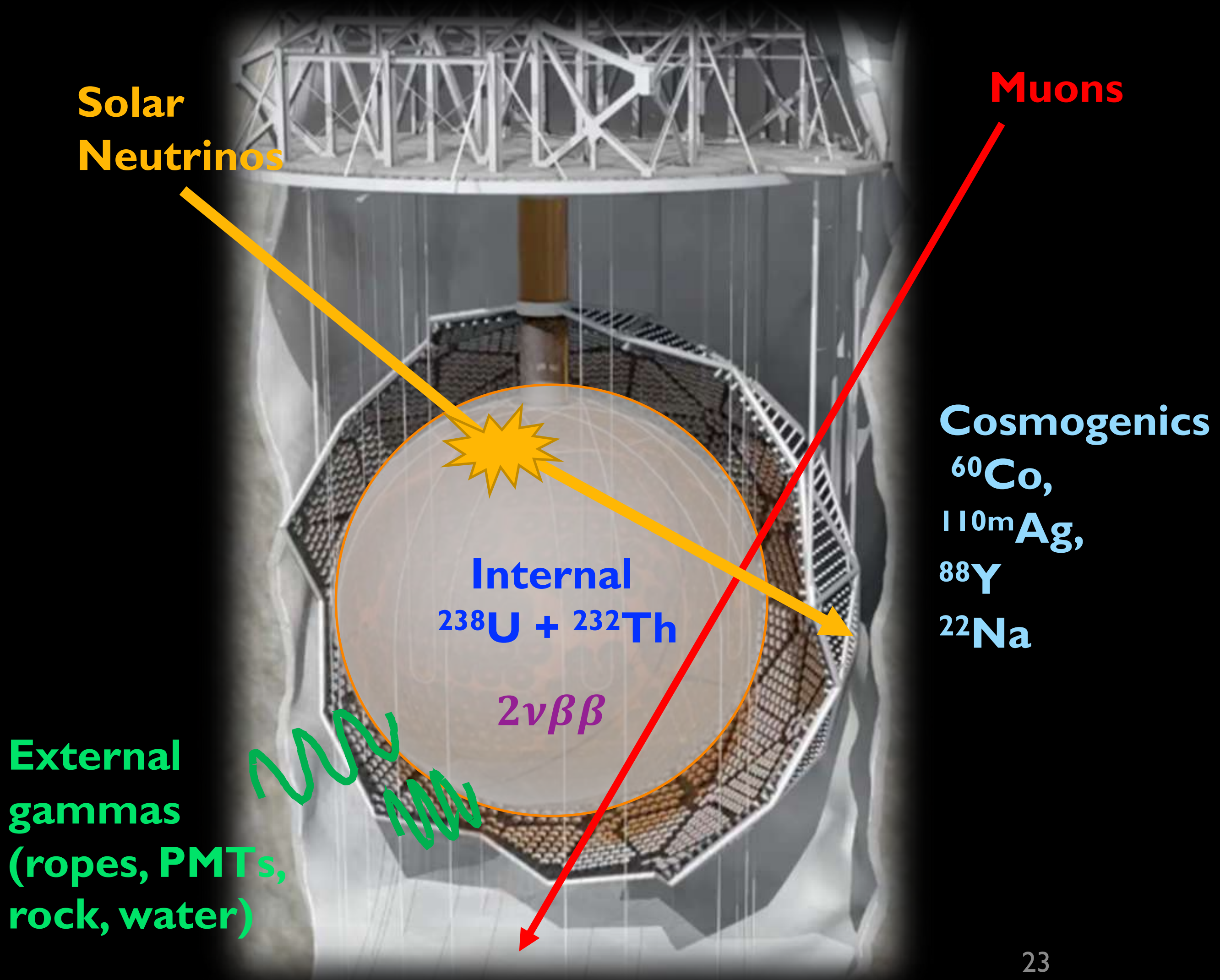
   - Highest natural abundance (34%), no enrichment needed – easily scalable at low cost.
   - Q-value at 2.527 MeV – less background from natural radioactivity
3. Liquid scintillator
   - Can be purified
   - Loading can be scaled

Challenges for $0\nu\beta\beta$ Search in SNO+

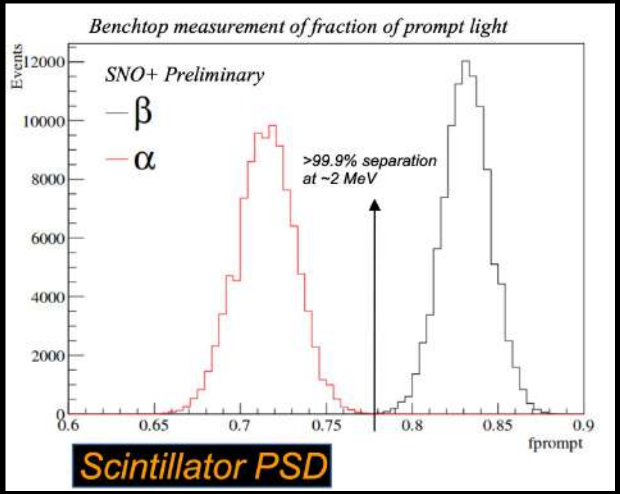
1. Backgrounds.

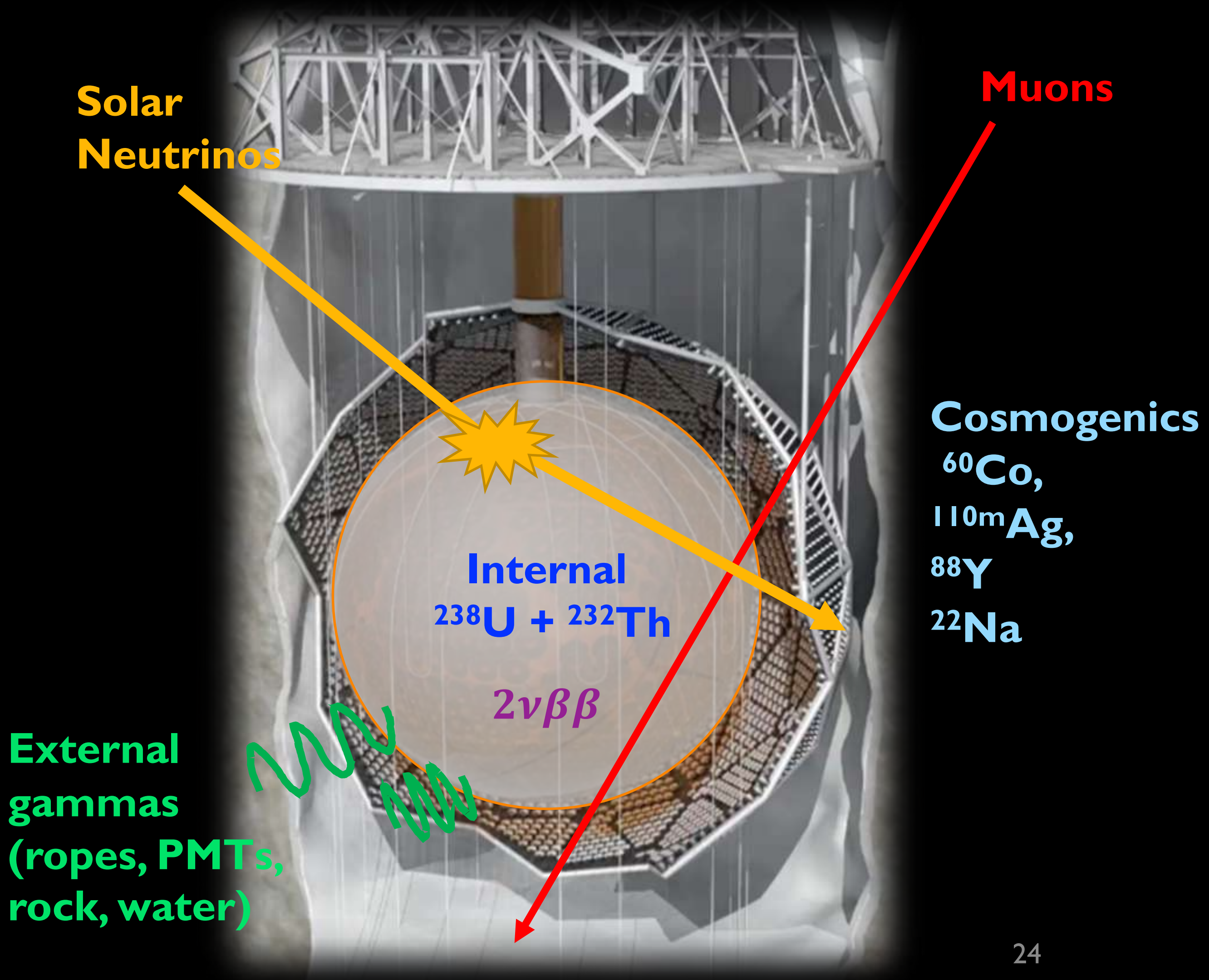


Challenges for $0\nu\beta\beta$ Search in SNO+

1. **Backgrounds.**

- Fiducial volume and other analysis cuts help reducing backgrounds:
  - Alpha-beta separation
  - Coincidence tagging
  - Muon tagging
  - …



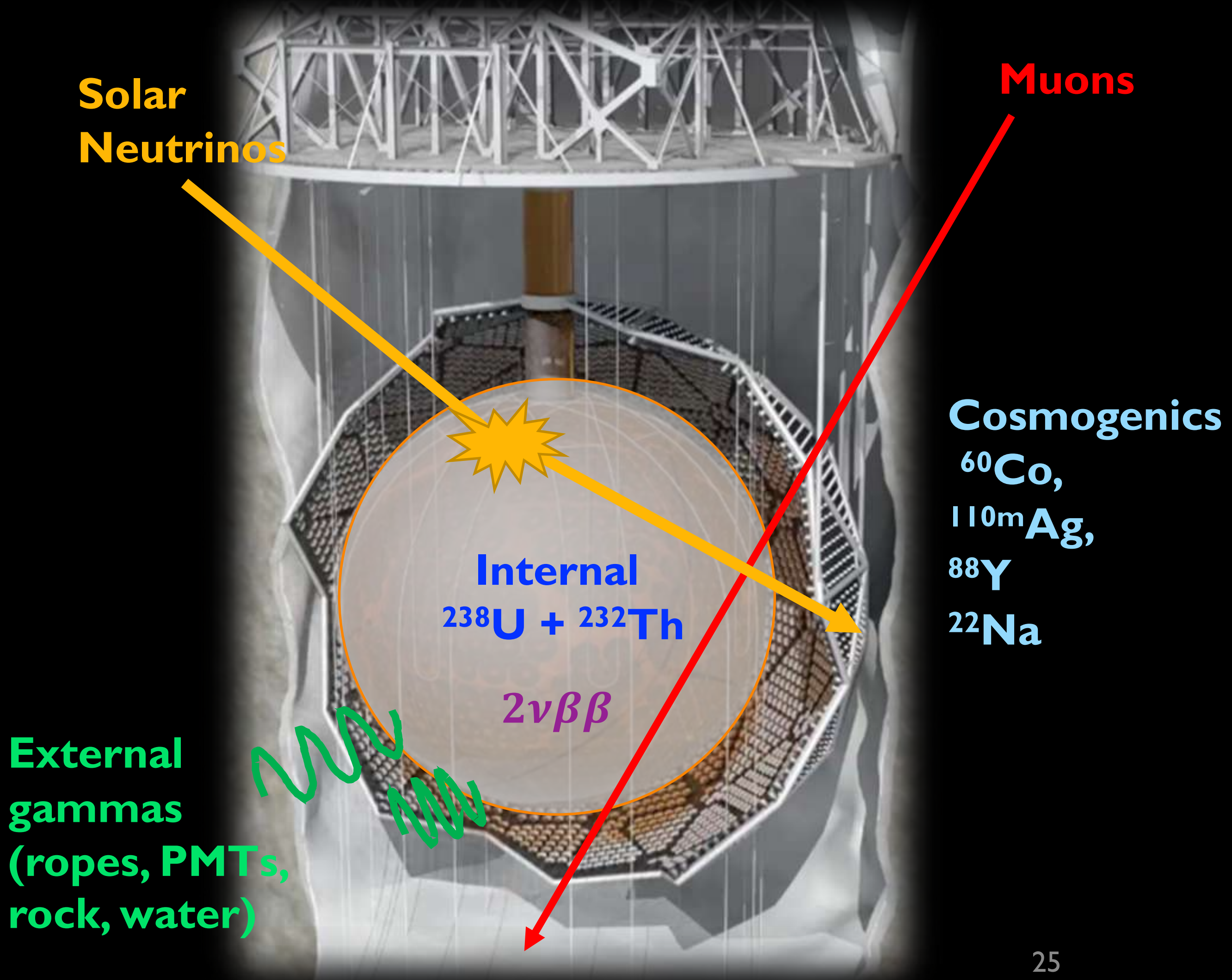


Challenges for $0\nu\beta\beta$ Search in SNO+

1. **Backgrounds.**

- Additional reduction of radio-impurities:
  - Telluric Acid stored underground since 2015
    - Mitigate cosmogenics

  - Scintillator purification
    - Reduce internal U and Th
  - Tellurium purification
    - Reduce cosmogenics

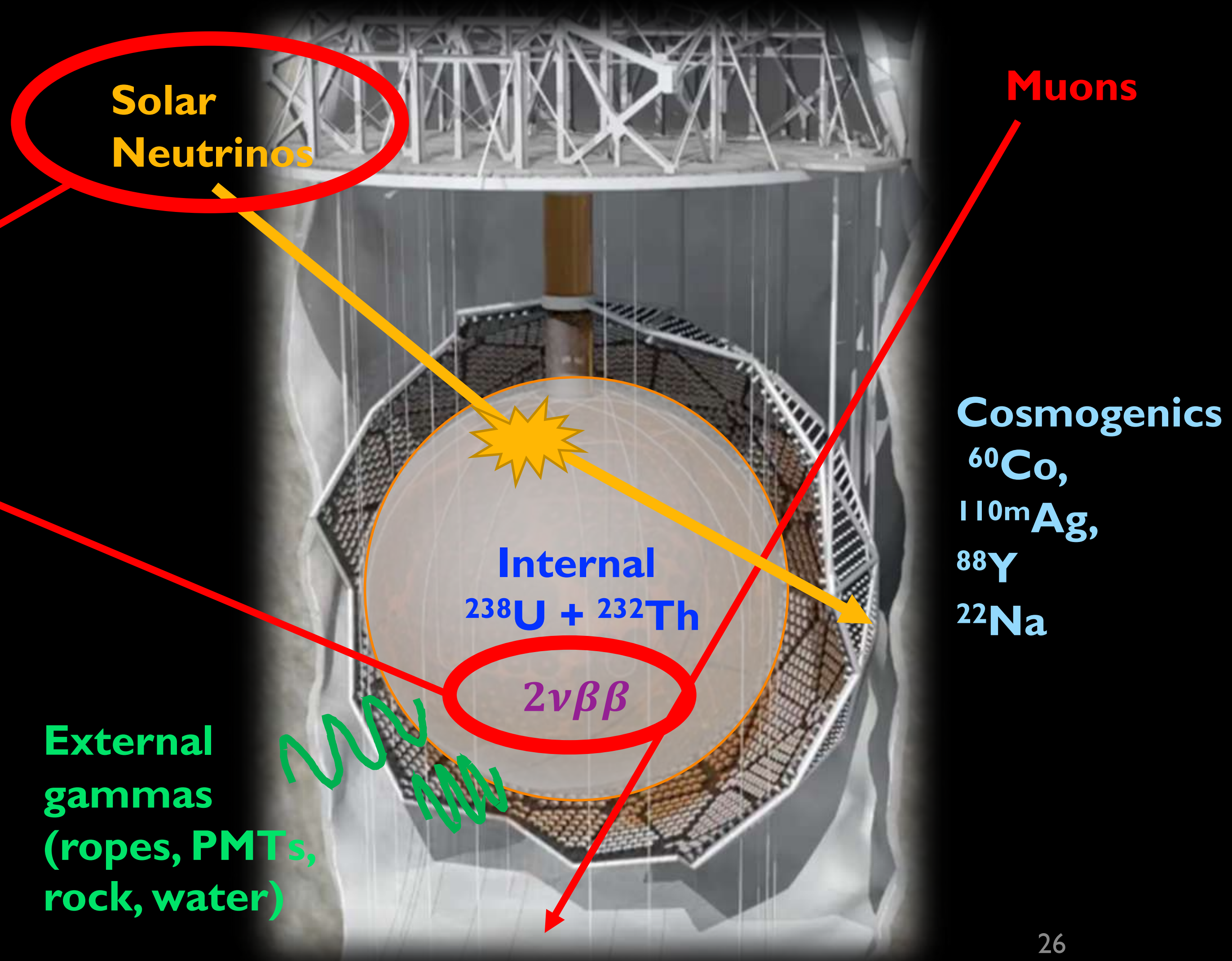


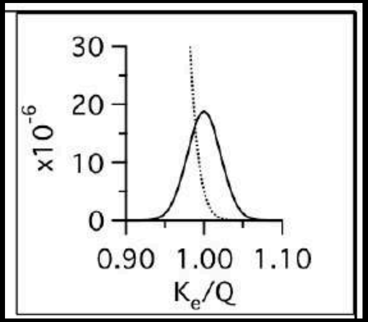
Challenges for $0\nu\beta\beta$ Search in SNO+

1. **Backgrounds.**

Irreducible Backgrounds

Require very good energy resolution and overall knowledge of the detector response.





