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

Cloé Girard-Carillo

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

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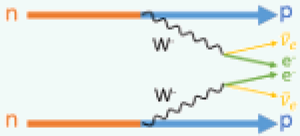
*Manuel Böhles, Sebastian Böser, Magdalena Eisenhuth, Cloé Girard-Carillo, Bastian Keßler, Kyra Mossel, Veronika Palušová, Stefan Schoppmann, Alfons Weber, Michael Wurm
Johannes Gutenberg-Universität Mainz

Outline

- Motivation
- Combining recent scintillator developments
- The NuDoubt^{++} experiment
  - Global idea
  - Enhanced photodetection
  - Gas isotope loading
  - Design of our test cell and first measurements
  - Sensitivity to β^{+} decays
  - Using NuDoubt^{++} for DM measurements?

Double Beta decays

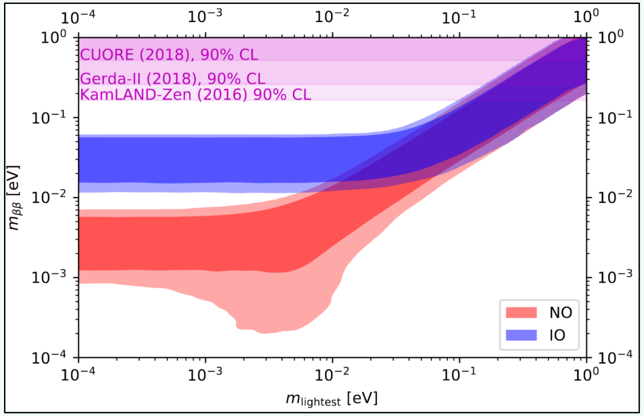
Big experimental & theoretical efforts on the study of $2\beta^-$



- Most promising mode for potential detection of $0\nu\beta\beta$
- Theoretical investigations focusing on underlying mechanisms & nuclear structure models
- Current $\beta\beta$ experiments $\sim 10^{26}$ y limit on $0\nu 2\beta^-$ $T_{1/2}$

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

- Larger isotope mass
- Excellent energy resolution ($2\nu\beta\beta$ irreducible bkg)
- Excellent radiopurity
- Bkg suppression in the ROI



Neutrino Mass Ordering from Oscillations and Beyond: 2018 Status and Future Prospects, P.F. de Salas et al., 2018

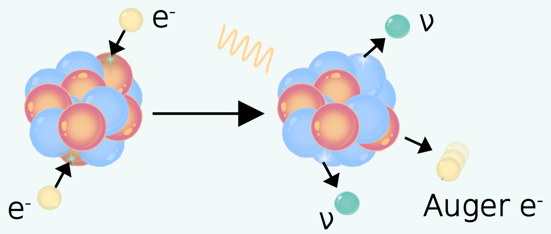
Double Beta decays

What about β^+ decays?

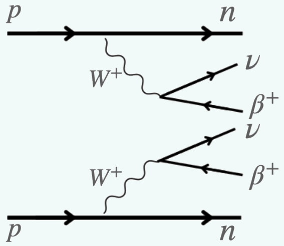
Proton-rich isotopes:

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

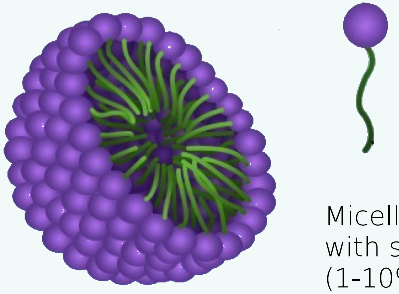
- Excellent background suppression
- High amount of isotope loading

On going effort to develop new scintillators

Hybrid liquid scintillator

Separate Cherenkov and scintillation lights

Water-based approach:



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

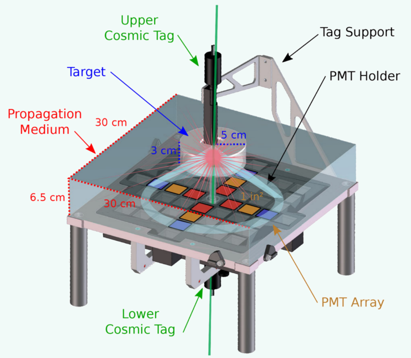
- Advantage: safe to handle
- Disadvantage: **low light yield**

Hybrid-slow approach: using slow solvents

Advantages:

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

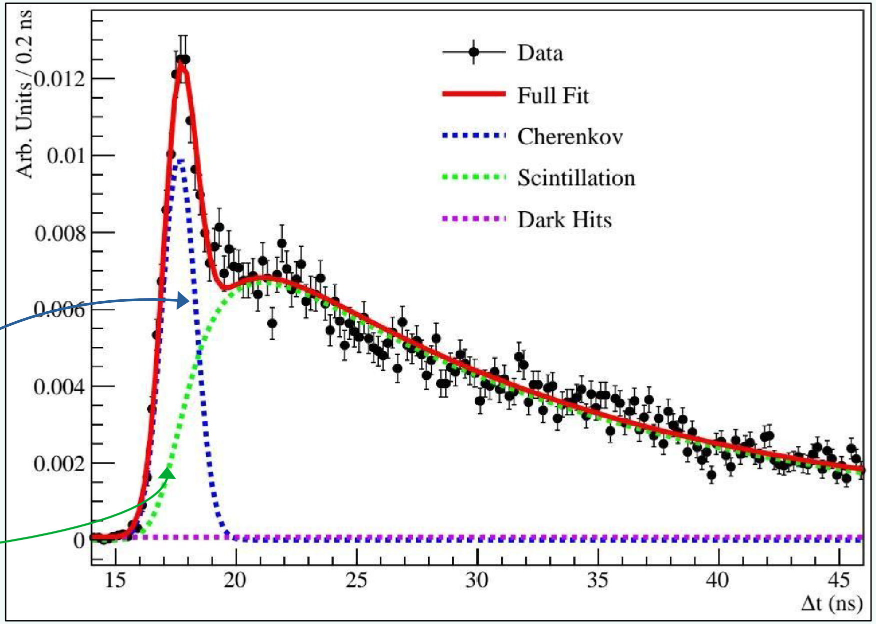
CHESS Setup:



