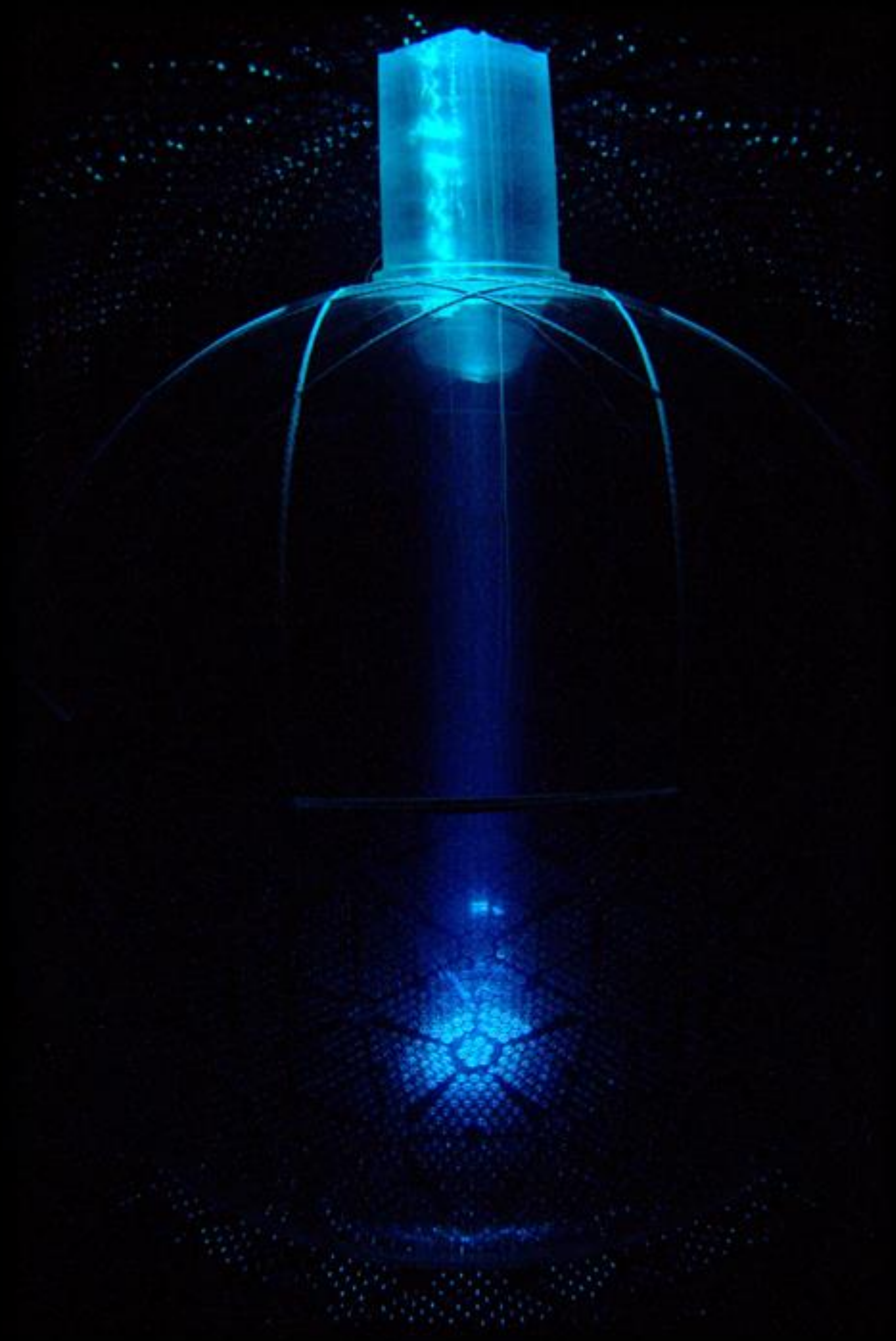

5th IDPASC /LIP PhD Student Workshop
Minho University, Braga – 1-3 July 2019

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

Ana Sofia Carpinteiro Inácio

Supervisors: Prof. José Maneira & Dr. Valentina Lozza

LIP Ciências ULisboa FCT Fundação para a Ciência e a Tecnologia IDPASC

Probing the properties of the elusive neutrino

- What we know:

Three neutrino flavours.

Neutrinos oscillate between flavour states.

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

Neutrinos have mass

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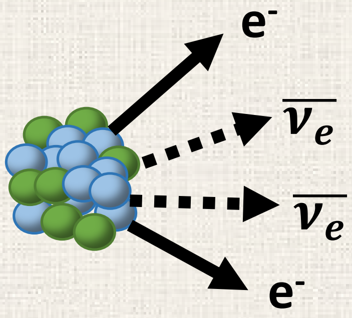
Neutrinos have mass

- What we don’t know:
  - What are the values of the neutrino masses?
  - What mechanism generates the neutrino mass?
  - Are neutrinos Dirac or Majorana particles?
  - Did neutrinos contribute to the matter/antimatter asymmetry in the Universe?

Search for the 0νββ Decay

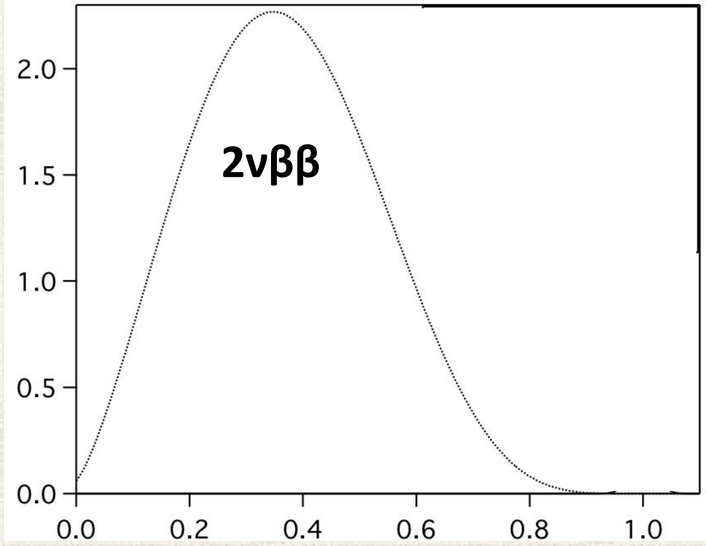
Double Beta Decay



- **2νββ decay:** Occurs in nuclei where single beta decay is energetically forbidden.

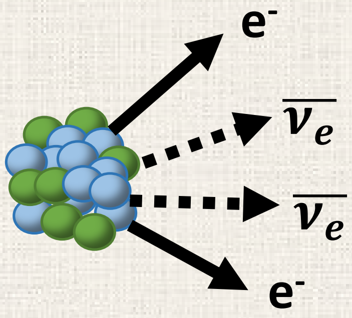
  35 naturally-occurring isotopes, observed in 11: ^{48}Ca, ^{76}Ge, ^{130}Te, ^{136}Xe…

  Long half-lives between 10^{19} and 10^{24} years.



Detected Kinetic Energy of the Two Electrons/Q

Double Beta Decay



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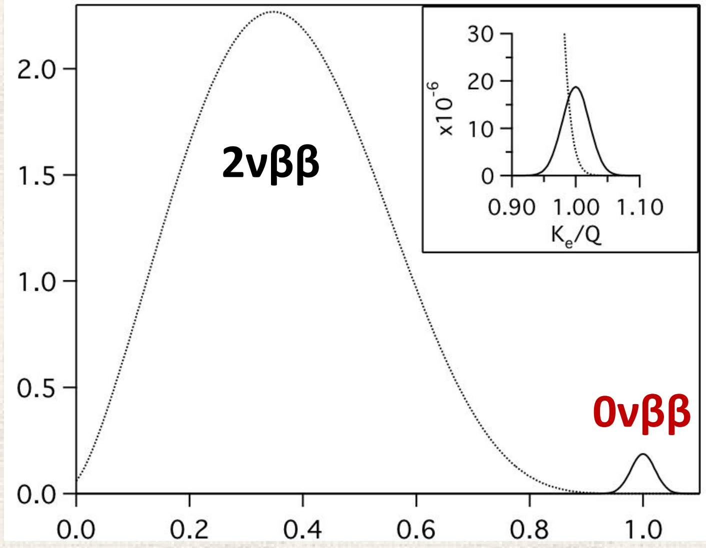
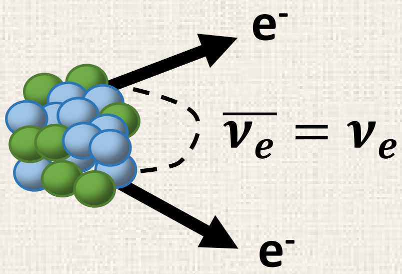


Detected Kinetic Energy of the Two Electrons/Q

- **0vββ decay**: Most promising way to prove the Majorana nature of neutrinos.
  Implies lepton number violation.



