Search for Double Beta Plus Decays with NuDoubt^{++}

Cloé Girard-Carillo (she/her)

on behalf of the NuDoubt^{++} Collaboration*

Rencontres de Moriond 2025 - 23rd-30th March 2025

*Manuel Böhles, Sebastian Böser, Magdalena Eisenhuth, Cloé Girard-Carillo, Kitzia M. Hernandez Curiel, Bastian Keßler, Kyra Mossel, Veronika Palušová, Stefan Schoppmann, Alfons Weber, Miriam Weigand, Michael Wurm

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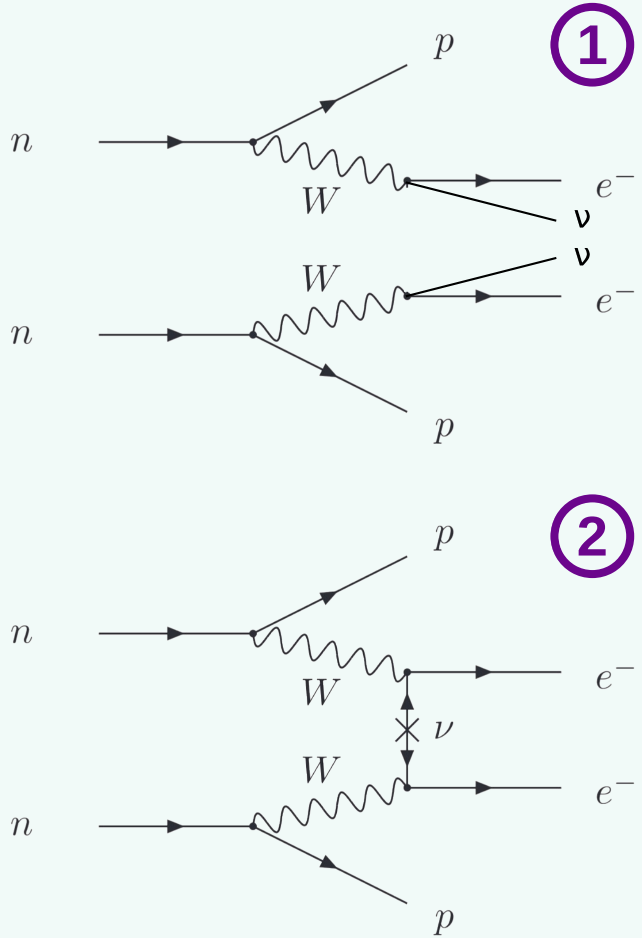
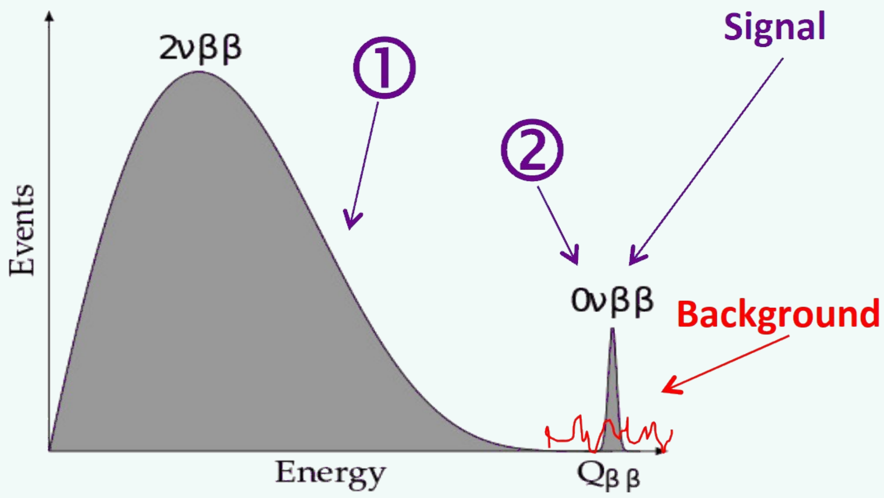
Double Beta decays

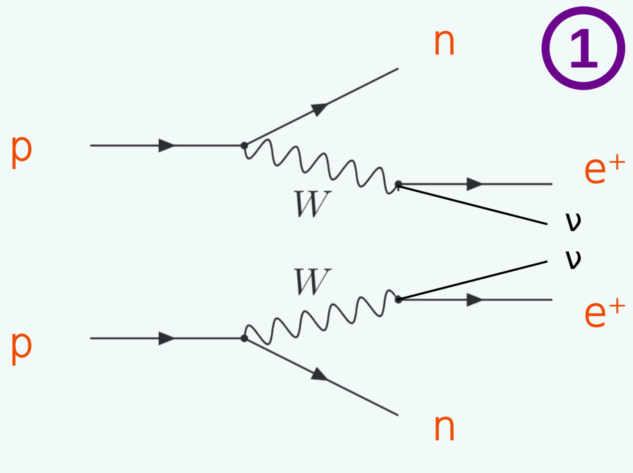
Today's status and challenges

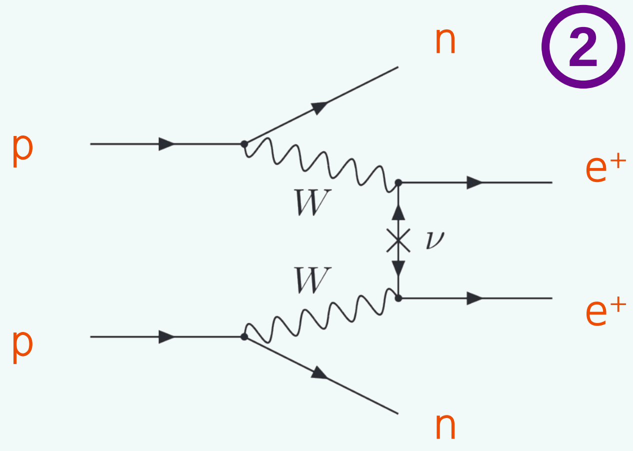


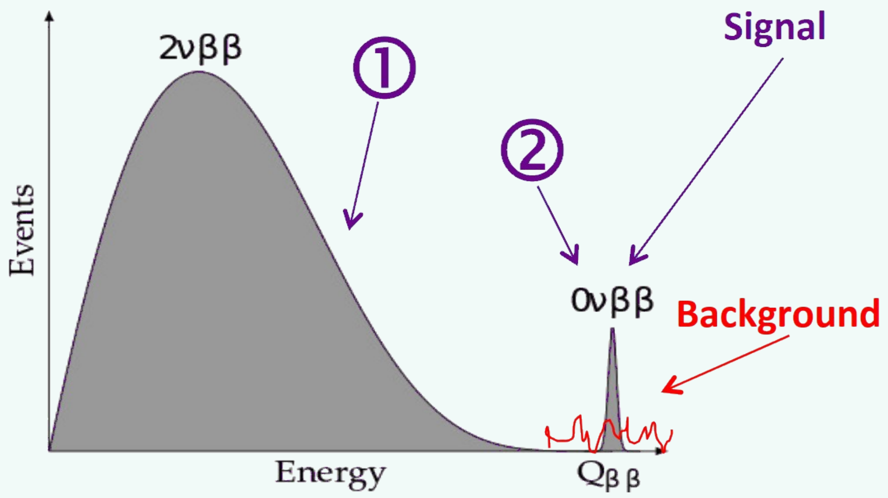


Best sensitivities on $T^{0\nu}_{1/2} > 10^{24\text{-}26}$ years

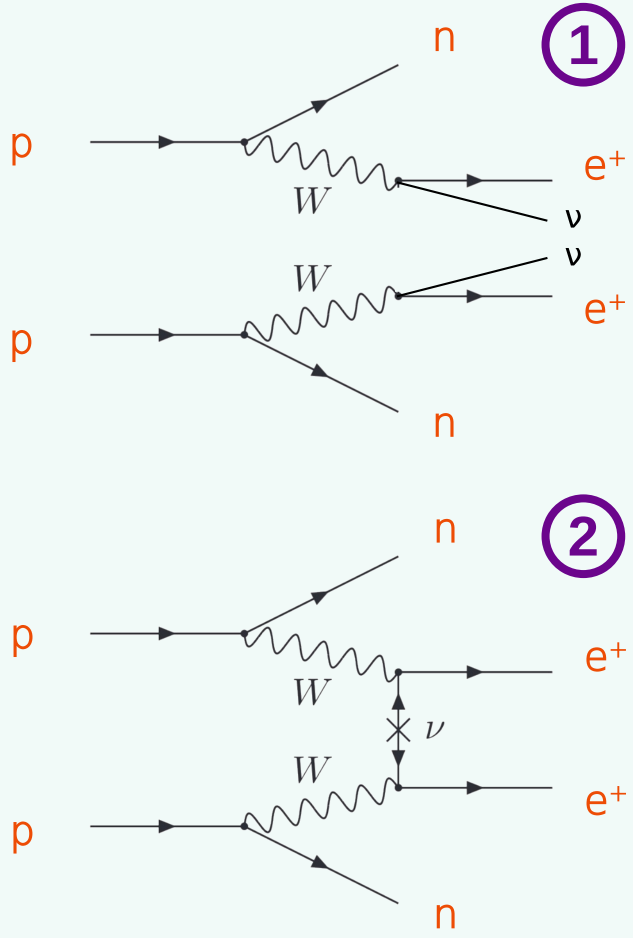
Double Beta decays

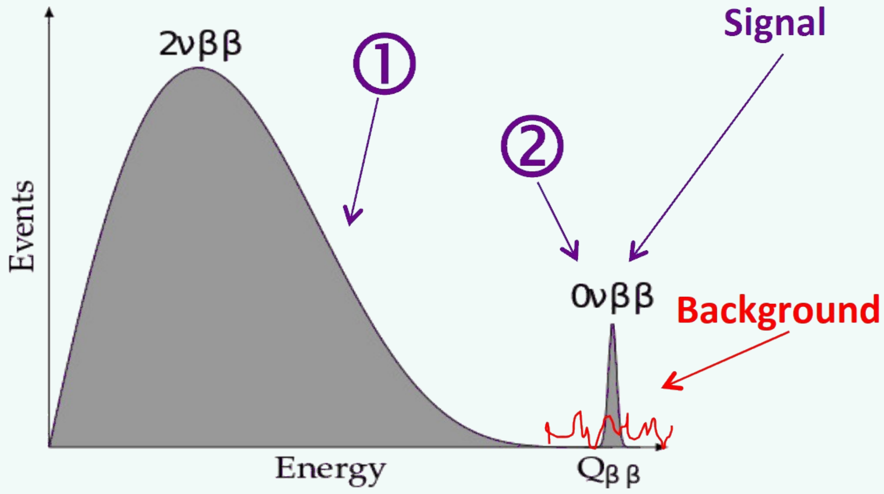






Double Beta decays





- Suppressed decay probabilities
- Less favourable Q-values
- Low natural abundances of nuclei
- Challenging signatures