Experiment to demonstrate separation of Cherenkov and scintillation signals, J. Caravaca et al., 2017

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

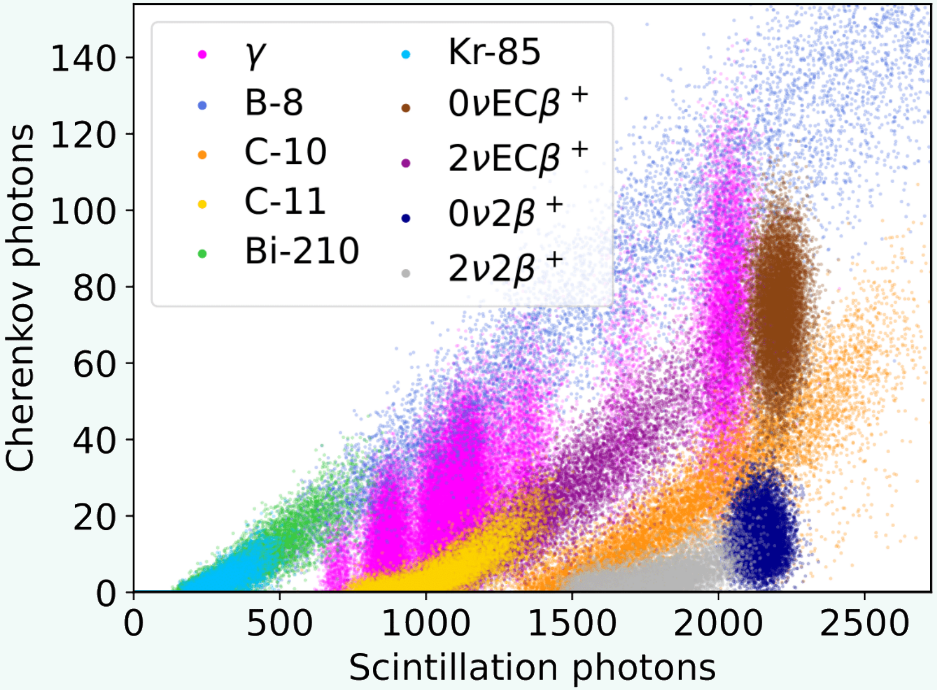
Particle ID through Č/S light separation

More massive particles produce less Č light
(they are closer to the c/n Č threshold)

- Gammas:
  Almost no Č light
  - Multiple Compton scatters
  - Energy transferred to e^- of scintillator which are close to or below Č threshold
- e^+ vs e^- of same kinetic energy:
  Similar amount of Cherenkov light
  - $e^+ \rightarrow$ more scintillation light: because of the two 511 keV annihilation gamma

  ~50% more scintillation light for 2 MeV e^+ compared e^- of same KE

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



Main disadvantage: bad spatial resolution

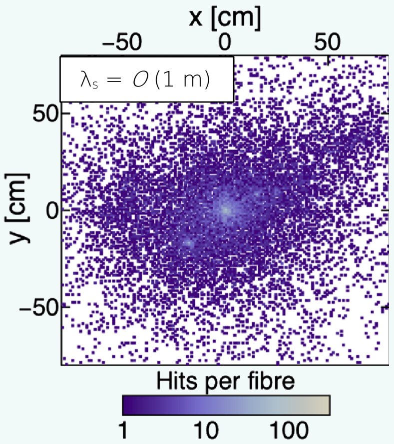
Opaque liquid scintillator

Confining optical light around interaction point

The path of optical light in LS depends on scattering length / opacity of the medium

Current technology

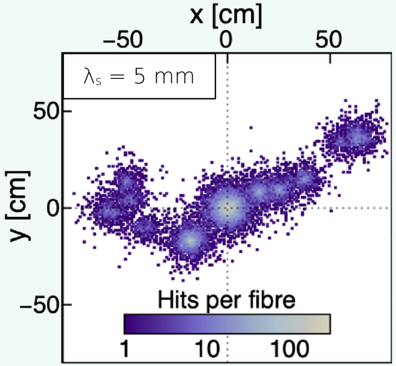
Event topology "blurred"



Simulation of e^+ 1 MeV KE

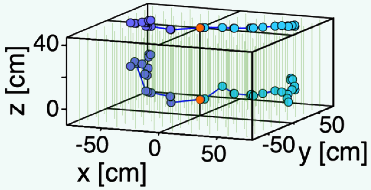
Opaque "LiquidO" technology

Light confined near creation point

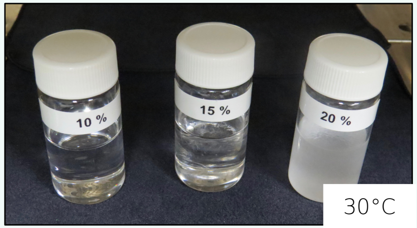


Simulation of e^+ 1 MeV KE

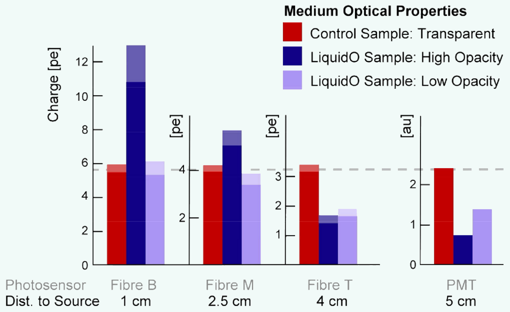
Readout with grid of
wavelength-shifting fibres & SiPMs

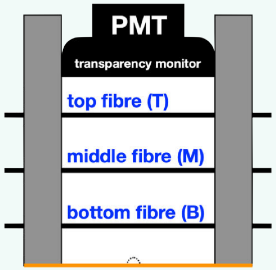


First implementation of opaque scintillator: adding wax to LS (NoWaSH)