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

Phase Space Factor

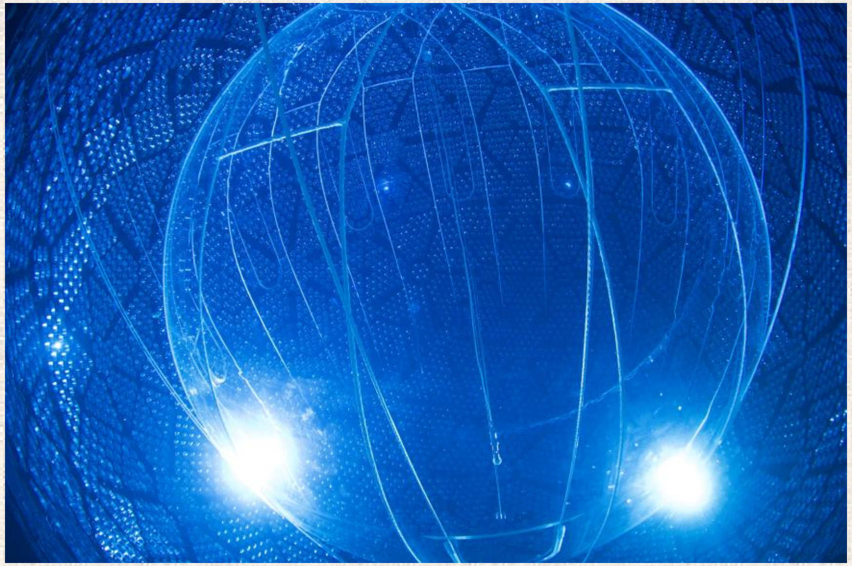
Nuclear Matrix Element (NME)

Effective Electron Neutrino Majorana Mass

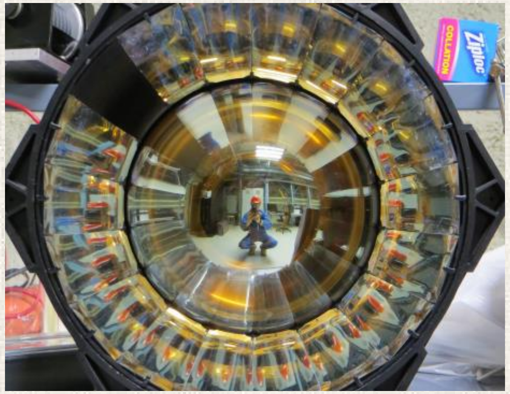
$$m_{\beta\beta} = \left|\sum_{i=1,2,3} e^{i\xi_i}\left|U^2_{ei}\right| m_i\right|$$

SNO+ Detector

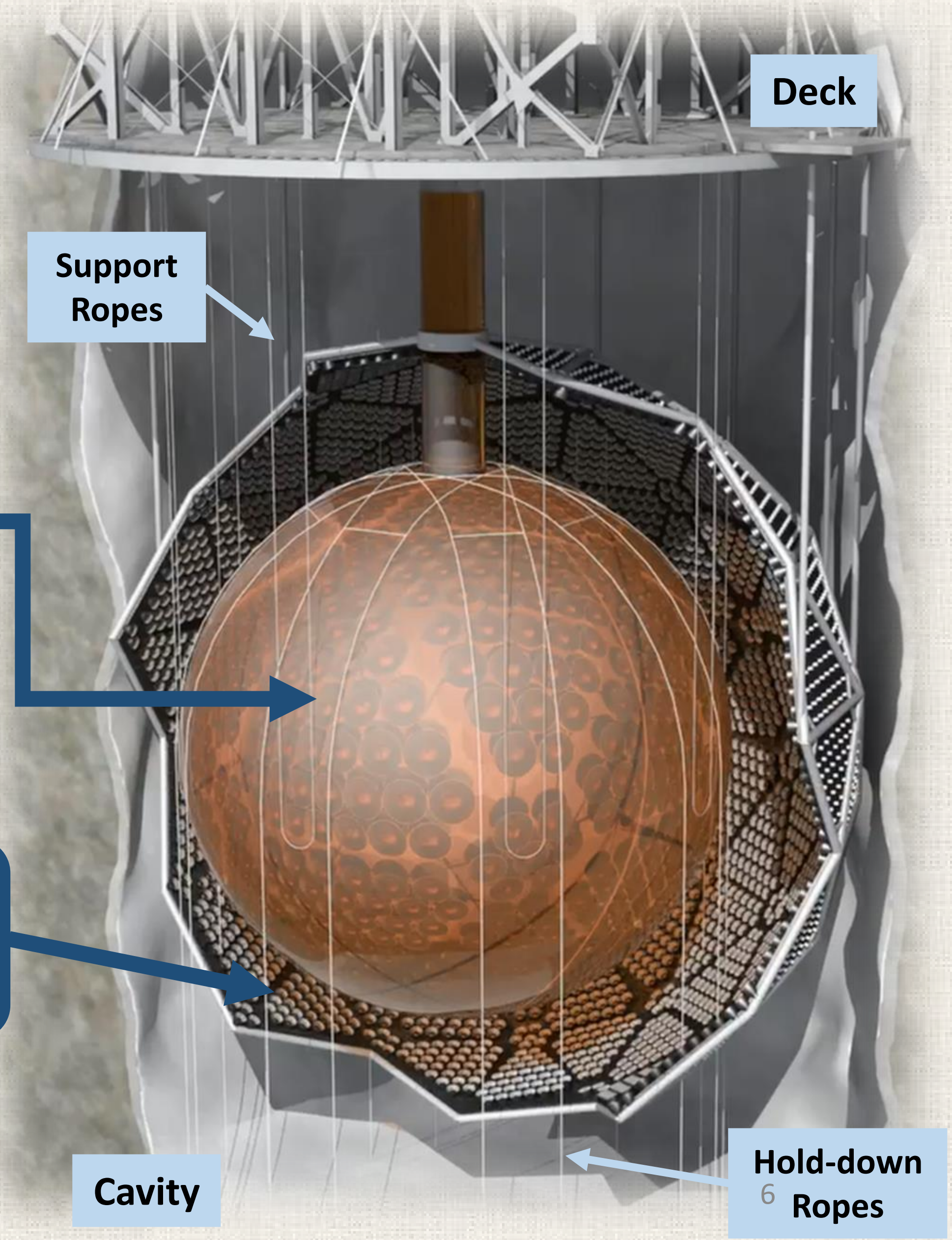
At a depth of 2km (rock, ~5900 mwe, ~63 cosmic muons/day)