Challenges for $0\nu\beta\beta$ Search in SNO+

2. **Understanding the detector response.**

From **PMT charge and time** to **energy, direction and particle type**.

Challenges for $0\nu\beta\beta$ Search in SNO+

2. **Understanding the detector response.**

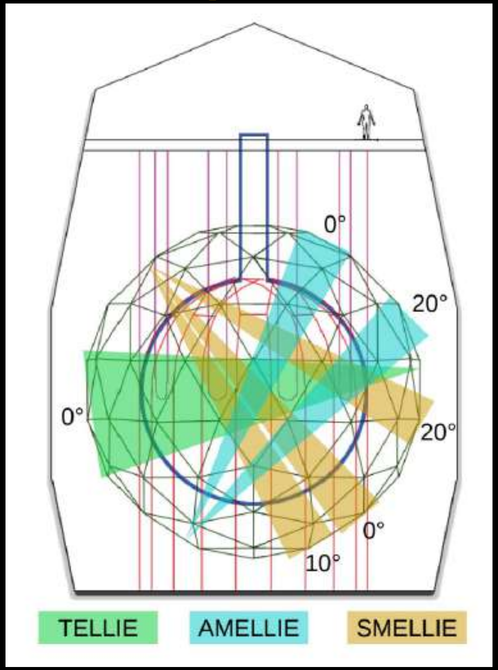
From **PMT charge and time** to **energy, direction and particle type**.

- Optical sources
  - Calibrate the PMT timing and optical properties (media and PMTs).

Cherenkov Source

Laserball

Fixed Optical Fibers



Challenges for $0\nu\beta\beta$ Search in SNO+

2. Understanding the detector response.

From **PMT charge and time** to **energy, direction and particle type**.

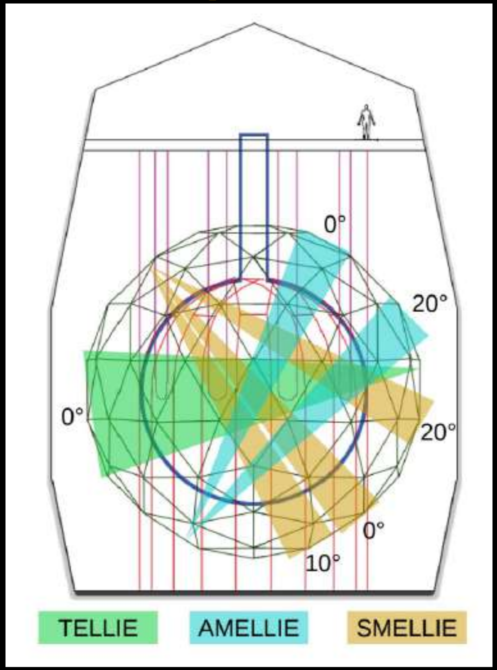
- Optical sources
  - Calibrate the PMT timing and optical properties (media and PMTs).
- Radioactive sources
  - Measure the energy scale and resolution of the detector.
  - Position and angular resolution, efficiencies…

Tagged and Untagged Radioactive Sources

Cherenkov Source

Laserball

Fixed Optical Fibers



SNO+ Timeline

SNO+ Timeline

2016 2017

Dec. 2016
Started taking
commissioning data

May 2017
Start of the
Water Phase

Dataset I: (115 live days)
May 4th 2017 -> December 2017

Dataset II: (190 live days)
October 2018 -> July 2019

^{8}B Solar Neutrinos

Detector Calibration

905 tonnes
of UPW

Nucleon Decay Searches

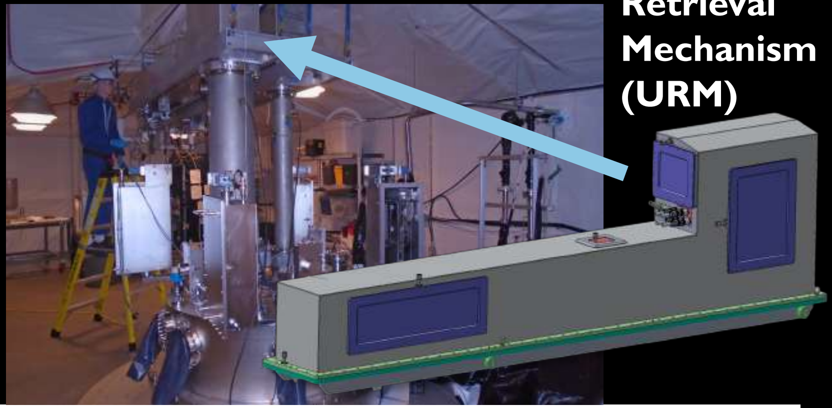
Measure External Backgrounds

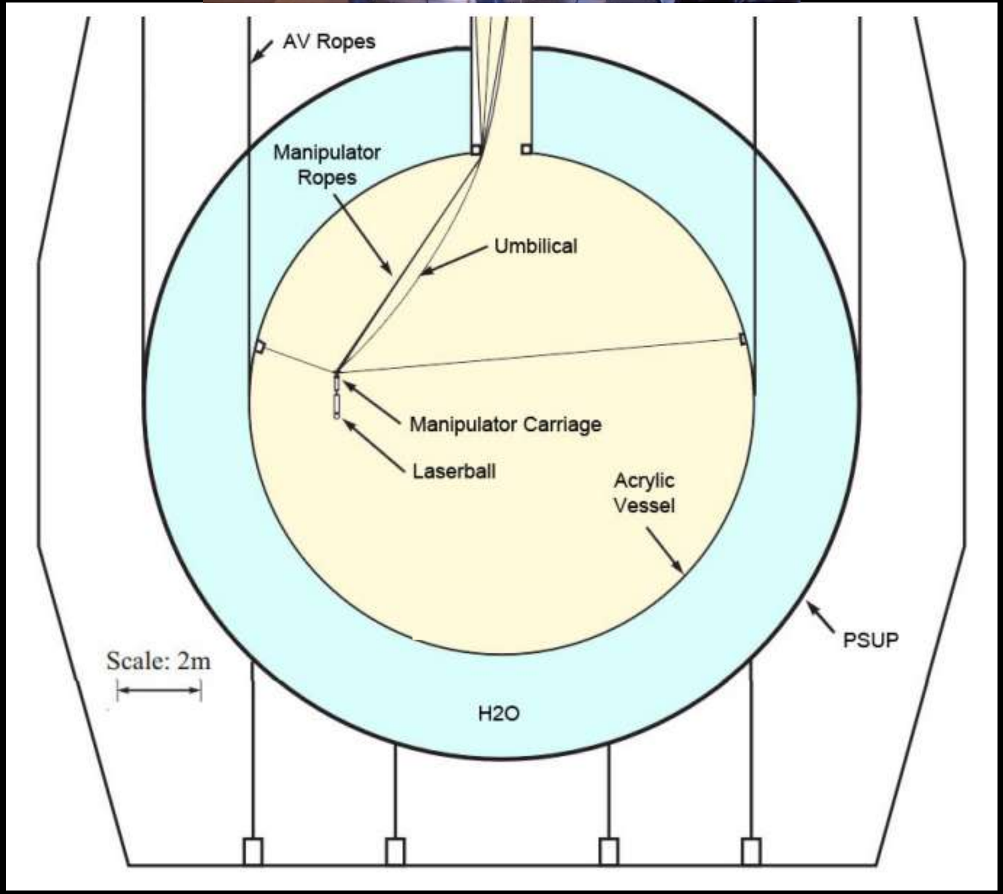
Neutron response
and Anti-neutrinos

SNO+ Water Phase

• Detector calibrations

Umbilical Retrieval Mechanism (URM)

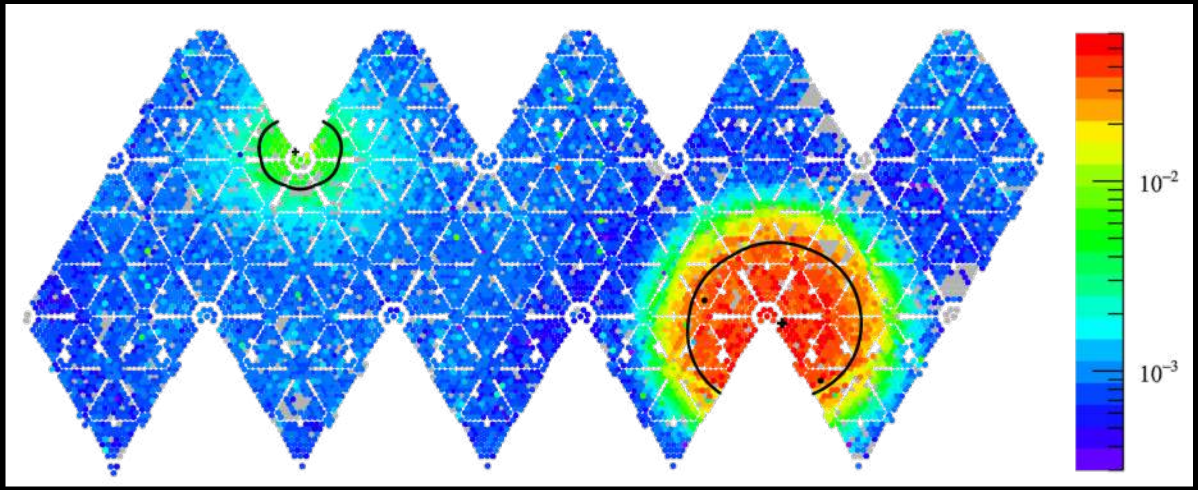


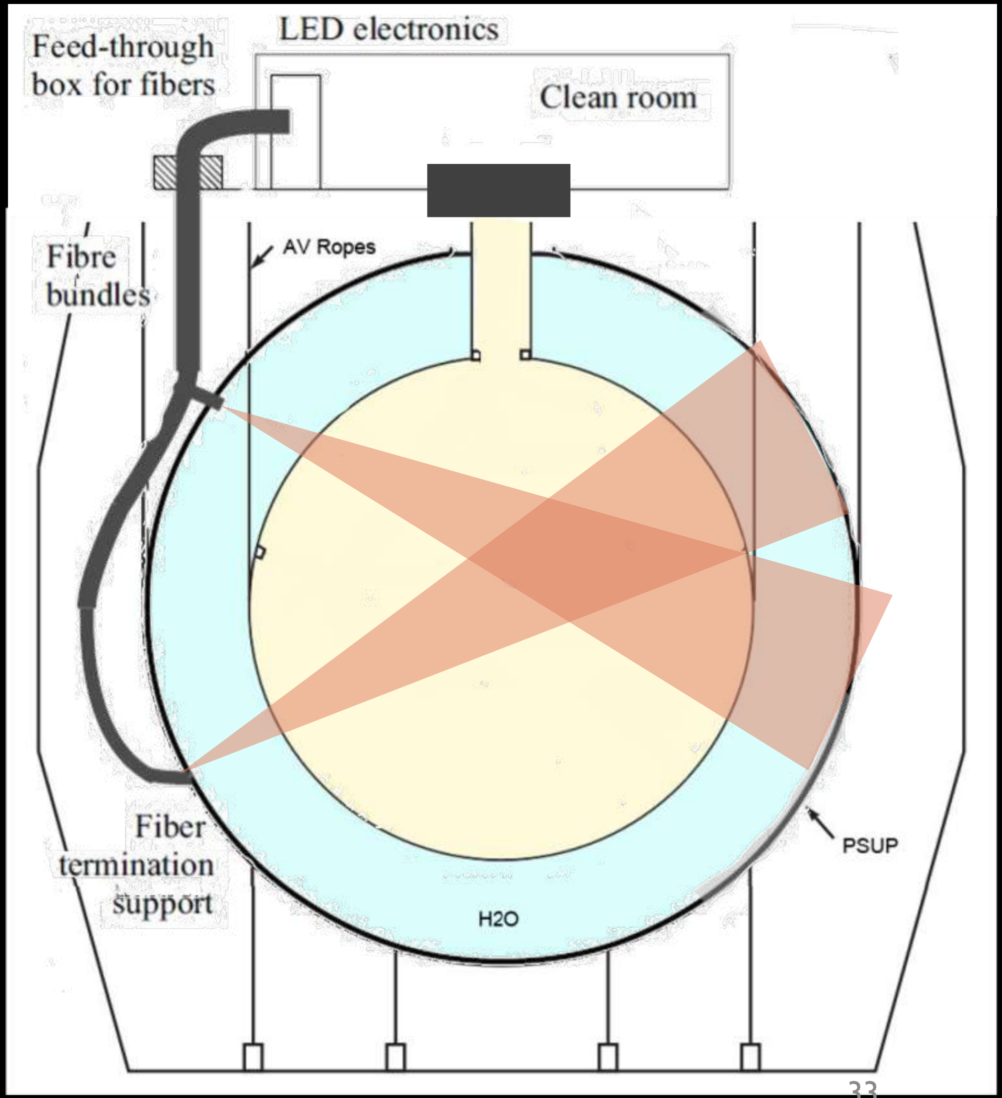


- Sources are deployed internally…
  - through the AV neck
- …and externally
  - via special calibration source guide tubes

SNO+ Water Phase

- **Detector calibrations**
  - ELLIE System - 106 LED/Laser injection points, based on PMMA and quartz fibers
    - 92 cover the whole 9400 PMT array for timing and charge calibration
    - 4 to monitor the optical attenuation
    - 10 for scattering measurements
  - Reduce contamination due to source deployment.



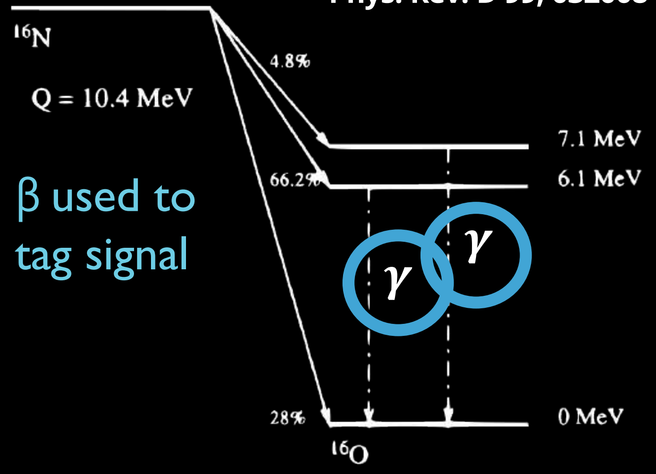


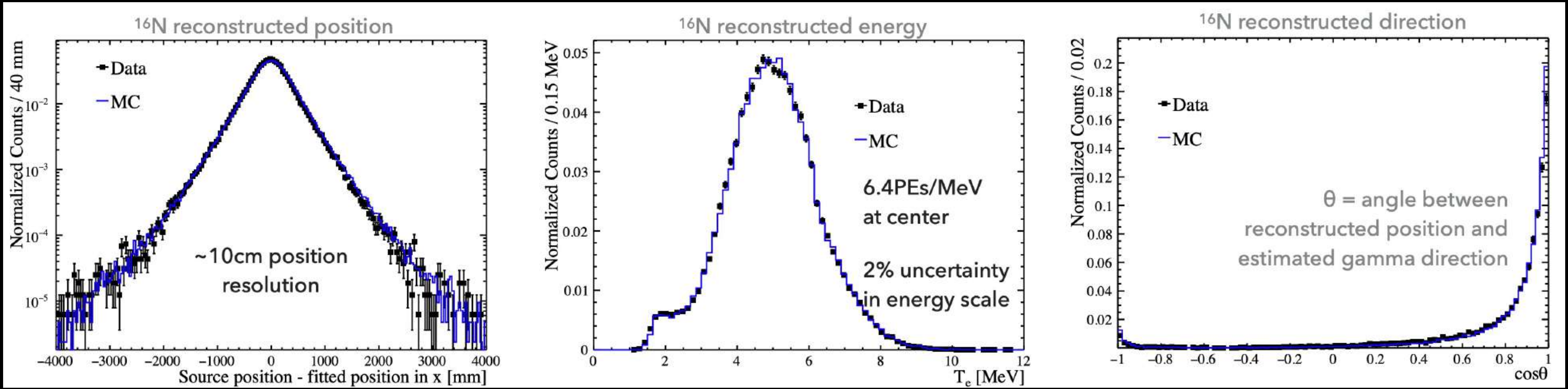
Phys. Rev. D 99, 012012 (2019)
Phys. Rev. D 99, 032008 (2019)

SNO+ Water Phase

- **Detector calibrations**
  - Energy calibration

Determine absolute energy scale

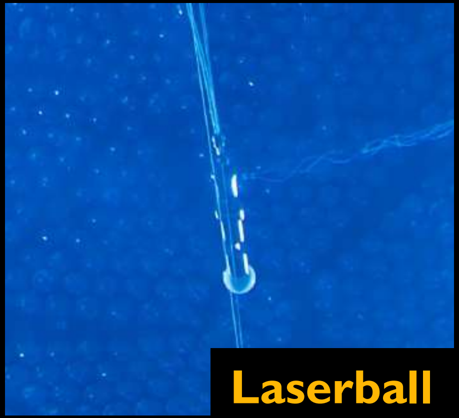


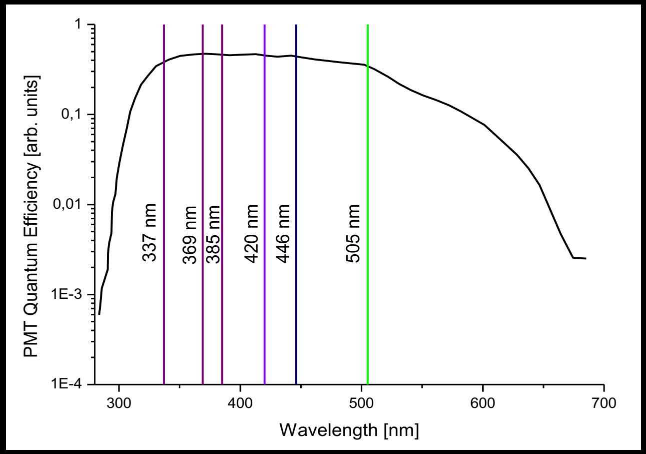


Publication coming soon!

