

Exploring Double Beta Plus Decays with NuDoubt⁺⁺

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(he/him/his)

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ENTENTE 2025

Sudbury

30th September 2025



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

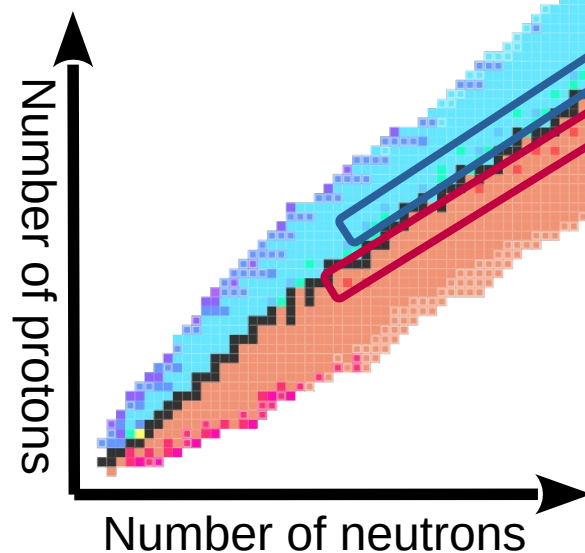


Proton-rich side

- little explored
- three decay modes
- only six isotopes can do all three modes

	2ν	0ν
$2\beta^+$	✗	?
$EC\beta^+$	✗	?
2EC	✓	?

This
Project



Primary Decay Mode



Neutron-rich side

- heavily explored
- one decay mode
- many isotopes

	2ν	0ν
$2\beta^-$	✓	?

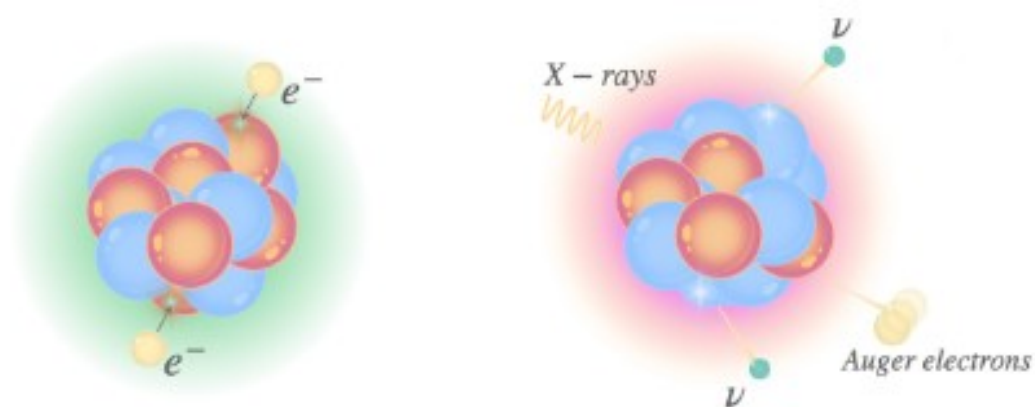
Positron emission requires more binding energy to be released