Acrylic Vessel (AV)
6 m radius, 5 cm thickness



PMT Support Structure (PSUP)
8.9 m radius
Holds 9400 PMTs + Concentrators



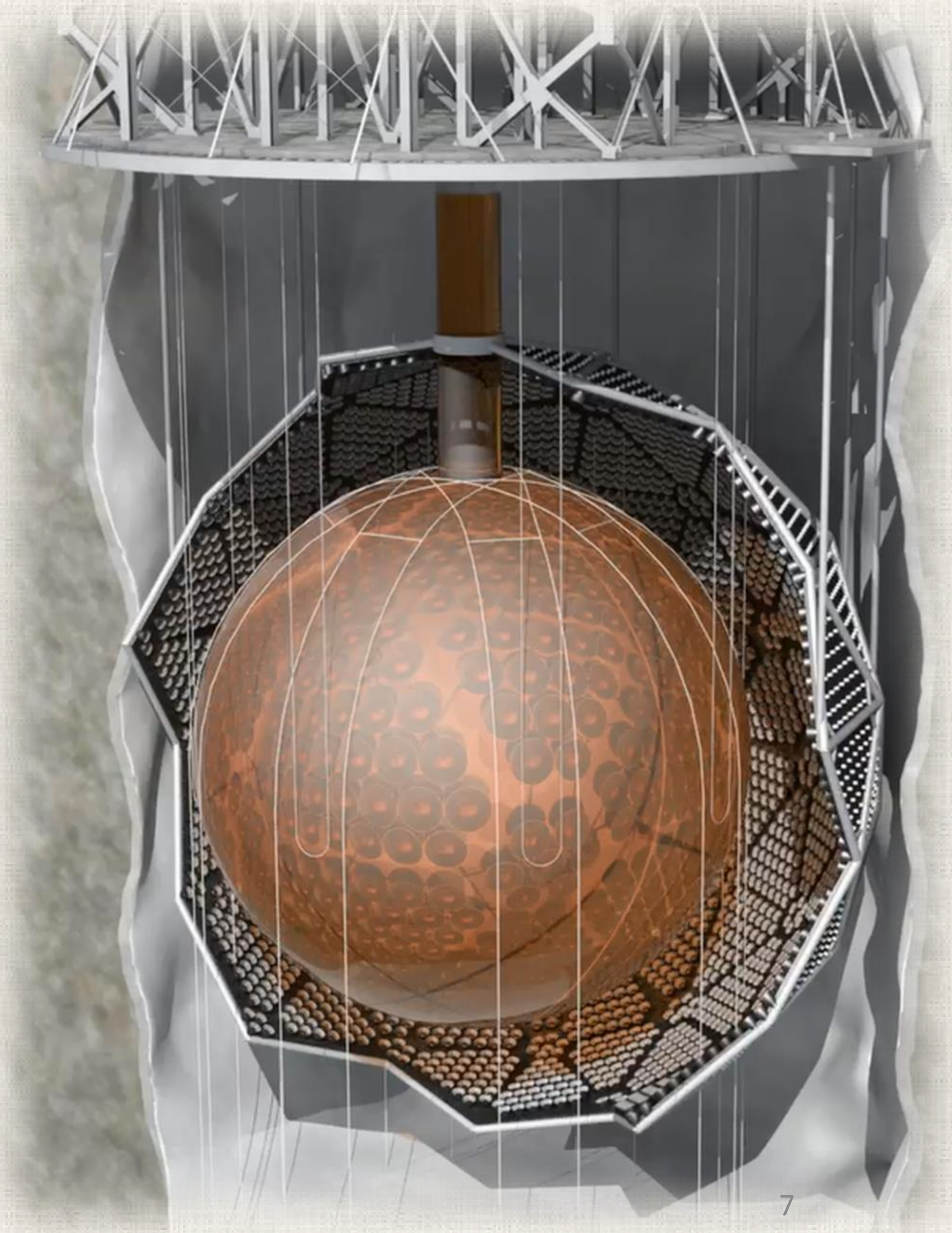
SNO+ Physics Goals

1. Water phase **(taking data since May 2017)**
   - Detector calibration
   - Background measurements
   - Nucleon decay searches
   - ^{8}B solar neutrino flux

2. Scintillator phase **(fill ongoing)**
   - Background measurements
   - Low energy solar neutrinos
   - Geo and reactor antineutrinos

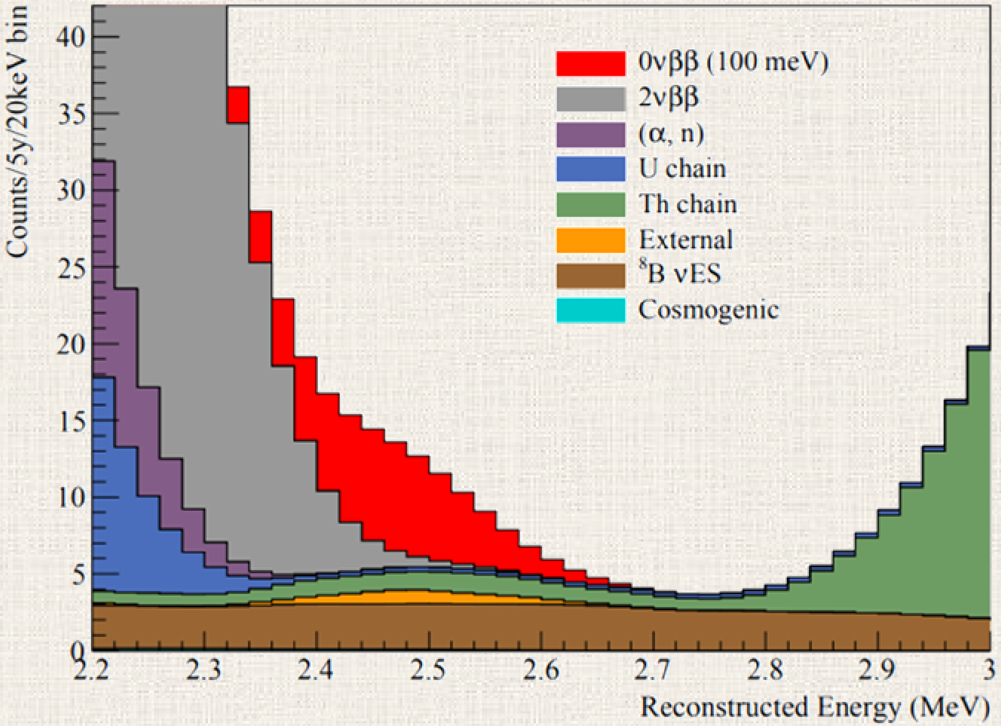
3. Tellurium phase **(planned for 2020)**
   - **2νββ decay lifetime of ^{130}Te**
   - **0νββ decay search with ^{130}Te**
   - Geo and reactor antineutrinos

- Supernova neutrinos in all phases!



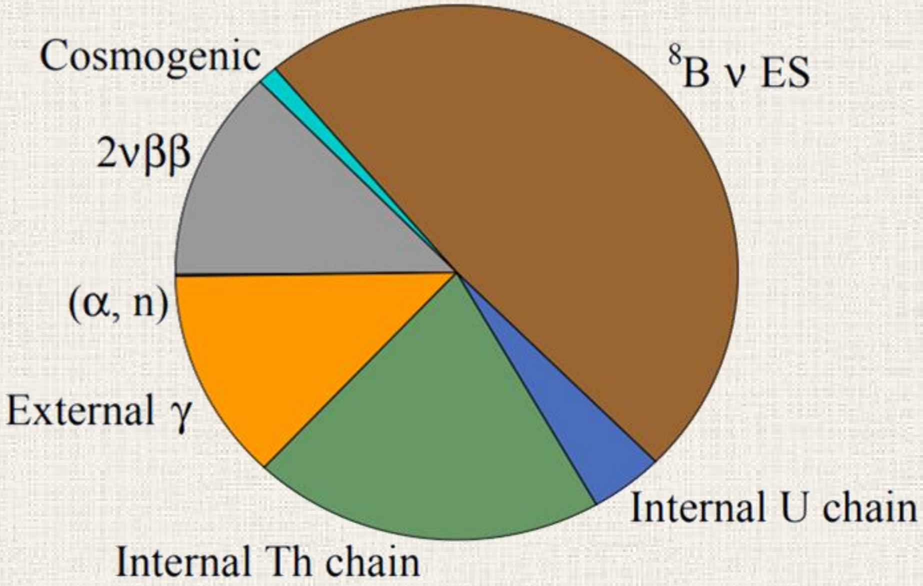
Double Beta Decay

Expected Energy Spectrum after 5 Years, Fiducial Volume of 3.3 m



Expected Background Contributions

ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47

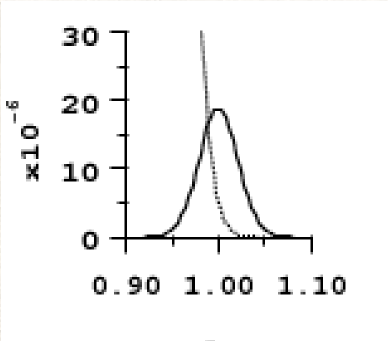


Expected Half-Life Sensitivity after 5 years: 2.1×10^{26} years
$m_{\beta\beta}$ range 37-89 meV (model dependent)

Challenges for the 0νββ Searches

- The detector has limited energy resolution.