SNO+ Water Phase

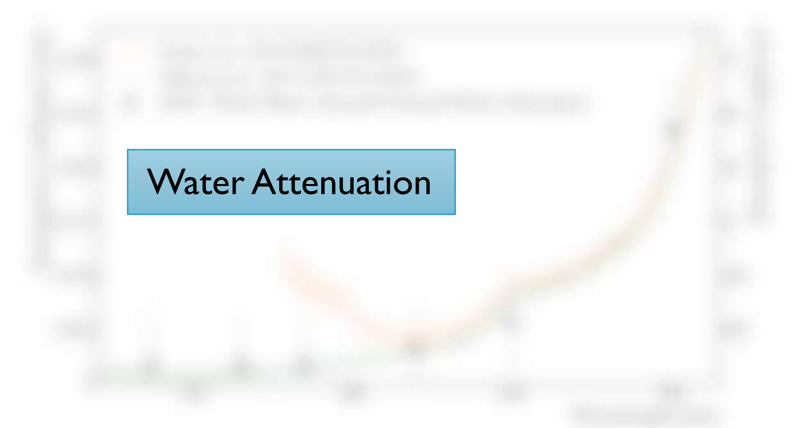
- **Detector calibrations**
  - Optical calibration

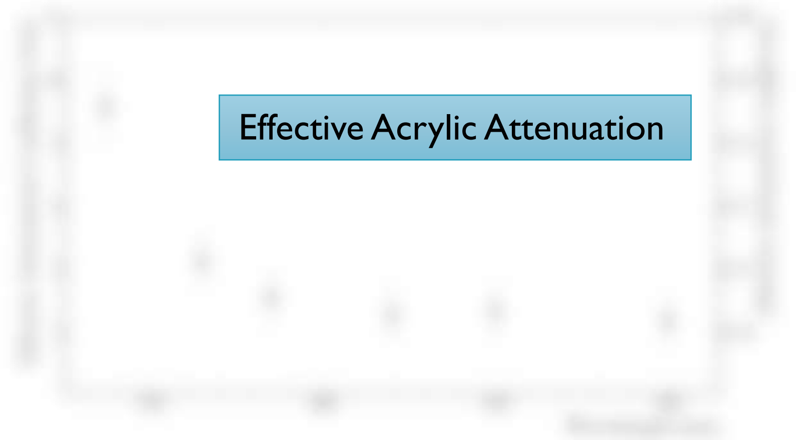




Characterizes how light propagates and is collected by the PMTs

New with respect to SNO:
– combine internal and external data

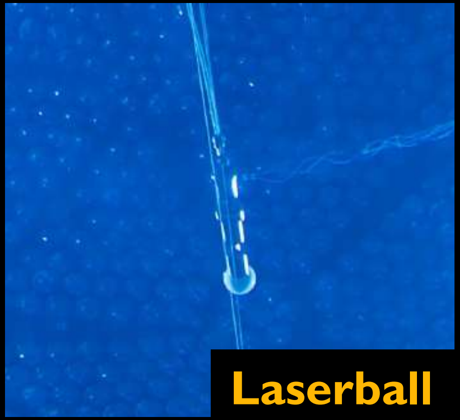




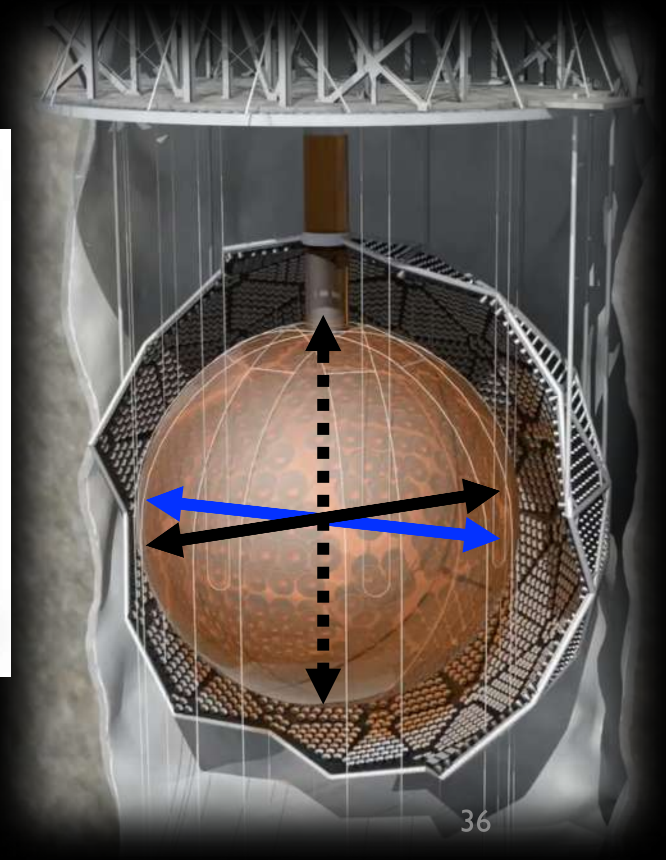
PMT Angular Response

SNO+ Water Phase

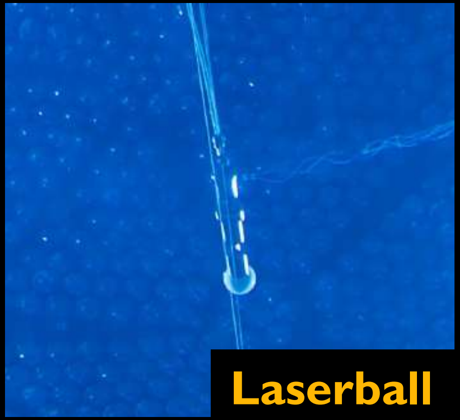
- **Detector calibrations**
  - Optical calibration



Validation of the optics measurements using the ^{16}N source



Publication coming soon!

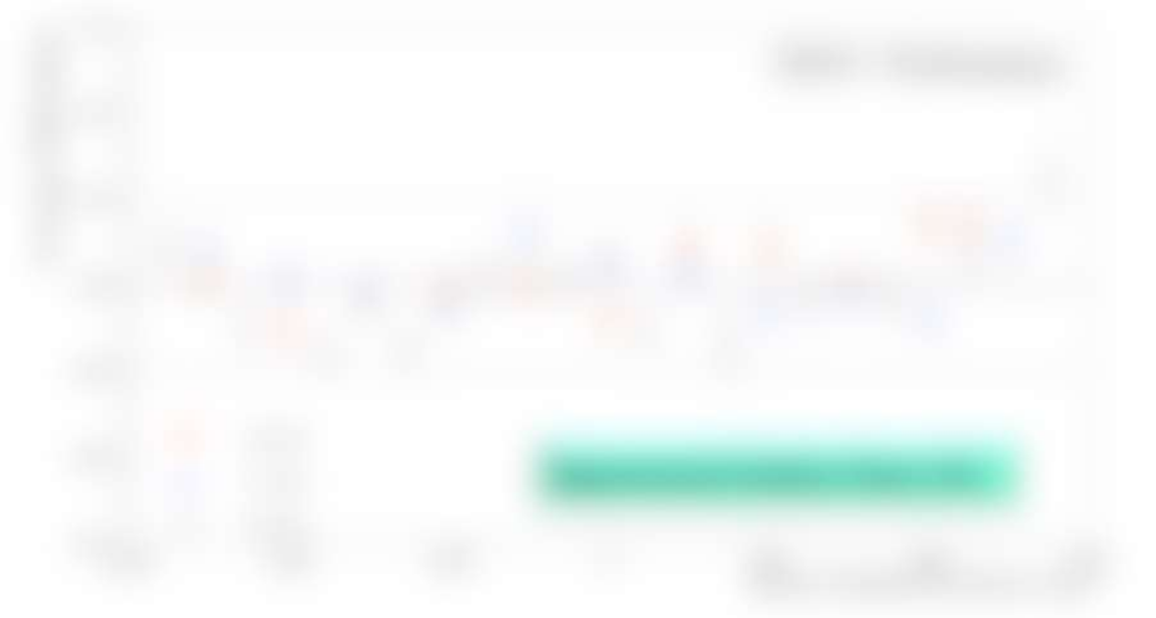


SNO+ Water Phase

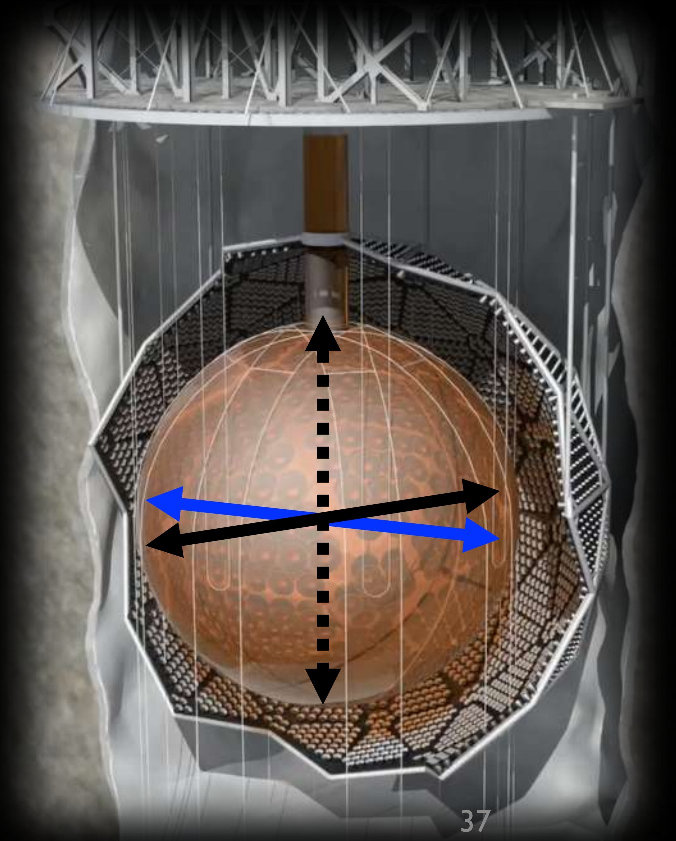
- **Detector calibrations**
  - Optical calibration

Validation of the optics measurements using the ^{16}N source

Ratio between Data and MC, as a function of position



Important measurements for an accurate detector model in the upcoming phases!



Phys. Rev. C 102, 014002 (2020)

SNO+ Water Phase

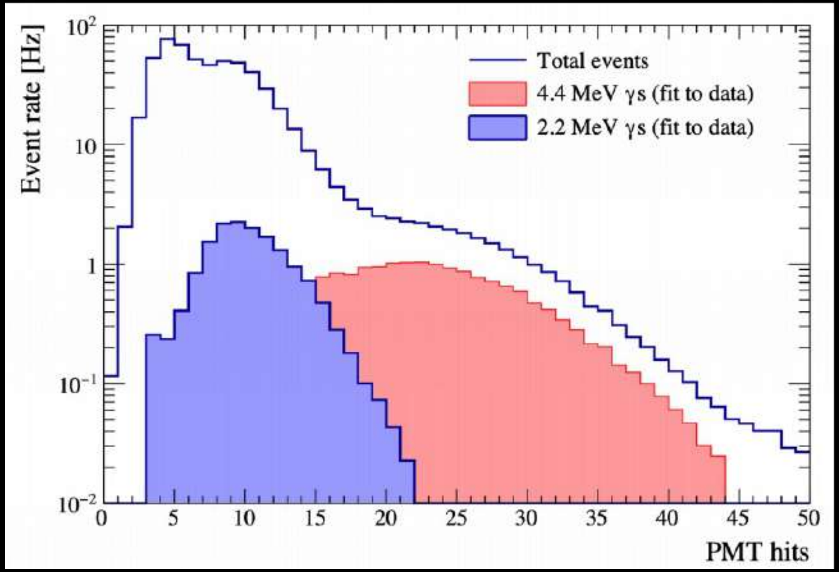
- **Detector calibrations**
  - Neutron detection efficiency

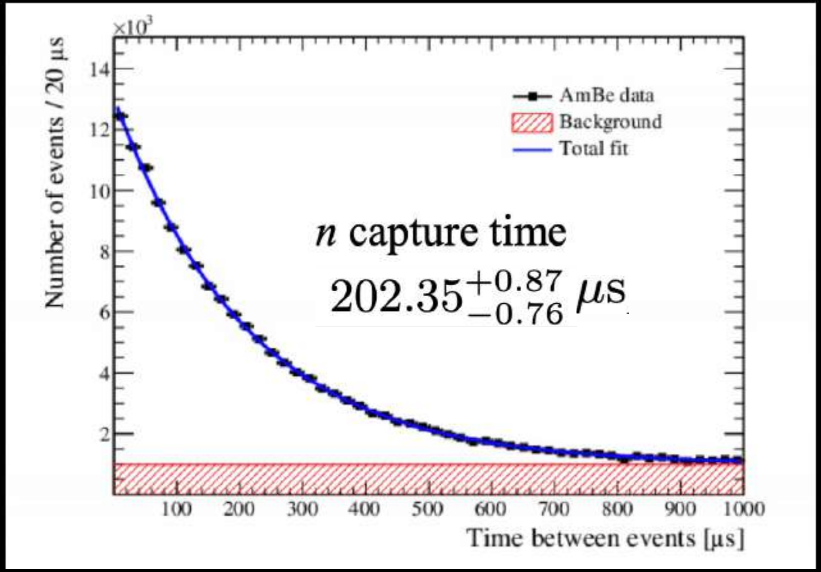
Important to study anti-neutrinos, which are detected via inverse beta decay:

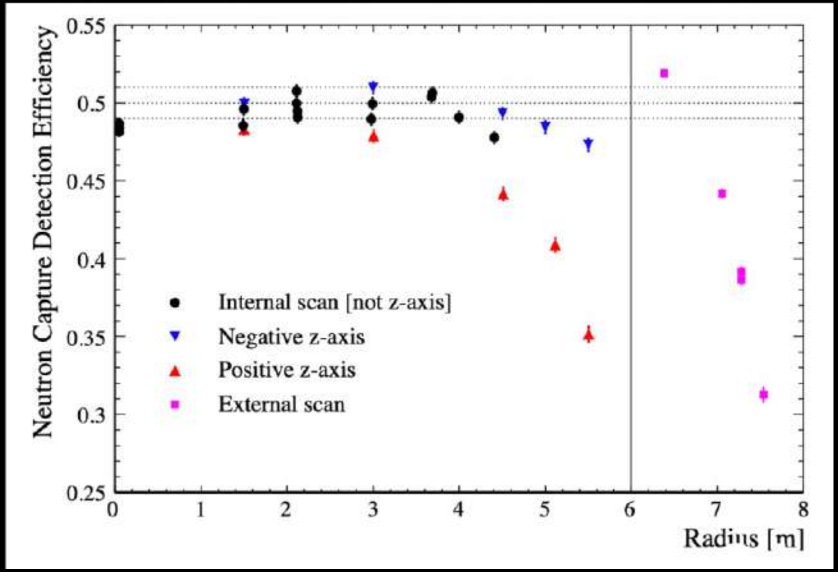
$$\bar{\nu} + p \rightarrow n + e^{+}$$

Using an $^{241}Am^{9}Be$ source
4.4-MeV γ and n (→ 2.2-MeV γ) coincidence

Efficiency for triggering on a neutron: ~50%



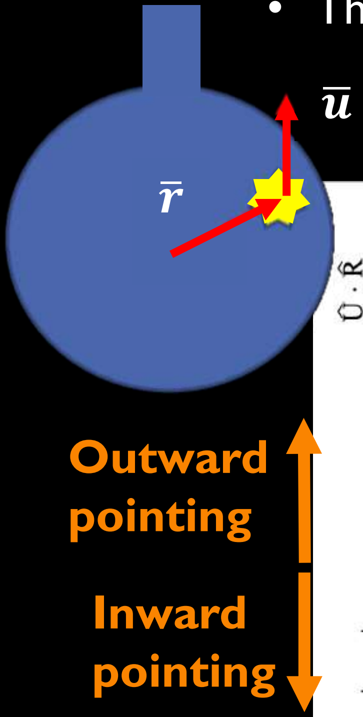


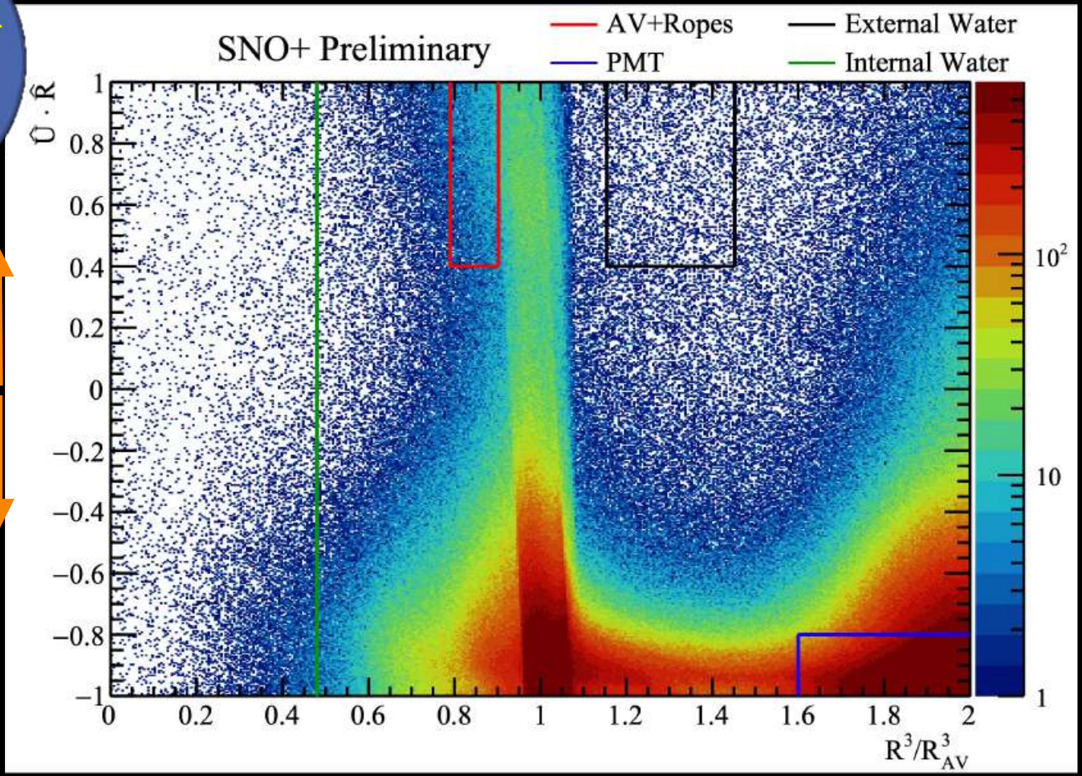


SNO+ Water Phase

- **External backgrounds measurements**
  - These components don't change with detector medium

Water Phase - simplest detector configuration to perform these measurements





AV+Ropes and External Water measurements lower than expectation.

