Search for Double Beta Plus Decays in Novel Scintillators in NuDoubt^{++}

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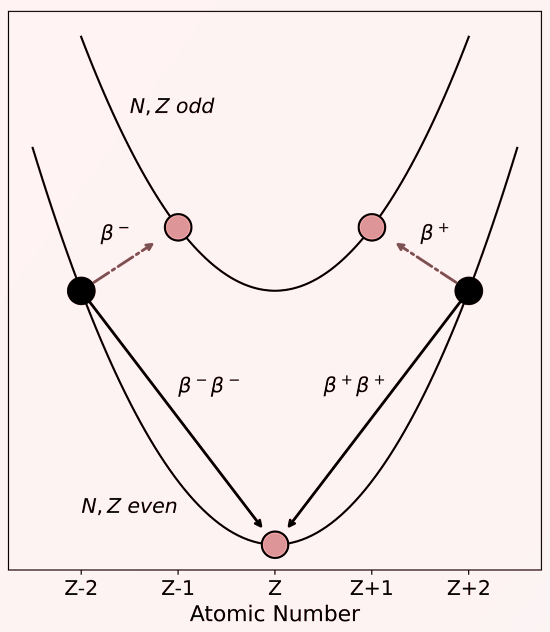
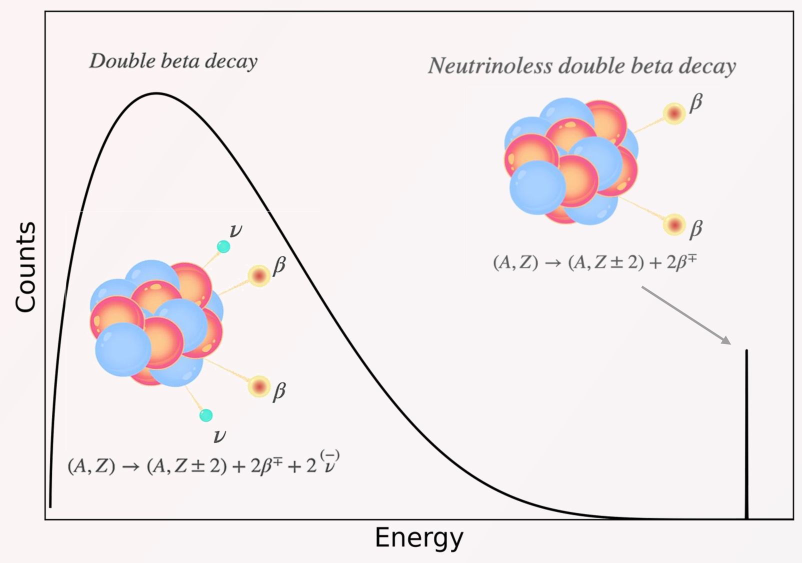
EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE

Understanding Double Beta Decay and Detection Challenges



Mass parabola for even mass number isotopes

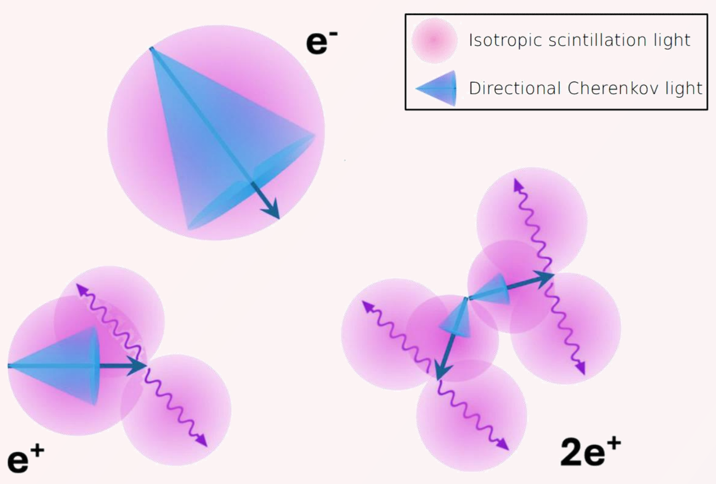
- **Single beta decay** is **not allowed** for certain even-even nuclei
- Only possible decay is **simultaneous** emission of two beta particles
  → **Double beta decay (DBD)**
- This process is possible as:
  - Double beta minus ($\beta^-\beta^-$) decay
  - Double beta plus ($\beta^+\beta^+$) decay
- $\beta^-\beta^-$ decay observed in 14 isotopes
- $\beta^+\beta^+$ decay unobserved … yet