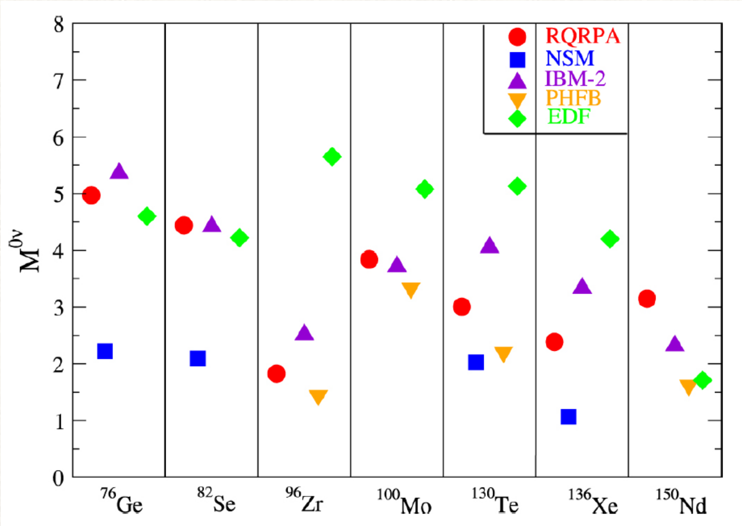
0νββ Half-Life Sensitivity: $S^{0\nu} \propto \epsilon\eta\sqrt{\frac{MT}{B\Delta E}}$



- For the same isotope, different nuclear models give different values of NME.

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

Nuclear Matrix Element (NME)



Challenges for the 0νββ Searches

- The detector has limited energy resolution.

0νββ Half-Life Sensitivity: $S^{0\nu} \propto \epsilon\eta\sqrt{\frac{MT}{B\Delta E}}$

Measuring the 2νββ Spectrum Tail

Allows to understand the background contribution of 2νββ to the 0νββ region-of-interest (ROI).

- For the same isotope, different nuclear models give different values of NME.

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

Nuclear Matrix Element (NME)

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.

Requirements to determine the ^{130}Te $2\nu\beta\beta$ decay half-life

… or, in other words, main tasks for my PhD!

Requirements to determine the ^{130}Te $2\nu\beta\beta$ decay half-life

… or, in other words, main tasks for my PhD!

- Response of the detector
  - Energy Calibration
  - Optical Calibration

Laserball

N16

Requirements to determine the ^{130}Te $2\nu\beta\beta$ decay half-life

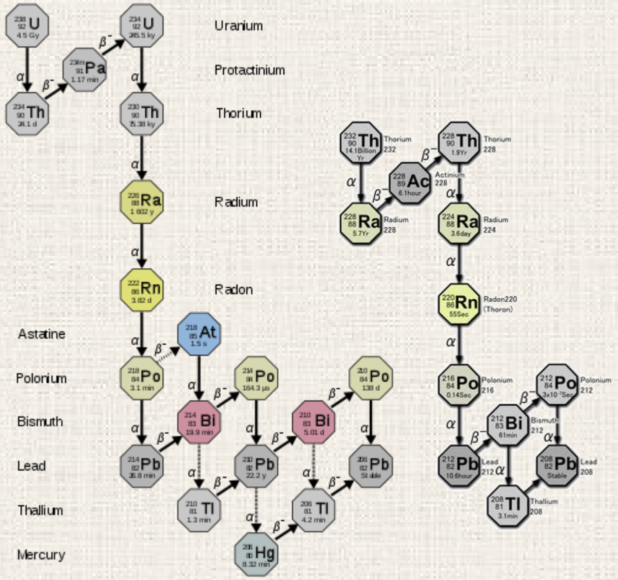
… or, in other words, main tasks for my PhD!

- Response of the detector
  - Energy Calibration
  - Optical Calibration

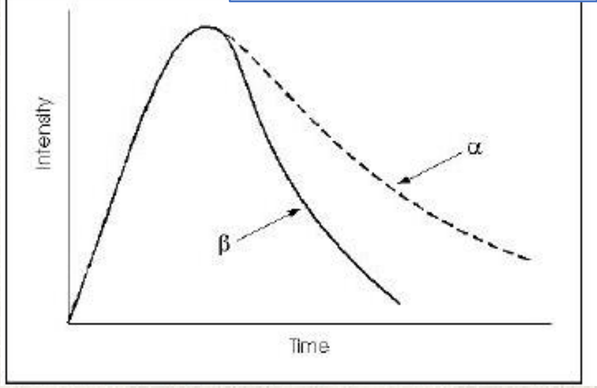
Laserball

N16

- Model of the backgrounds in the detector and scintillator
  - Determine contamination levels
  - Have accurate rejection techniques

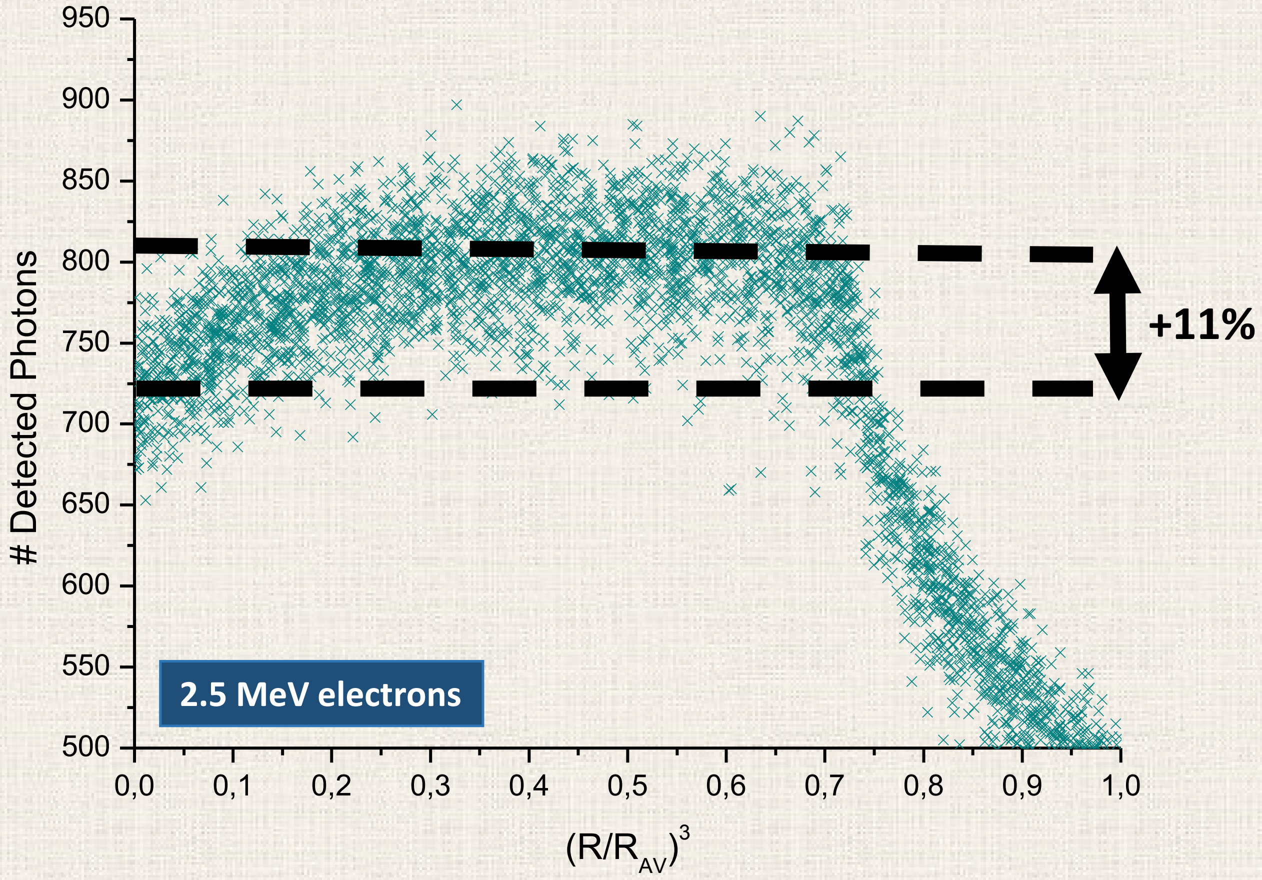


α-β discrimination



Optical Calibration with the Laserball

Why is it important?