Double Beta decays

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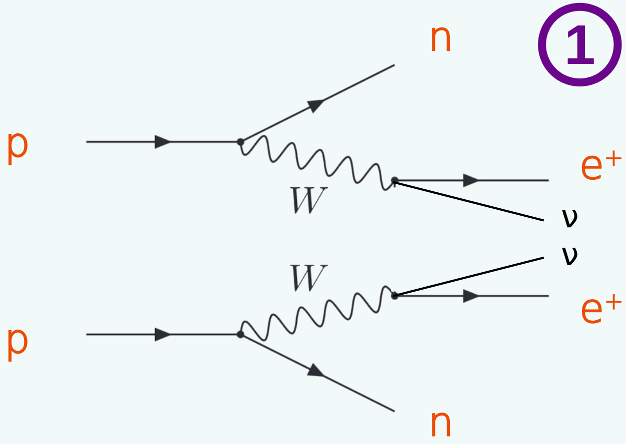

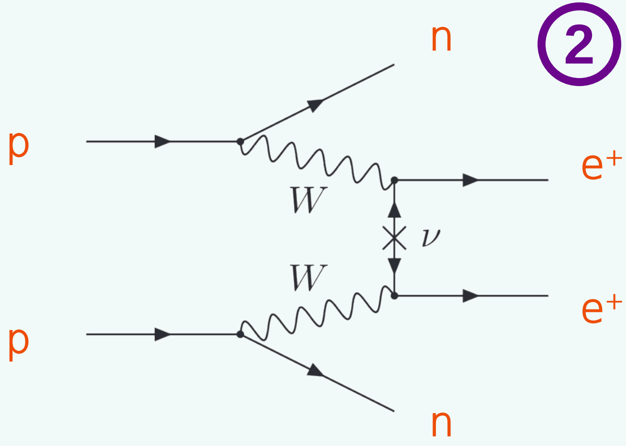

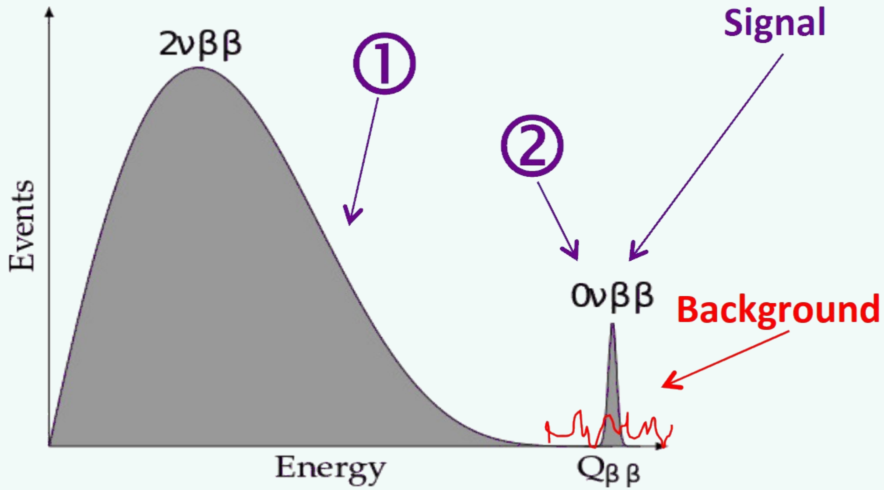

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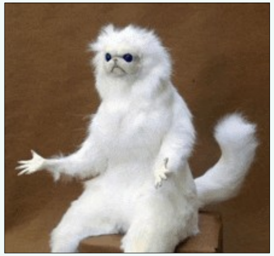

Double Beta decays

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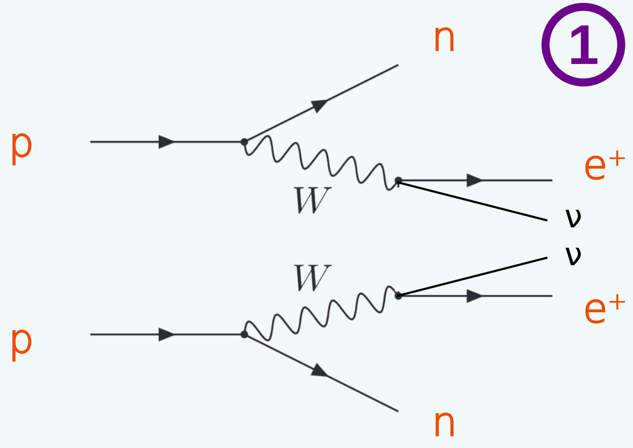

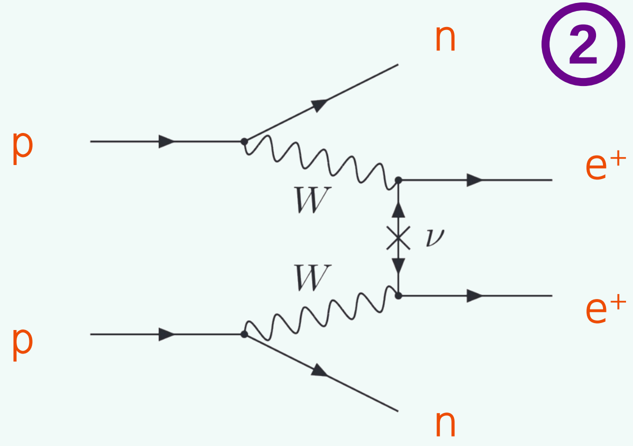

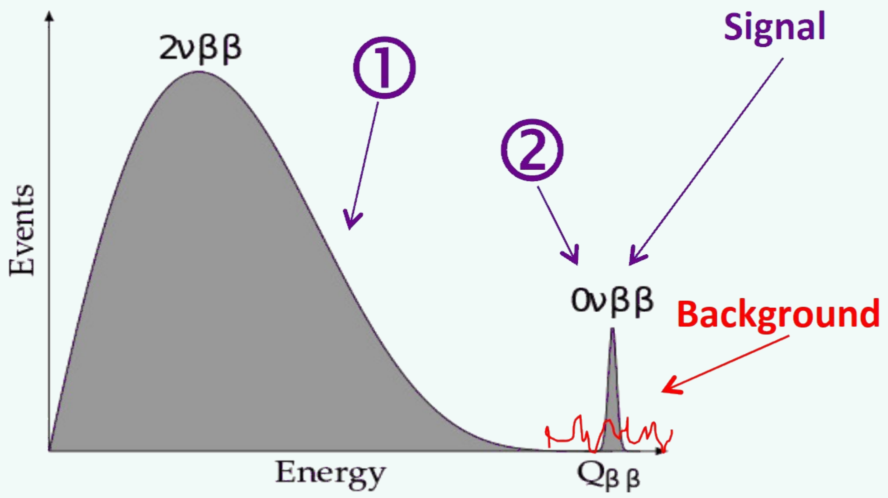

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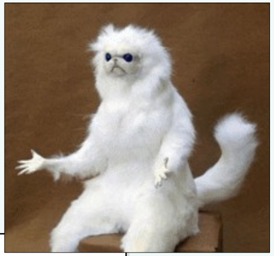
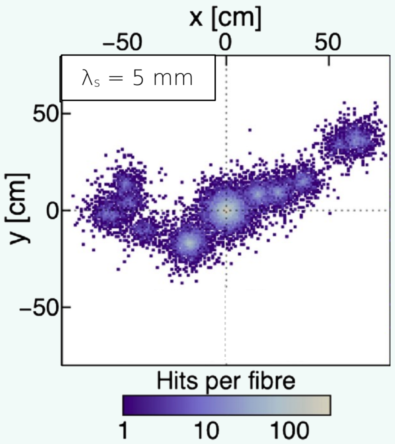


- Studies of nuclear structure models
- Valuable constraints on theoretical models
  → deeper understanding of underlying nuclear physics

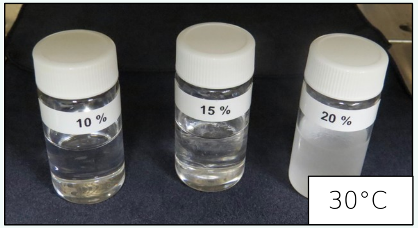
Development of new scintillators

Opaque scintillator
Confine light around vertex



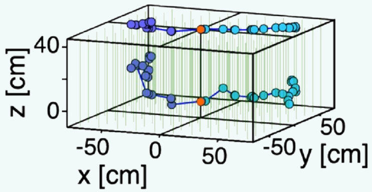
Simulation of e⁺ 1 MeV KE

First implementation of opaque scintillator: adding wax to LS (NoWaSH)



Novel Opaque Scintillator for Neutrino Detection C. Buck et al., 2019

Readout with grid of
wavelength-shifting fibres & SiPMs



Advantages

- **Good spacial resolution** (X,Y) → PID capabilities
- Tunable opacity

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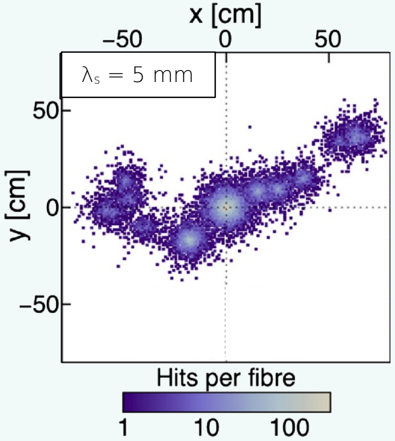