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

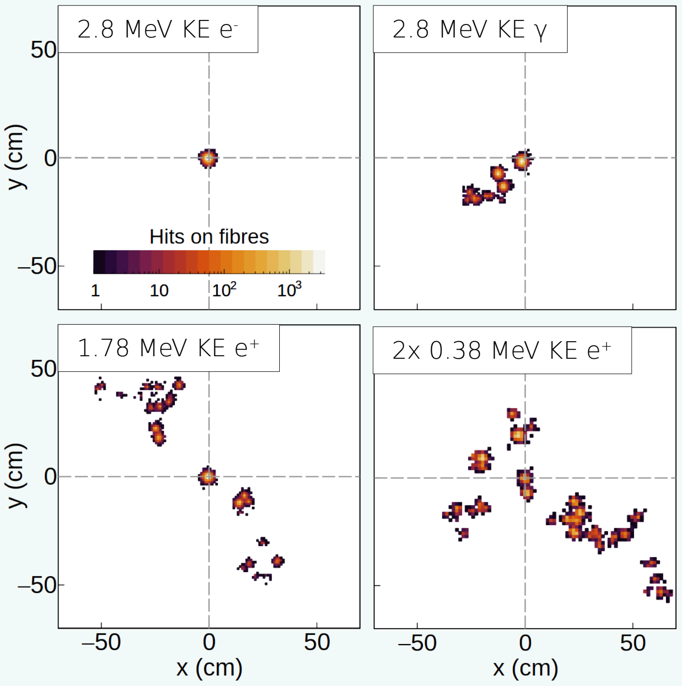




Neutrino physics with an opaque detector,
LiquidO Consortium, 2021

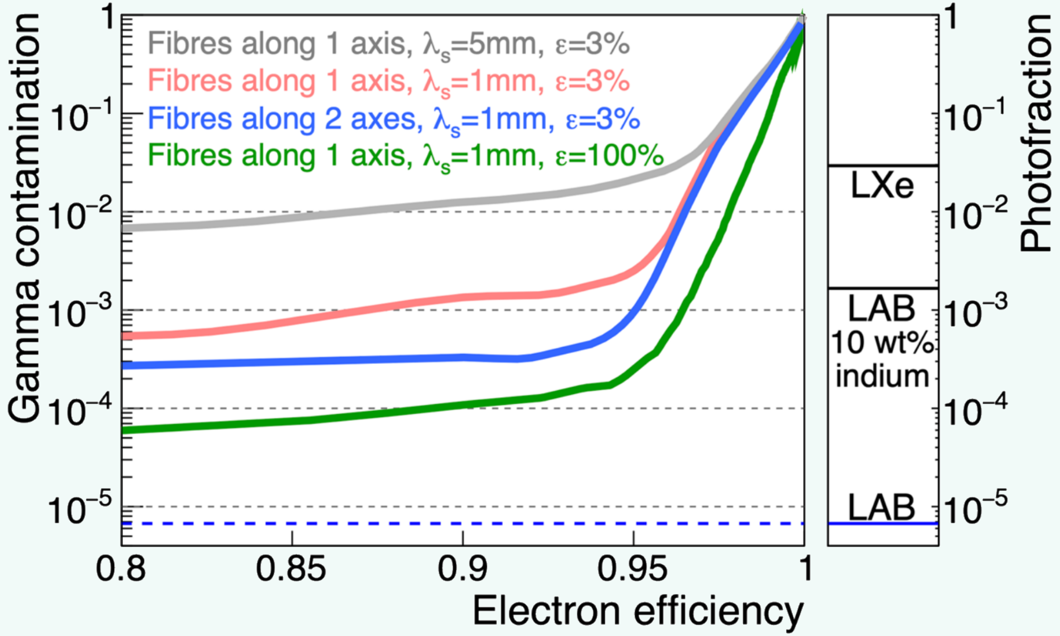
Particle ID through Opacity

Simulations



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



Combining opaque and hybrid technologies

Our shopping list:

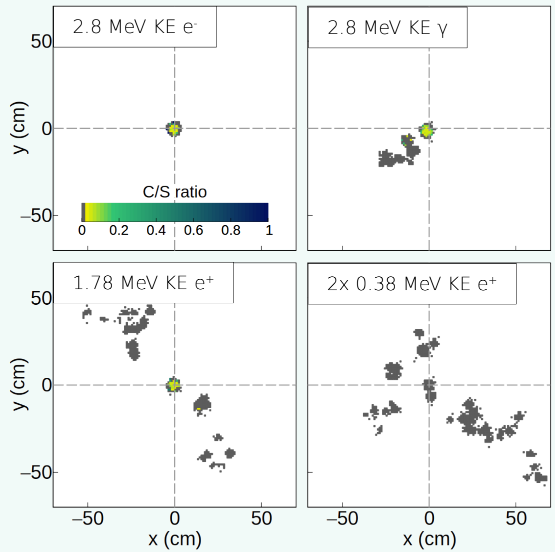
- Hybrid
- Opaque
- High light yield
- Stable
- High loading possibilities

What we have: extended NoWaSH with minimal wax loading and various solvents

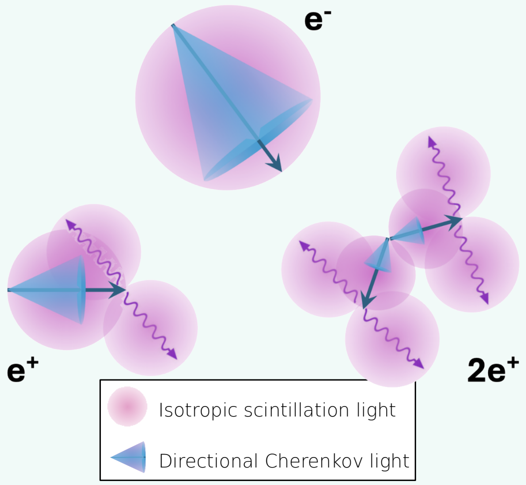
- Light yield > 10000 ph/MeV
- Scattering length tuneable between 1.3 and 1.6 mm
- Scintillation time constant tuneable between 5 and 20 ns
- Viscosity tunable between something like custard and something like yogurt

Combining hybrid & opaque PID capabilities

Simulations



- **Gammas**: Almost no Č light
- e⁺ vs e⁻ of same kinetic energy: Similar amount of Cherenkov light