Scintillator Experiments

Light is emitted isotropically

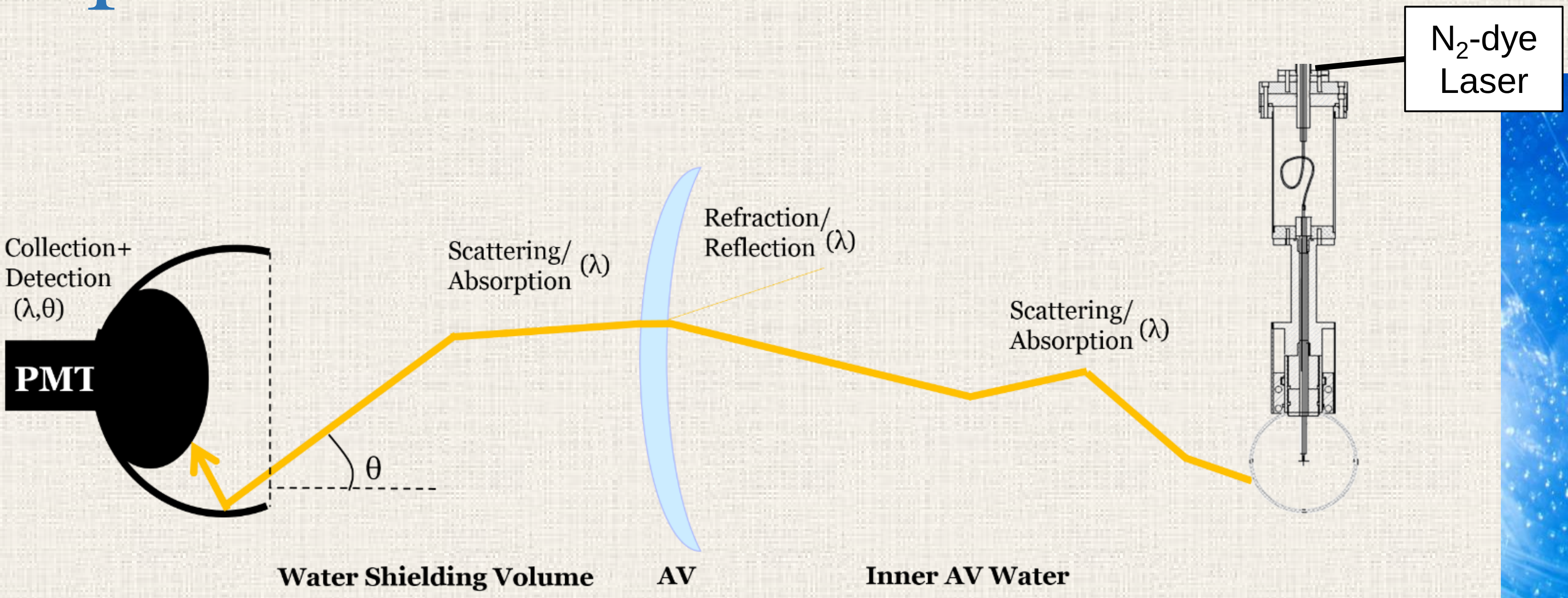
$$E \propto kN$$

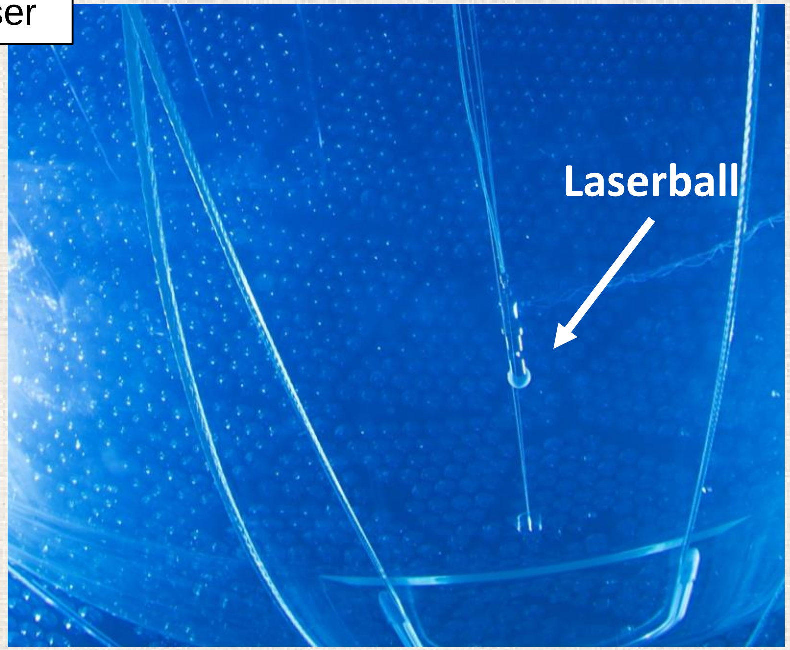
Detector energy response should be independent of position.

↓

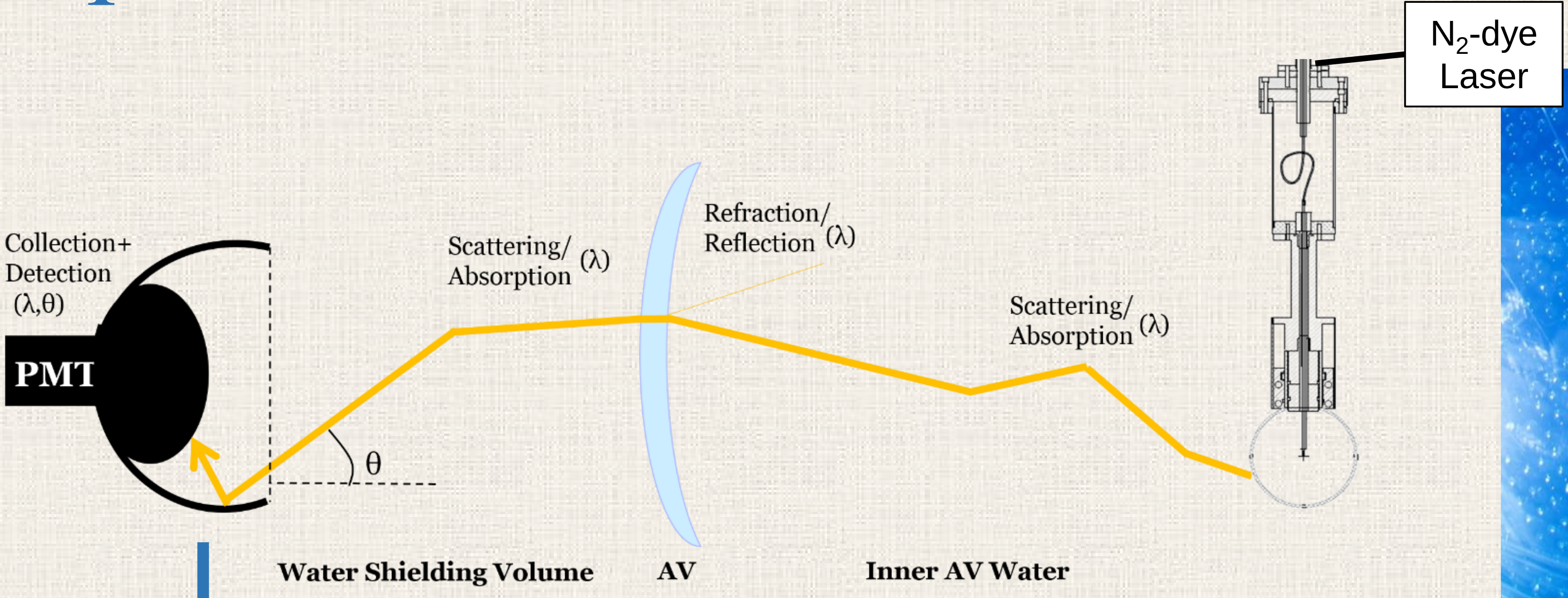
Need to account for the propagation and collection of light.