$$K_{\beta^+\beta^+} = M(A, Z) - M(A, Z - 2) - 4m_e,$$

$$K_{\beta^+\text{EC}} = M(A, Z) - M(A, Z - 2) - 2m_e - \epsilon_b$$

$$K_{2\text{EC}} = M(A, Z) - M(A, Z - 2) - \epsilon_{b_1} - \epsilon_{b_2},$$

$$\epsilon_b \ll m_e$$



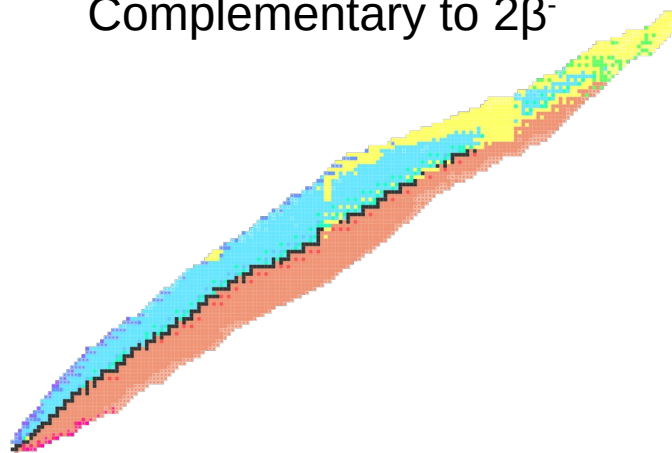
$2\beta^+$
 $\text{EC}\beta^+$
 2EC

$\text{EC}\beta^+$
 2EC

2EC

Transition	ΔM (keV)	Natural Abundance (%)
$^{124}\text{Xe} \rightarrow ^{124}\text{Te}$	2863.9	0.095
$^{78}\text{Kr} \rightarrow ^{78}\text{Se}$	2847.67	0.355
$^{106}\text{Cd} \rightarrow ^{106}\text{Pd}$	2775.39	1.245
$^{96}\text{Ru} \rightarrow ^{96}\text{Mo}$	2714.5	5.54
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$^{120}\text{Te} \rightarrow ^{120}\text{Sn}$	1730	0.09
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$^{108}\text{Cd} \rightarrow ^{108}\text{Pd}$	271.8	0.88
$^{40}\text{Ca} \rightarrow ^{40}\text{Ar}$	193.51	96.94

Complementary to $2\beta^-$

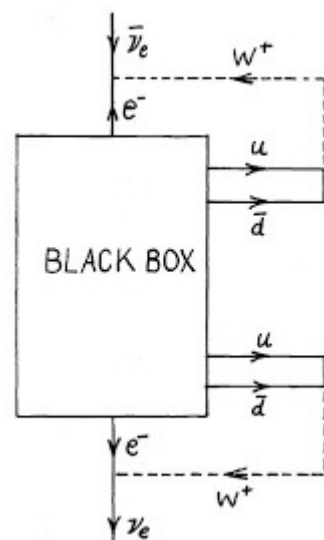


Probe of intermediate state

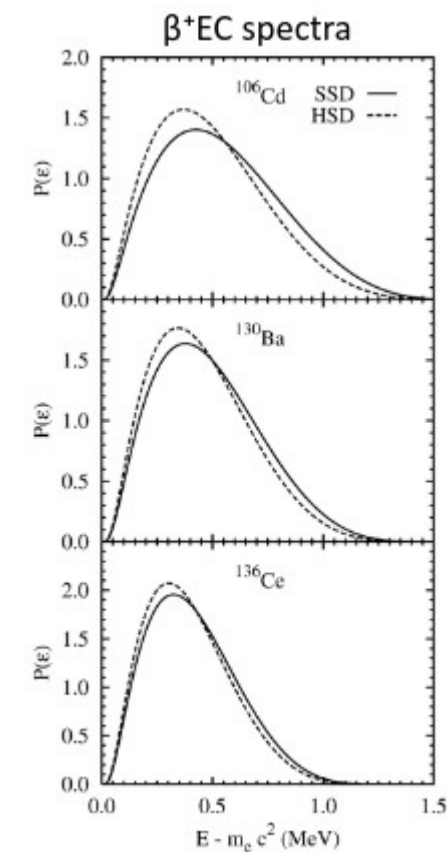
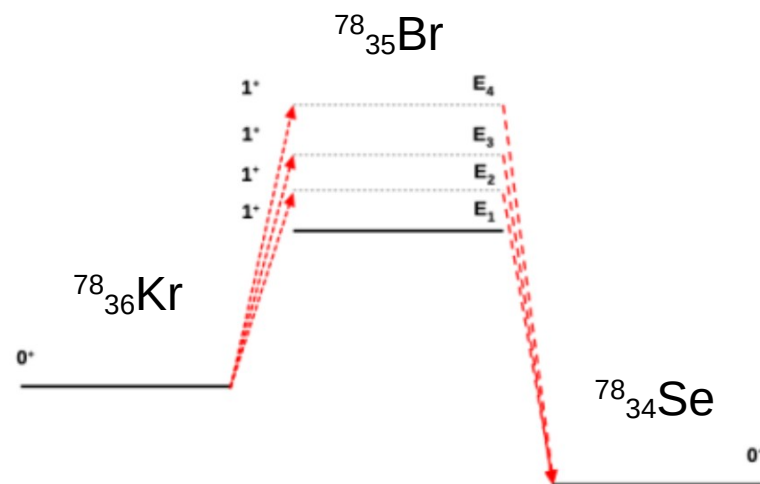
$$(A, Z) \rightarrow (A, Z \pm 1) \rightarrow (A, Z \pm 2)$$