PMT background measurement compatible with expectation, although with large uncertainties.

Contribution of the external backgrounds to the 0νββ ROI **below expectation (<80%).**

Plan to continue to monitor the rate and source of the external backgrounds in the next phases.

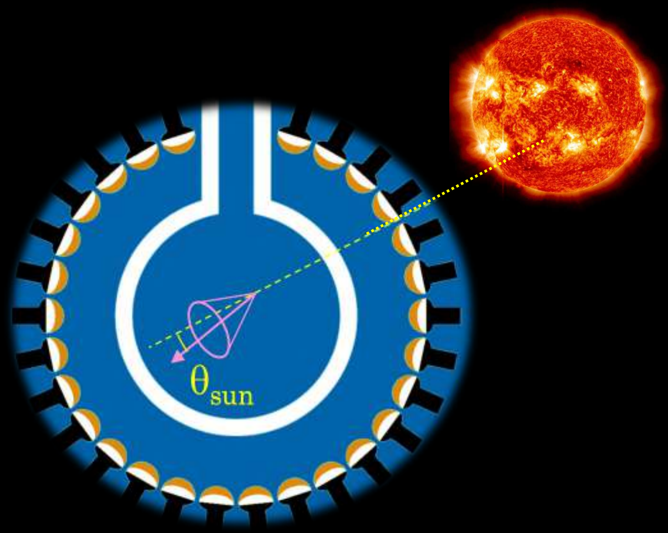
Phys. Rev. D 99, 012012 (2019)

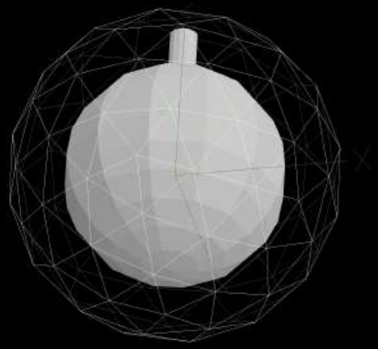
SNO+ Water Phase

- ^{8}B Solar Neutrino Flux

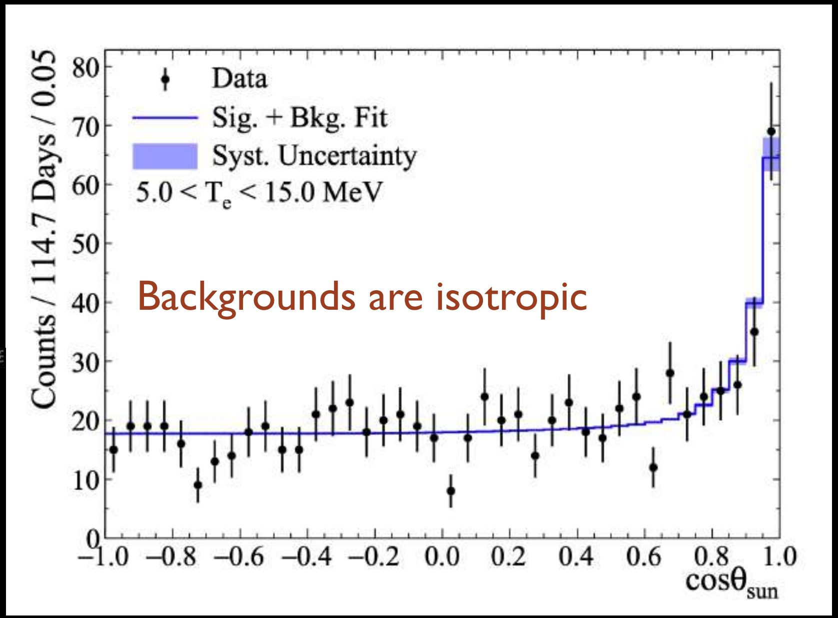
$$\Phi_{^8\mathrm{B}} = 5.95^{+0.75}_{-0.71}(\mathrm{stat.})^{+0.28}_{-0.30}(\mathrm{syst.}) \times 10^{6}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Compatible with previous measurements

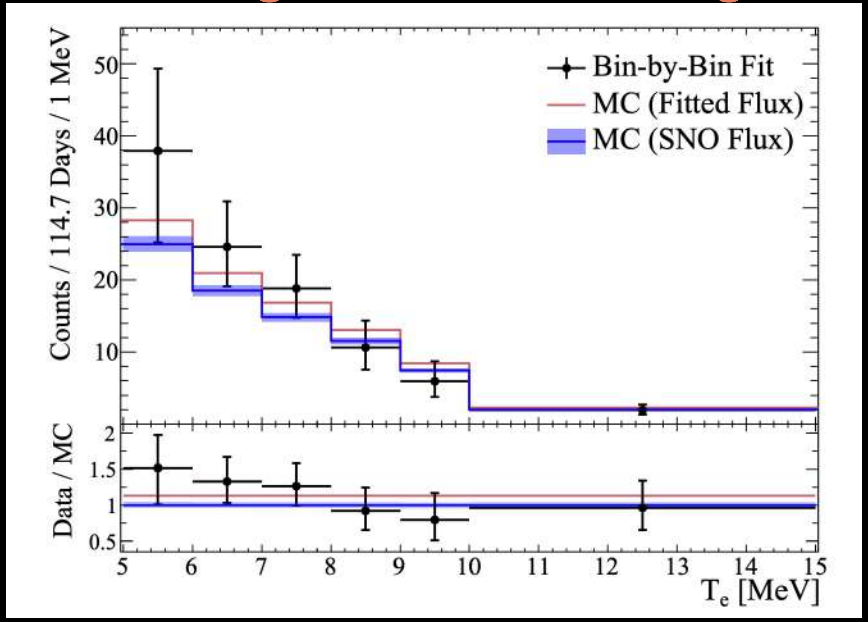




Angle between electron and Sun direction



Electron kinetic energy distribution for background subtracted signal

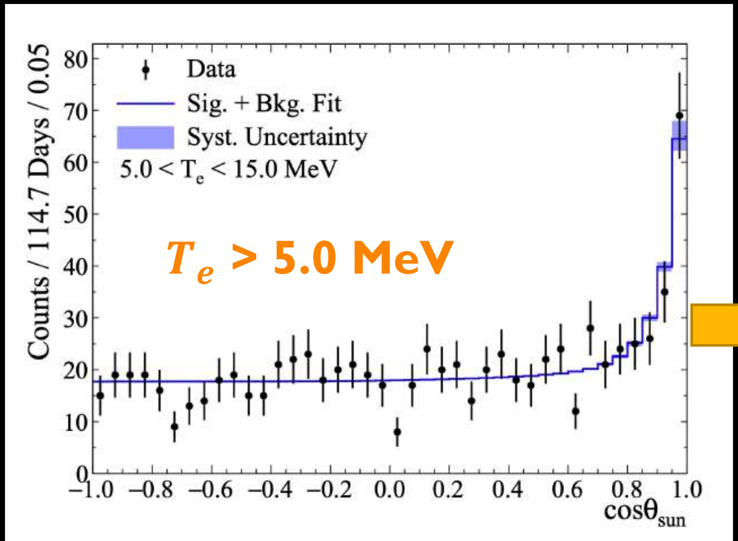


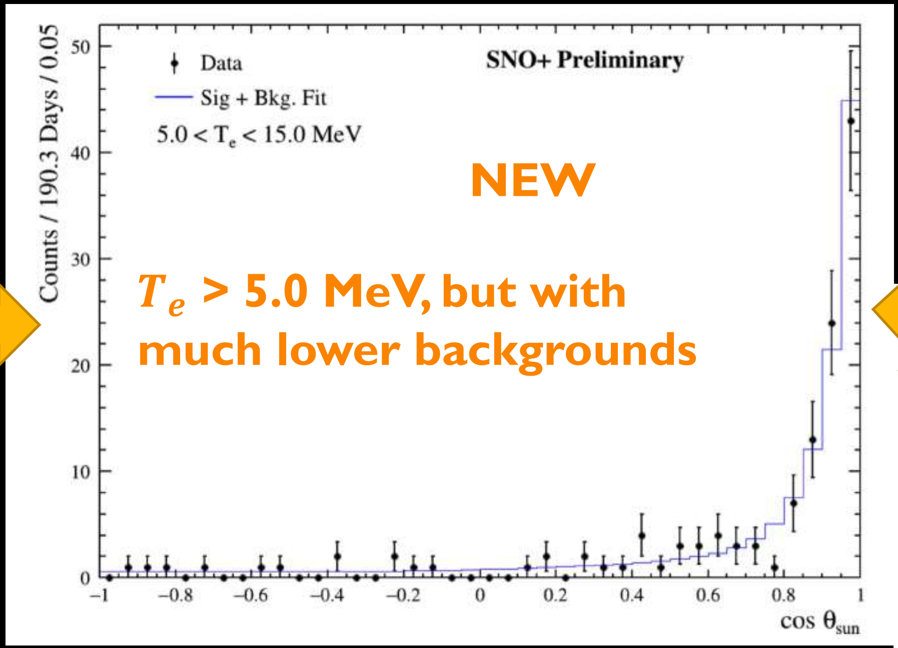
SNO+ Water Phase

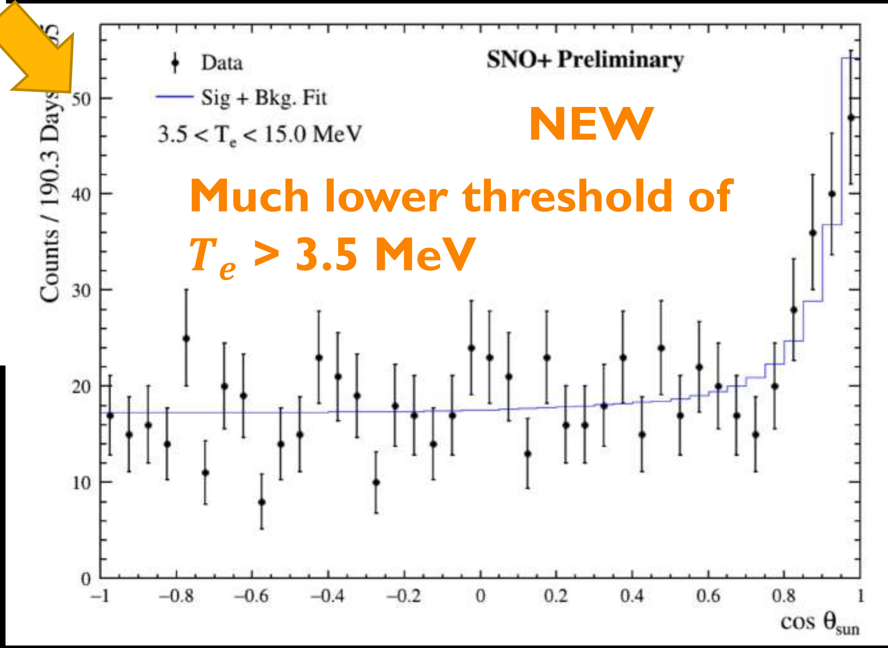
- ^{8}B Solar Neutrino Flux

Results from Dataset II coming soon!

Updating analyses with:
(1) completed optical calibration
(2) > twice the statistics
(3) lower Rn backgrounds.







Radon ingress down the neck mitigated with a N_2 cover gas.

U and Th levels one order of magnitude lower!

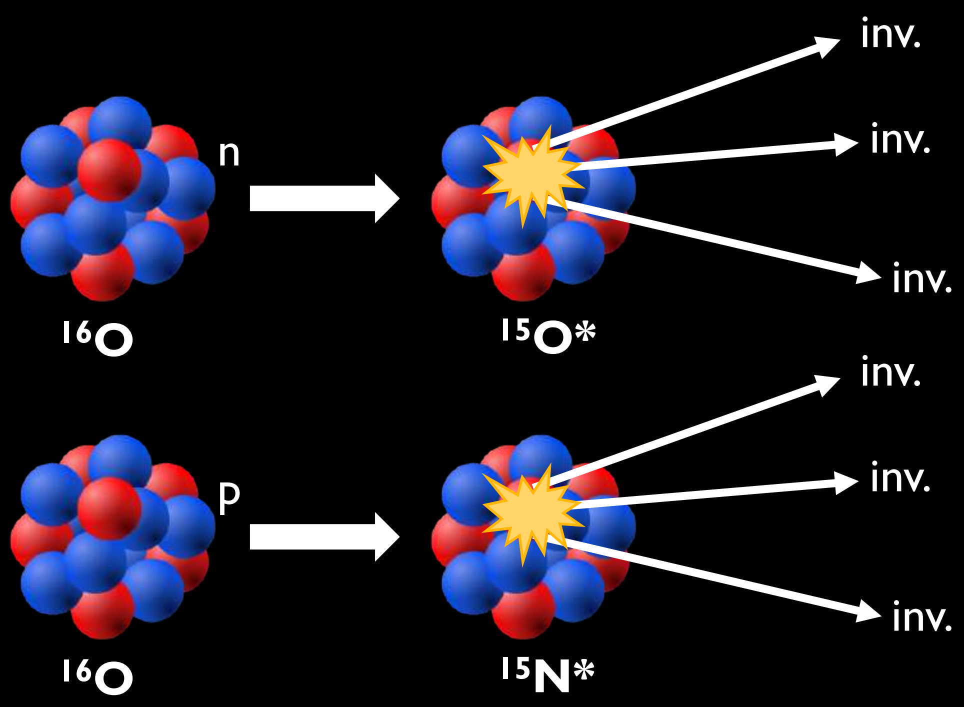
	gU/gH2O	gTh/gH2O
Dataset I	$(3.6 \pm 0.9^{+1.0}_{-0.7}) \times 10^{-14}$	$< 1.3 \times 10^{-14}$(95%CL)
Dataset II	$(3.2 \pm 0.7^{+1.1}_{-0.9}) \times 10^{-15}$	$< 1.1 \times 10^{-15}$(95%CL)

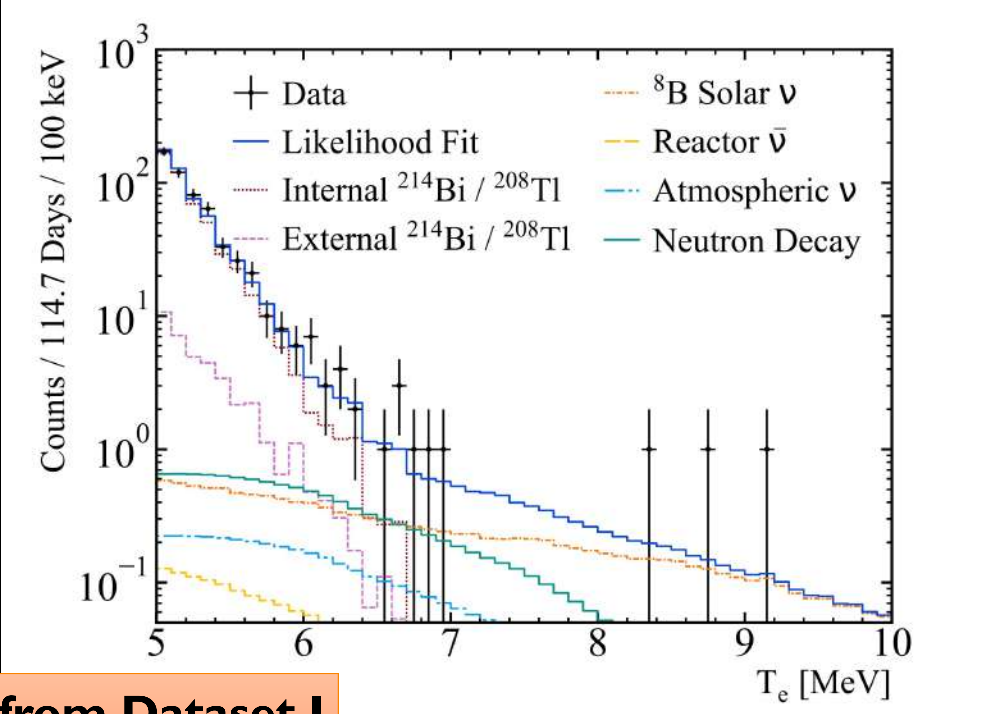
Phys. Rev. D 99, 032008 (2019)

SNO+ Water Phase

- **Invisible Nucleon Decay Searches**

Detect the de-excitation gammas (6-7 MeV)





Results from Dataset I

	Spectral analysis	Counting analysis	Existing limits	
n	2.5×10^{29} y	2.6×10^{29} y	5.8×10^{29} y	KamLAND
p	3.6×10^{29} y	3.4×10^{29} y	2.1×10^{29} y	SNO
pp	4.7×10^{28} y	4.1×10^{28} y	5.0×10^{25} y	Borexino
pn	2.6×10^{28} y	2.3×10^{28} y	2.1×10^{25} y	V.Tretyak *et al*
nn	1.3×10^{28} y	0.6×10^{28} y	1.4×10^{30} y	KamLAND

*90% C.I. lifetime limits

Results from Dataset II coming soon!

