4th IDPASC Students Workshop
Physics Department - University of Coimbra, Portugal

Measurement of the ^{130}Te Two-Neutrino Double Beta Decay Half-life with the SNO+ Experiment

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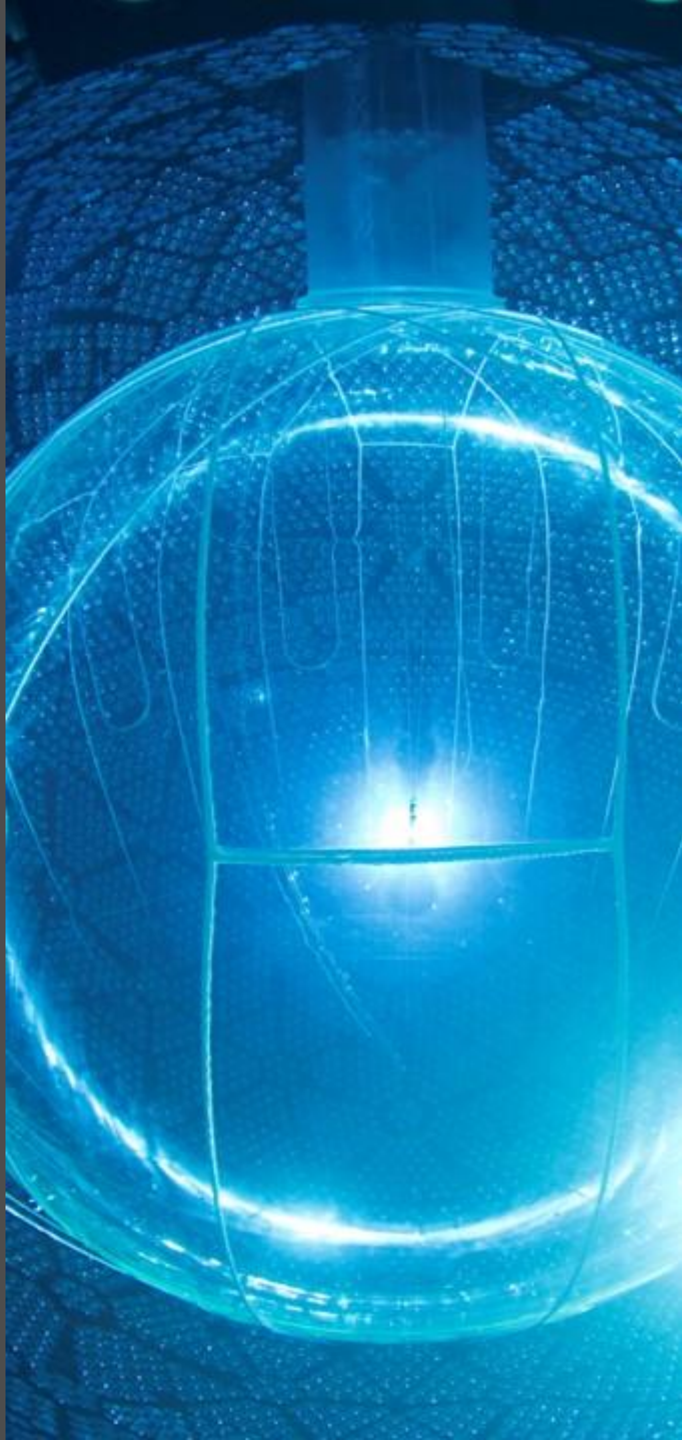
June 28th, 2018



A Brief Introduction About Neutrinos

What we know:

Elementary neutral particles, **three** flavours.

Produced in particle interactions and decays.

Interact very **weakly** with matter.

Oscillate from one flavour to another as a function of energy and length travelled

→ because of that we know that neutrinos have a **non-zero mass**.

Oscillation Probability

$$P_{\nu_\alpha\to\nu_\beta}(L,E_\nu)=\sum_{k,j=1}^{3}U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}exp\left(-i\frac{\Delta m^2_{kj}L}{2E_\nu}\right)$$

α, β neutrino flavours
= electron,
muon,
tau

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What we don't know:

What are the **values** of the neutrino masses?

Why is the mass so small when compared with other fermions?

Through **what mechanism** does the neutrino mass arise? Dirac or Majorana?

Dirac: implies the existence of right-handed neutrinos, not predicted by the SM.
Majorana: $\nu = \bar{\nu}$, physics beyond the SM, predicts heavy neutrinos.

Do neutrinos contribute to the **matter/anti-matter asymmetry** in the Universe?

Possible if:

- Charge-parity symmetry is violated;
- Neutrinos are Majorana particles (Seesaw Mechanism).