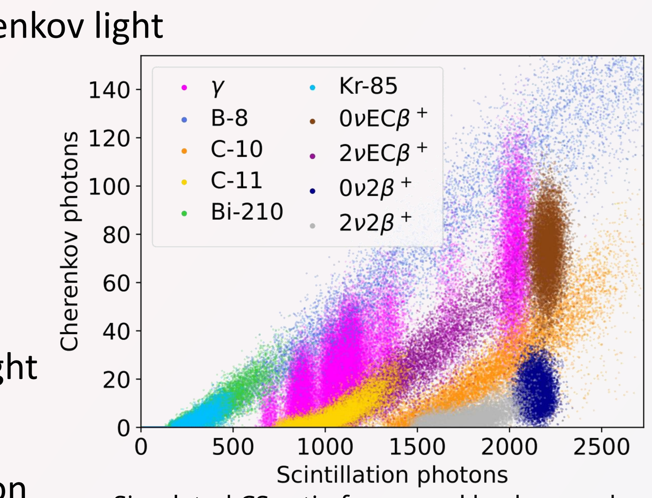
Scheme of the energy spectrum of a neutrinoless double beta decay

- Three possible **Double beta plus** modes:
  - **$\beta^+\beta^+$** – double positron emission
  - **ECβ^+** – electron capture + positron emission
  - **ECEC** – double electron capture
- All three modes can occur **without neutrino emission**, violating **lepton number conservation** and one of the few ways to probe the **Majorana nature** of neutrinos
- Energy **spectrum** of double beta decay is **continuous**
- Neutrinoless mode introduces a **sharp peak** at the endpoint
- Requirements for detecting double beta decay:
  - Excellent **energy resolution** especially at the endpoint
  - Effective **background suppression** due to the long half-life
- **Decay signature** → better background discrimination of positrons than electrons
- **New detector technologies** needed to enable detection of Neutrinoless decay

Hybrid Scintillator



- Separation of **Cherenkov (C)** and **scintillation (S)** light
- Enables better **particle discrimination**
- Slow organic scintillators with slow flours
  → delay scintillation by 10 ns causes **time separation** from prompt Cherenkov light
- Different particles create different amounts of C and S light

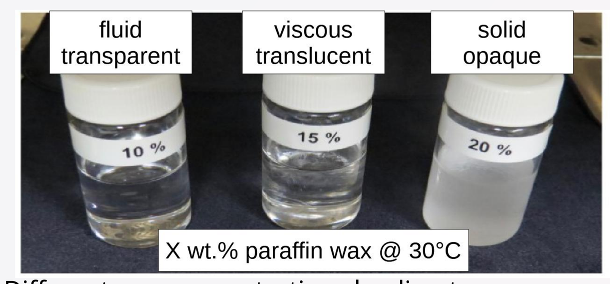


Simulated CS-ratio for several backgrounds and signals *

- Electrons emit Cherenkov and scintillation light
- Positrons with same scintillation yield, produce less Cherenkov light due to **annihilation gammas** → **clear distinction** from electrons
- **Cherenkov-to-scintillation ratio** (CS-ratio) → particle discrimination
- Different particles form distinct populations in CS-ratio space