Updating analyses with: (1) completed optical calibration (2) > twice the statistics (3) lower Rn backgrounds.

SNO+ Timeline

2016 — Dec. 2016: Started taking commissioning data

2017 — May 2017: Start of the Water Phase

2019 — Start of Scintillator Fill

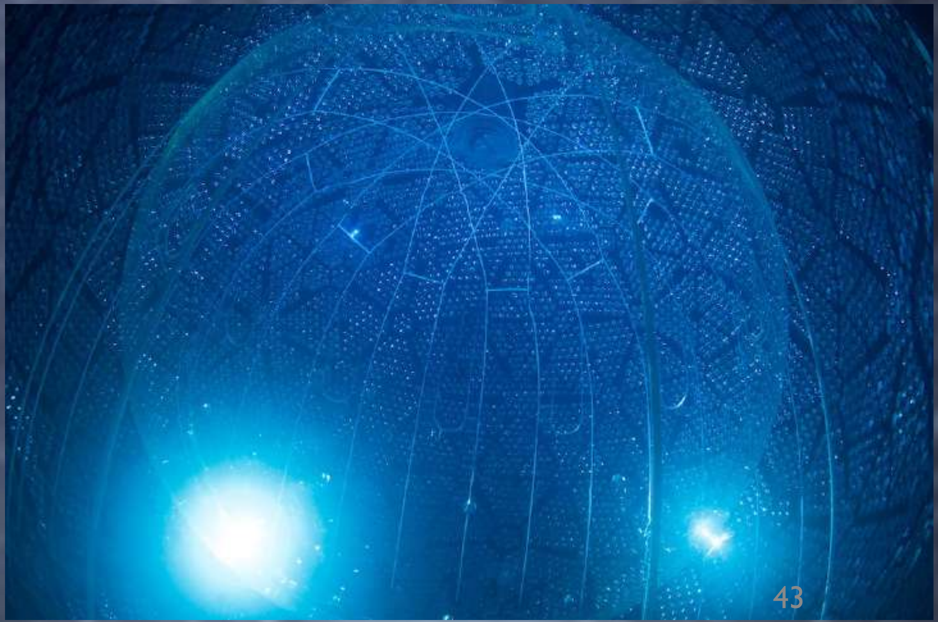
2021 — End of Scintillator Fill

We are here!

Thousands of photons per MeV → hundreds of PMT hits / MeV

Much lower energy threshold

Isotropic light – almost no particle direction information



SNO+ Timeline

2016 — 2017 — 2019 — 2021

- **Dec. 2016** Started taking commissioning data
- **May 2017** Start of the Water Phase
- **Start of Scintillator Fill**
- **End of Scintillator Fill**

We are here!

^{8}B + Low Energy Solar Neutrinos

Reactor Anti-neutrinos

Nucleon Decay Searches

Geo Anti-Neutrinos

Measurement of Internal Backgrounds before adding the Tellurium

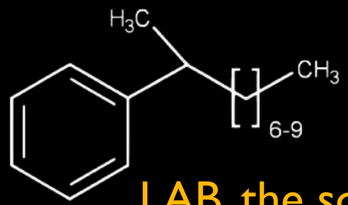
Perform a "target out" $\beta\beta$ analysis
→ prepare/test analysis and techniques using real data
→ determine count rate in the ROI in the absence of Tellurium

Scintillator Filling and Purification

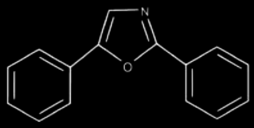
Quebec

Transfer of LAB from surface to underground in tank railcars at SNOLAB

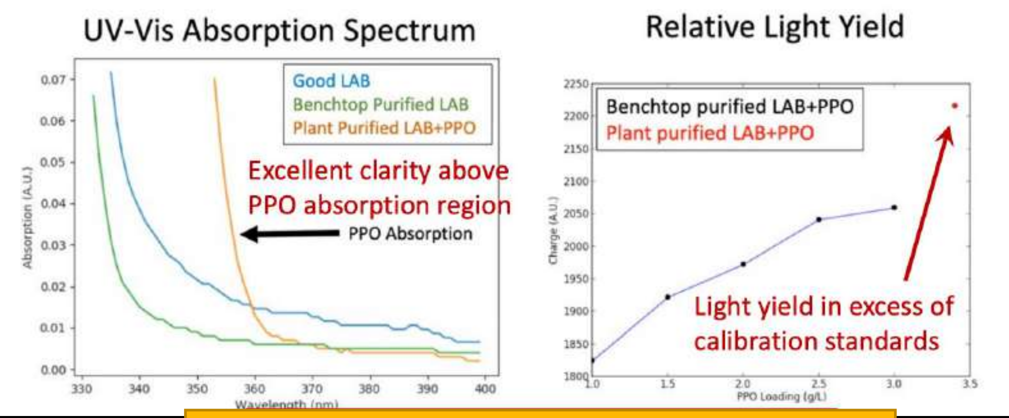
Purification and Filling Systems



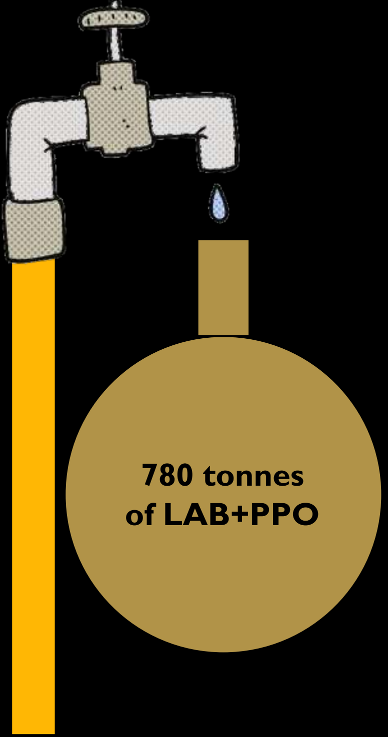
LAB, the solvent



PPO,
the fluor



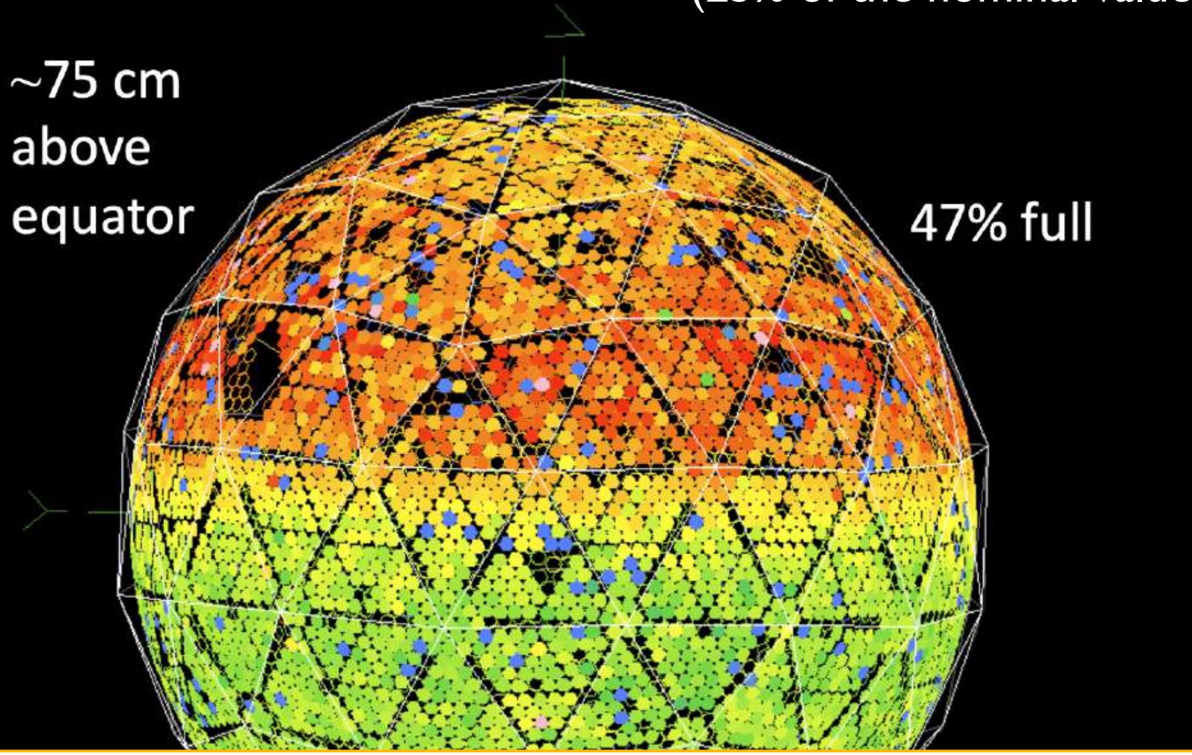
LS quality is better than expected!



SNO+ Scintillator Phase

“Partial Fill Phase”

PPO concentration of only 0.5 g/L (25% of the nominal value)



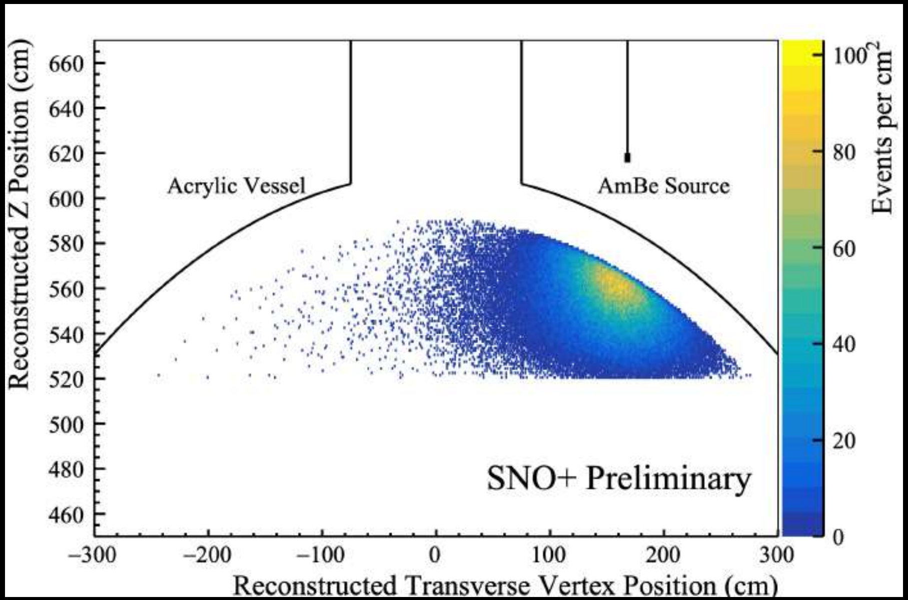
- Almost 7 months in a half-filled configuration.
- Data during the fill used to **measure and monitor the backgrounds** in the liquid scintillator.
- Several physics topics being explored using these data:
  - Solar neutrinos, anti-neutrinos…

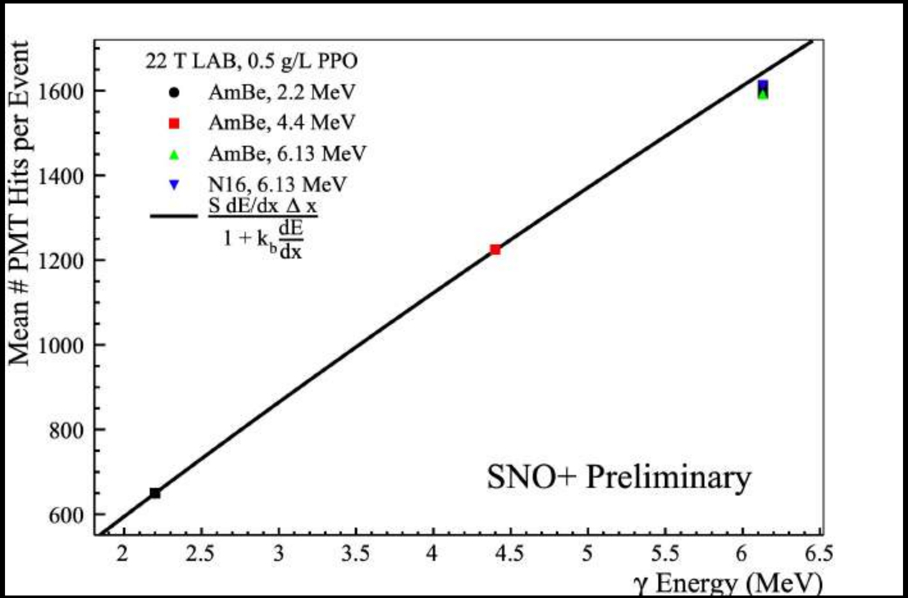
SNO+ Scintillator Phase

"Partial Fill Phase"

- Detector response during LS fill was measured with optical and radioactive source calibrations
- Source deployments performed outside the acrylic vessel
  - Leave the scintillator undisturbed and avoid contamination
  - Demonstrated the capability to reconstruct events in a hybrid LS/water detector

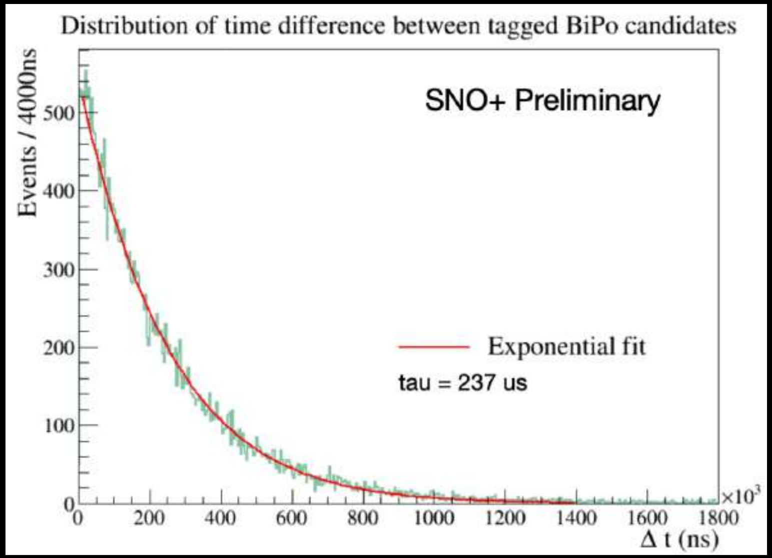
- With a PPO concentration of only 0.5 g/L we see a light yield equivalent to ~300 p.e. / MeV
- Extrapolates to ~650 p.e. / MeV at 2.0 g/L PPO



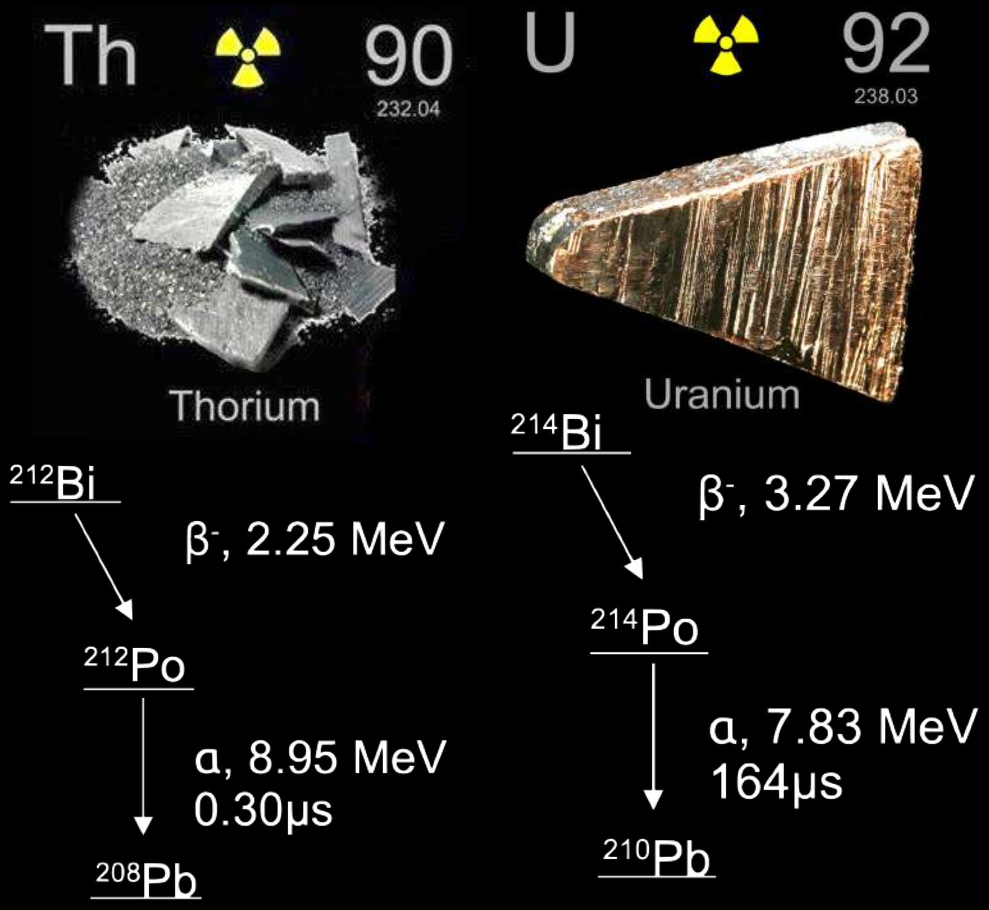


SNO+ Scintillator Phase

- Measure intrinsic U and Th levels in the scintillator.
    - From ^{212}Bi and ^{214}Bi, which can be tagged by looking for the Po follower.