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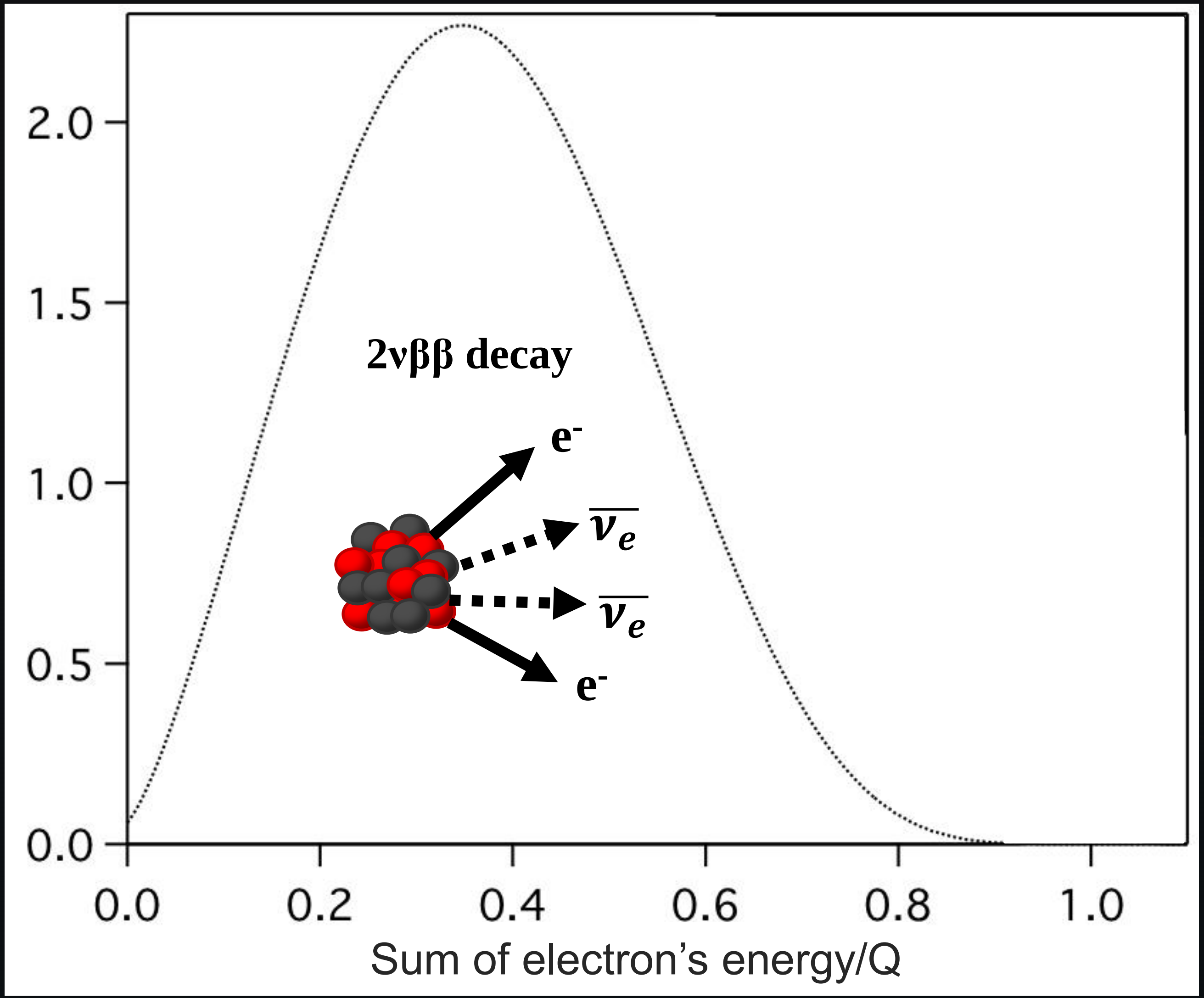
SNO+

Searching for the $0\nu\beta\beta$ decay process

Two-Neutrino Double Beta Decay



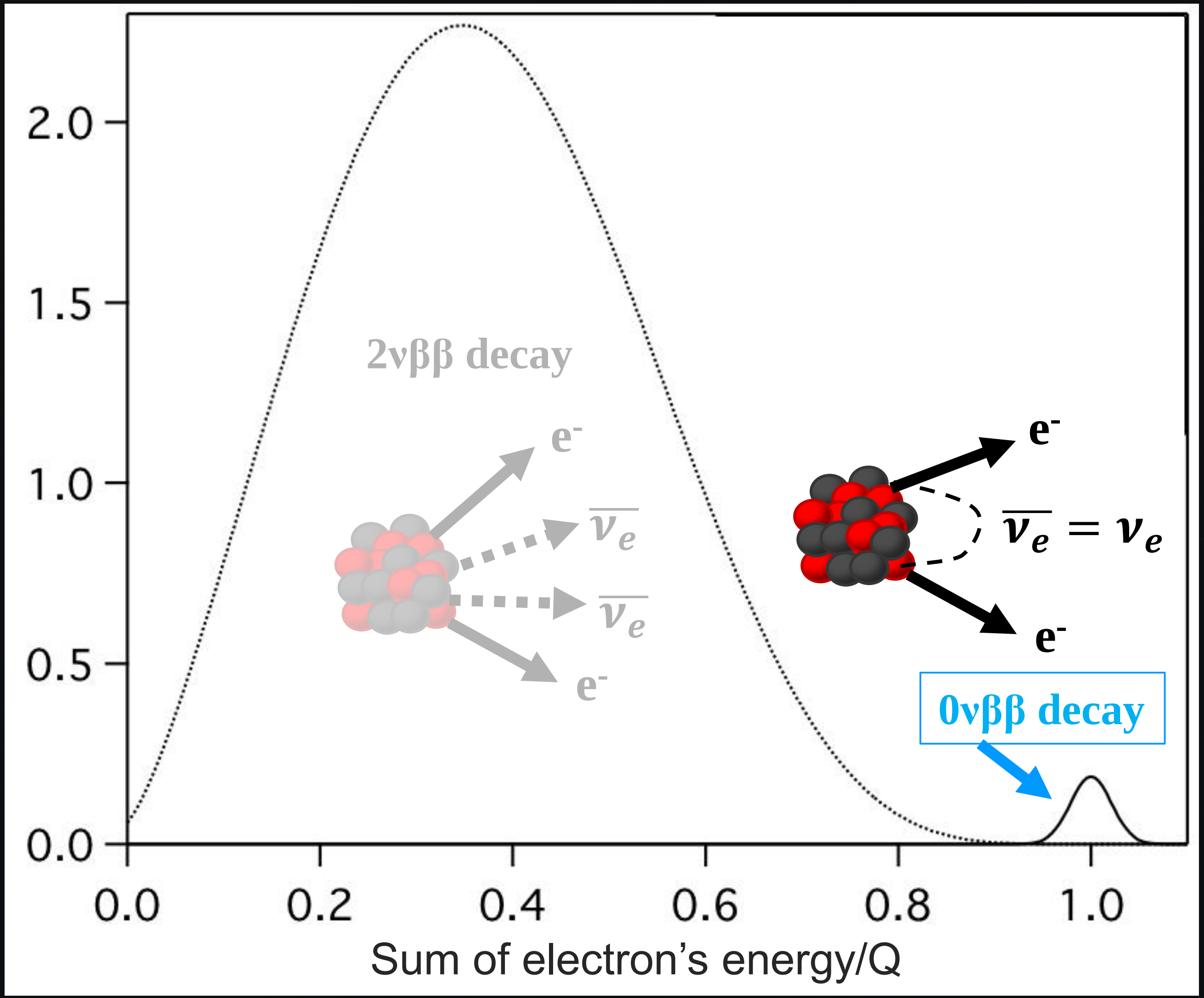
- Very rare nuclear decay.
- Possible when normal beta decay is not energetically allowed.
- Can happen for 35 natural isotopes.