The NuDoubt^{++} concept

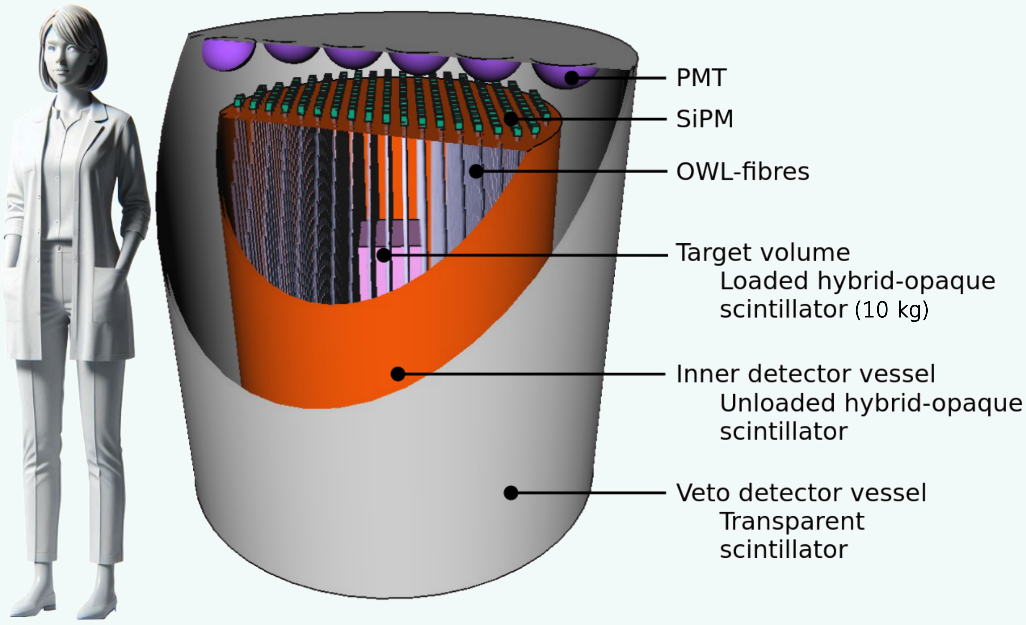
Search for double beta plus decays using a combined hybrid-slow opaque scintillator

- Isotope-loaded liquid scintillator detectors to higher loading factors with small impact on LY
  - Good energy resolution
- Enhanced discrimination capabilities
  - Hybrid scintillators: C/S light ratio
  - Opaque scintillators: cm-scale event topology
- Proposition of a tonne-scale experiment
  - Fiducial volume 1 m^3 of hybrid-slow opaque scintillator densely instrumented with novel OWL fibers
  - First measurements of 2ν double weak decays ($2\nu2\beta^+$ & $2\nu EC\beta^+$)
  - Set limits on $T_{1/2}$ for the corresponding neutrinoless ($0\nu EC\beta^+$ & $0\nu2\beta^+$)
  - Isotopes: ^{78}Kr, ^{124}Xe and ^{106}Cd

Gas
Q-value 2.881 MeV

Gas
Q-value 2.857 MeV

Solid
Q-value 2.775 MeV



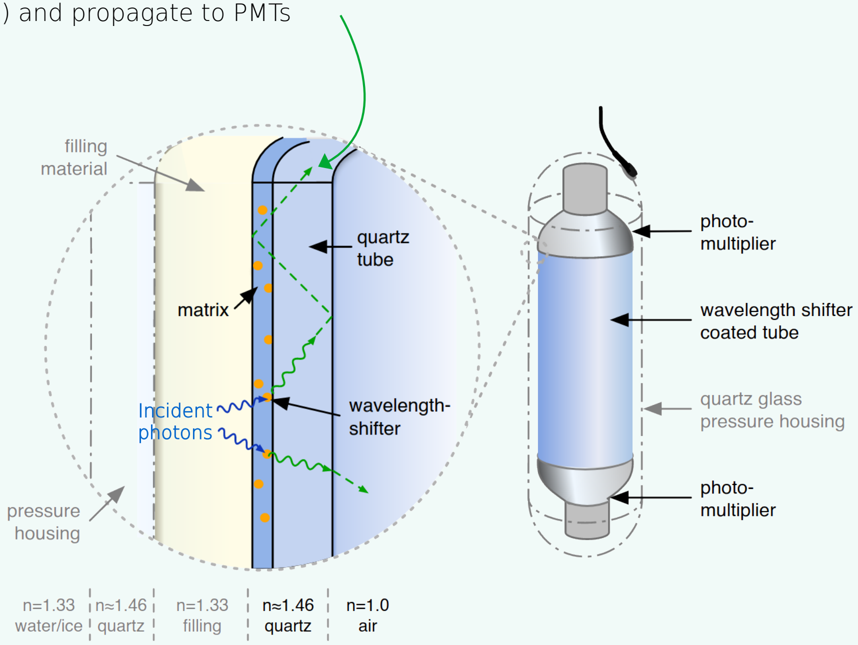
Let's talk about optical light collection

WOMs for IceCube Upgrade

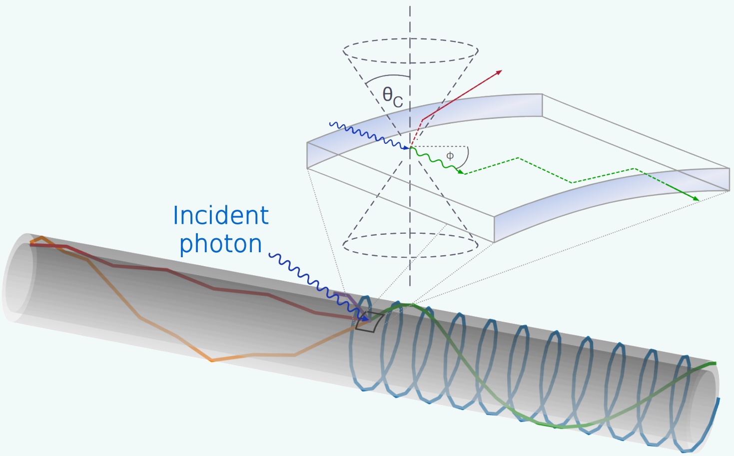
Goal: improve signal-to-noise ratio by maximizing light capture