Time difference between ^{214}Bi beta and ^{214}Po alpha candidates



SNO+ Scintillator Phase

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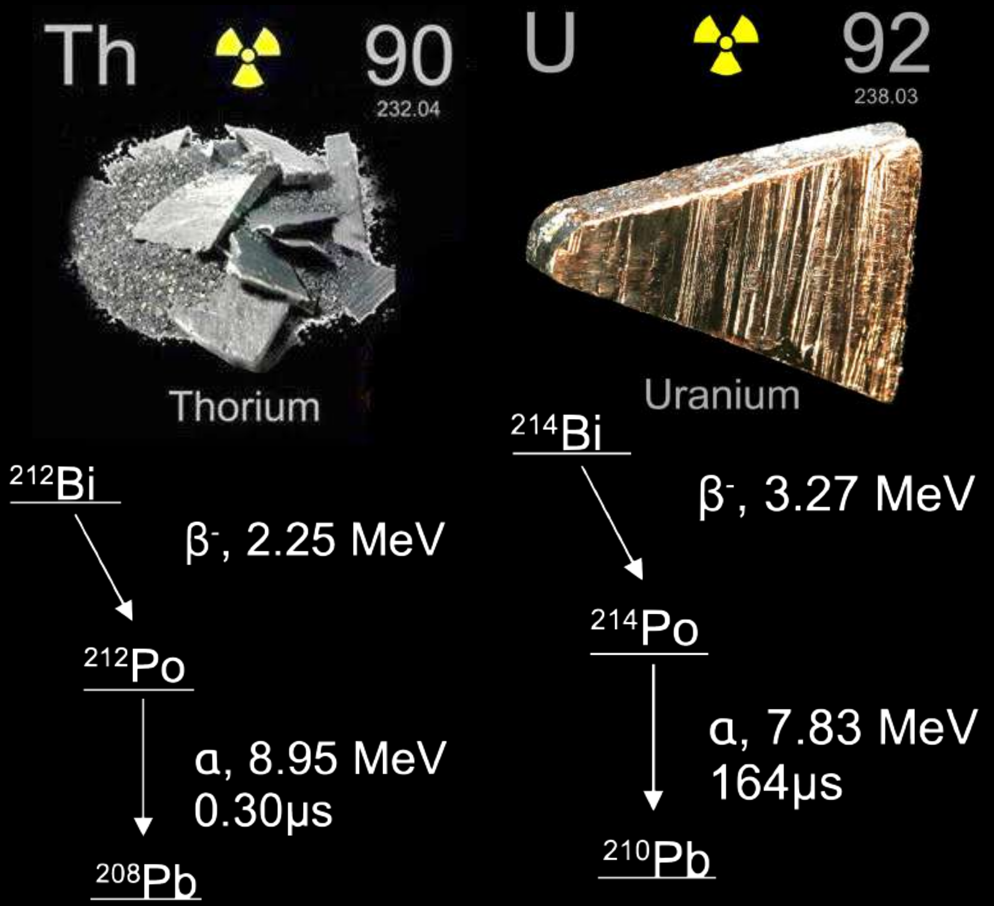
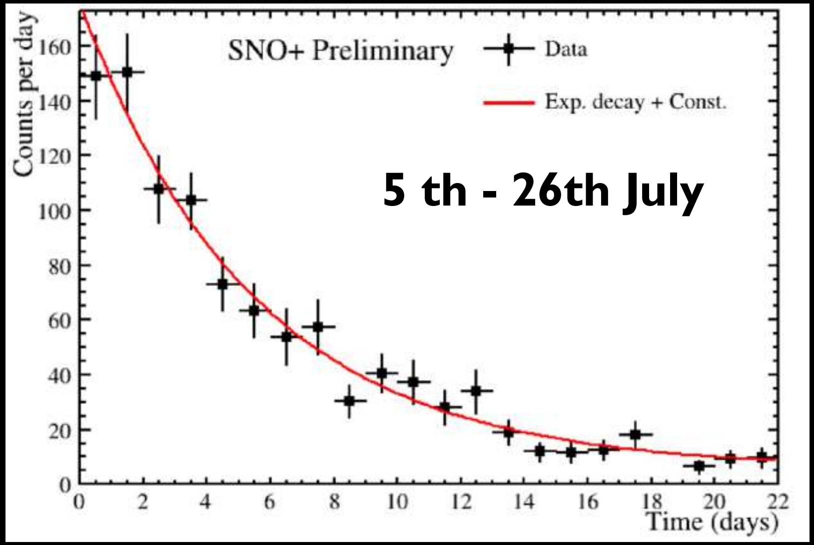




So far, measurements using the partial fill data show that our U and Th rates are below the requirements for the $0\nu\beta\beta$ search.

U Rate: 4.6±1.1$\times10^{-17}$ gU/gScint

Th Rate: ~6$\times10^{-17}$ gTh/gScint

SNO+ Timeline

2016

Dec. 2016
Started taking commissioning data

2017

May 2017
Start of the Water Phase

2019

Start of Scintillator Fill

780 tonnes of LAB+PPO

+0.5% Te loading

2021

End of Scintillator Fill

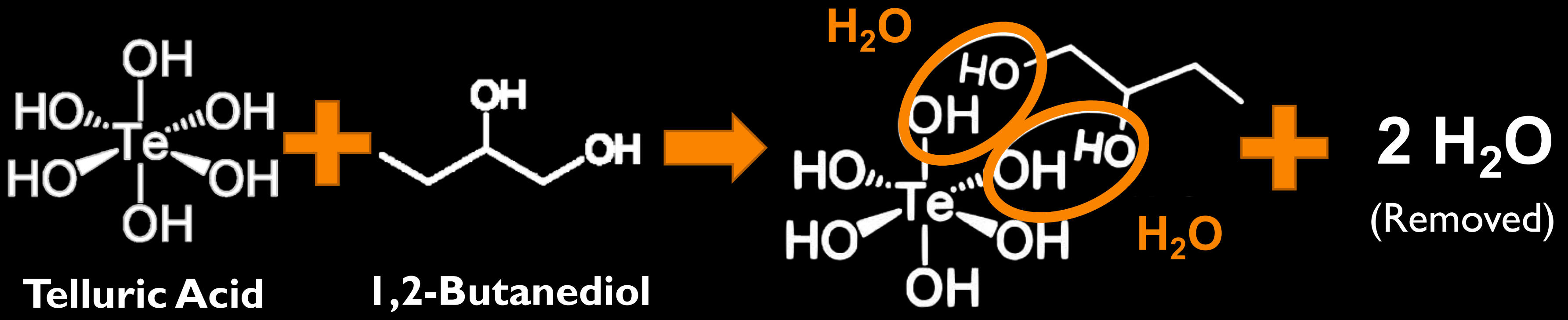
2022

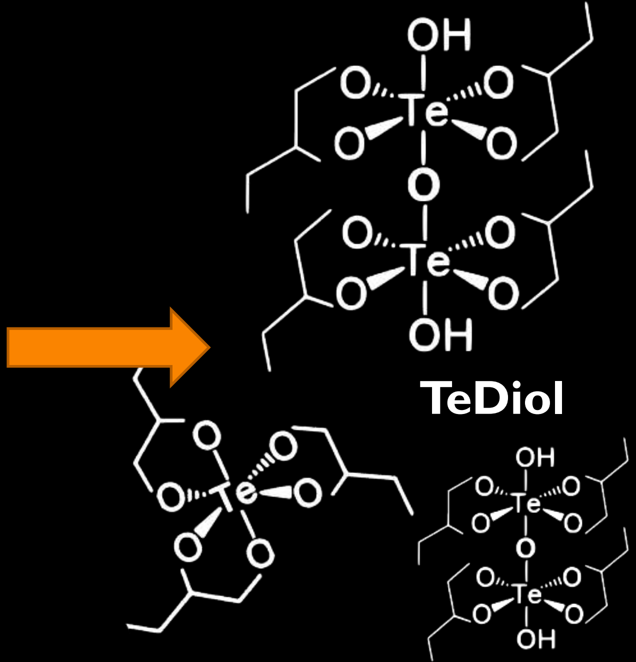
Tellurium is added to the scintillator

$0\nu\beta\beta$ Search

Tellurium Loading

- Forming an organometallic compound from telluric acid and butanediol:

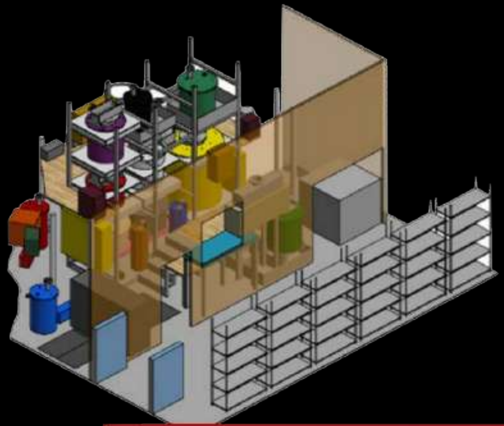




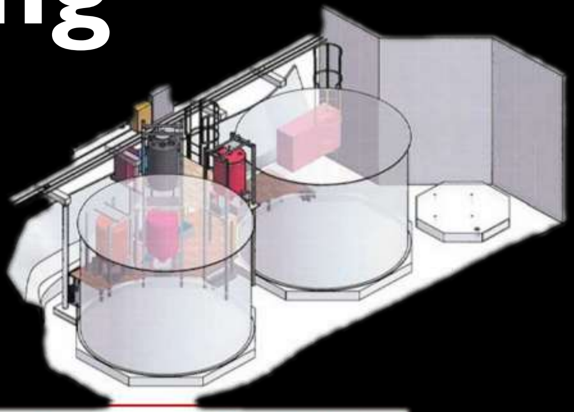
- TeDiol is mixed directly into **SNO+ liquid scintillator (LAB+PPO)** with 15 mg/L bis-MSB and a stabilizer called Dimethyldodecylamine (DDA).

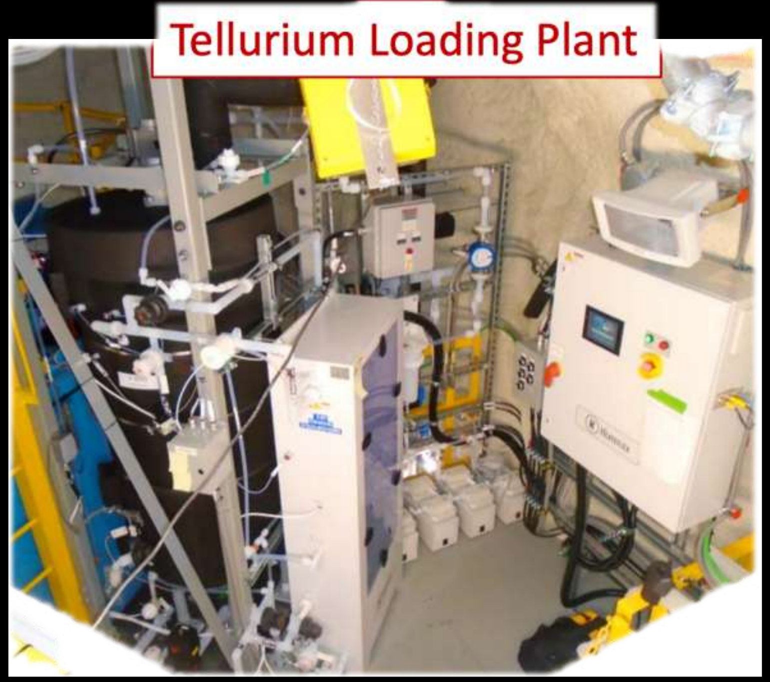
- Optical transparency and light yield of the final Te-loaded LS cocktail are expected to produce ~ 460 p.e. / MeV in SNO+ for 0.5% natural Te loading by weight

Tellurium Purification and Loading



- ~8 tons of telluric acid has been "cooling" underground for several years.
- Ton-scale underground purification of telluric acid for further background reduction
- Target purification:
  - 10^{-13} gU238/gTeA
  - $5x10^{-14}$ gTh232/gTeA



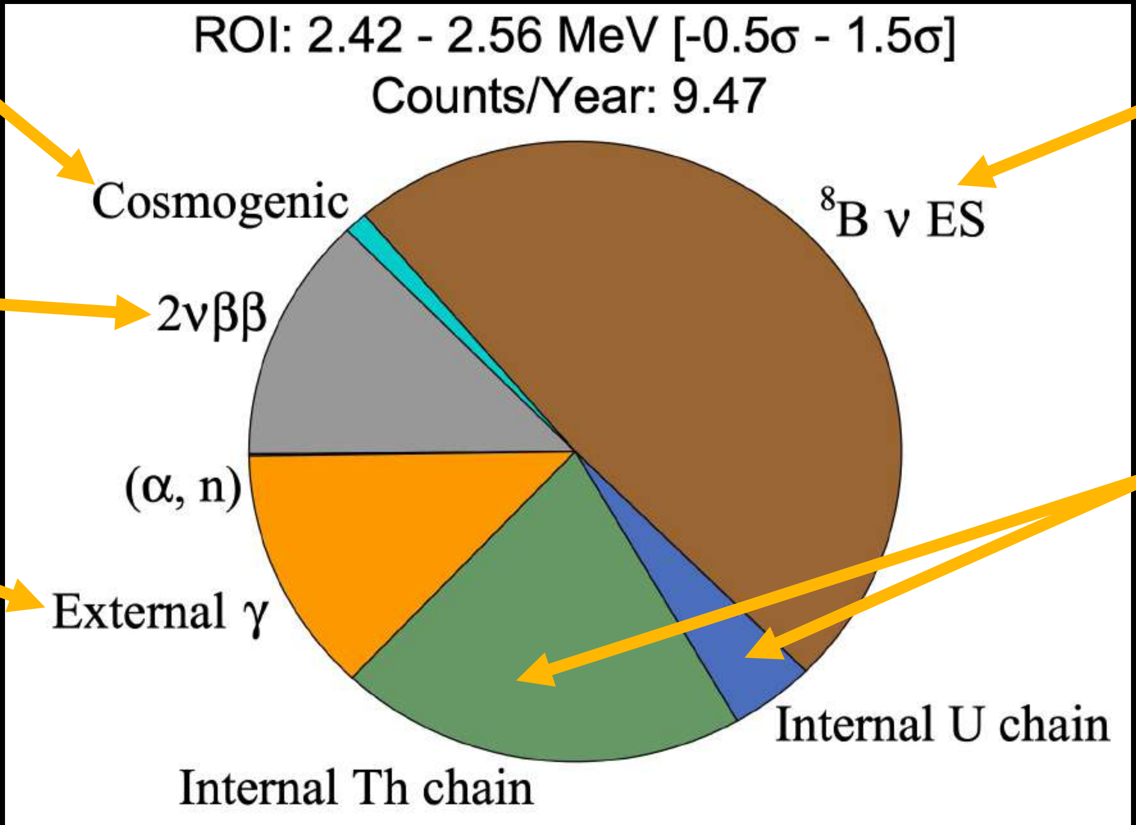


SNO+ Tellurium Phase - Prospects

Telluric acid has been "cooling" underground for several years + Te purification

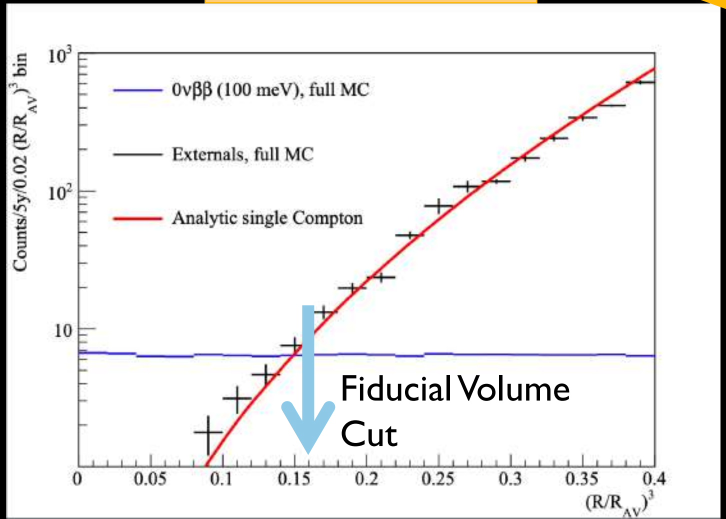
Suppressed by asymmetric ROI

Measured in Water Phase.