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

Trying to probe the Majorana nature (and mass) of the neutrino!



- Possible if neutrinos are Majorana particles (their own anti-particles).
- Violates lepton number conservation.
- Rate depends on the effective electron neutrino Majorana mass.

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

Challenges for the 0νββ Searches

Challenges when estimating the effective ν_e mass

Measured Rate

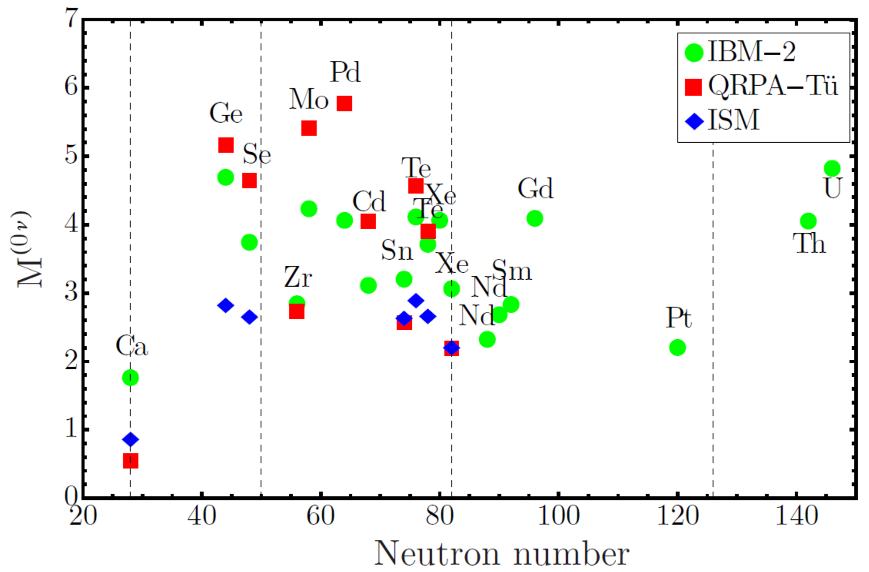
$$\left[T_{0\nu}^{1/2}\right]^{-1} = G_{0\nu}\left|\mathcal{M}_{0\nu}\right|^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

Phase Space Factor

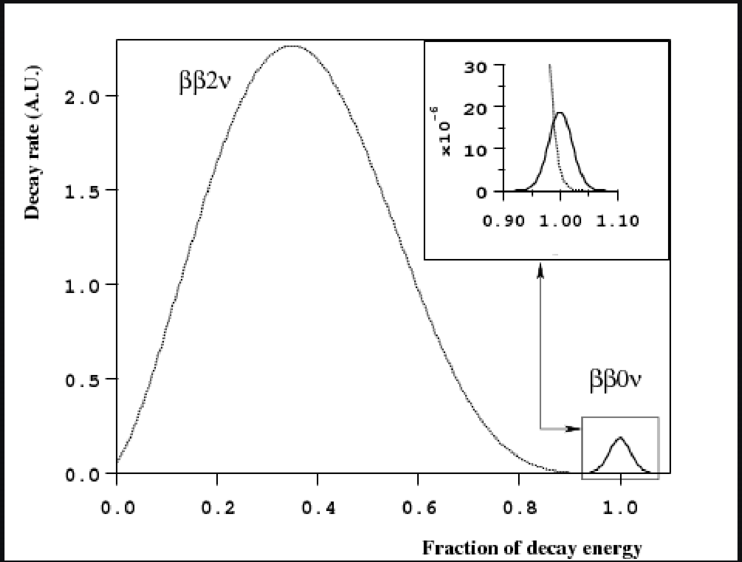
Nuclear Matrix Element (NME)

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

Large uncertainty in the NMEs:
- for the same isotope, different models give different values.



Challenges for the 0νββ Searches



Main Experimental Challenge

→ **2νββ decay is an intrinsic background!**

Ways to improve the 0νββ Search Sensitivity

Importance of measuring with precision the 2νββ Half-life

Experimentally verify the nuclear models used for the NMEs calculation.

⇓

Validated models can then be used to evaluate the NME for the 0νββ mode.

⇓

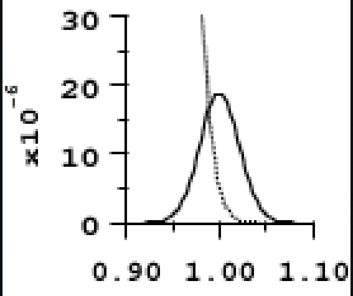
Necessary to extract the effective neutrino mass from 0νββ half-life.

Importance of measuring the 2νββ Spectrum Tail

Due to the limited energy resolution of the detectors, the events in the tail of the 2νββ spectrum will leak into the 0νββ region-of-interest (ROI).

⇓

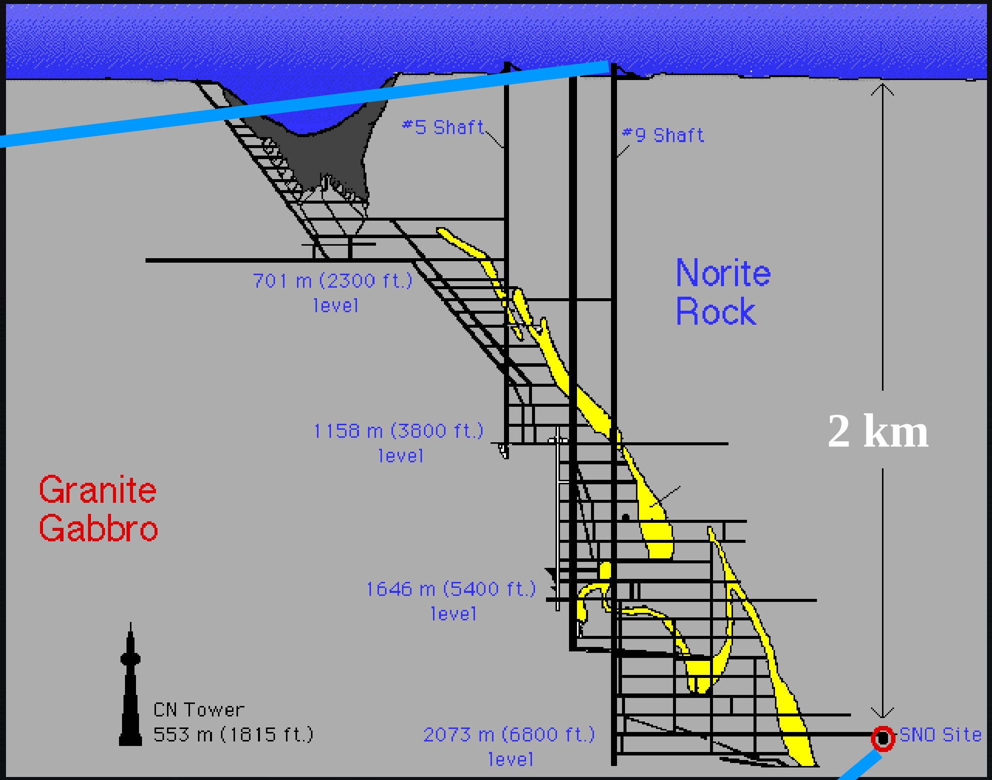
Measurement allows to understand the background contribution of 2νββ.