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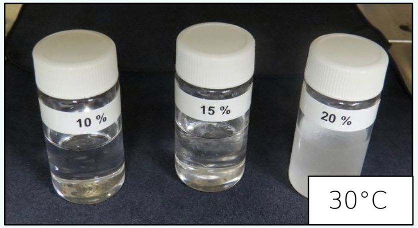

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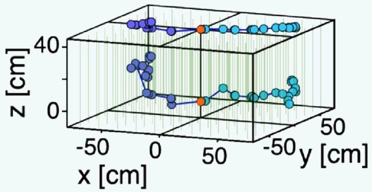

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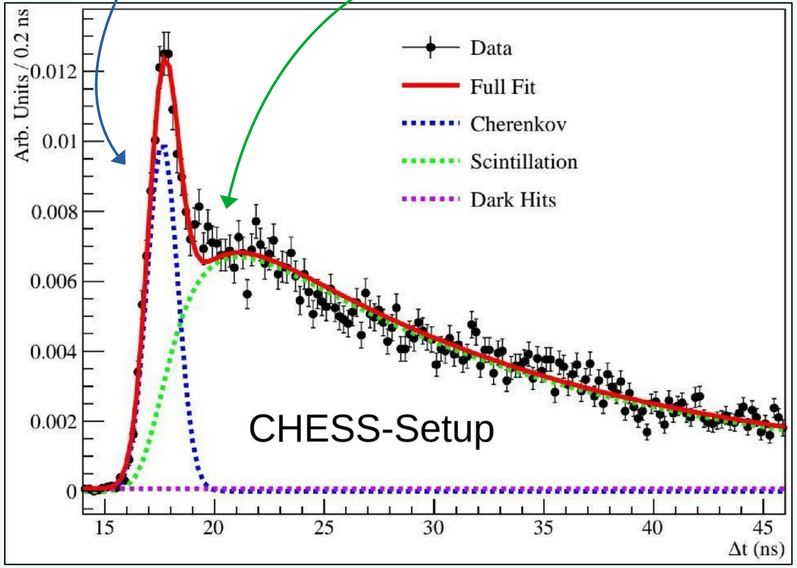
Slow scintillator
Separate Cherenkov and Scintillation light

Small Cherenkov peak visible in the beginning of light emission

Scintillation light delayed in time (τ >10 ns)



Development of a Bi-solvent Liquid Scintillator with Slow Light Emission, H.Th.J. Steiger et al., 2024

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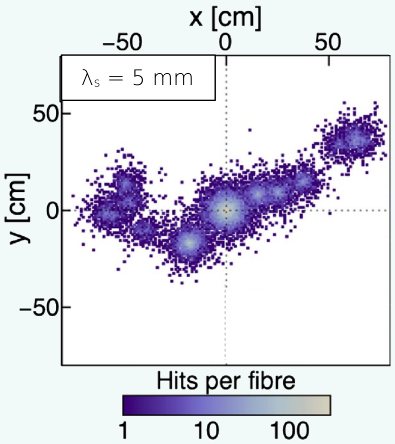

Simulation of e^+ 1 MeV KE

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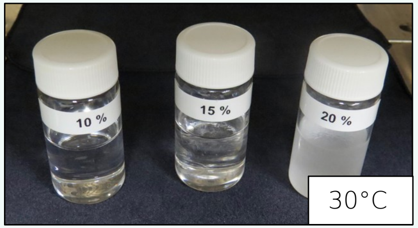

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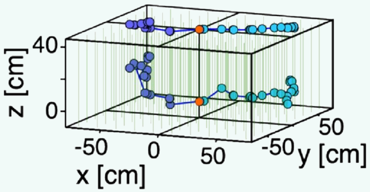

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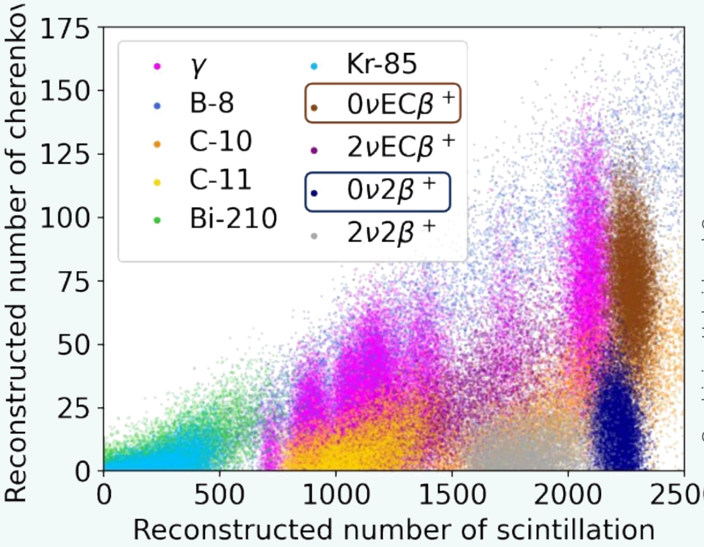

Combining Hybrid and Opaque Scintillator Techniques in the Search for Double Beta Plus Decays, M. Böhles et al., 2025

Advantages

- **PID using Č/S ratio**
- **High scintillation LY** → good energy resolution
- Low energy threshold

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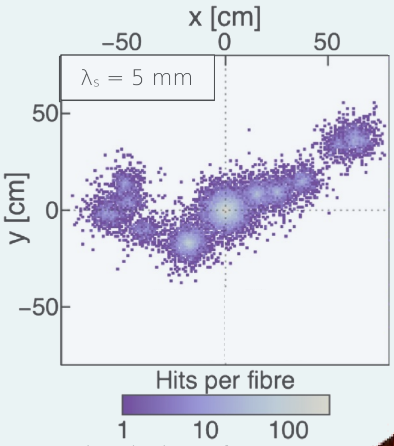

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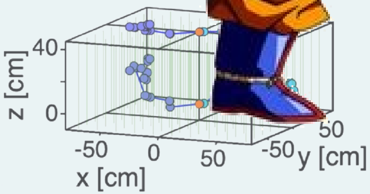

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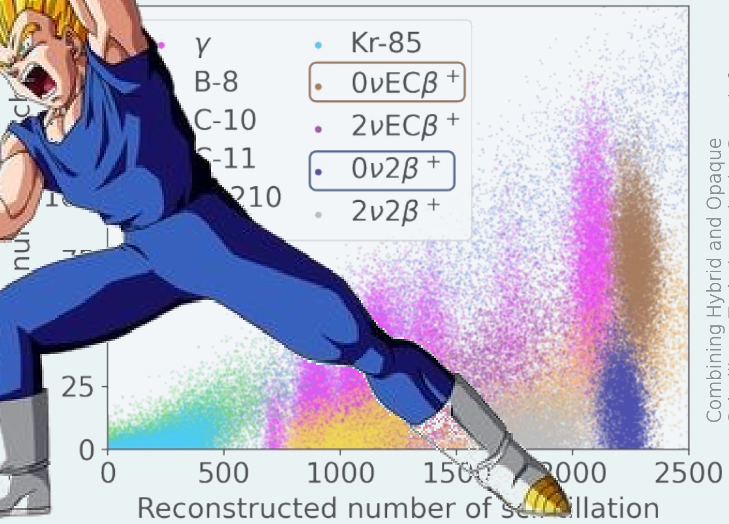

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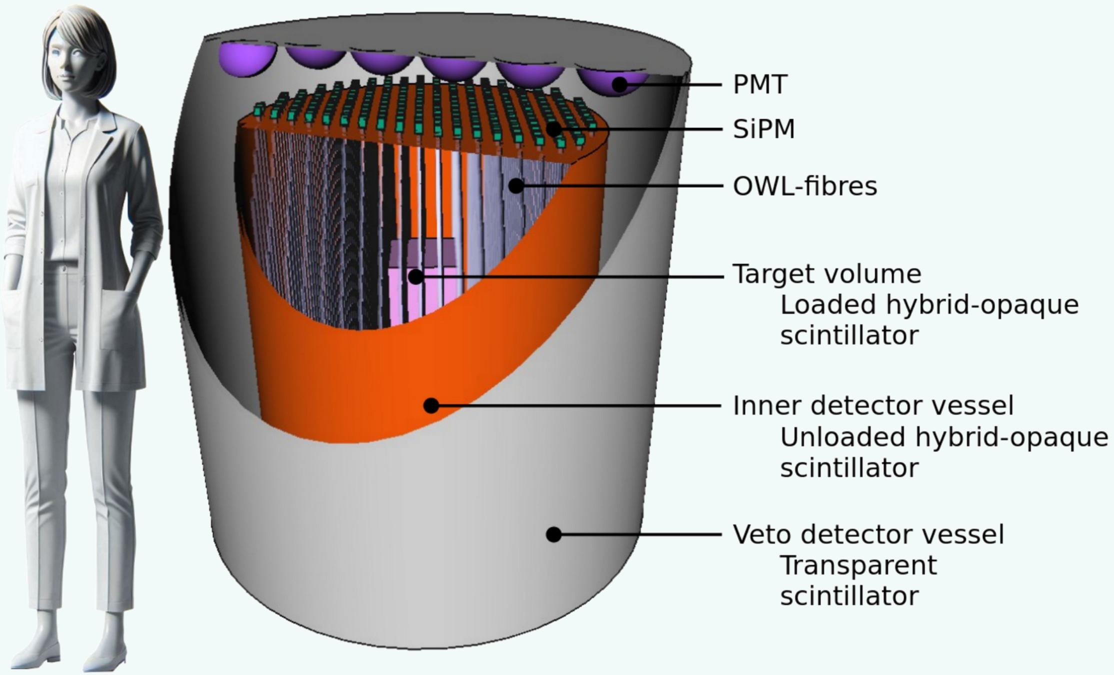
The first NuDoubt^{++} prototype

- 50% **enriched** krypton-78 gas
- 5 bar **overpressure**
- 10 kg (scintillator Mass) in central fiducial vessel