Probe of Majorana Mechanisms



Branching ratio
 $2\beta^+ / \text{EC}\beta^+$

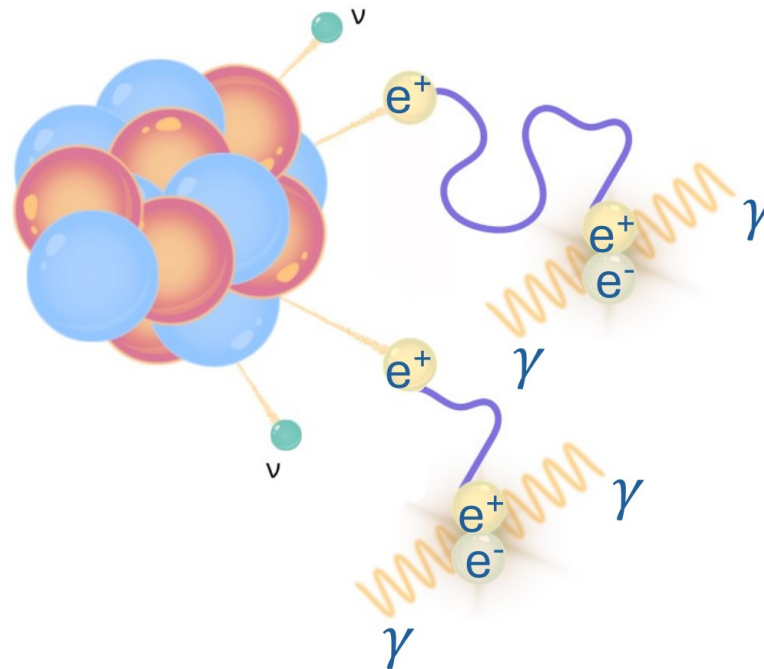


Challenges

- extremely rare
 $T_{1/2} > 10^{22}$ years
- low natural abundances