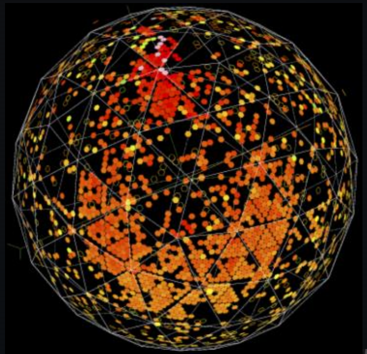


The SNO+ Experiment

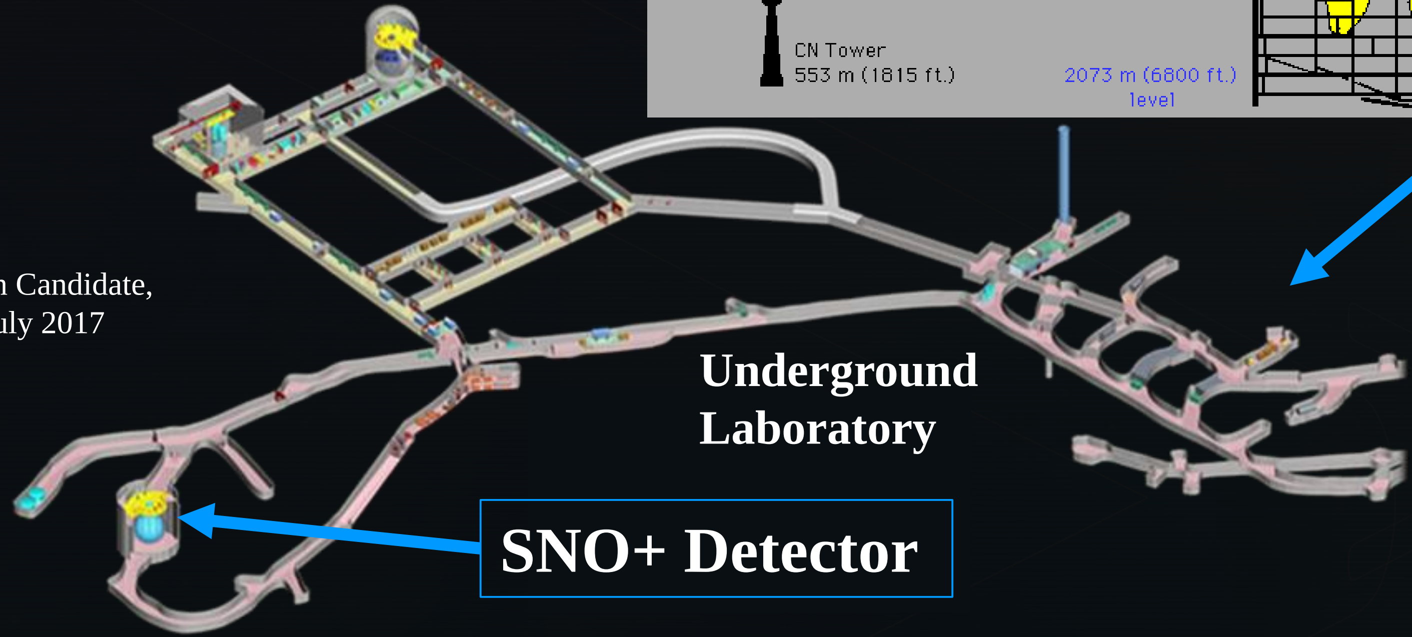
Sudbury, Ontario

Surface Building





Muon Candidate, July 2017



Underground Laboratory

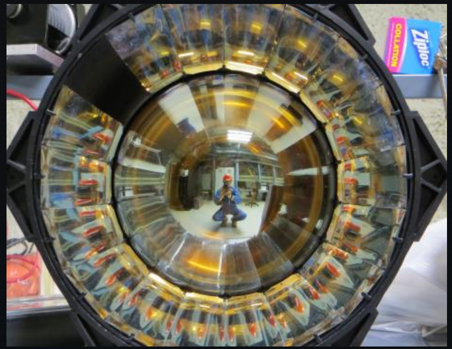
SNO+ Detector

The SNO+ Experiment

Ultra-pure water (**now**)