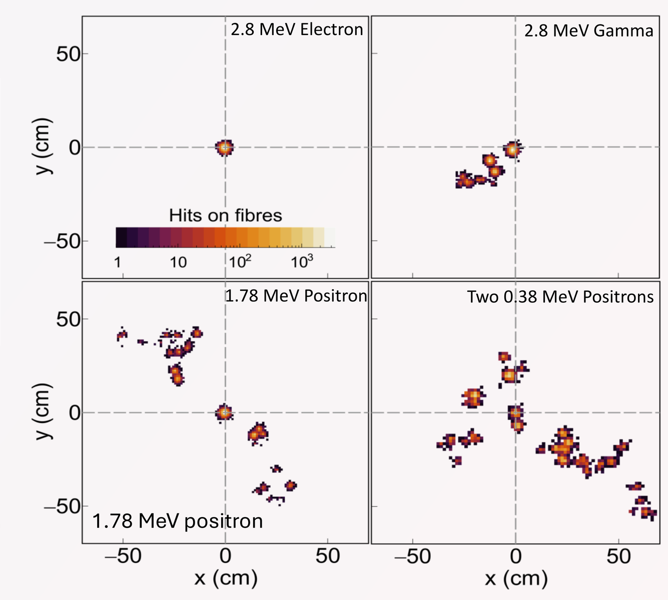
Opaque Scintillator

- Mie scattering → **confine light** near its creation point
- **Reduces scattering length** to few millimeters
- Opacity is achieved by adding **wax** to the scintillator
- **Topology** read out with optical fibers



Different wax concentrations leading to an opaque sample **

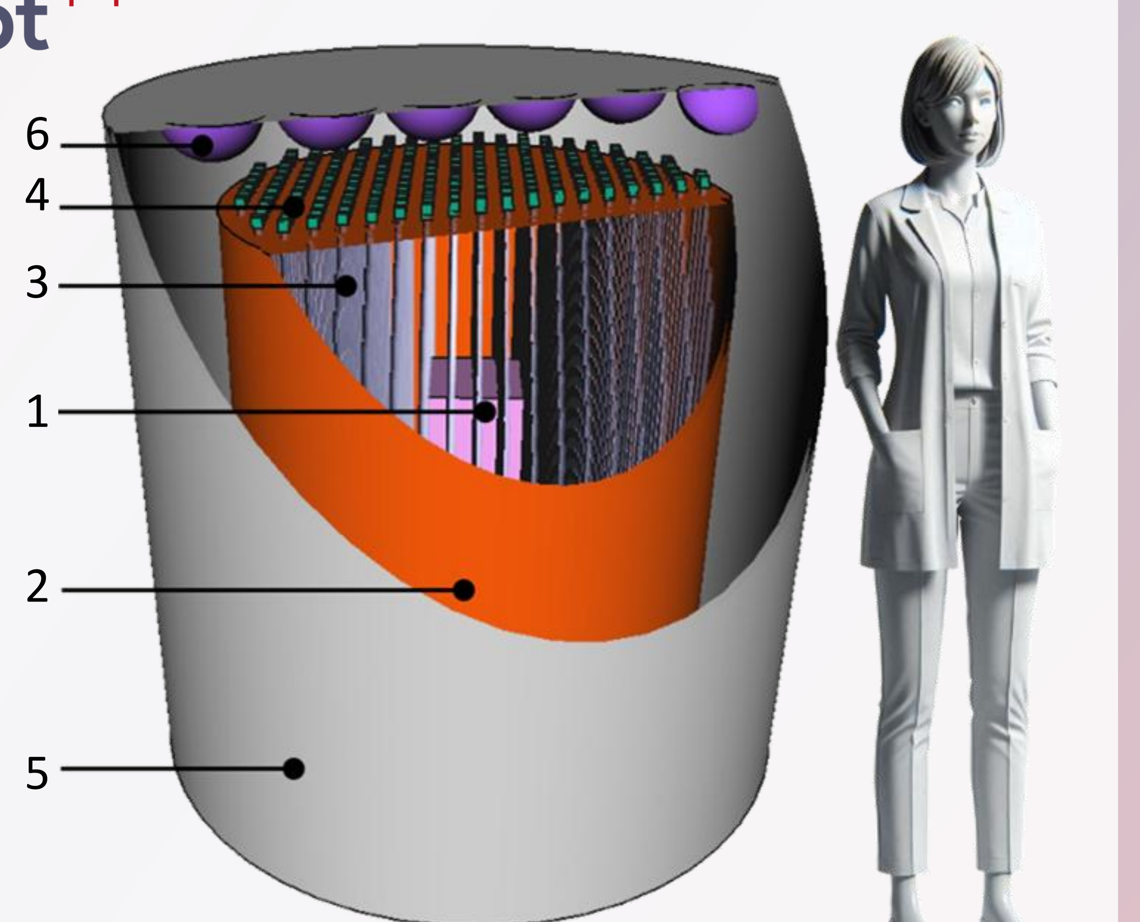
- Event topology depends on the particle
  - **Electrons:** Create a short ionization trail → **single blob**
  - **Gammas:** Undergo multiple Compton scatters → **multiple blobs**
  - **Positrons: Combination** of electron like blobs and two gamma scatters