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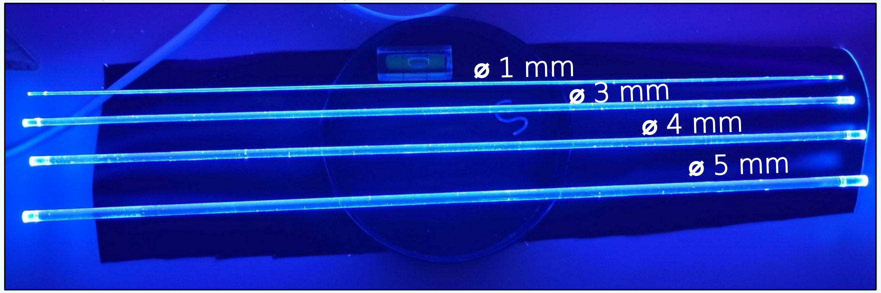
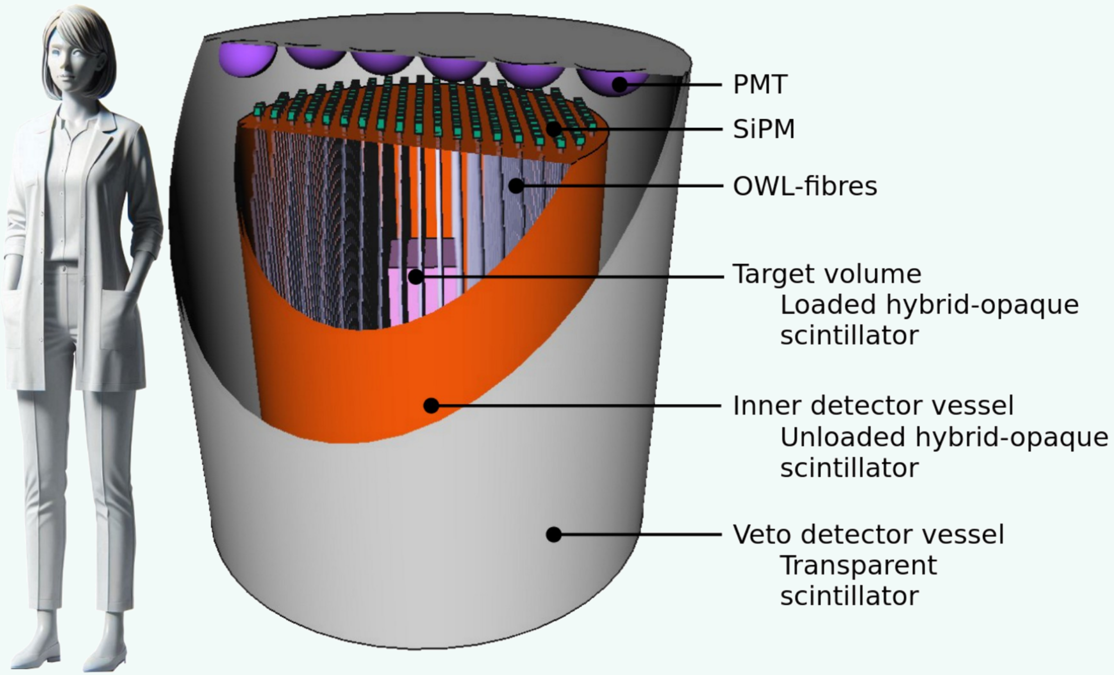
First prototypes of polystyrene-based OWL-fibers



OWL = Optimised Wavelength-shifting fibres
PMMA fibers of ~mm diameter, coated with wavelength-shifting paint



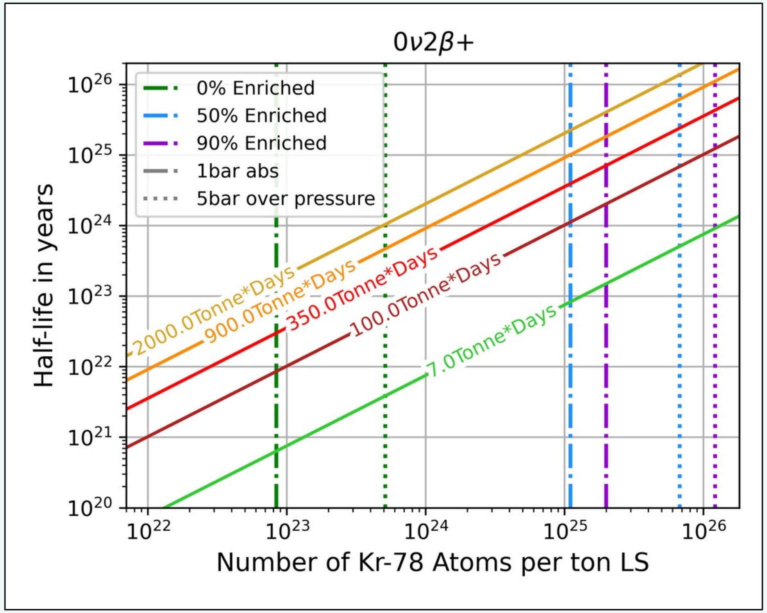
Expected sensitivity of NuDoubt^{++}

After 20kg.year exposure (∼1 year operation):

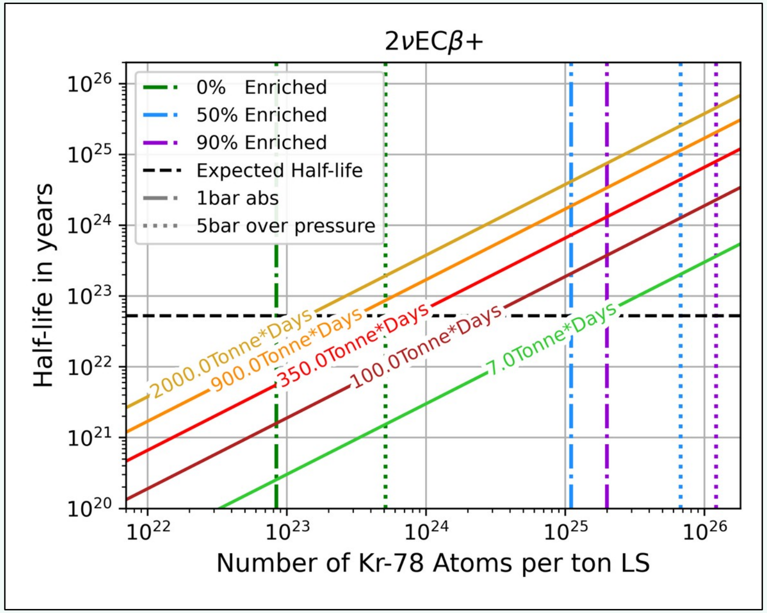
- Improvement of limits on neutrinoless modes by almost **3 orders of magnitude**
- First-time **5σ observation** of SM modes $2\nu EC\beta^+/2\nu 2\beta^+$