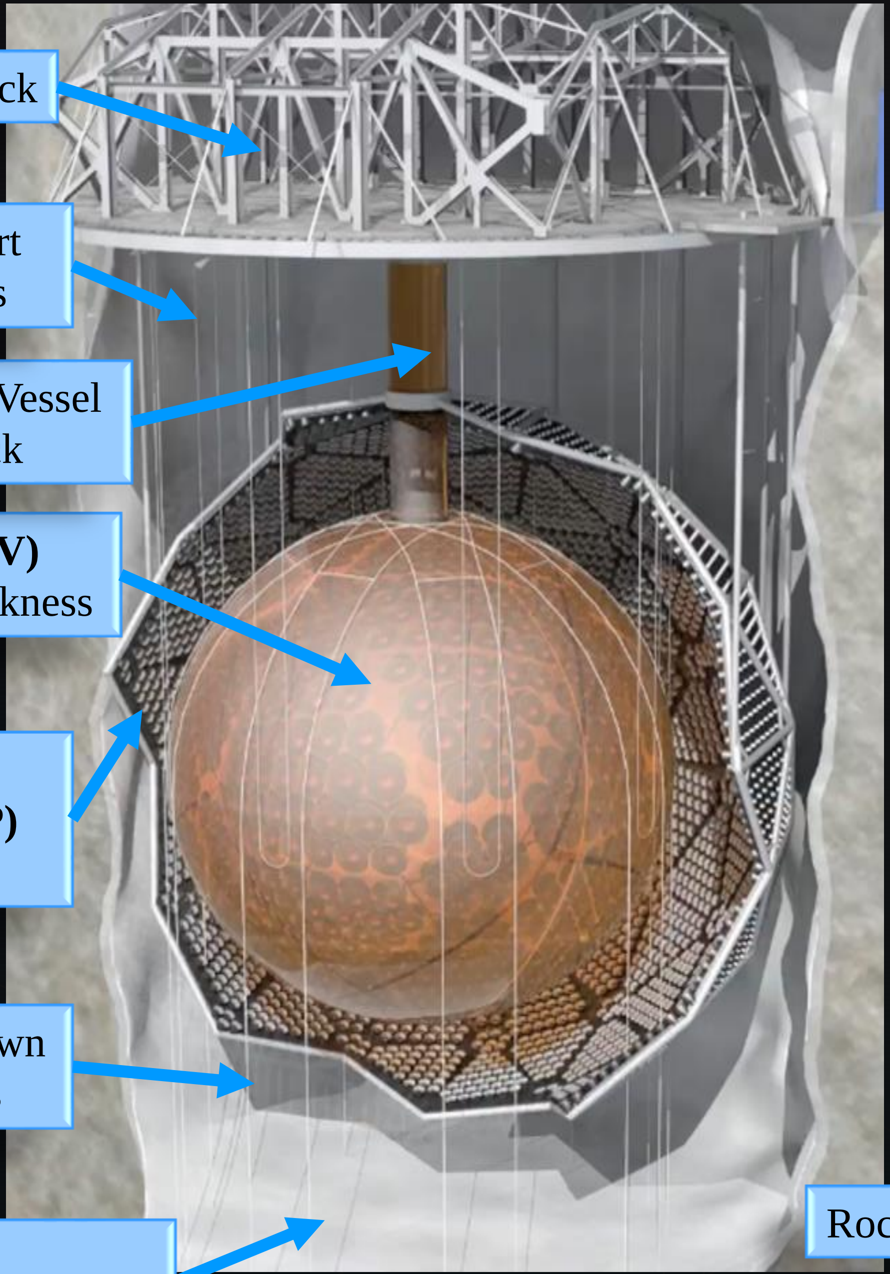
Liquid Scintillator (this summer)

+ 3.9 tonnes of natural Tellurium



×9400

PMT + Concentrator



The SNO+ Experiment

SNO+ Challenges for the 0νββ Searches:

- Purify and deploy large quantities of the isotope;
- Achieving a very high efficiency in analysis-based background reduction methods;
- Obtain a detailed and regularly monitored model of the detector response.

Working Programme

Liquid Scintillator Phase	Te-loading Phase

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Characterize the Energy Response and Uncertainties		

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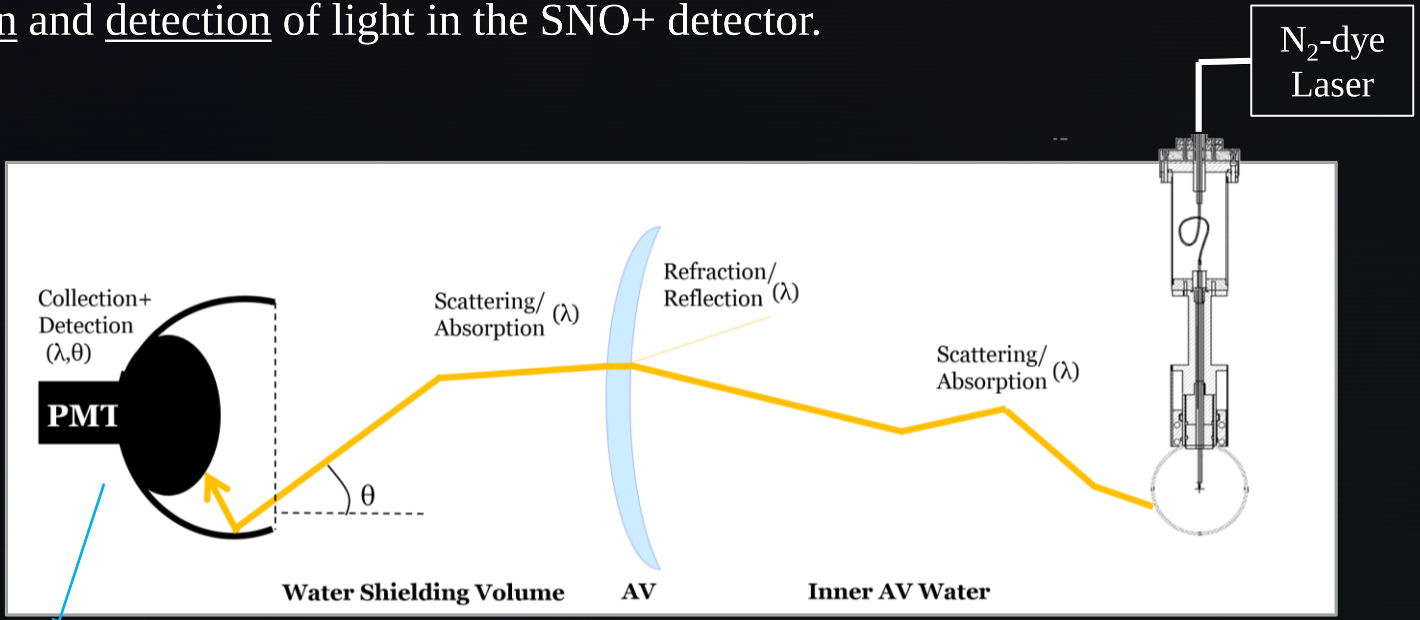
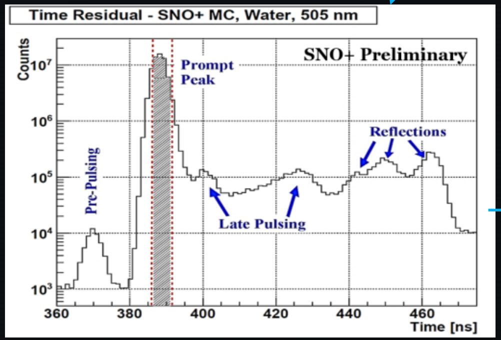
Characterize the Energy Response and Uncertainties	Optical Calibration • Adapt/Improve the analysis tools; • Characterize the optical properties of the detector;	

Optical Calibration

Goal: characterize the propagation and detection of light in the SNO+ detector.