Well known from other measurements.

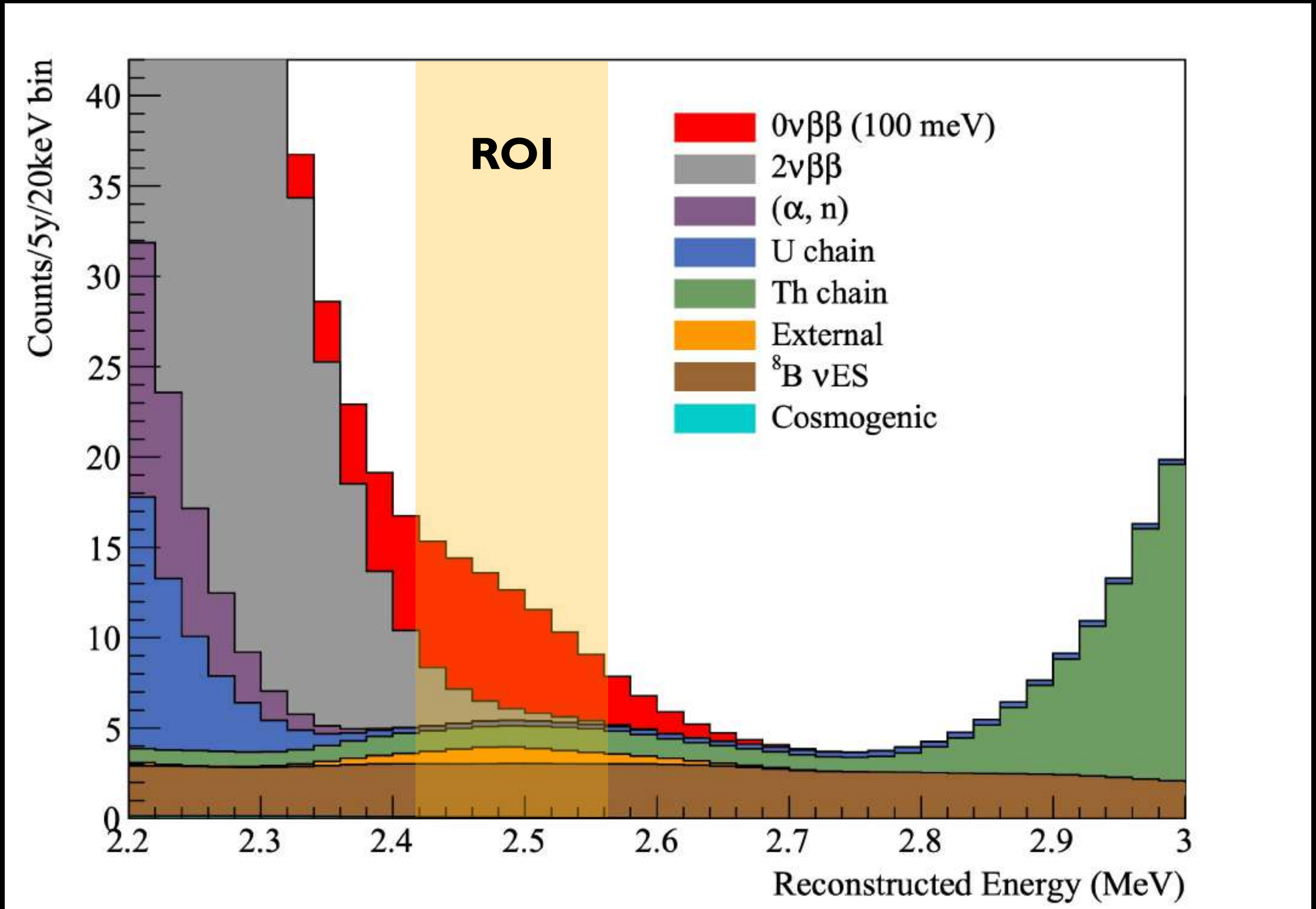
LS contribution measured during the partial fill, below our target.
U and Th from the Te addition to be minimized with the purification systems-



Remaining backgrounds will be measured during Te-loading!

SNO+ Tellurium Phase - Prospects

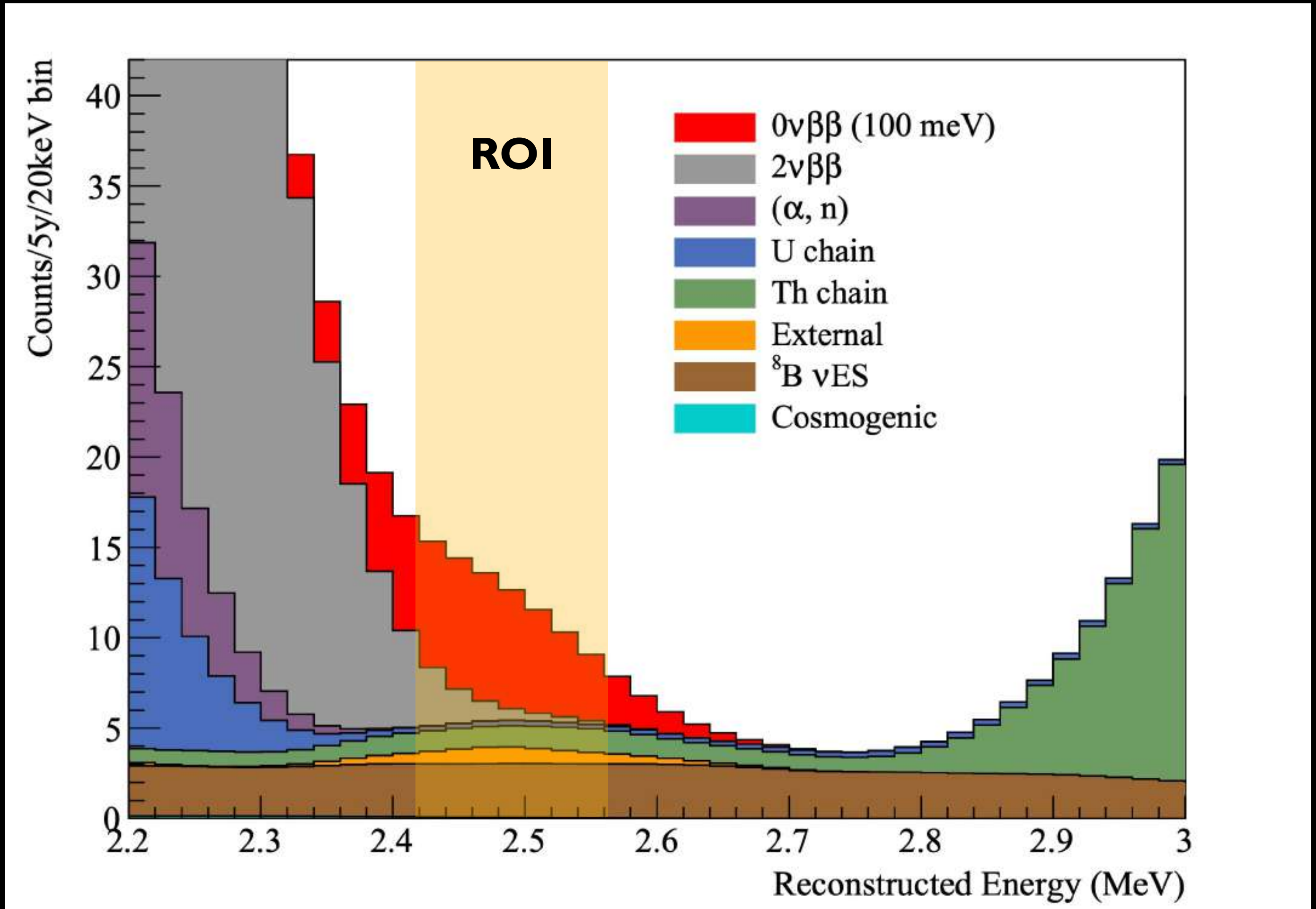
Expected Energy Spectrum after 5 Years with 0.5% Te loading, Fiducial Volume of 3.3 m radius



Expect 9.47 events / year in the ROI (with our target background levels)

SNO+ Tellurium Phase - Prospects

Expected Energy Spectrum after 5 Years with 0.5% Te loading, Fiducial Volume of 3.3 m radius



From a simple counting analysis, for 5 years, in an optimized energy ROI and fiducial volume

Expected Half-Life Sensitivity > 2.1×10^{26} years

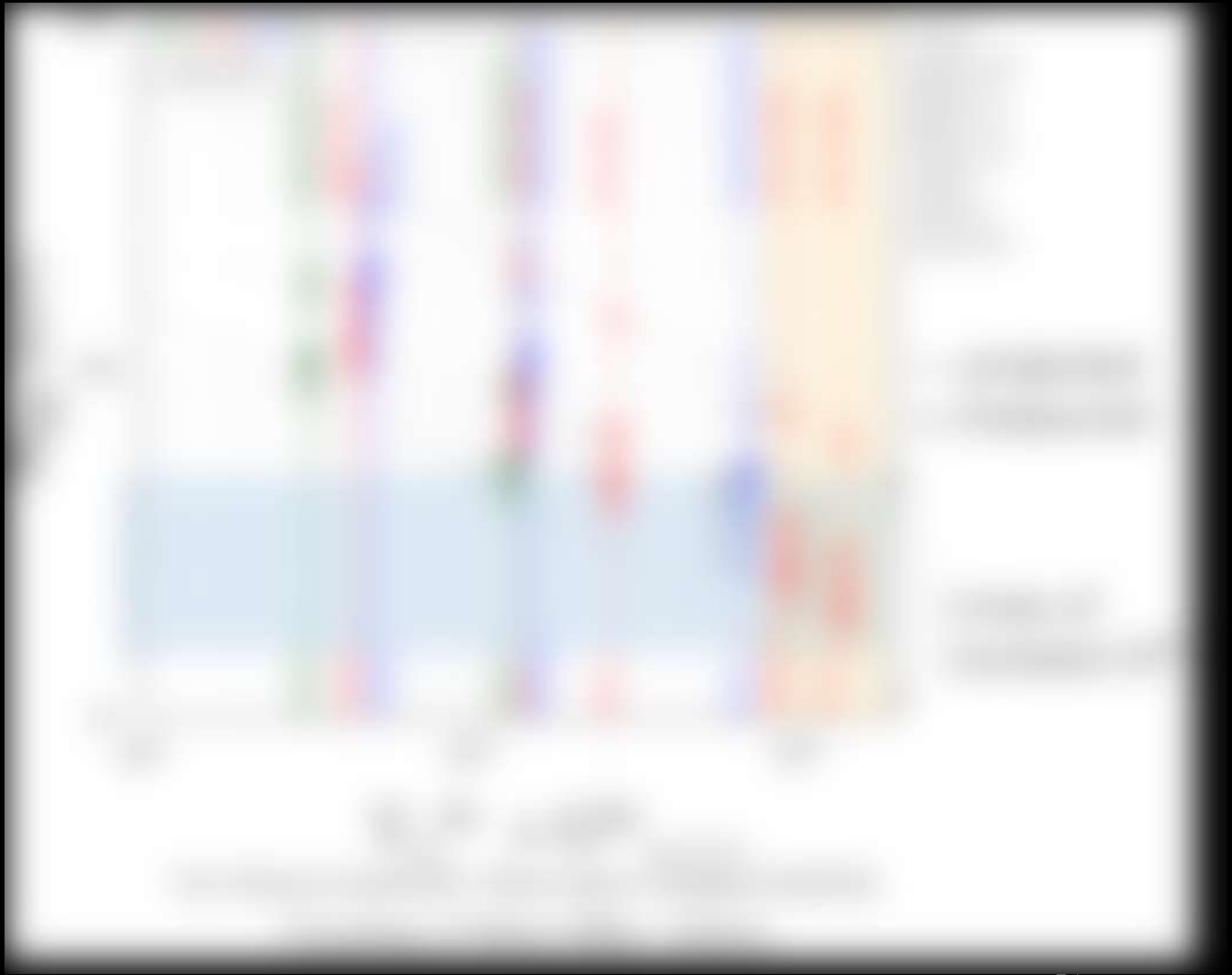
$m_{\beta\beta}$ range 37-89 meV (model dependent)

SNO+ Tellurium Phase - Prospects

- Expect world-leading sensitivity with 0.5% loading!

- SNO+ approach can be scaled up.
    - R&D has shown that Te loading can be increased by a factor of 5-10
    - Cost is relatively very low (< $2M per ton of decay isotope)

SNO+ Phase II

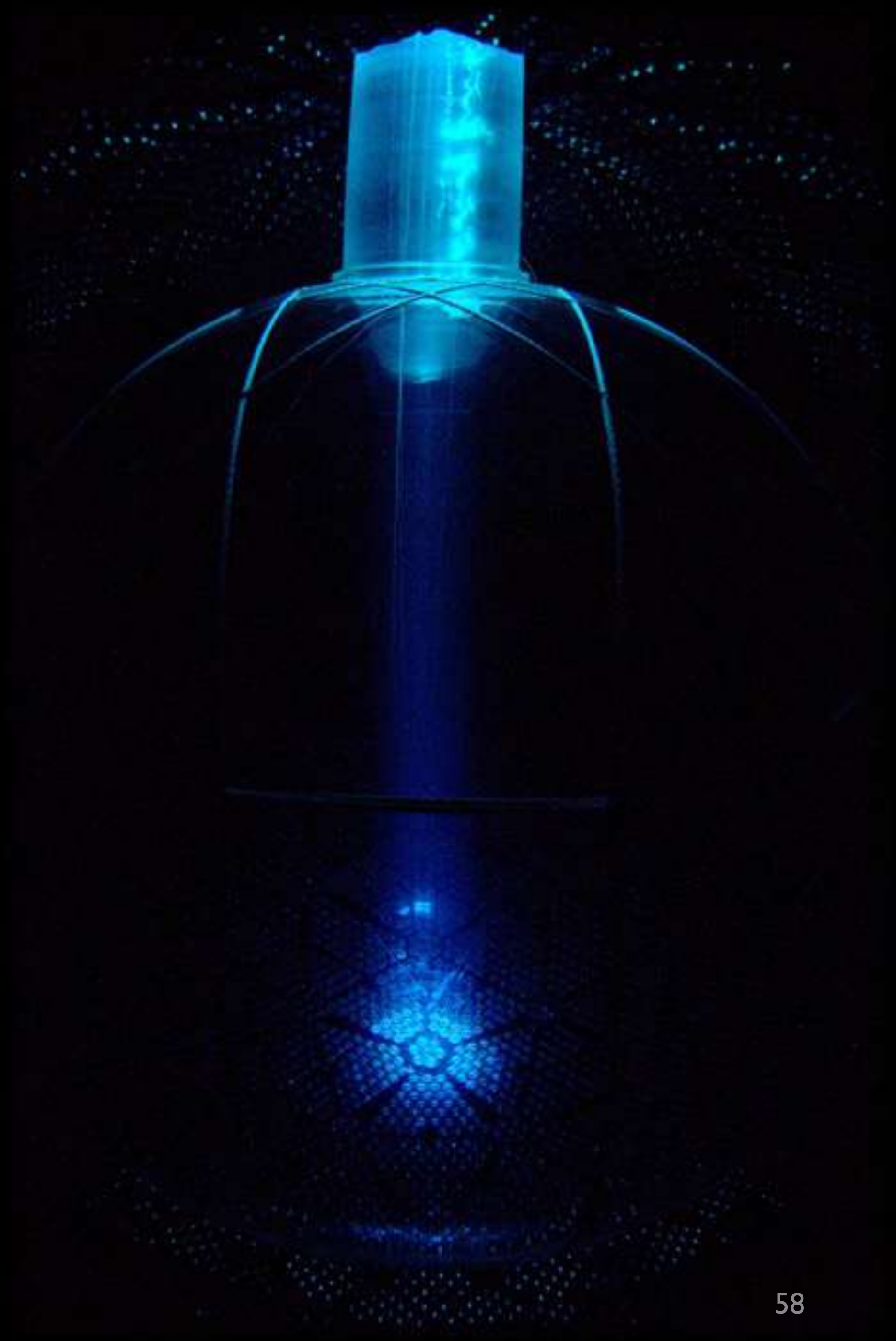


Summary

- SNO+ completed its water phase:
  - Two physics analyses completed: invisible nucleon decay and solar neutrinos
  - Measured external backgrounds
  - More analyses to come!
- SNO+ started pure scintillator phase:
  - Low energy solar neutrino physics
  - Reactor and geo-neutrino physics
- SNO+ will start deploying Te by 2022 to search for $0\nu\beta\beta$!