Assuming Gran Sasso overburden

Expected 90% C.L. exclusion sensitivity

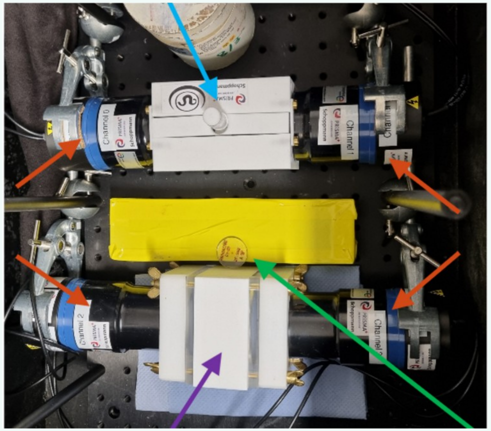


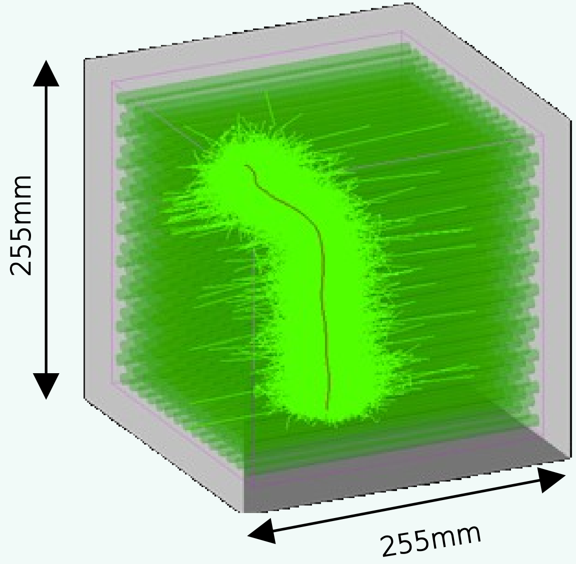
Expected 5σ observation sensitivity



Current operations

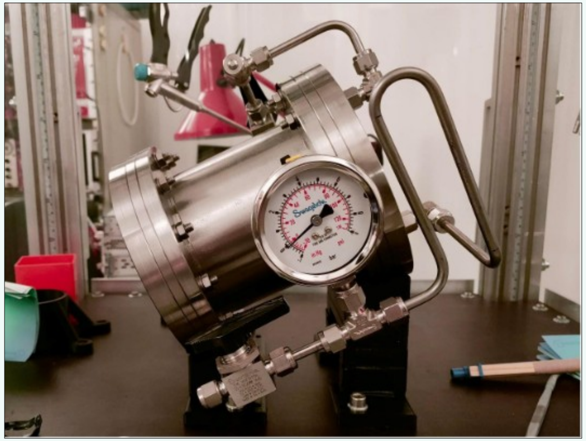
Fiber/scintillator test bench



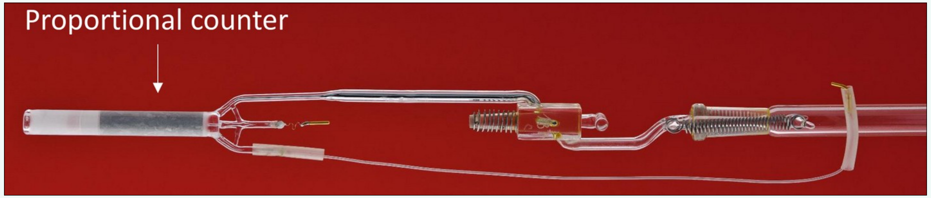


Prototype to test with electron beam

Investigating gas loading with overpressure

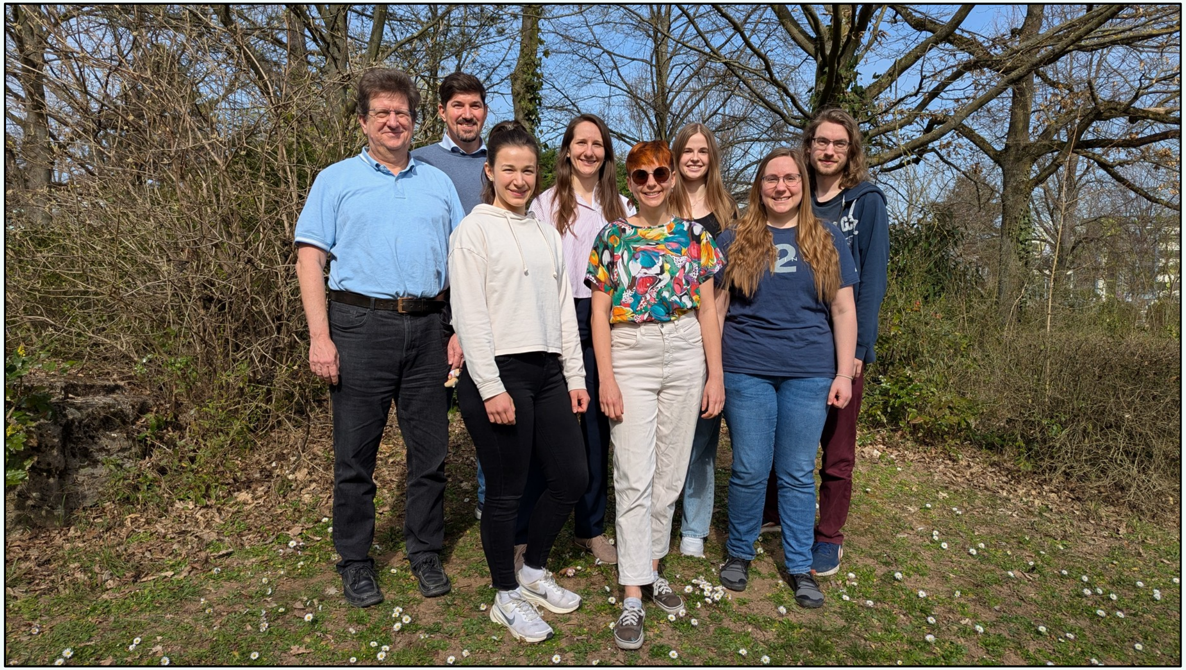


Testing gas isotope composition with a proportional counter



The NuDoubt^{++} collaboration

- **Our website**: nudoubt.uni-mainz.de
- **Our first publication**: Böhles, M. et al. Combining hybrid and opaque scintillator techniques in the search for double beta plus decays. Eur. Phys. J. C 85, 121 (2025)
- Stay tuned for a postdoc offer



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Some additional references

- Idea to exploit 4 or 2 annihilation gamma-rays unique signature for background suppression in search of $2\nu2\beta^+$ or $2\nu EC\beta^+$
  - Study of the neutrino mass in a double β decay, Zel'dovich Ya. B., Khlopov M. Yu.
- Ideas on hybrid detection using Cherenkov + scintillation lights to discriminate double electron decays from solar B-8 neutrino background
  - Separating double-beta decay events from solar neutrino interactions in a kiloton-scale liquid scintillator detector by fast timing, Andrey Elagin et al.
  - Space-Time Discriminant to Separate Double-Beta Decay from 8B Solar Neutrinos in Liquid Scintillator, Runyu Jiang, Andrey Elagin
- Using slow scintillators to improve separation of Cherenkov and scintillation light
  - Slow-fluor scintillator for low energy solar neutrinos and neutrinoless double beta decay, Jack Dunger, Edward J. Leming, Steven D. Biller
- Idea of exploiting ratio of Cherenkov and scintillation light in hybrid detector for the search of $\beta^+\beta^+$ decays @DBD 2022
  - Neutrinoless Double-Beta Decay Sensitivity in Hybrid Detectors, talk by Michael Wurm
- First demonstrations of the hybrid detector concept through small scale prototypes
  - Cherenkov and scintillation light separation in organic liquid scintillators, J. Caravaca et al.
  - Characterization of water-based liquid scintillator for Cherenkov and scintillation separation, J. Caravaca et al.
- Idea of opaque liquid scintillators and applications in neutrino physics
  - Neutrino physics with an opaque detector
- Concept of searches for double weak decays in opaque media by the LiquidO consortium
  - R&D on 2beta with LiquidO
  - Double Beta Decay Searches with LiquidO, LiquidO consortium, to be published

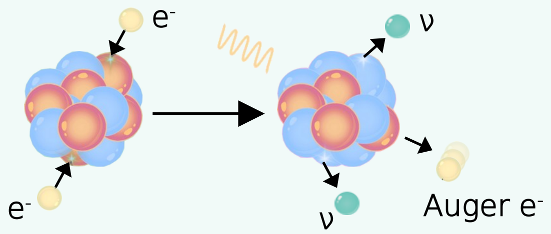
Double Beta decays

What about β^+ decays?

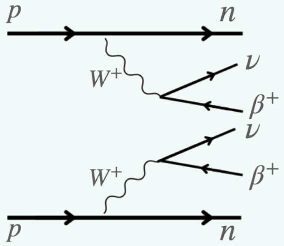
Proton-rich isotopes:

- SM: $2\nu2\beta^+$, $2\nu EC\beta^+$ and $2\nu2EC$ allowed
  → only $2\nu2EC$ has been observed
- BSM: $0\nu\beta^+EC$ and $0\nu2\beta^+$
  → mono-energetic e^+

2ν2EC



2ν2β+



But limited exploration of these transitions

- Suppressed decay probabilities
- Less favourable Q-values
- Low natural abundances of nuclei

- Challenging signatures:
  - 2EC signature: detection of cascade of X-rays & Auger e^- after EC
    → Q mostly carried away by the 2 ν (undetected)
    → ROI upper bound typically ~100 keV
  - β^+ decays signatures: 1 ($EC\beta^+$) or 2 ($2\beta^+$) positrons

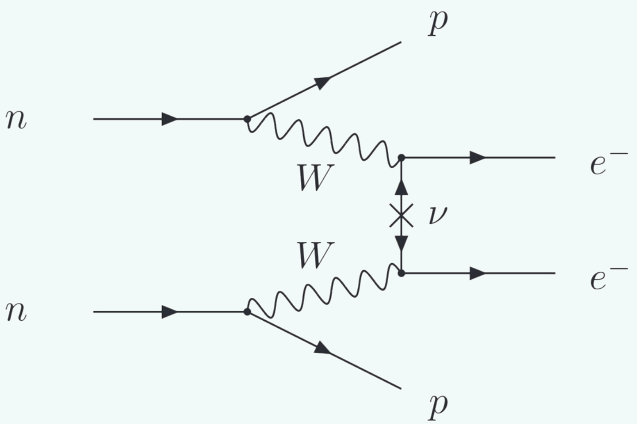
So why are we interested in it?

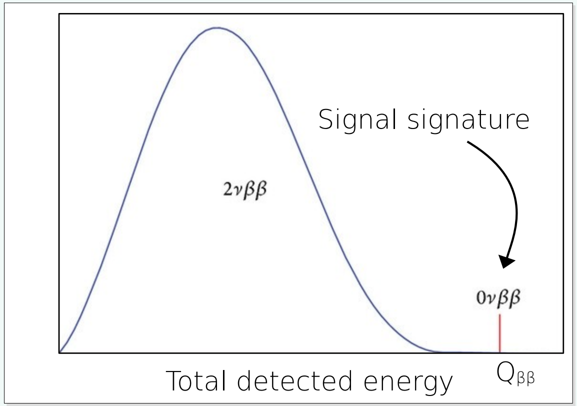
- Studies of nuclear structure models
- Valuable constraints on theoretical models and calculations of NMEs
  → deeper understanding of underlying nuclear physics governing 2β

Requirements

- Excellent background suppression
- High amount of isotope loading

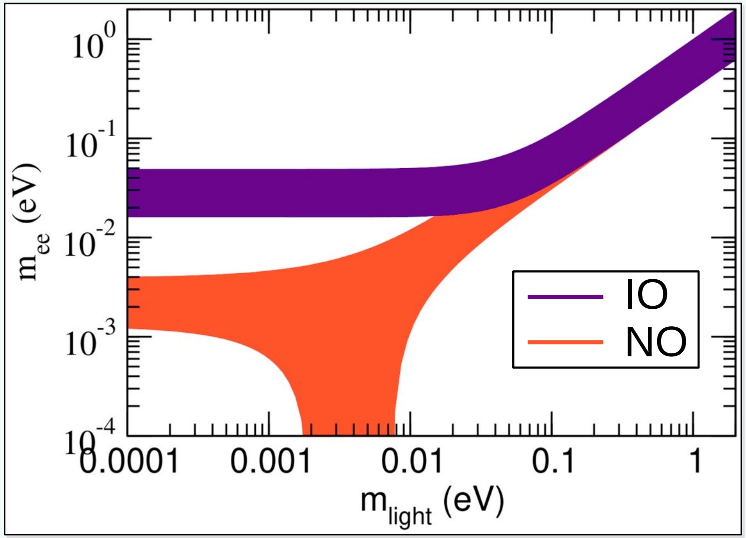
Double Beta decays





Why is it important?

- Lepton number violation: neutrinos are **Majorana** particles
- Insight into neutrinos **absolute mass scale**
- BSM



Experimental Challenges

- Ultra-rare process (if it exists) → long half-life (>10^{26} years)
- Low-background experiments needed → deep underground labs, radio-pure materials, advanced detection techniques, high amount of isotopes

Current and Future Experiments

- Ongoing: GERDA, EXO, CUORE, KamLAND-Zen, SuperNEMO, etc.
- Next-gen: LEGEND, nEXO, CUPID, SNO+, etc.