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:

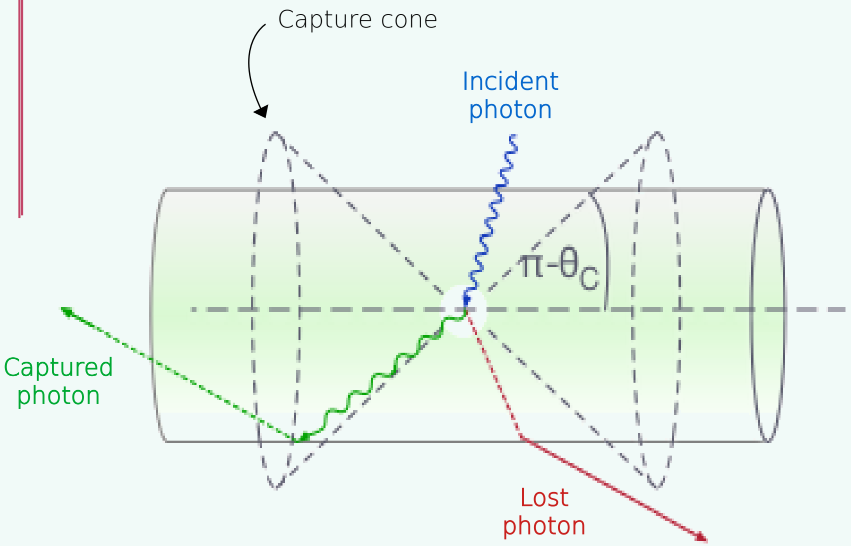


The Wavelength-Shifting Optical Module, B. Bastian-Querner et al., 2022

Changing the wavelength shifting point

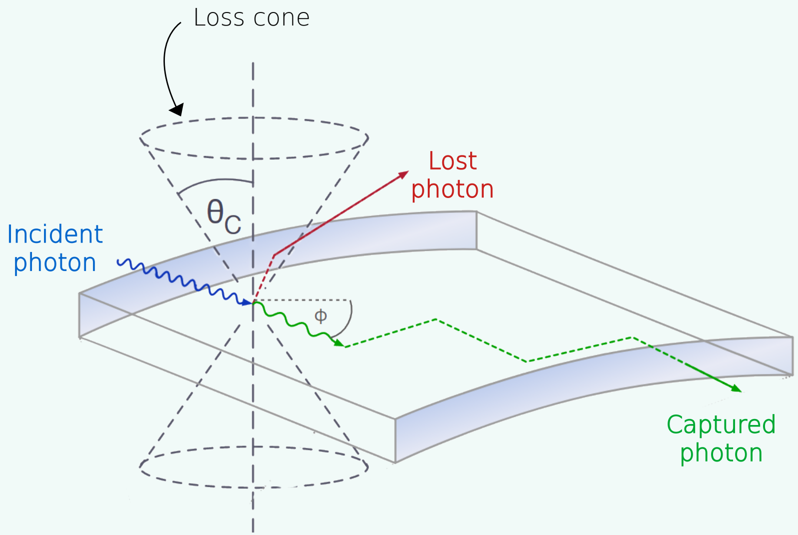
Wavelength-shifting fibers

For an incident photon in center of fiber:

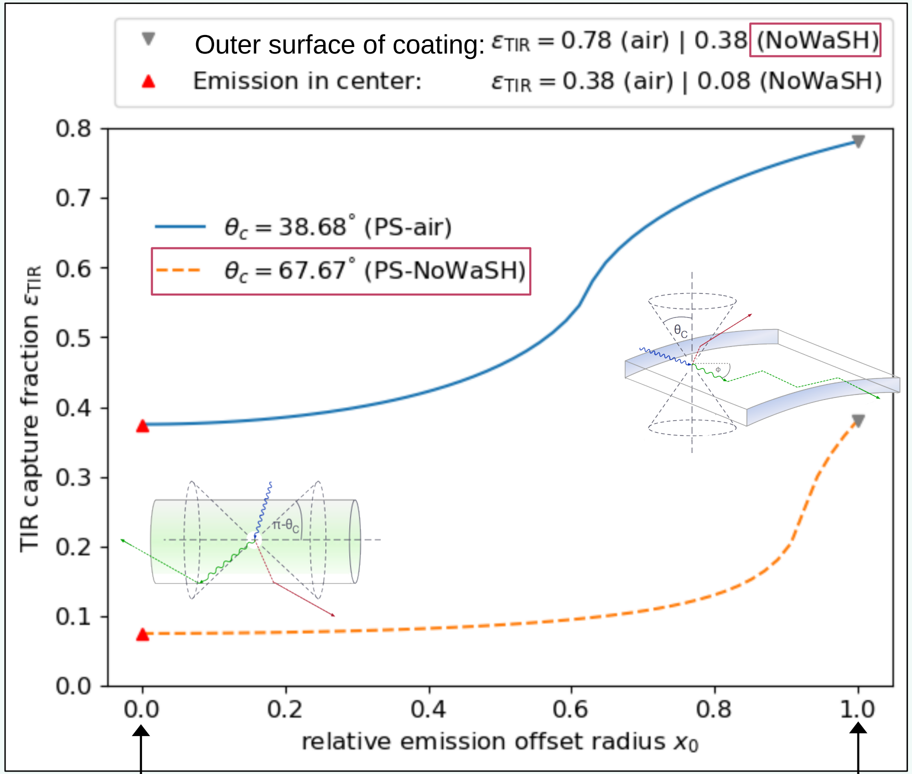


WOM principle

Incident photons on outer surface of fiber (tube) only



Adaptation of WOM idea for NuDoubt^{++}



Center of fiber

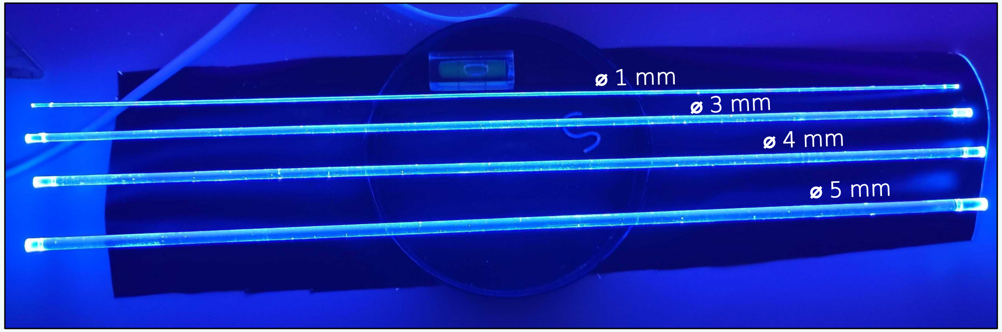
$$x_0 = |\vec{r}|/R$$

Outer surface of fiber

Photons absorbed and emitted on the outer surface of the fibre have a higher chance of being captured by total internal reflection (TIR) compared to those closer to the centre of the fiber

Gain in sensitivity is mostly in the UV regime
→ WOM is an ideal sensor for Cherenkov and scintillation detectors!

First prototypes of polystyrene-based OWL-fibers

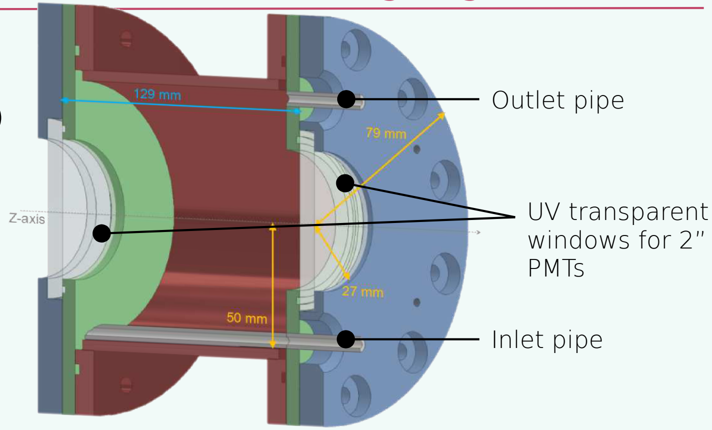


OWL = Optimised Wavelength-shifting fibres
PMMA fibers of ~mm diameter, coated with wavelength-shifting paint

A cell to test isotope loading & scintillator characteristics

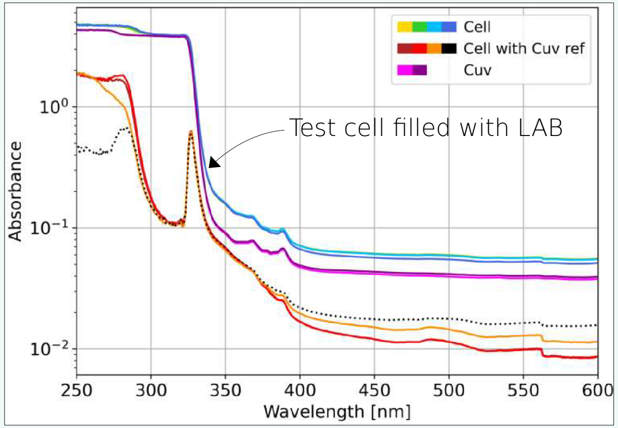
Gas isotope loading

- Gaseous ββ isotope loaded in LS
- Geant4 simulations to optimize design/light collection of test cell (geometry, materials)
- 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



The test cell is ready to be filled

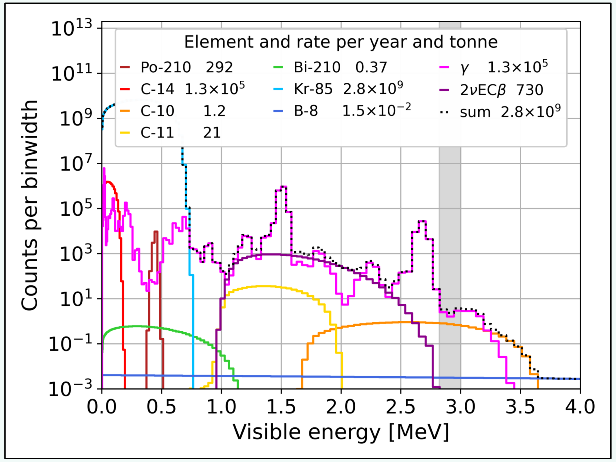
LAB transparency measurements with the test cell



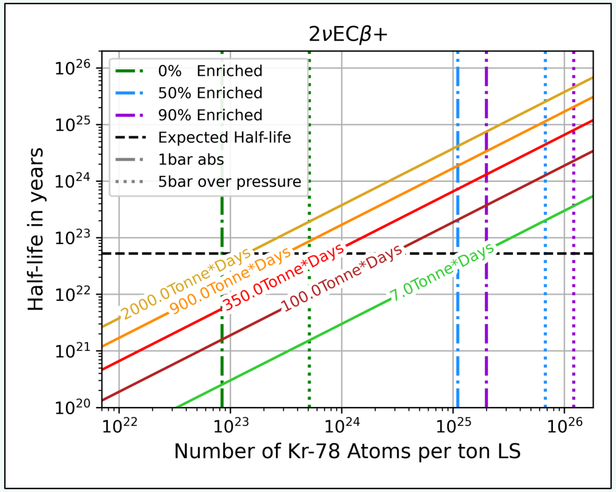
Next steps:
→ Loading LS with ^{85}Kr gas isotope
→ Measure optical properties of scintillator as function of pressure