Thank You!

SNO+ Collaboration 2020



Acknowledgements

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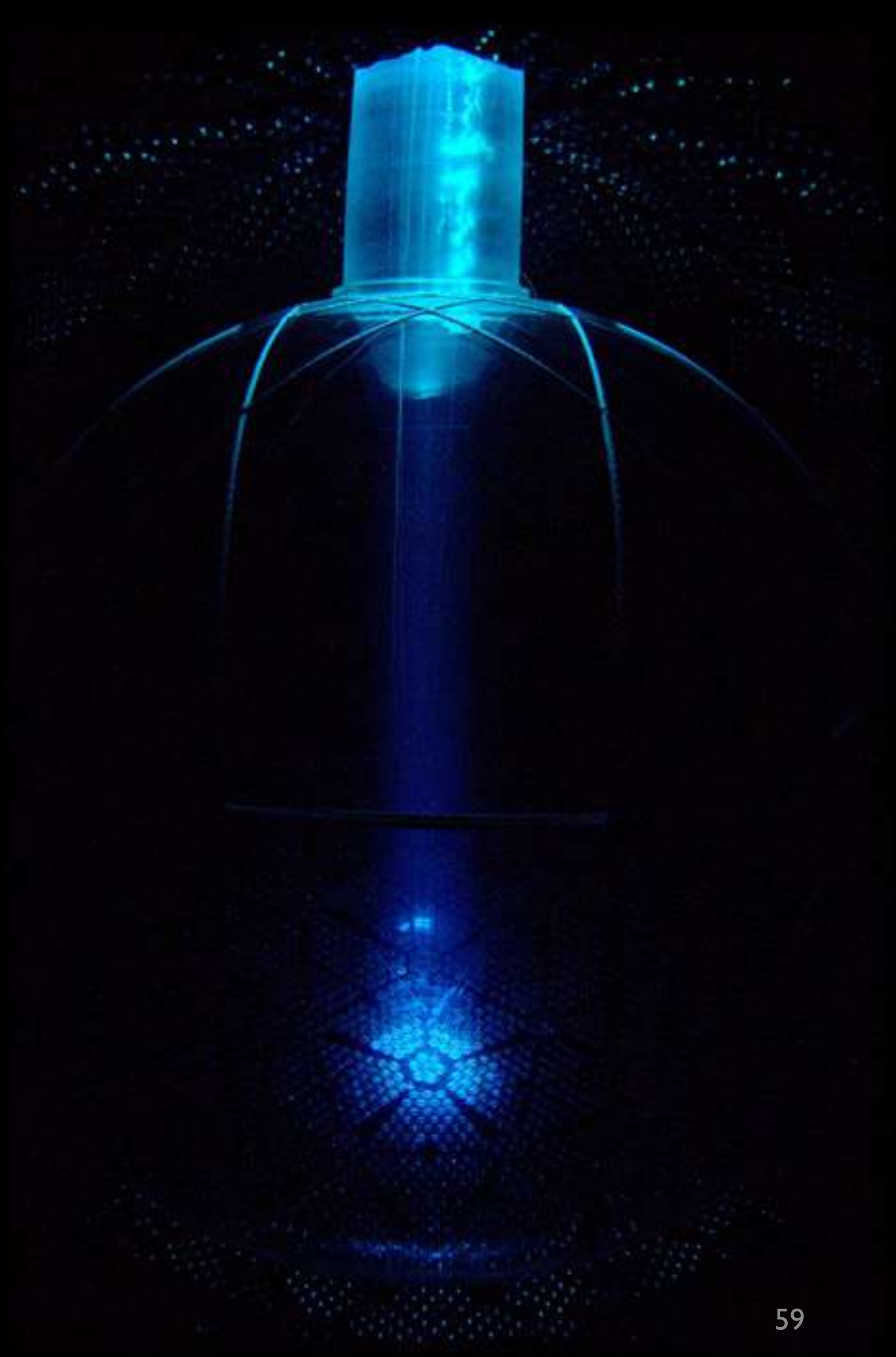
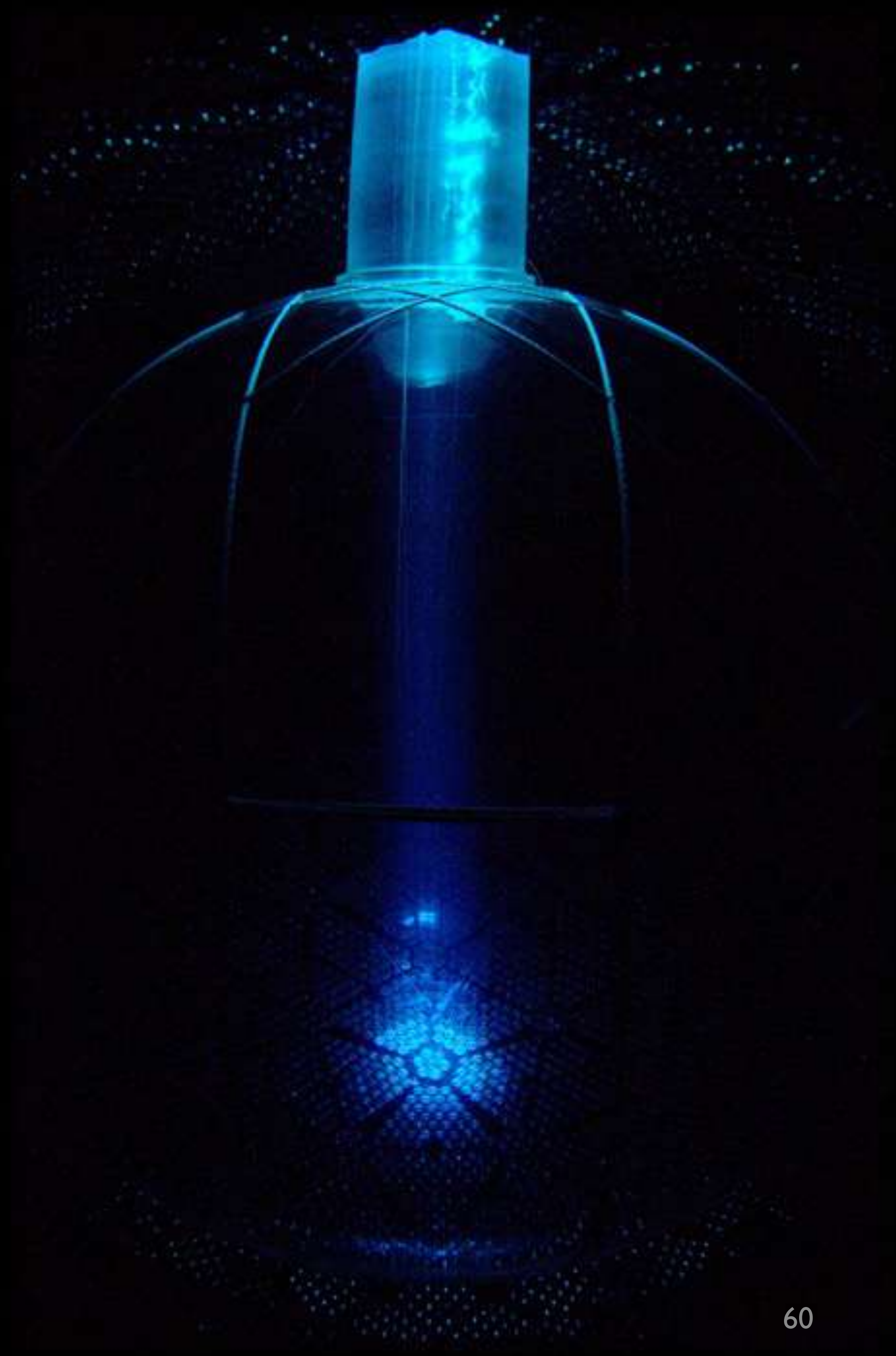
We thank SNOLAB and Vale for their valuable support.

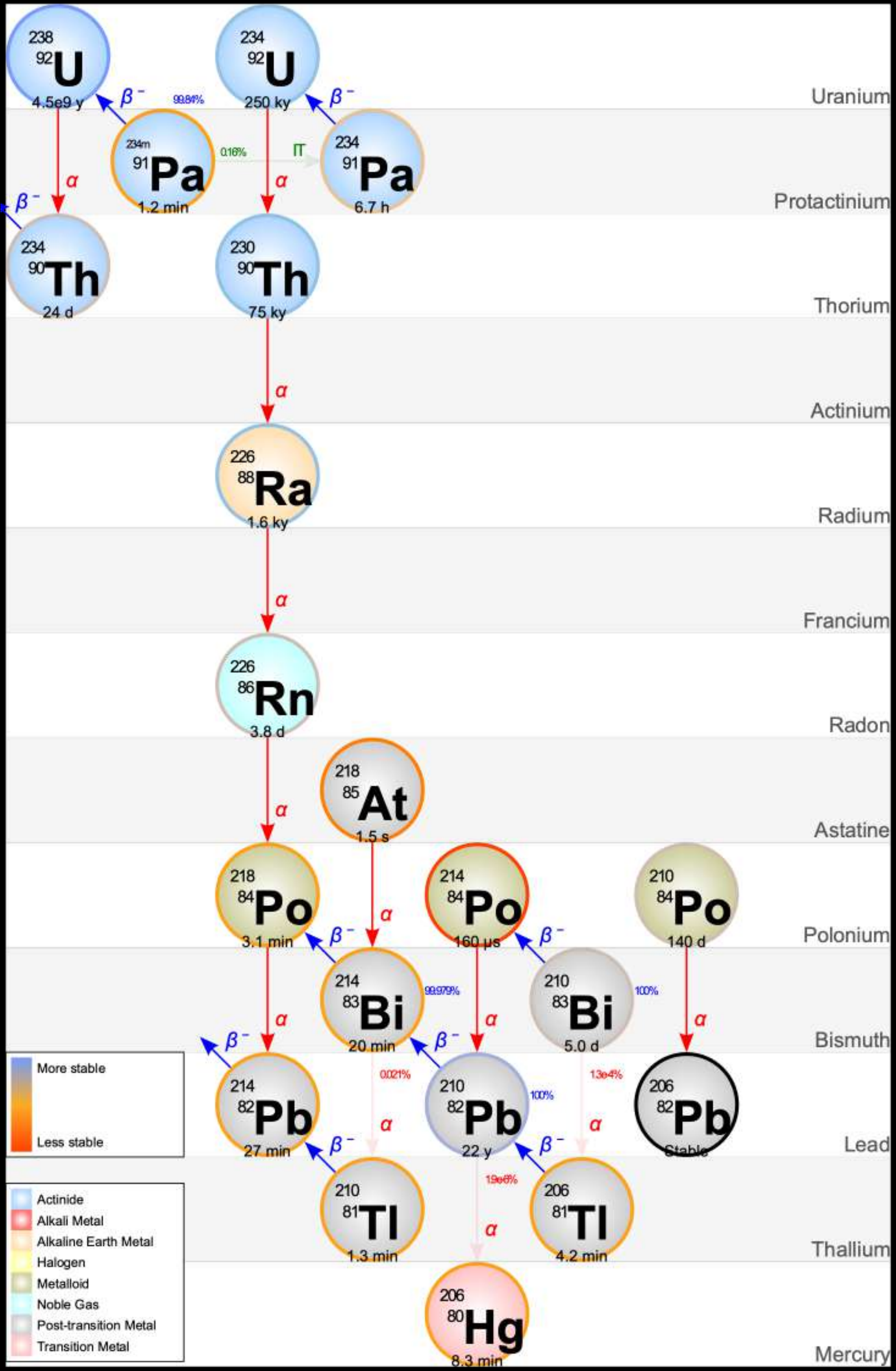
FCT Fundação para a Ciência e a Tecnologia

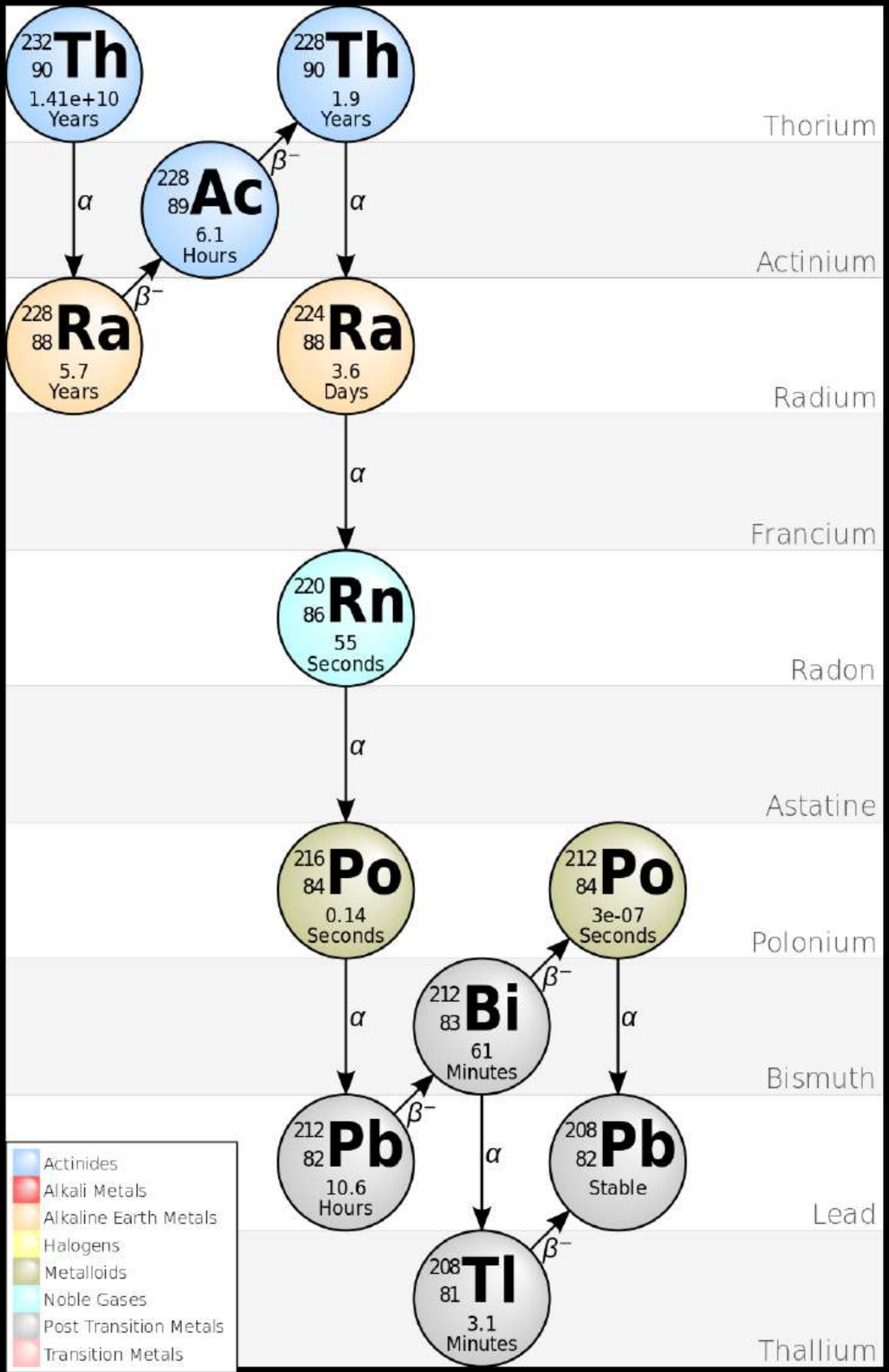
IDPASC



Backup




Uranium
Protactinium
Thorium
Actinium
Radium
Francium
Radon
Astatine
Polonium
Bismuth
Lead
Thallium
Mercury
238 92 U 4.5e9 y
234 92 U 250 ky
234m 91 Pa 1.2 min
234 91 Pa 6.7 h
234 90 Th 24 d
230 90 Th 75 ky
226 88 Ra 1.6 ky
226 86 Rn 3.8 d
218 85 At 1.5 s
218 84 Po 3.1 min
214 84 Po 160 μs
210 84 Po 140 d
214 83 Bi 20 min
210 83 Bi 5.0 d
214 82 Pb 27 min
210 82 Pb 22 y
206 82 Pb Stable
210 81 Tl 1.3 min
206 81 Tl 4.2 min
206 80 Hg 8.3 min
99.84%
0.16%
IT
99.979%
0.021%
100%
1.3e-4%
1.9e-6%
More stable
Less stable
Actinide
Alkali Metal
Alkaline Earth Metal
Halogen
Metalloid
Noble Gas
Post-transition Metal
Transition Metal


Thorium
Actinium
Radium
Francium
Radon
Astatine
Polonium
Bismuth
Lead
Thallium
232 90 Th 1.41e+10 Years
228 90 Th 1.9 Years
228 89 Ac 6.1 Hours
228 88 Ra 5.7 Years
224 88 Ra 3.6 Days
220 86 Rn 55 Seconds
216 84 Po 0.14 Seconds
212 84 Po 3e-07 Seconds
212 83 Bi 61 Minutes
212 82 Pb 10.6 Hours
208 82 Pb Stable
208 81 Tl 3.1 Minutes
Actinides
Alkali Metals
Alkaline Earth Metals
Halogens
Metalloids
Noble Gases
Post Transition Metals
Transition Metals