- Optical Parameters
- ⬇
- Validate the simulation model
- Input for the reconstruction algorithms
- ⬇
- Uniformity of the energy response





PMT Signal

Source

$$O_{ij} = N_i L_{ij} \Omega_{ij} T_{ij} R_{ij} \epsilon_j exp\left(-\sum_{Medium\ k} d_{ij,k}\alpha_k\right)$$

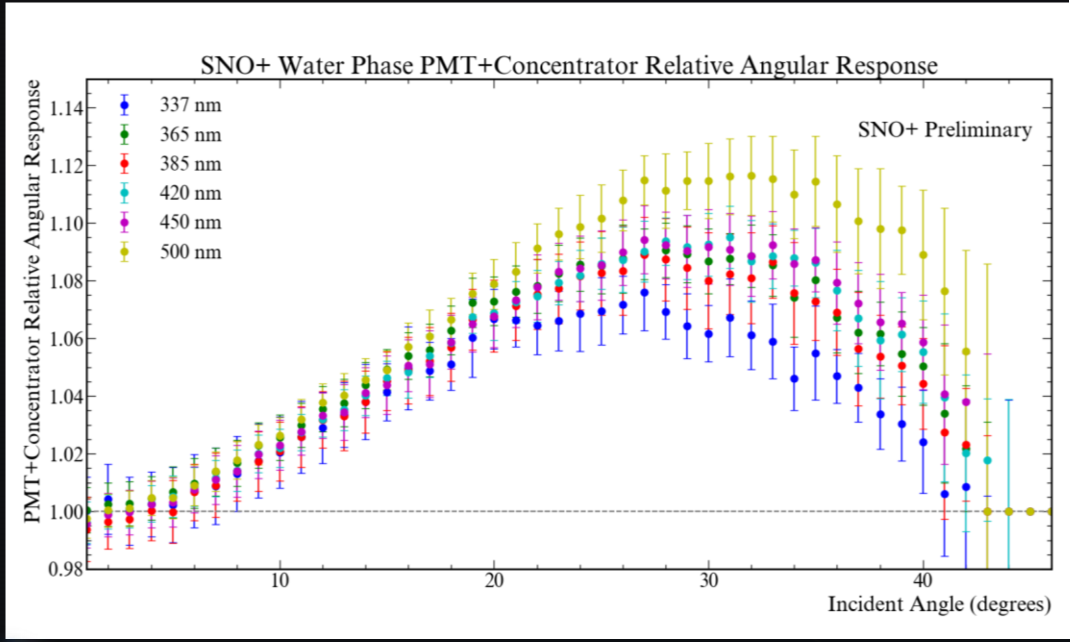
Direct light detected; Solid Angle; Fresnel; PMT Response; PMT Efficiency; Distance travelled; Attenuation

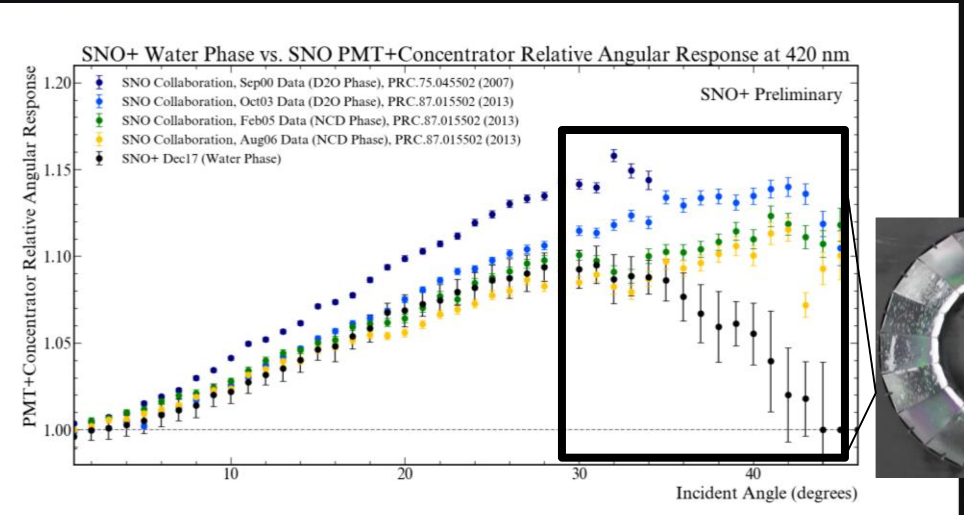
The Optical Model

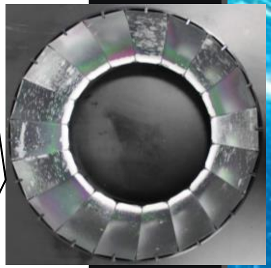
Optical Calibration

Results from the December 2017 Water Phase scan.