Experimental Opportunity

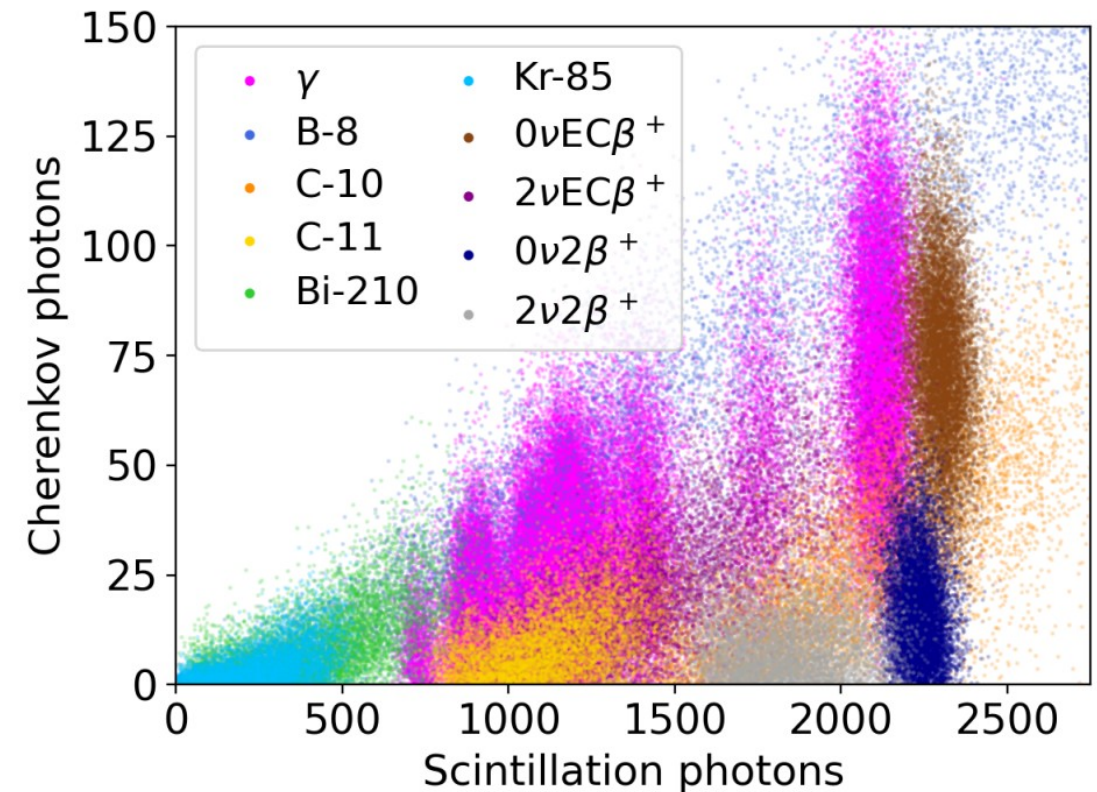
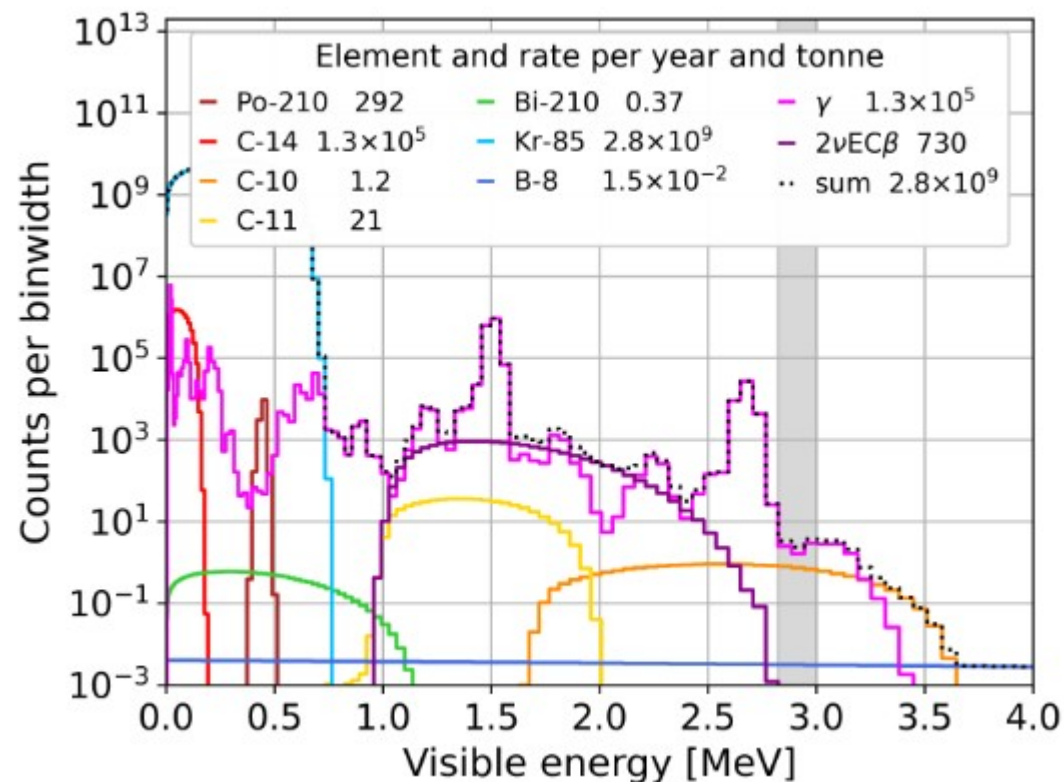
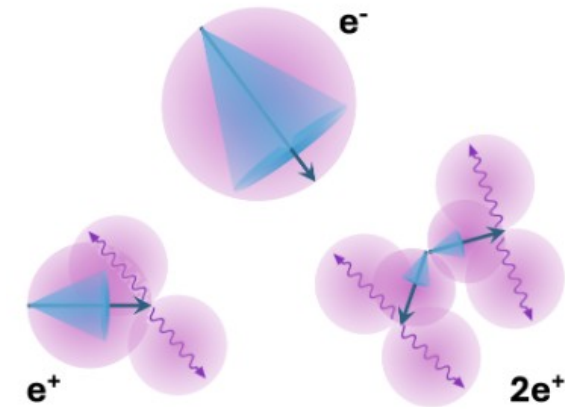
- unique signature via annihilation gammas