Expected sensitivity of NuDoubt^{++}

Background model
Assuming Gran Sasso-like overburden

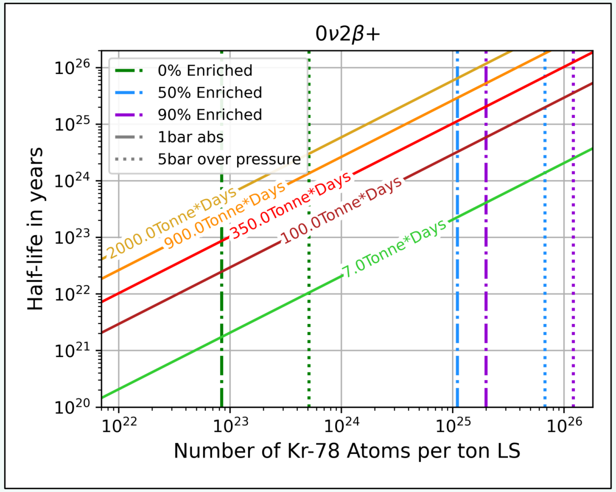


Expected 5σ observation sensitivity



Detectable half-life, depending on the minimum rate required to exclude the background-only hypothesis, for various amounts of Kr-78 atoms per tonne of loaded scintillator mass

Expected 90% C.L. exclusion sensitivity

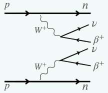
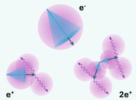
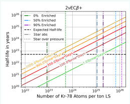


Longest rejected half-life, depending on the highest rate required to exclude the corresponding signal+background hypothesis.

Within first year of measurement with NuDoubt^{++}:

- First-time 5σ observation of SM $2\nu EC\beta^+/2\nu 2\beta^+$
- Improvement of limits on BSM $0\nu EC\beta^+/0\nu 2\beta^+$ limits by 3 orders of magnitude

Summary

- Searches for double beta plus decays (SM and BSM) 
- Advanced scintillator development (opaque / hybrid-slow) → C/S light separation + PID + High LY 
- Highly isotope-loaded scintillation detector for improved sensitivity
- Improved light collection in coated light guides (OWLs) 
- Design and production of our first test cell achieved 
- Sensitivity towards 2νββ and potentially 0νββ with high loading factors 
- Investing the possibility of using NuDoubt^{++} for light DM direct detection (DarkMESA)
- Our first publication: arxiv.org/abs/2407.05999
- Website: nudoubt.uni-mainz.de
- Master's theses and talks: nudoubt.uni-mainz.de/publications

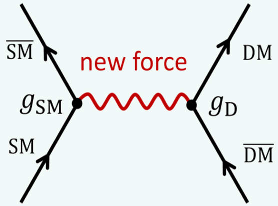
Some additional references

- Idea to exploit 4 or 2 annihilation gamma-rays unique signature for background suppression in search of $2\nu 2\beta^+$ 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

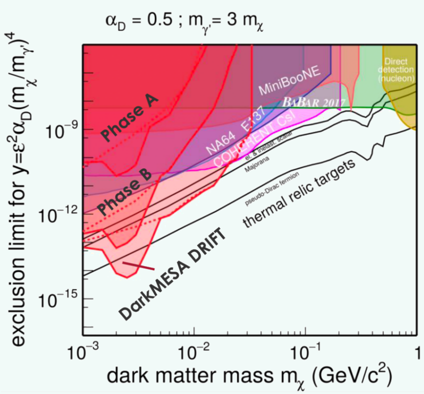
Thank you!

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

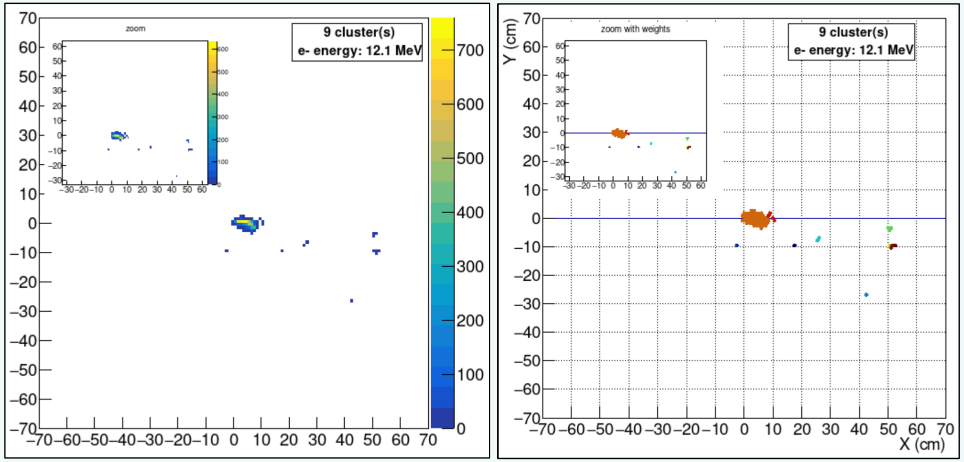
- DarkMESA
- Search for direct detection of Light Dark Matter
- Especially interesting for low-energy accelerators
- The MESA Accelerator
  - Electron accelerator
  - 150 MeV @ 0.15 mA
  - Currently under construction in Mainz, Germany