Half life limits need to be improved by several orders of magnitude to reach Normal Ordering

EC = Electron Capture

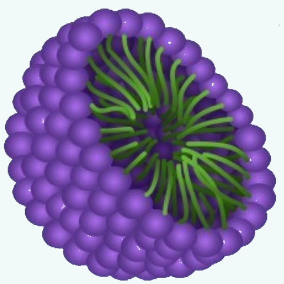
Double Beta decays

	Isotope	$T_{1/2}(2\nu)$ / years			$T_{1/2}(0\nu)$ / years			C.L./	E_{max}/	a_{nat}/
		$\beta\beta$	ECβ^+	2EC	$\beta\beta$	ECβ^+	2EC	%	MeV	%
$2\beta^+$	Kr-78	$> 2.0\ 10^{21}$	$> 1.1\ 10^{20}$	$9.2\ 10^{21}$	$> 2.0\ 10^{21}$	$> 5.1\ 10^{21}$		68	2.881	0.4
	Cd-106	$> 1.7\ 10^{21}$	$> 2.1\ 10^{21}$	$> 3.1\ 10^{20}$	$> 4.0\ 10^{21}$	$> 1.2\ 10^{21}$	$> 2.9\ 10^{21}$	90	2.775	1.3
	Xe-124			$1.1\ 10^{22}$					2.857	0.1
$2\beta^-$	Ge-76	$1.9\ 10^{21}$	–	–	$> 1.8\ 10^{26}$	–	–	90	2.039	7.8
	Te-130	$8.2\ 10^{20}$	–	–	$> 2.2\ 10^{25}$	–	–	90	2.528	34.0
	Xe-136	$2.3\ 10^{21}$	–	–	$> 2.3\ 10^{26}$	–	–	90	2.459	8.9

Hybrid liquid scintillator

Separate Cherenkov and scintillation lights

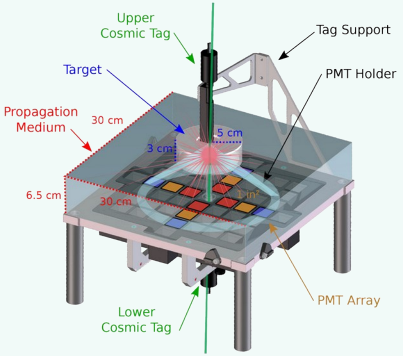
Water-based approach:



Micelles suspended in water with surfactant interface (1-10% scintillator loading)

- Advantage: safe to handle
- Disadvantage: **low light yield**

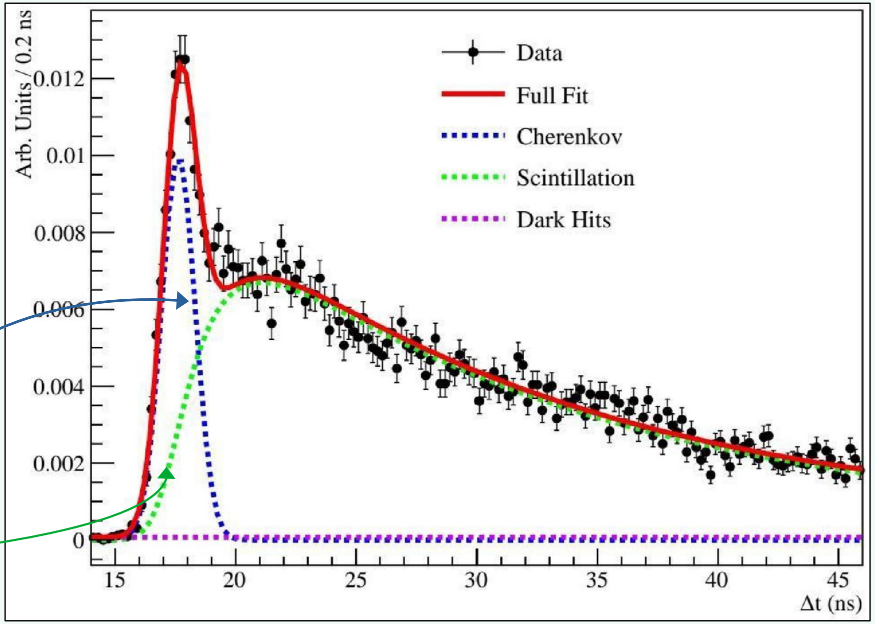
CHESS Setup:



Hybrid-slow approach: using slow solvents

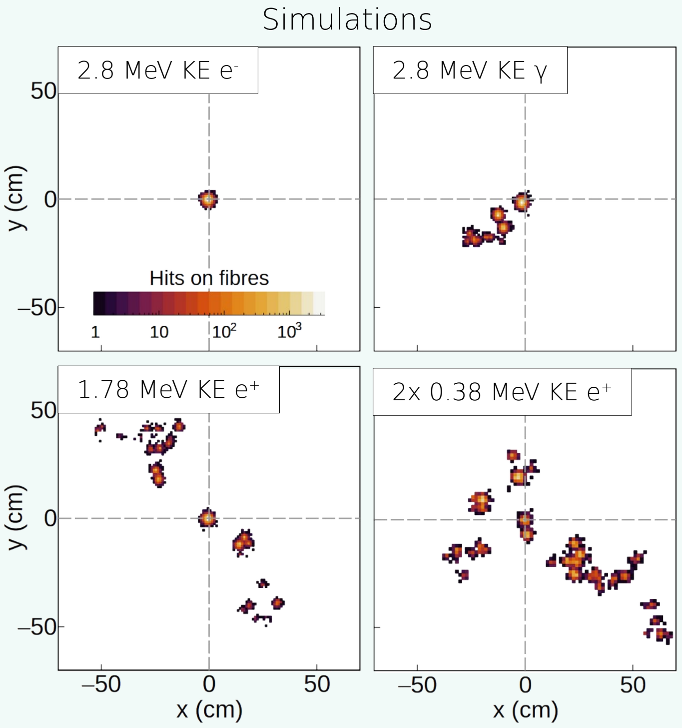
Advantages:

- **High scintillation LY** → good energy resolution
- Low energy threshold



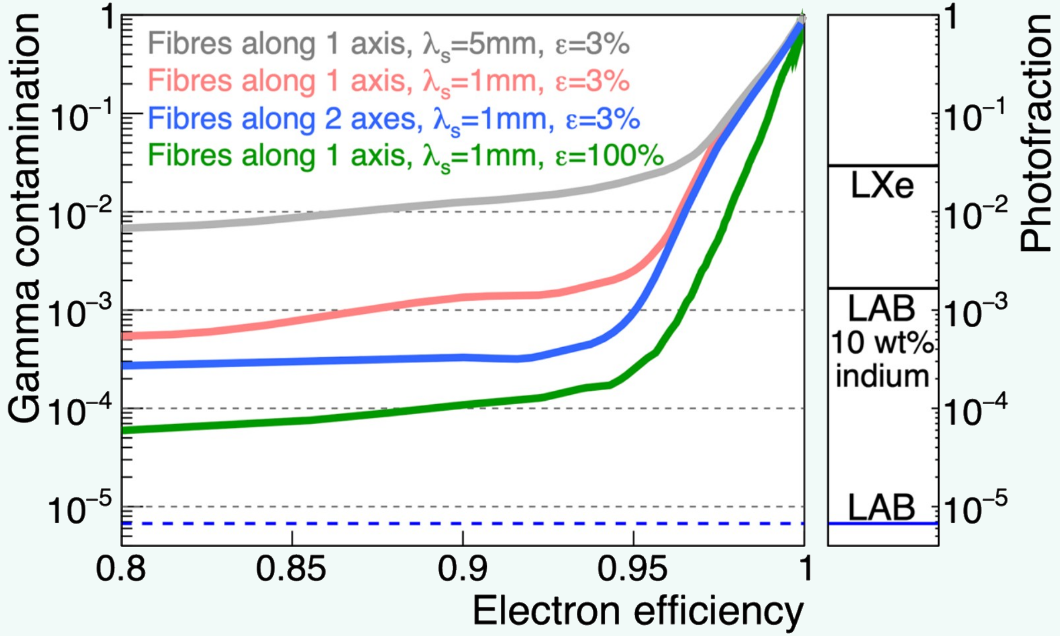
Development of a Bi-solvent Liquid Scintillator with Slow Light Emission, H.Th.J. Steiger et al., 2024

Particle ID through Opacity

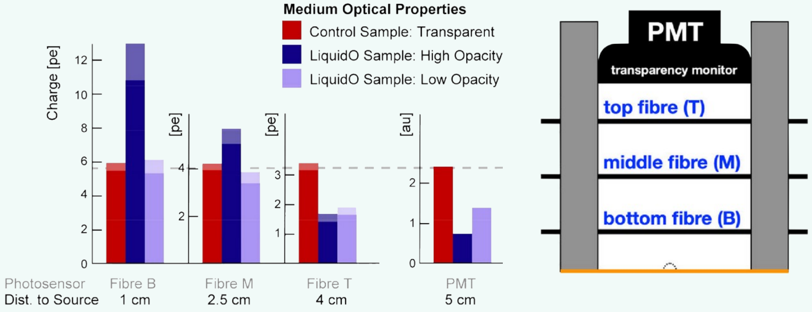


Combining Hybrid and Opaque Scintillator Techniques in the Search for Double Beta Plus Decays, M. Böhles et al., 2024