Technology Requirements

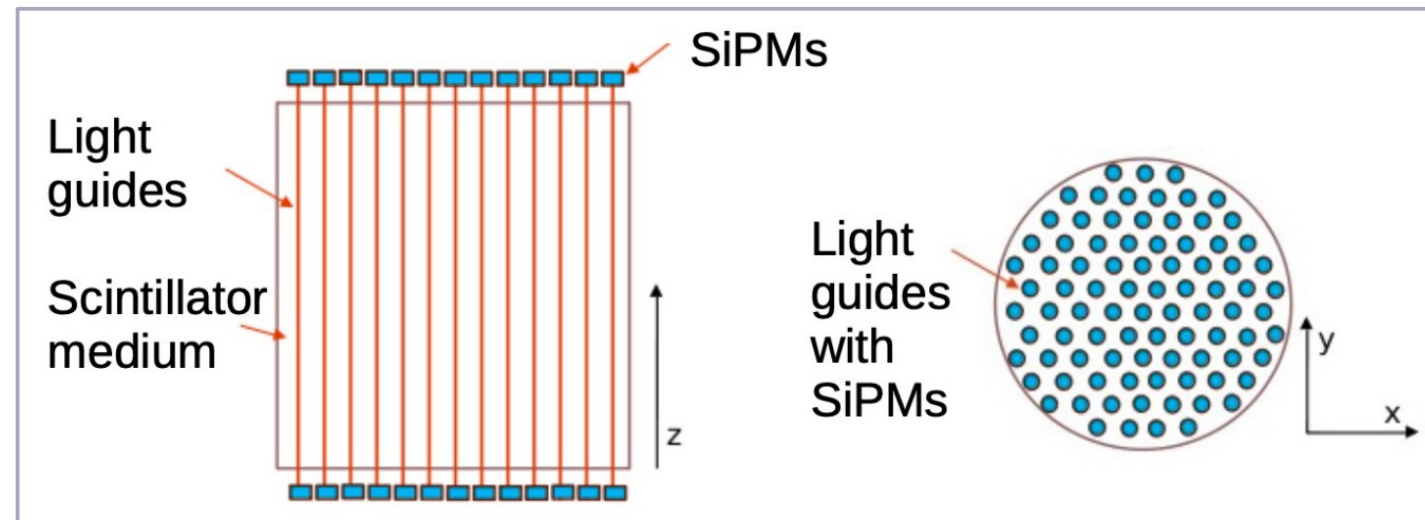
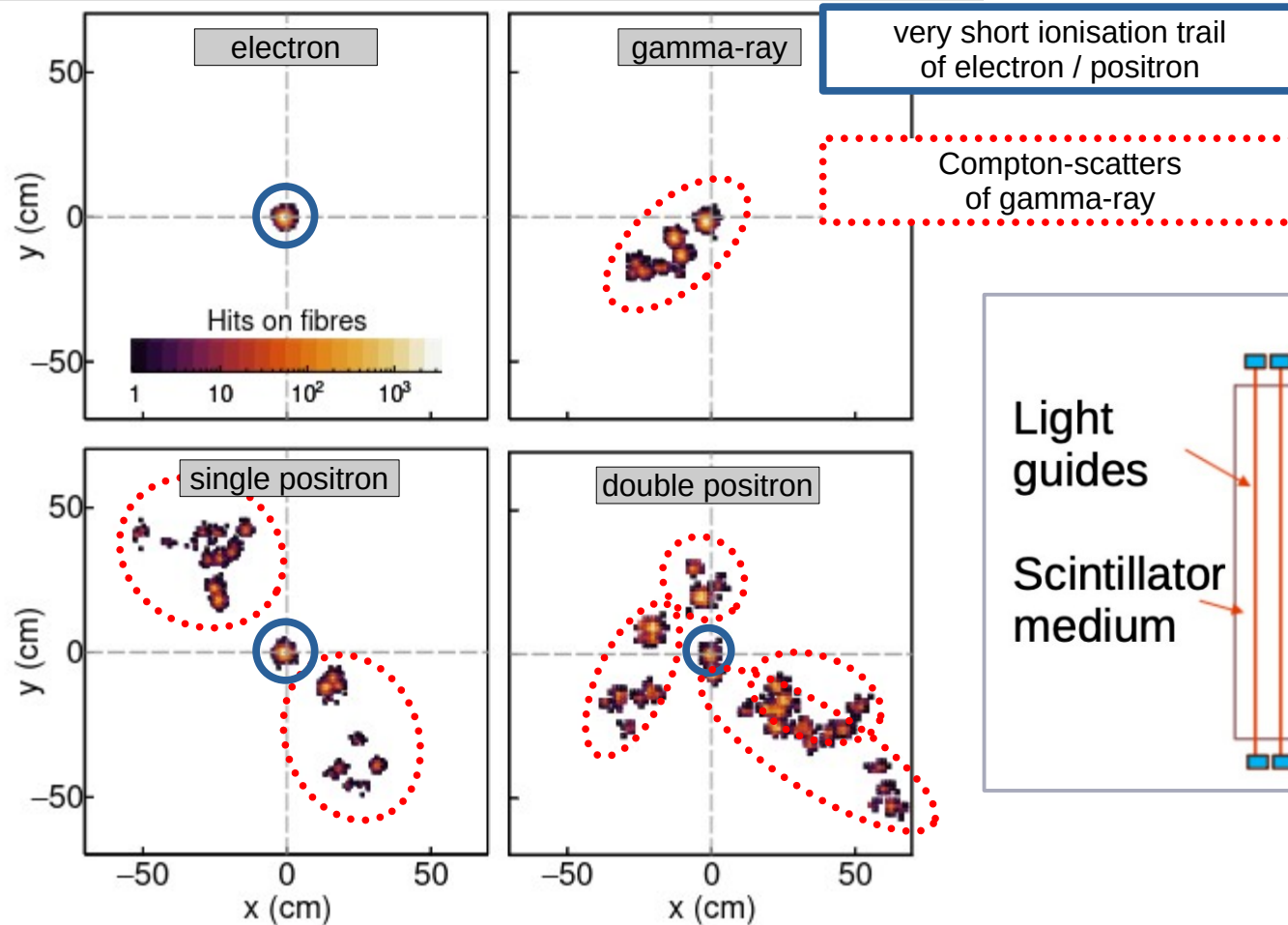
- strong background suppression
- high signal rates
- good energy resolution