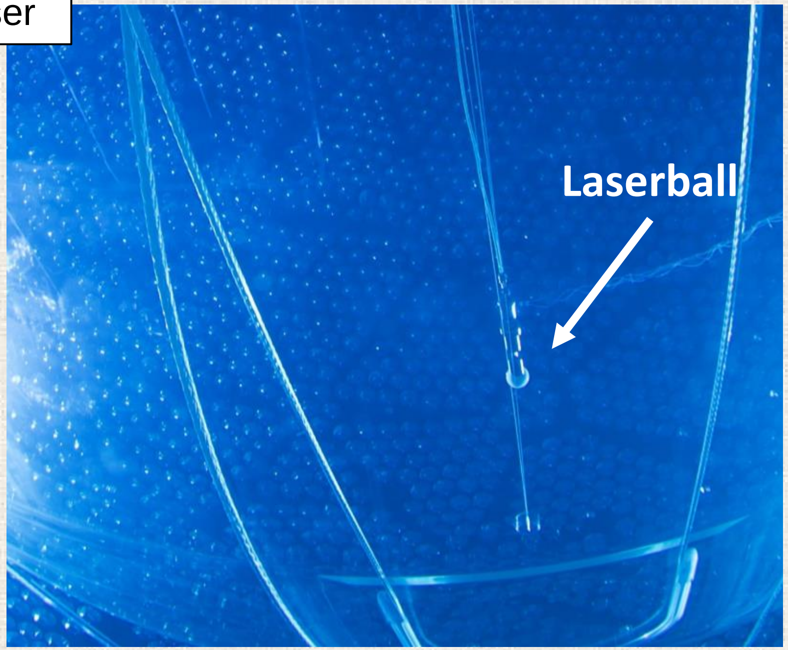
Optical Calibration with the Laserball

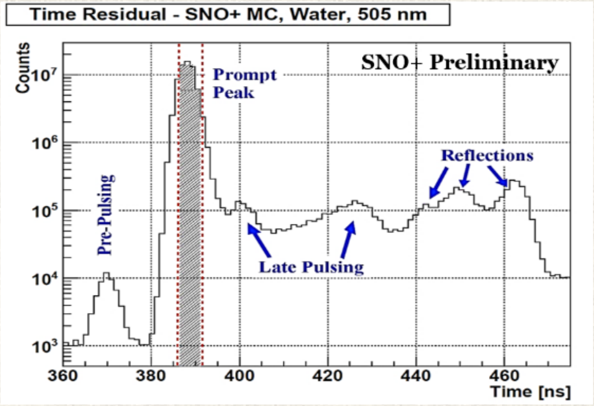




Optical Calibration with the Laserball

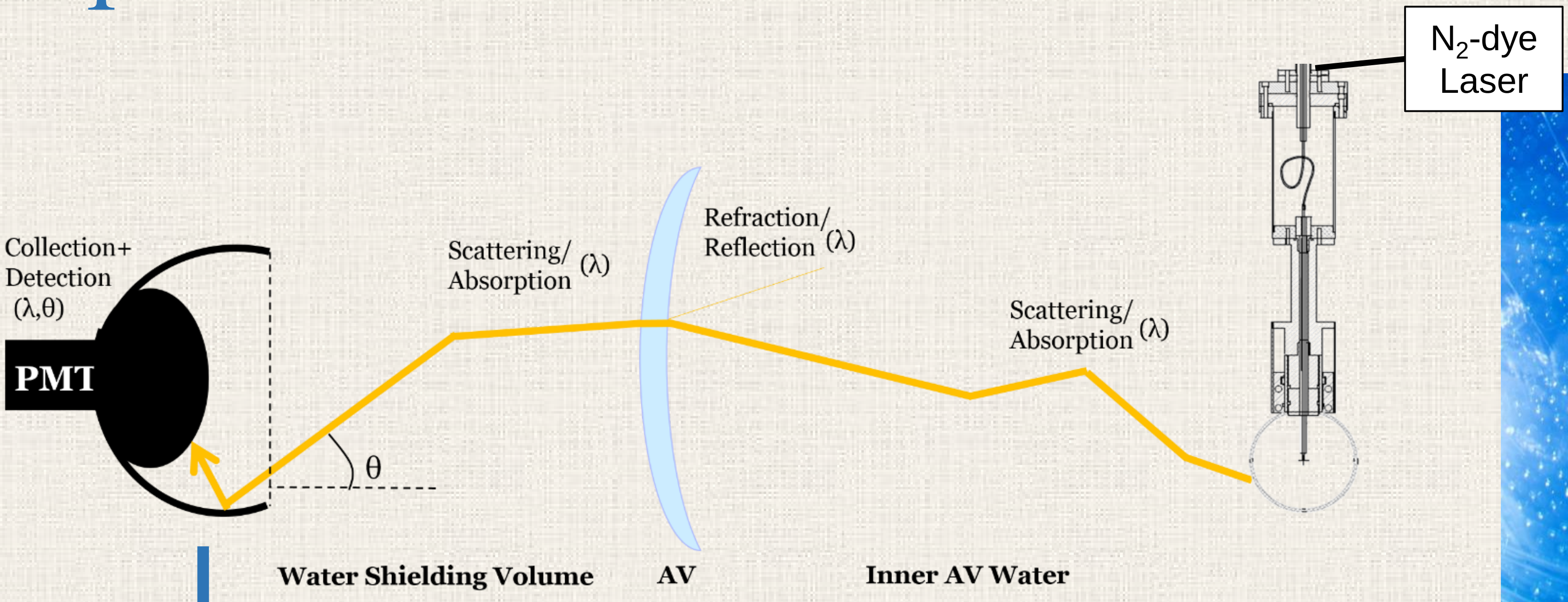


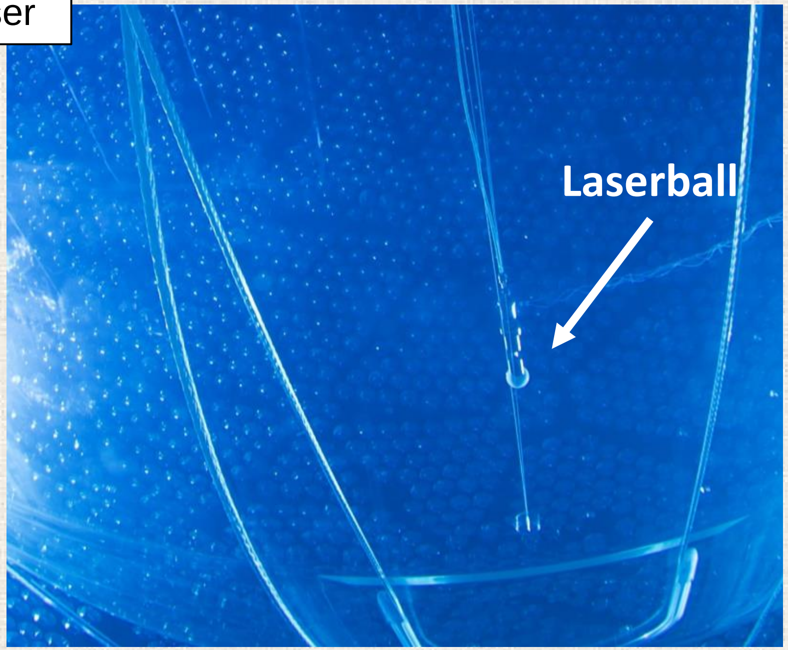


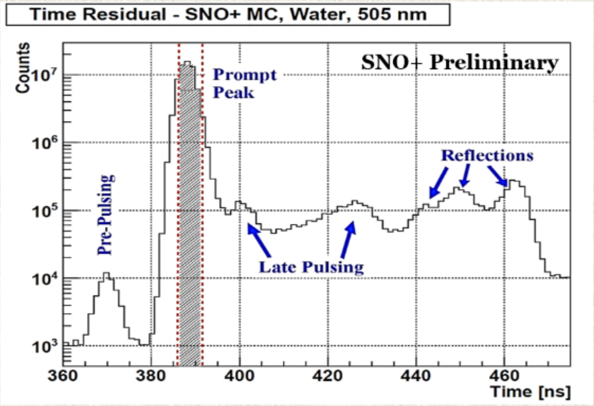


PMT Signal

Optical Calibration with the Laserball







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

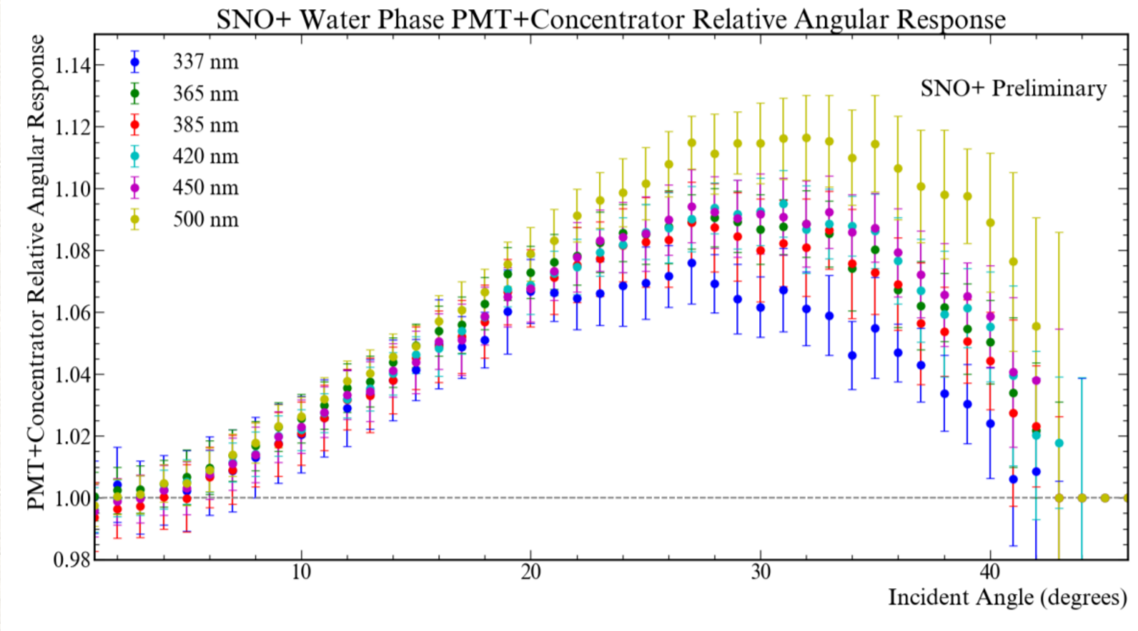
The Optical Model

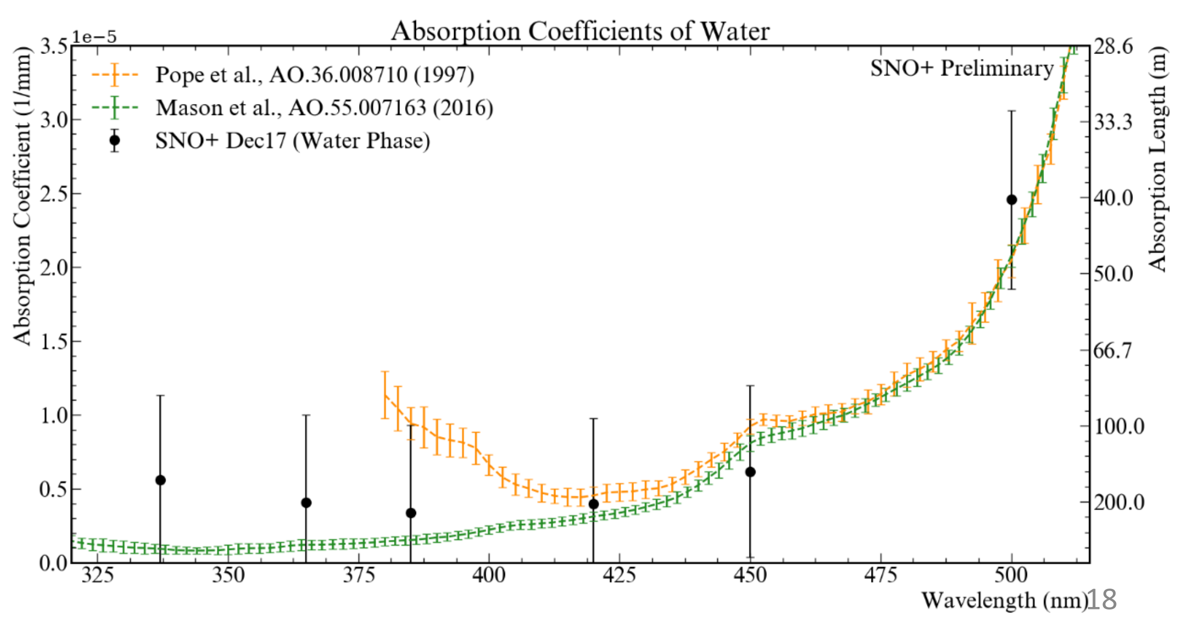
Optical Calibration with the Laserball

- Analysis of the December 2017 and July 2018 internal scans.
  - Laserball deployed inside the acrylic vessel.

Measured:
✓ Internal and external water attenuations
✓ Laserball parameters
✓ PMT angular response up to 45 degrees