Simulation of different particles to demonstrate particle discrimination strategy *

Combined Double Beta Plus Detector

- **Neu**trinoless **Dou**ble **b**eta **P**lus **P**lus detector → NuDoubt^{++}
- Combined **hybrid and opaque** scintillator technologies
  - event reconstruction and strong **particle discrimination**
  - especially good for **beta plus signatures**
- Primary goal is the search for neutrinoless double beta **plus** decay
- Also suitable for other **background-sensitive** experiments
- **Krypton-78** as the double beta decay isotope
- **First observation** of standard double beta plus decay
- Setting new **limits** on the neutrinoless mode
- NuDoubt^{++} detector consists of:
  - Active **target volume** (1) in the center
    → hybrid opaque scintillator, loaded with krypton-78
  - **Inner detector** (2)
    → hybrid opaque scintillator but without Krypton
  - **Wavelength-shifting optical fibers** (3) through target and inner vessel → read out by **SiPMs** (4)
  - **Outer veto** layer (5)
    → transparent scintillator volume with **PMT** (6) readout



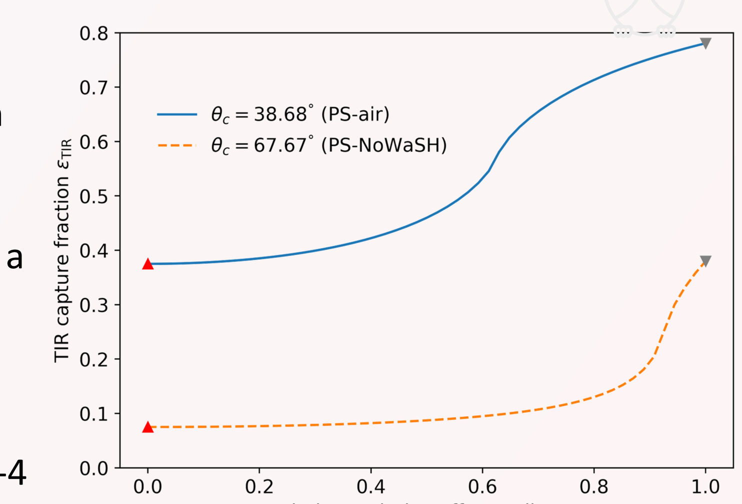
NuDoubt^{++} detector *

OWL fibers

- **O**ptimised **W**ave**L**ength-shifting (OWL) fibers
  → optical fibers with high **photon capture rate**