Neutrino physics with an opaque detector, LiquidO Consortium, 2021



Particle ID through Opacity



Neutrino physics with an opaque detector,
LiquidO Consortium, 2021

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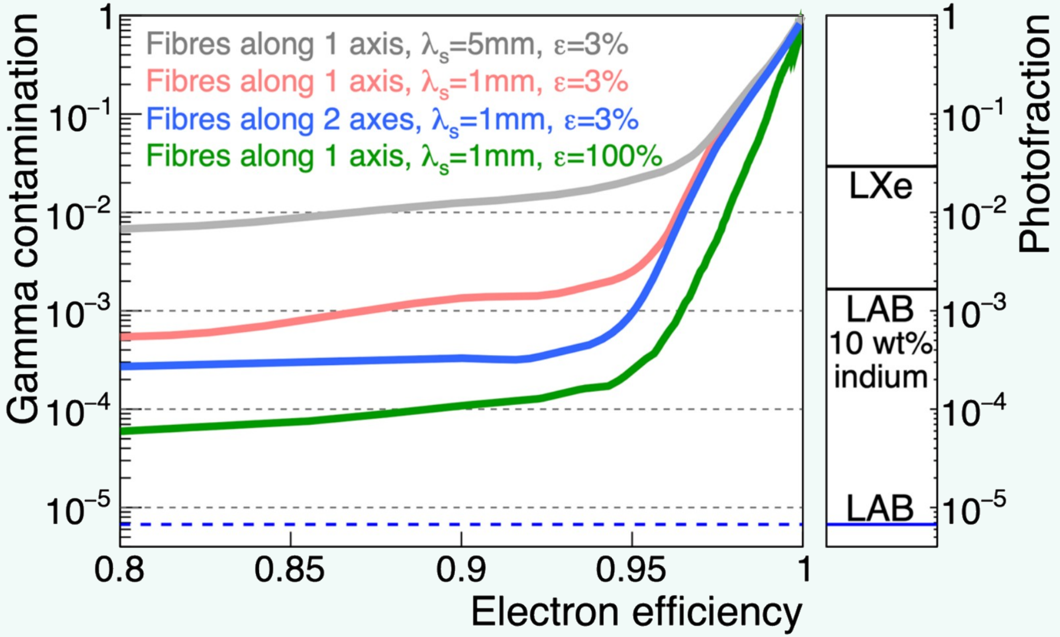
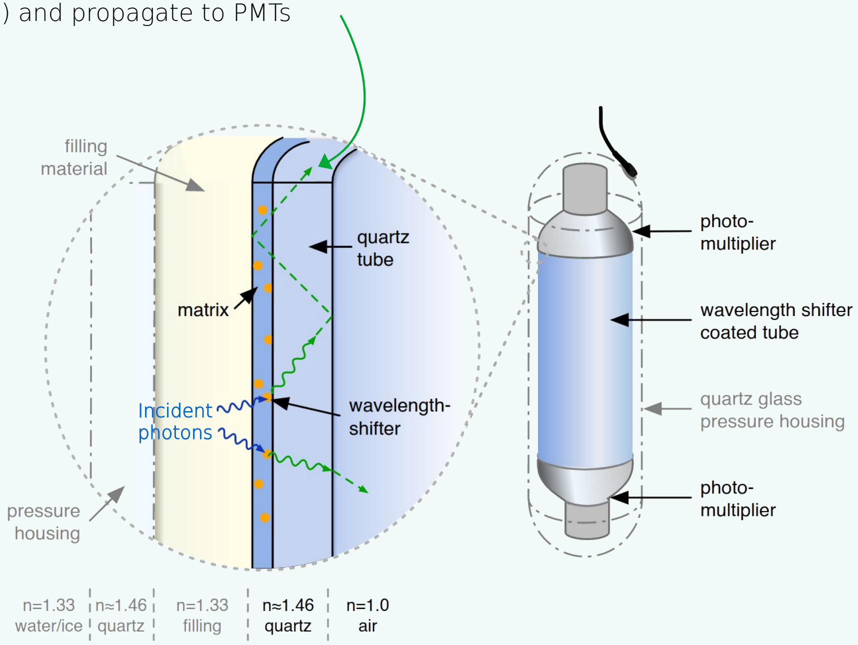


WOMs for IceCube Upgrade

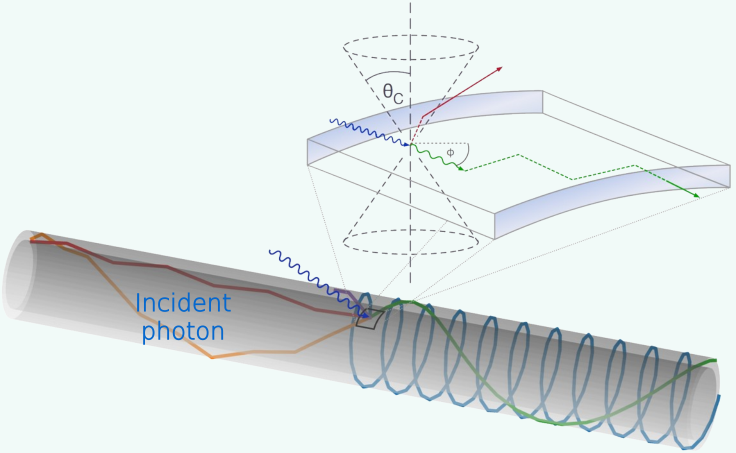
Goal: improve signal-to-noise ratio by maximizing light capture

Idea: decouple photosensitive area and cathode of PMT → Transparent tube + two PMTs at each end

Re-emitted optical photons can be captured by total internal reflection (TIR) and propagate to PMTs



These re-emitted photons can propagate with different paths in the coated tube:

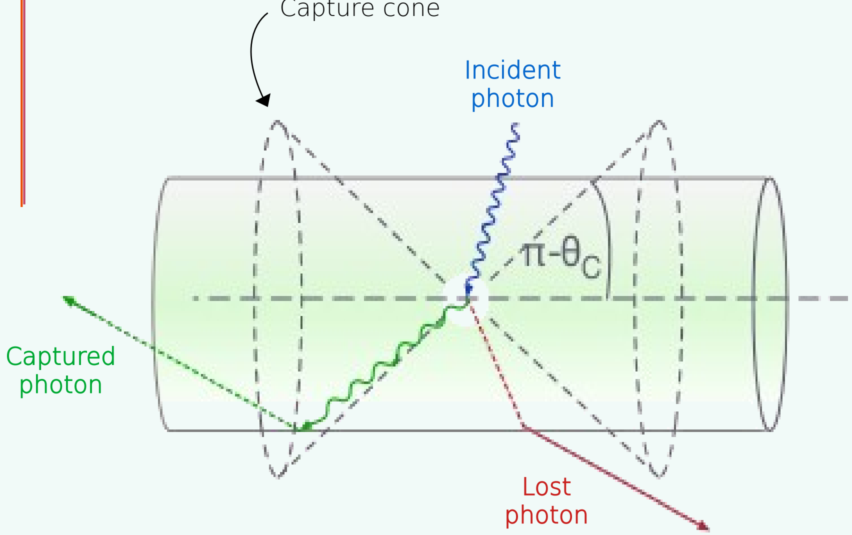


The Wavelength-Shifting Optical Module, B. Bastian-Querner et al., 2022

R&D on improved light readout

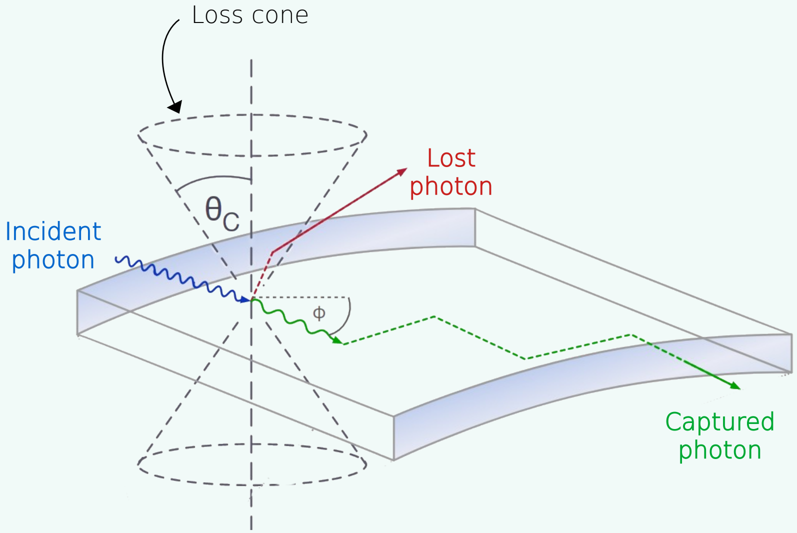
Commercial Wavelength-shifting fibers

For an incident photon in center of fiber:

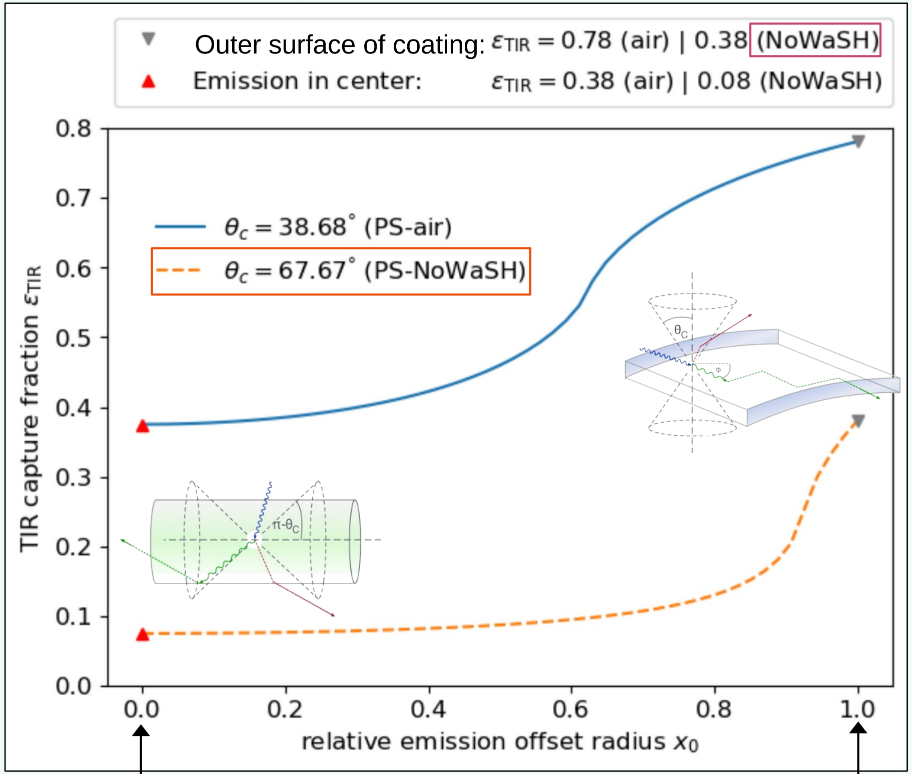


Modules developed for IceCube Upgrade

Incident photons on outer surface of fiber (tube) only



R&D on improved light readout



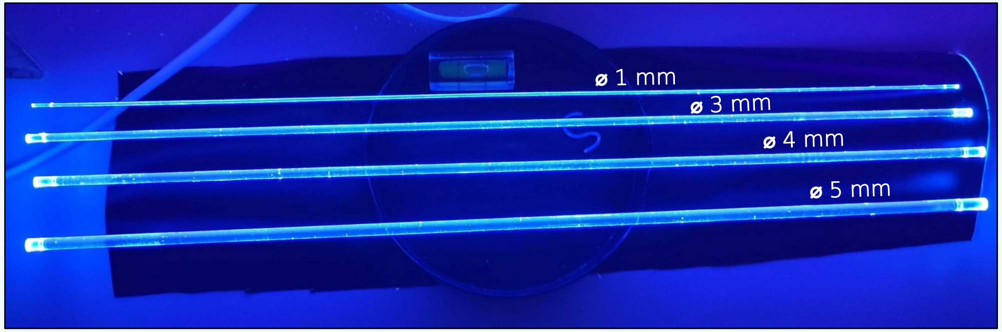
Center of fiber

$$x_0 = |\vec{r}|/R$$

Outer surface of fiber

Photons absorbed and emitted on outer **surface of fibre** have **higher chance** of being captured by total internal reflection (TIR)

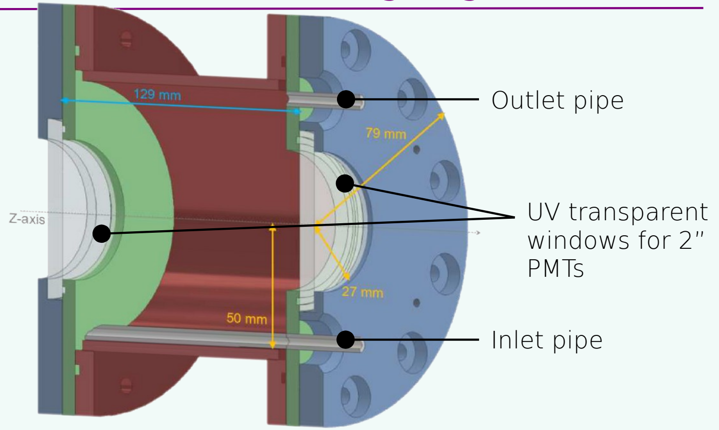
First prototypes of polystyrene-based OWL-fibers



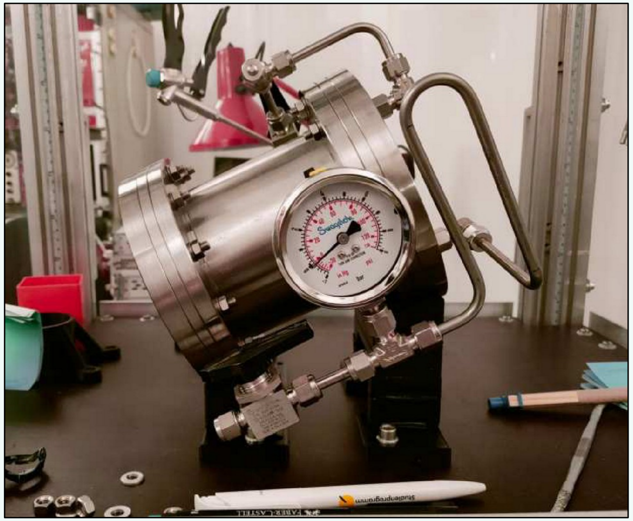
OWL = Optimised Wavelength-shifting fibres
PMMA fibers of ~mm diameter, coated with wavelength-shifting paint

Gas isotope loading

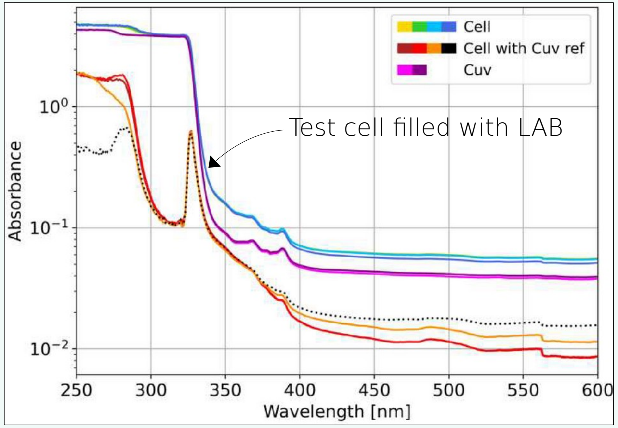
- Gaseous ββ isotope loaded in LS
- Henrys law: amount of dissolved gas isotope in LS proportional to its pressure
  - We want overpressure in the NuDoubt^{++} detector
- Test cell to verify amount of gas loaded in the scintillator
  - Weighing of the cell
  - ^{85}Kr β decays when loaded in LS
- Geant4 sims to optimize design/light collection of test cell (geometry, materials)



The test cell is ready to be filled



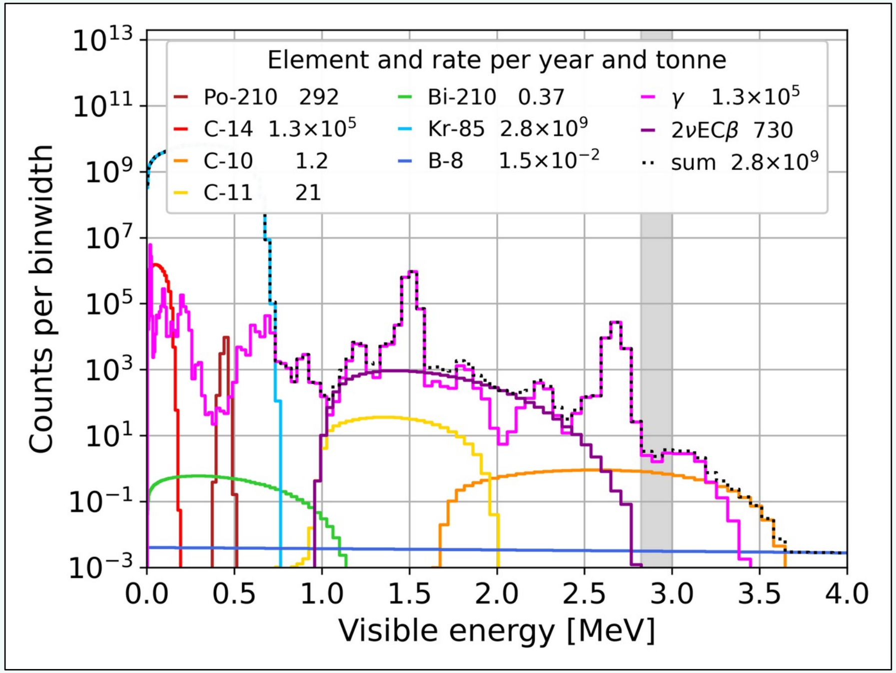
LAB transparency measurements with the test cell



Next step:
Loading LS with ^{85}Kr gas isotope

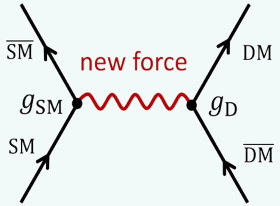
Background model of NuDoubt^{++}

Background model
Assuming Gran Sasso-like overburden

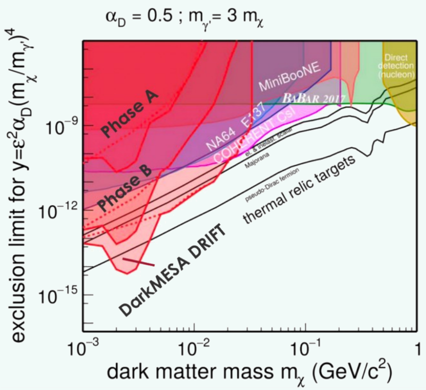


Using the NuDoubt^{++} concept for dark matter?

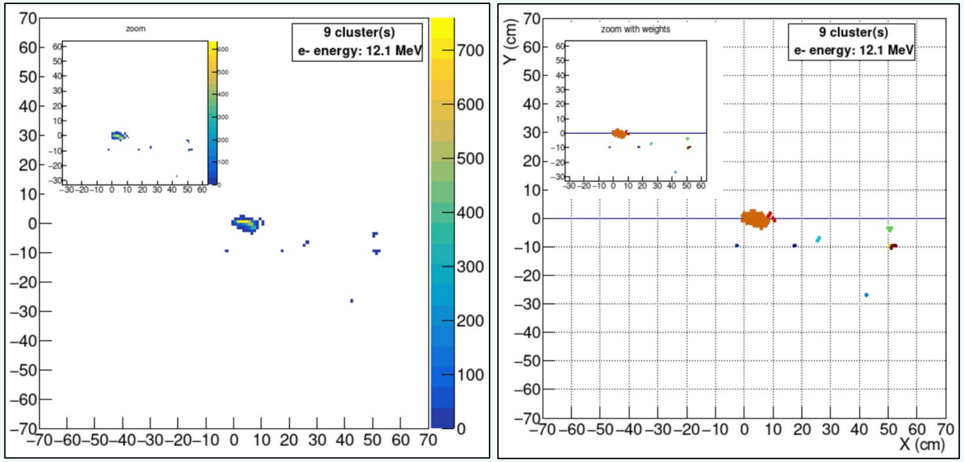
- DarkMESA
- Search for direct detection of Light Dark Matter
- Especially interesting for low-energy accelerators
- The MESA Accelerator
  - Electron accelerator
  - 150 MeV @ 0.15 mA
  - Currently under construction in Mainz, Germany



The DarkMESA experiment



Idea: Use the NuDoubt detector with its PID/tracking capabilities for the search of dark photons



Simulations