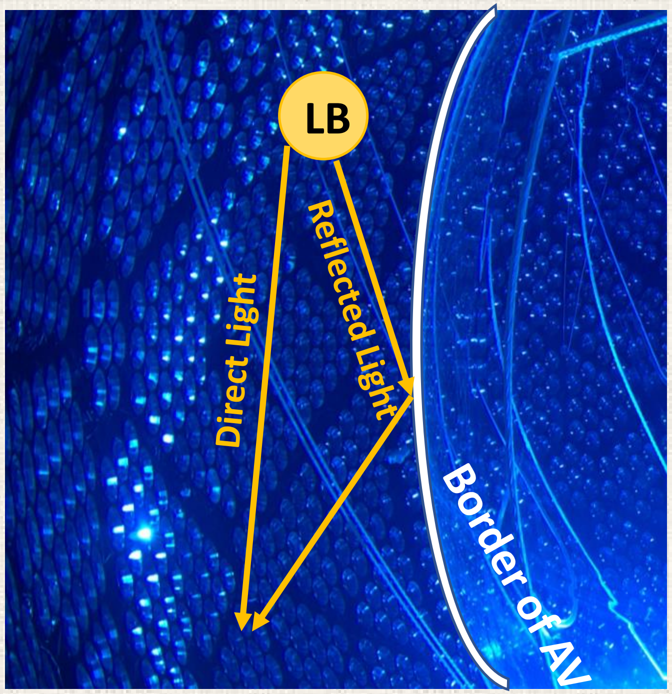
➡ Constants propagated to the simulation software and reconstruction algorithms





Optical Calibration with the Laserball

- Analysis of the July 2018 external scan.
  - Laserball deployed outside the acrylic vessel.
  - Requirements:
    - Determine the orientation of the source (not given by deployment hardware in this type of scan);
    - Identify and exclude PMTs with occupancy contaminated by reflected light.



Measured:

✓ Internal and external water attenuation with better precision
✓ Measured PMT angular response up to 60 degrees
✓ Measured acrylic attenuation

} Measurements never done before in-situ!

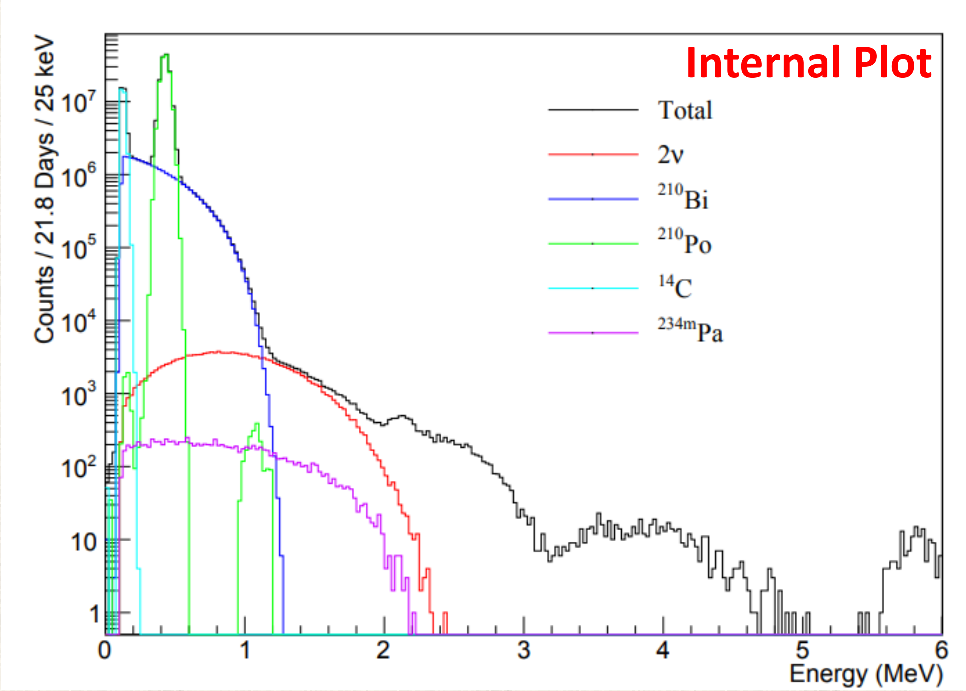
Important measurements for an accurate detector model in the upcoming phases!