OWL-fibers under UV light

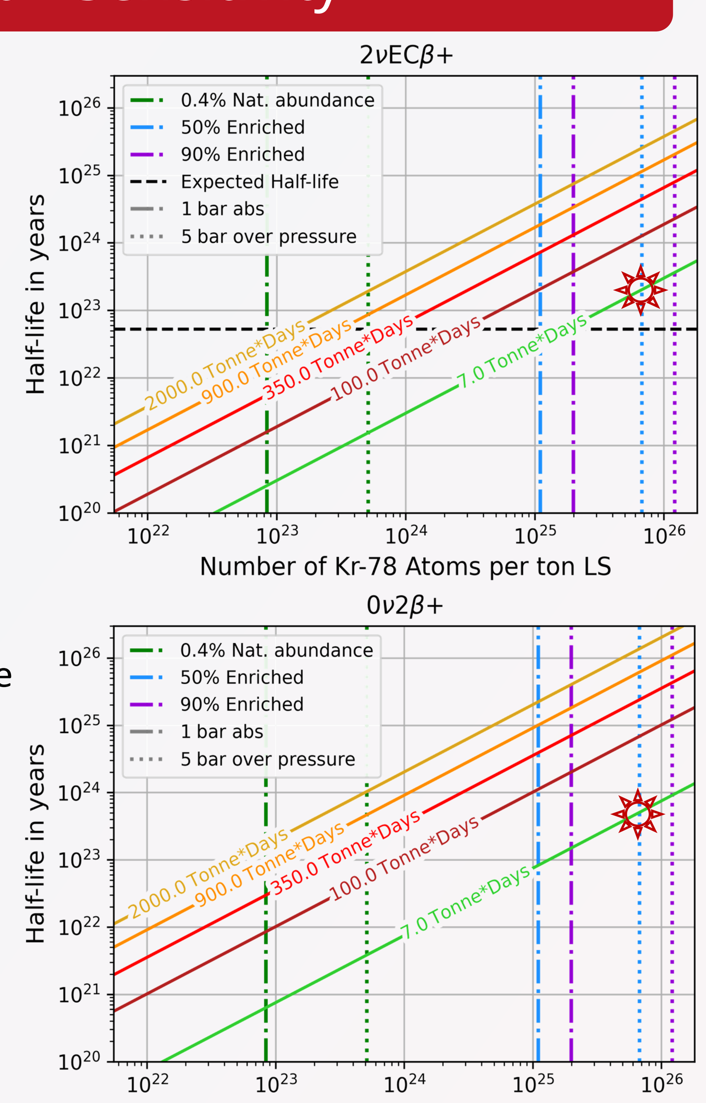
- Absorb photons and isotropic reemission at higher wavelength
- Only photons at specific angles fulfill the **total internal reflection (TIR)** condition and get trapped inside the fiber
  → larger trapping cone for photons emitted at larger radii
- Commercial fibers:
  - wavelength shifter in **the whole fiber**
- OWL fibers:
  - shifter-free core and a **highly doped outer coating**
- This design improves trapping by a factor of 2-4 compared to commercial fibers



Simulated trapping efficiency along the fiber radius for polystyrene fibers with contact to air or NoWaSH (Wax) *