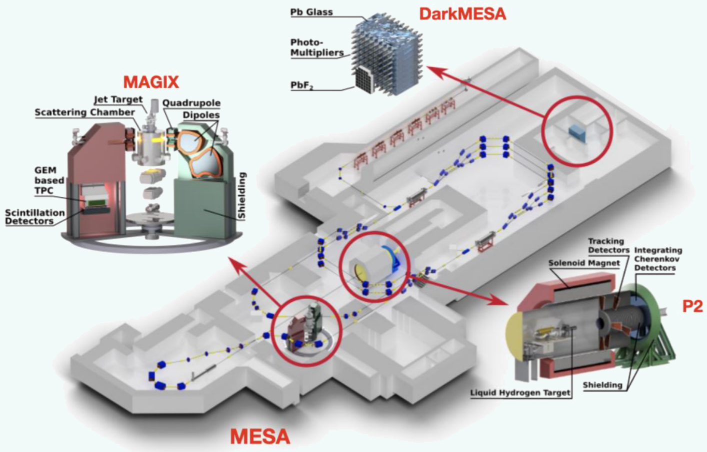
The DarkMESA experiment



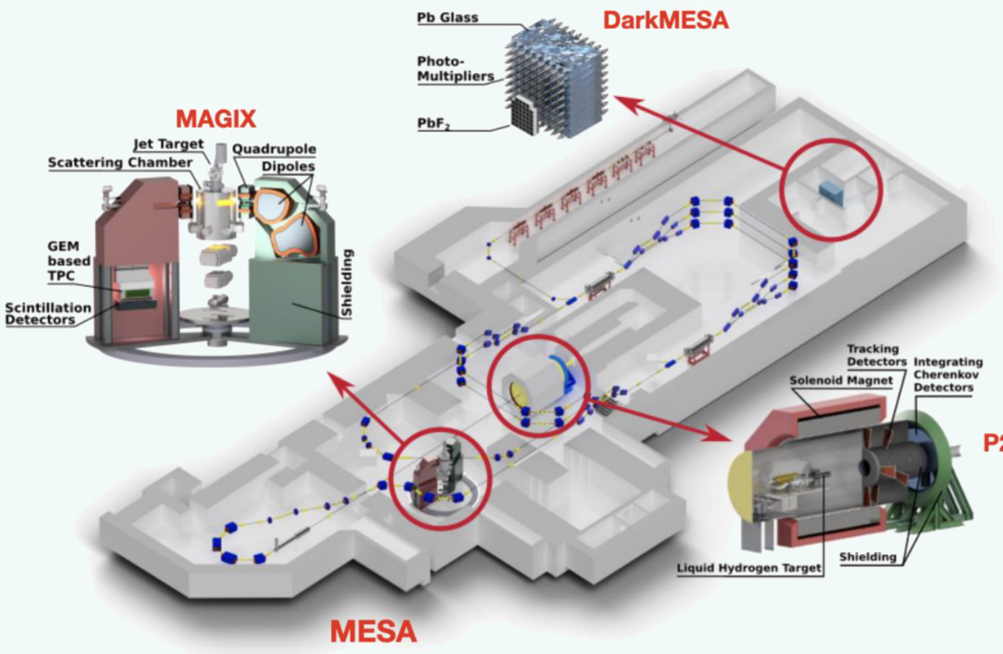
Idea: Use the NuDoubt^{++} detector with its PID/tracking capabilities for the search of dark photons



Simulations

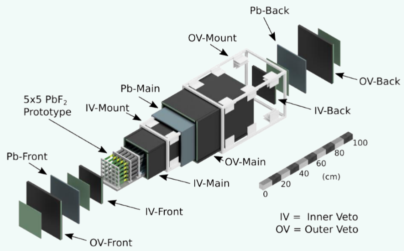


DarkMESA

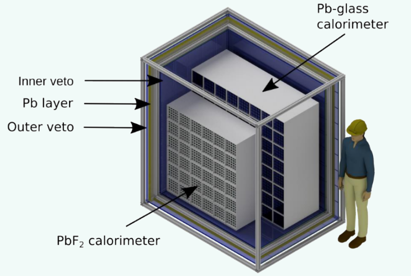


https://magix.uni-mainz.de/mesa.php

- Phase A: 1 PbF_2 module, 0.004 m^3 active volume

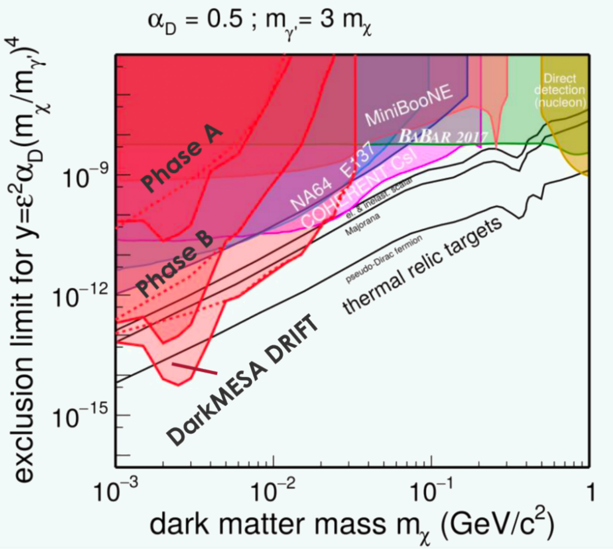


- Phase B: 36 PbF_2 + 64 SF5 modules, 0.7 m^3 active volume



https://magix.uni-mainz.de/DarkMESA.php

- Phase C (projected): Phase B setup + 1m^3 negative ion TPC



- Limits are calculated for $m_{\gamma'} = 3\, m_\chi$ and $\alpha_D = 0.5$
- Considered decay processes:
  - Dark Bremsstrahlung
  - Positron Annihilation

Phase	Time	EOT
A	2.000 h	$6.74 \cdot 10^{21}$
B	6.000 h	$2.02 \cdot 10^{22}$
C	6.600 h	$2.22 \cdot 10^{22}$

2ν2EC

Absorption of two atomic electrons → conversion of a pair of protons into neutrons + simultaneous emission of two neutrinos

$$\left(T_{1/2}^{2\nu 2\mathrm{EC}}\right)^{-1} = G_{2\nu}^{2\mathrm{EC}} g_A^4 \left| m_e c^2 M^{(2\nu)} \right|^2$$

$G_{2\nu}^{2\mathrm{EC}} \propto$ (Q-value)^5

Has only been observed for ^{130}Ba, ^{78}Kr and ^{124}Xe

Mainly produced through neutron activation during calibration campains → ^{125}I

Source	ROI signature	Half-life
^{125}I	Multiple EC peaks	59.4 d
^{127}Xe	K-shell EC (33.2 keV)	36.3 d
^{129m}Xe	γ (39.6 keV)	8.9 d
^{133}Xe	$\beta + \gamma$ (81.0 keV)	5.2 d
^{136}Xe $2\nu\beta\beta$	continuous	-
^{212}Pb	continuous	-
^{214}Pb	continuous	-
^{85}Kr	continuous	-
Solar neutrinos	continuous	-
Materials	continuous	-

Two-neutrino double electron capture of 124Xe in the first LUX-ZEPLIN exposure, The LUX-ZEPLIN (LZ) Collaboration

Underground labs in the world