PMT+Concentrator Angular Response

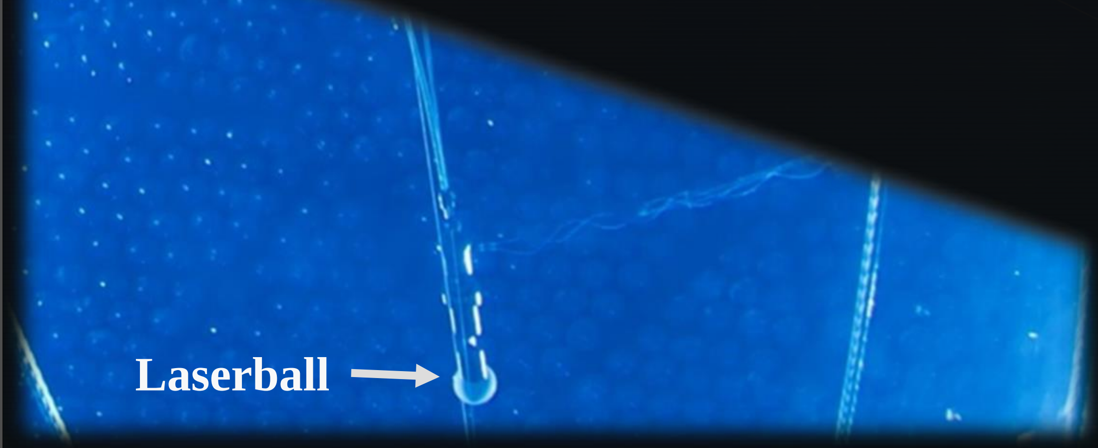


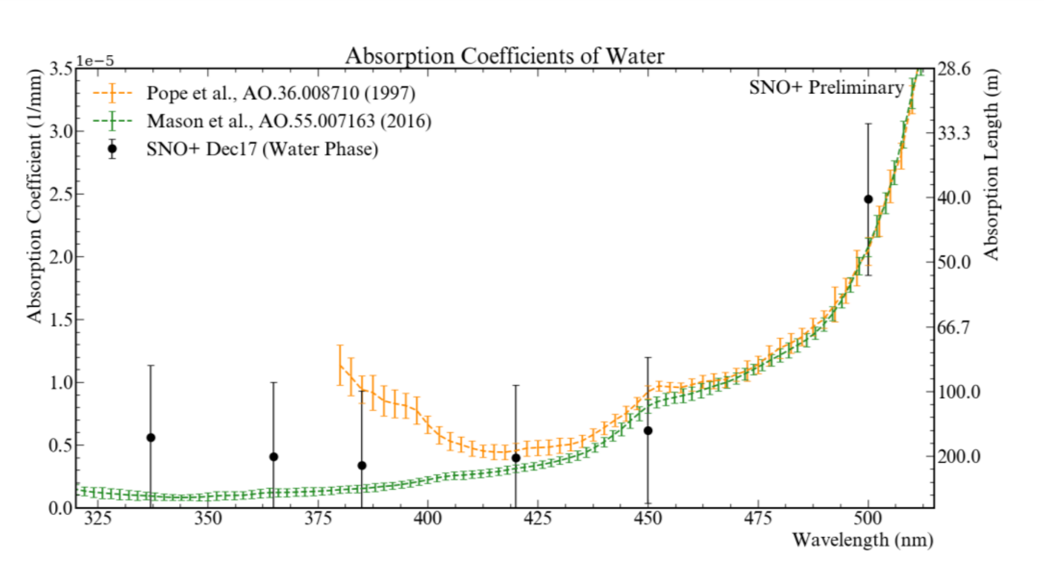




Changes at high incident angles with time due to degradation of the reflectors.

Water Properties: characterized the absorption and group velocity of water.





In preparation for the next phases!

Working Programme

	Liquid Scintillator Phase	Te-loading Phase
Characterize the Energy Response and Uncertainties	Optical Calibration • Adapt/Improve the analysis tools; • Characterize the optical properties of the detector;	
	Energy Calibration • Calibration sources, ex. AmBe; • Naturally present backgrounds, ex. ^{208}Tl;	

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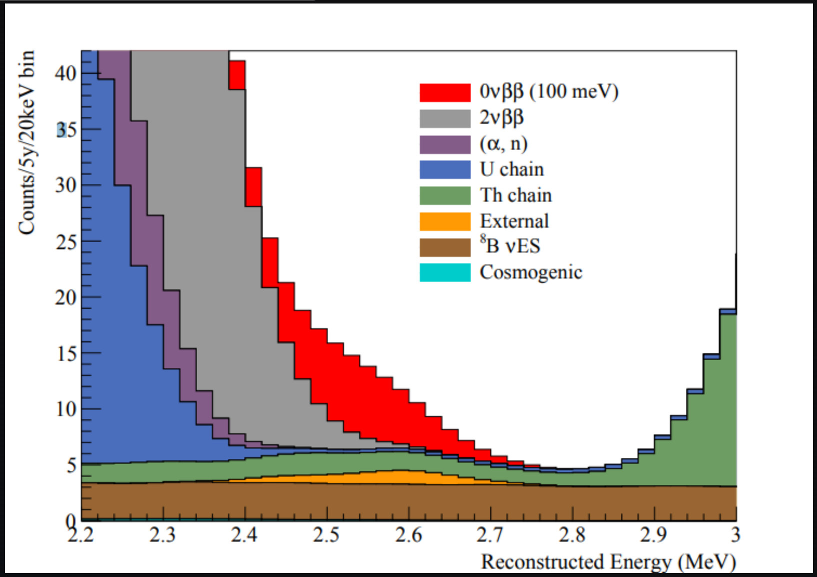
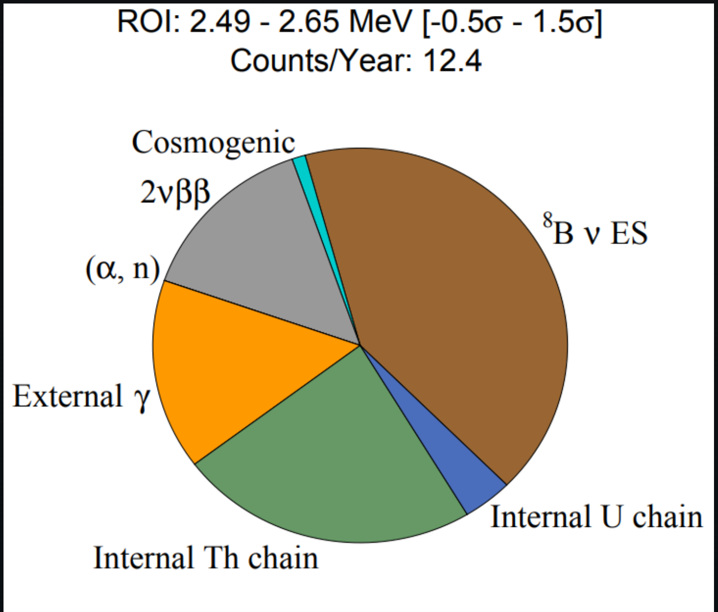
Detailed Model of the Backgrounds	• Contamination of different isotopes:
	  • In the scintillator (^{238}U and ^{232}Th chains, cosmogenics).
	  • In the detector components (^{208}Tl in the PMTs, external water and AV).
	• Characterize the energy spectra and other variables useful for the analysis.	