2νββ Analysis

- Developing a Binned Maximum Likelihood Analysis.
  - Optimize cuts (energy, FC) and event selection.
  - Fit MC Distributions to Data using energy, R^3 and particle ID variables.

↓

Measure 2νββ half-life



  - Current best measurement by CUORE

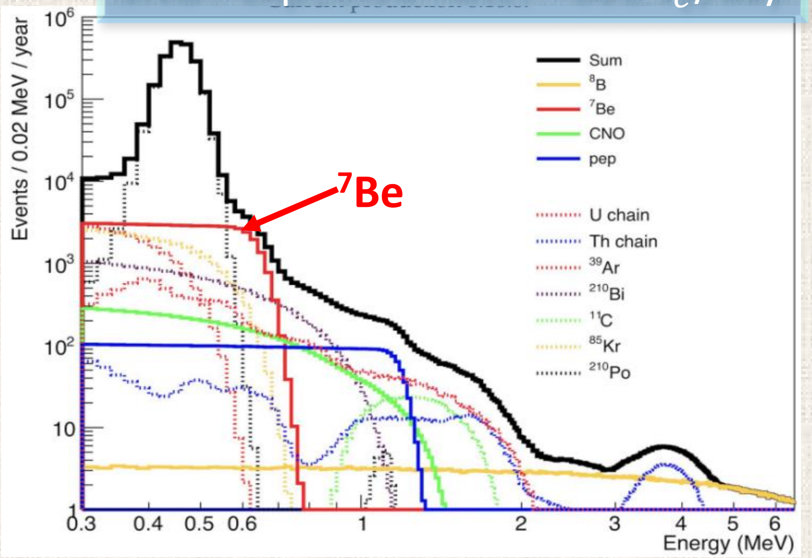
$$T_{1/2}^{2\nu} = [7.9 \pm 0.1\,(stat.) \pm 0.2\,(syst.)] \times 10^{20}\ yr$$

Reference: Caminata, A. *et al.*, *"Results from the Cuore Experiment"*. *Universe* **2019**, *5*, 10.

2νββ Analysis

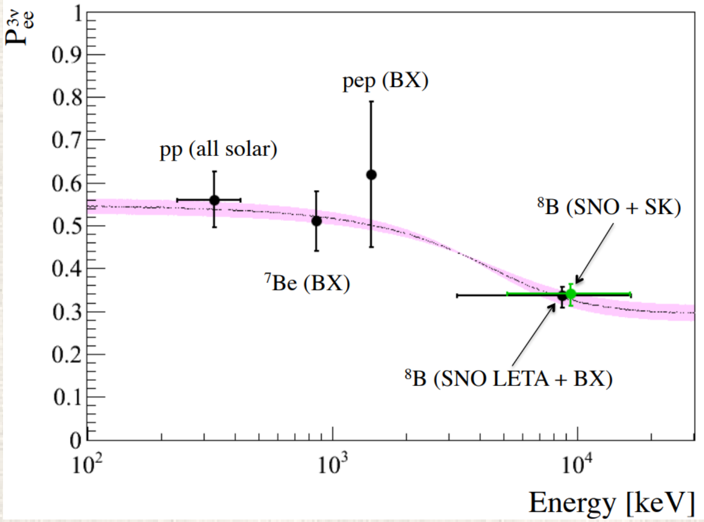
- Developing a Binned Maximum Likelihood Analysis.
  - Optimize cuts (energy, FC) and event selection.
  - Fit MC Distributions to Data using energy, R^3 and particle ID variables.
- Will be **tested during the Scintillator Phase** to independently extract the **^{7}Be solar neutrino signal** and determine the flux.
  - Cross-check with the SNO+ solar neutrino multi-component likelihood analysis.

SNO+ Expected Rate: ~600 ν_e/day



^{7}Be solar neutrinos Mono-energetic neutrinos – 0.86 MeV

Standard Solar Model Expected Flux: (4.93 ± 0.29) ×10^9 cm^{-2} s^{-1}
Measured Flux by Borexino: (2.79 ± 0.13) ×10^9 cm^{-2} s^{-1} (ν_e only)
(4.43 ± 0.22) ×10^9 cm^{-2} s^{-1} (3-flavour oscillation)

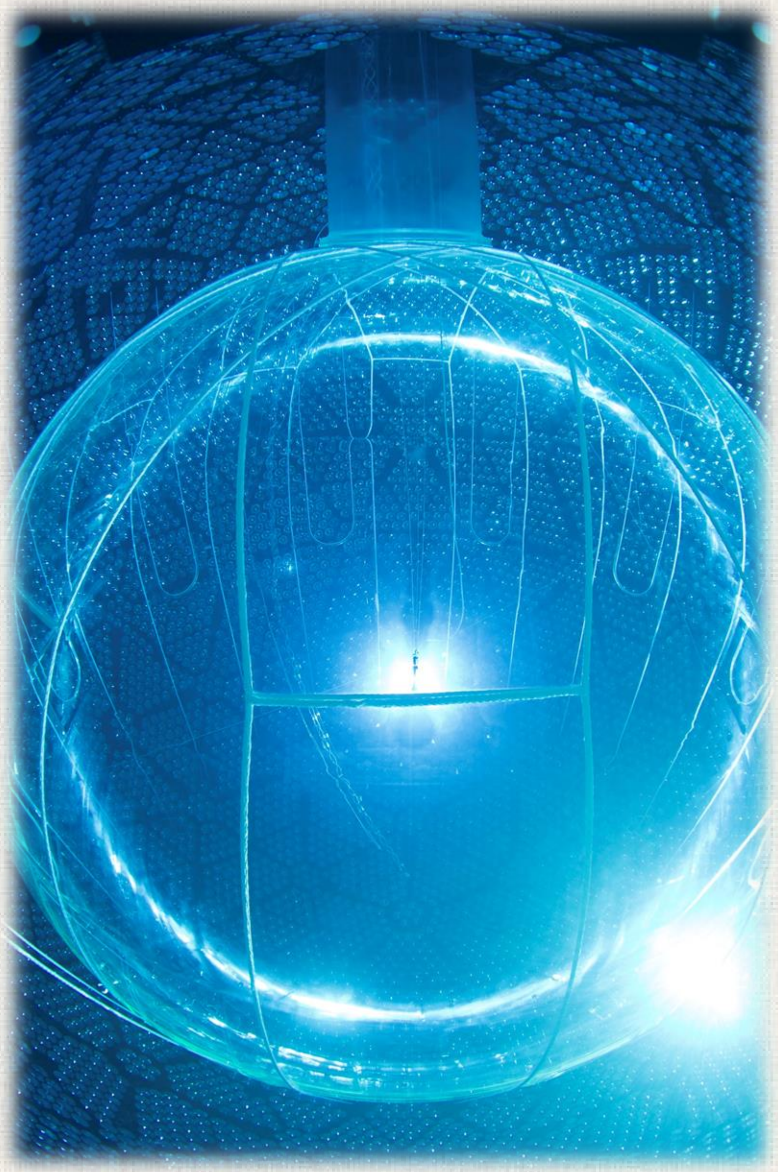


Reference: Bellini, G. *et al.*, *"Final results of Borexino Phase-I on low energy solar neutrino spectroscopy"*. Phys. Rev. D 89, 112007 (2014)

Summary

- A precise measurement of the 2νββ-decay half-life and energy spectrum is crucial for the 0νββ-decay searches.
    - Allows to test the nuclear models, whose results are necessary to extract $m_{\beta\beta}$.
    - Improves the SNO+ sensitivity to 0νββ.
    - Requirements:
        - Detailed characterization of the detector response;
        - Knowledge of the background contributions and effective rejection techniques.
- SNO+ moving towards Scintillator Phase!
    - Finalized Optical Calibration analysis in the Water Phase.
    - Preparing likelihood analysis.

Exciting times ahead!



Acknowledgements

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