NuDoubt^{++} Sensitivity

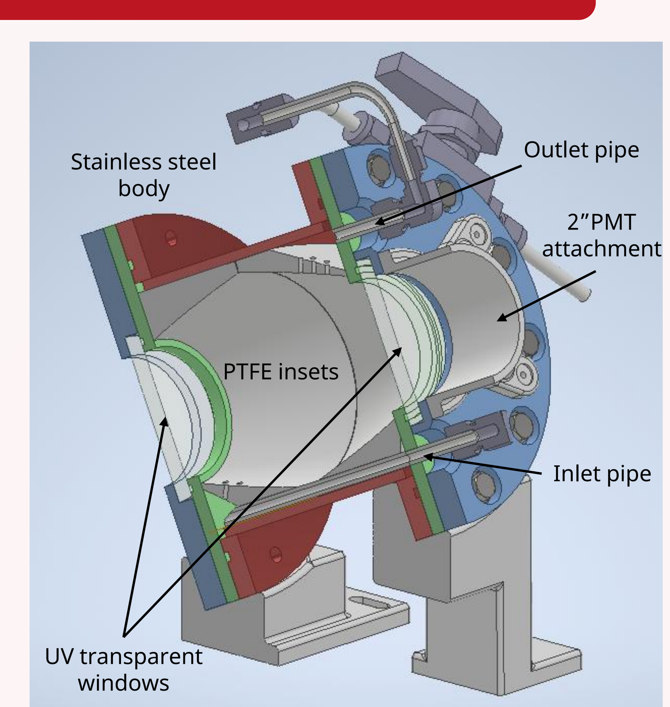
- 34 known $\beta^+\beta^+$ isotopes but only few have **high** enough **Q-values**
  → above 2.6 MeV Thallium-208 background
- Krypton-78 is a promising candidate but **0.4% natural abundance**
- Increase number of Kr-78 atoms:
  - Isotope **enrichment** up to 50%
  - **Pressure loading** up to 5 bar to increase how much gas can be dissolved → Henry's law
- NuDoubt sensitivity study shows the **half-life limits** based on:
  - Detector **mass** and **runtime**
    → slanted lines
  - **Enrichment** and **overpressure**
    → vertical lines and linestyle
- Half-life expectation for the normal ECβ^+ mode
  → horizontal dashed line
- NuDoubt^{++} prototype



Sensitivity limits for normal (top) and neutrinoless (bottom) double beta decay for a NuDoubt^{++} style detector *

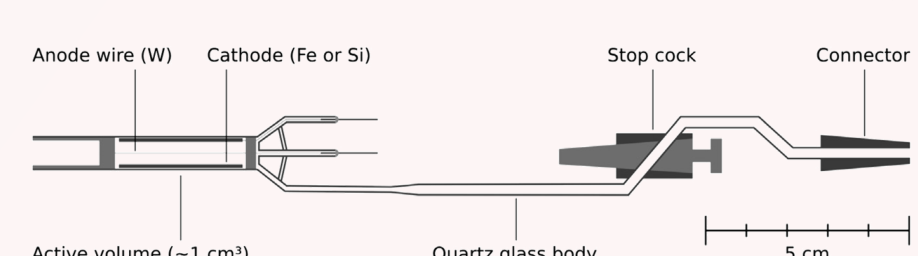
High-Pressure Scintillator Test Cell

- Scintillator loading with krypton tested with dedicated test cell (0.5 L)
- Possibility to measure:
  - **Pressure-dependent loading** factor up to 5 bar overpressure
  - **Transparency** of loaded scintillators
- Krypton gas is **bubbled** through the scintillator at controlled pressure
- Loading factor is measured using single beta decay of **krypton-85**
- Two 2-inch PMTs detect scintillation light via **UV-transparent windows** on opposite sides of the cell
- Additional **PTFE inserts** improve light collection properties by altering shape and reflectivity
- Kr-85 isotope **not naturally occurring**, produced near nuclear power plants
  → Abundance depends on the source of extraction



Cut view scheme of the test cell

- Calibration with ultra low background proportional counters in collaboration with the MPIK for Nuclear Physics
  - Optimized for **radon contamination** in xenon
  - For krypton activity measurement
    → mixture of **krypton–xenon–methane** combining energy calibration from xenon and actual krypton activity measurement



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Sketch of the miniaturized ultra-low background proportional counter ***

PRISMA$^+$ | Graduate School GSPD Particle Detectors | JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U

Sources:
* Combining Hybrid and Opaque Scintillator Techniques in the Search for Double Beta Plus Decays, M. Böhles et al., 2024
** Novel Opaque Scintillator for Neutrino DetectionC. Buck et al., 2019
*** Detection of 133Xe from the Fukushima nuclear power plant in the upper troposphere above Germany, Hardy Simgen et al, 2014