Speeding Up the Simulation of the Backgrounds

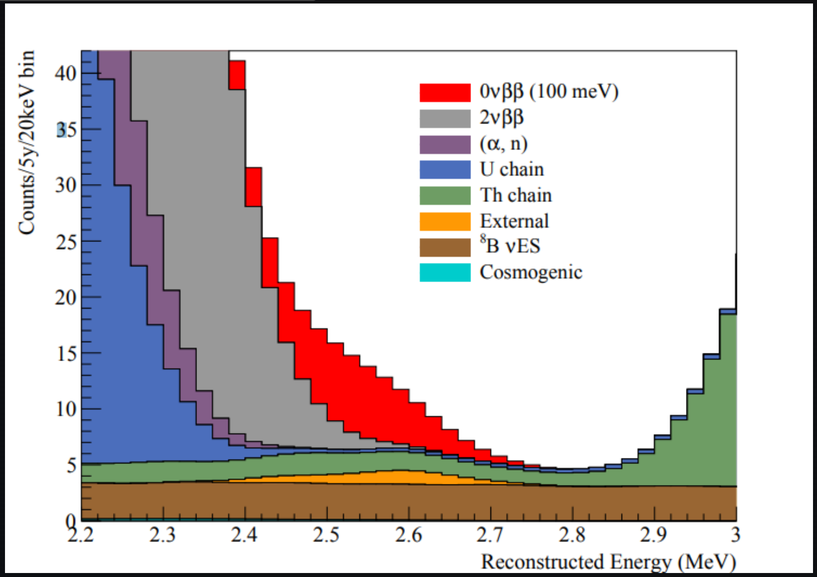
	Decays in 5 years	Fraction in FV (3.3m)	Fraction in ROI
2νββ, inside the LS	2.65×10^{7}	0.07	$3\times\mathbf{10^{-7}}$
^{208}Tl, inside the LS	8.89×10^{4}	0.14	0
^{208}Tl, external water	1.96×10^{7}	$4\times\mathbf{10^{-8}}$	$2\times\mathbf{10^{-8}}$
PMT β-γ	2.2×10^{11}	$1\times\mathbf{10^{-11}}$	$1\times\mathbf{10^{-11}}$





Although only a small fraction of the background events enter the 0νββ ROI, large numbers have to be simulated in order to have detailed distributions for the analysis.

Speeding Up the Simulation of the Backgrounds

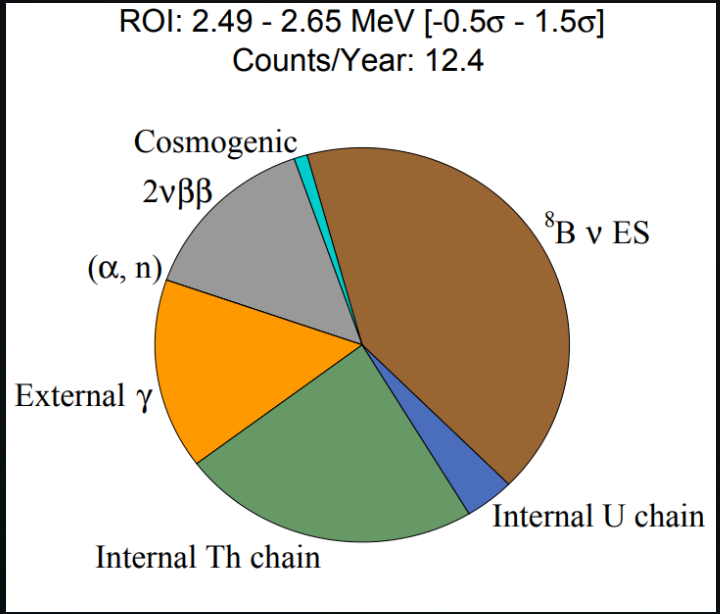


Photon Propagation

In the 2νββ decay simulations takes 1.3 seconds per event

$$1.3 \text{ seconds} \times 2.65 \times 10^{7} \text{ simulated decays}$$
$$=$$
$$18 \text{ hours with 300 cores}$$

… but we need to simulate more events than we expect (similar for all the other backgrounds).



Speeding up the simulation

- Use a simplified detector geometry;
- Weighted position and energy spectrum generation;
- Simulate less photons and increase the PMT efficiency;
- …

On-going work!

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↓

Extract the **^{130}Te 2νββ decay half-life** by fitting the physics data to the expected spectra

+

Propagation of systematic uncertainties

Summary

- A precise measurement of the $2\nu\beta\beta$ decay half-life and energy spectrum is crucial for the $0\nu\beta\beta$ decay searches.
  - Allows to test the nuclear models, whose results are necessary to extract the effective electron neutrino mass.
  - Improves the SNO+ sensitivity to $0\nu\beta\beta$.
  - Will be achieved with a detailed characterization of the detector response and of the backgrounds.

Thank you!

This work is supported by FCT (Fundação para a Ciência e a Tecnologia), Portugal, through the research grant PTDC/FIS-NUC/0640/2014 and through the IDPASC PhD grant PD/BD/135468/2017.

Backup

The SNO+ Experiment

Phases and Physics Goals

Water (on-going)	Liquid Scintillator (Summer 2018)	Te-loading (2019)
905 tonnes of ultra-pure water	780 tonnes of LAB+PPO	+ 3.9 tonnes of natural Tellurium
Supernova neutrinos	Supernova neutrinos	Supernova neutrinos
Invisible Nucleon Decay		
	Reactor anti-neutrinos	Reactor anti-neutrinos
	Geo-neutrinos	Geo-neutrinos
	Solar neutrinos	Solar neutrinos
		$0\nu\beta\beta$