- ratio between Cherenkov and scintillation light at certain energy depends on:
 - particle type
 - event type
- discrimination power based on separation of event populations in Cherenkov-scintillation-plane
- hybrid scintillator technology currently explored by e.g. Theia / Eos / NuDot / ANNIE



opaque scintillator technology
currently explored e.g. by LiquidO /
AntiMatter-OTech / CLOUD / L-PET

Simulation, 2.8 MeV total energy, 1 cm fibre pitch, 2 mm scattering length,
Eur. Phys. J. C 85 (2025) 121



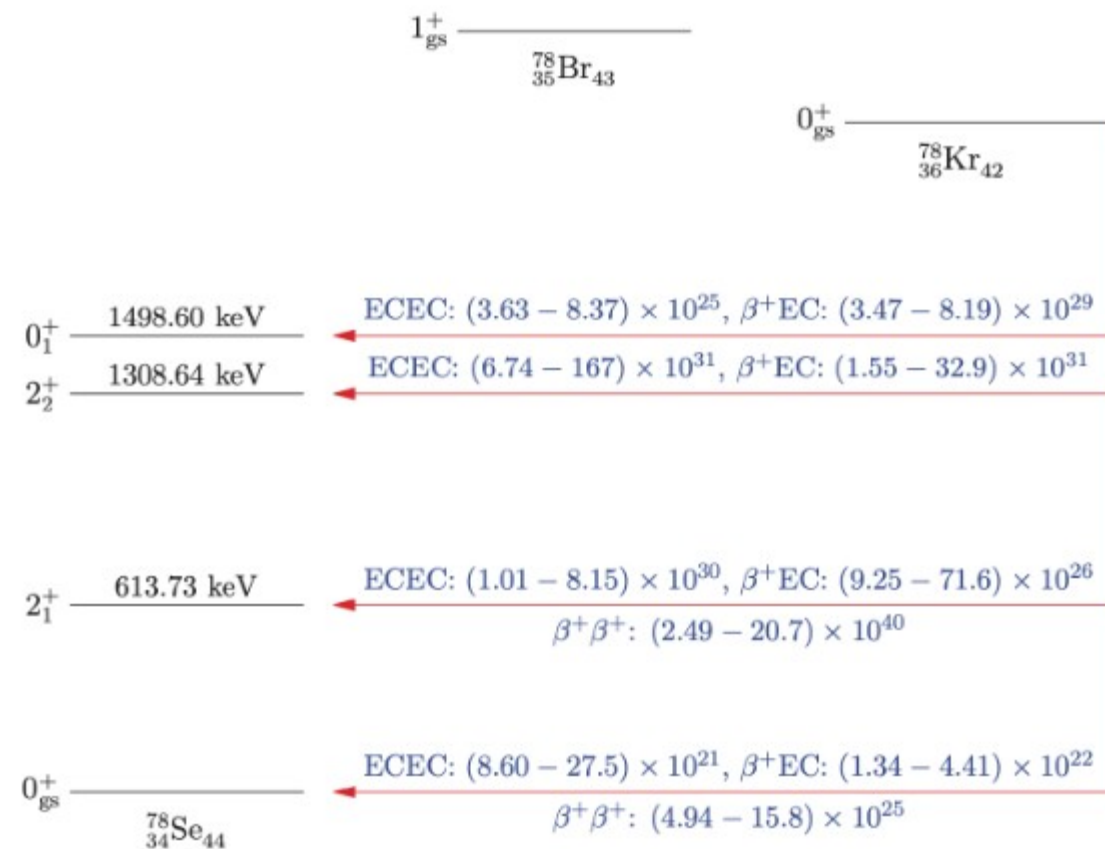
Experimental signature:

- additional gamma-ray visible
 - in lower C/S ratio and
 - by more blobs

Branching ratios between

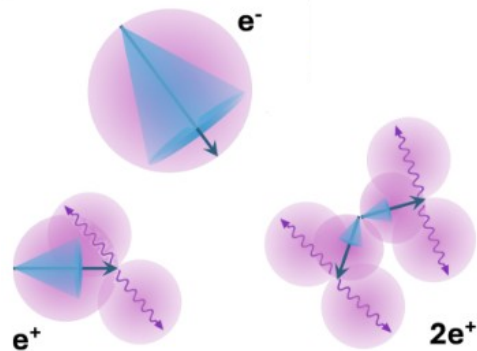
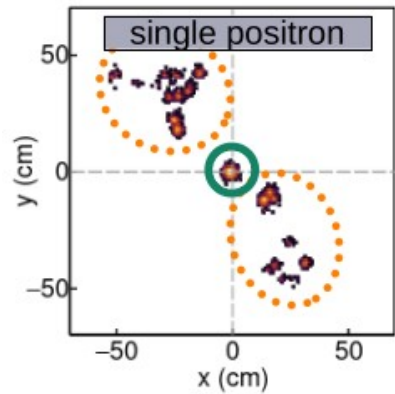
- decay modes and
- decay states

provide sensitive probe of nuclear matrix elements



PHYSICAL REVIEW C 86, 024301 (2012)

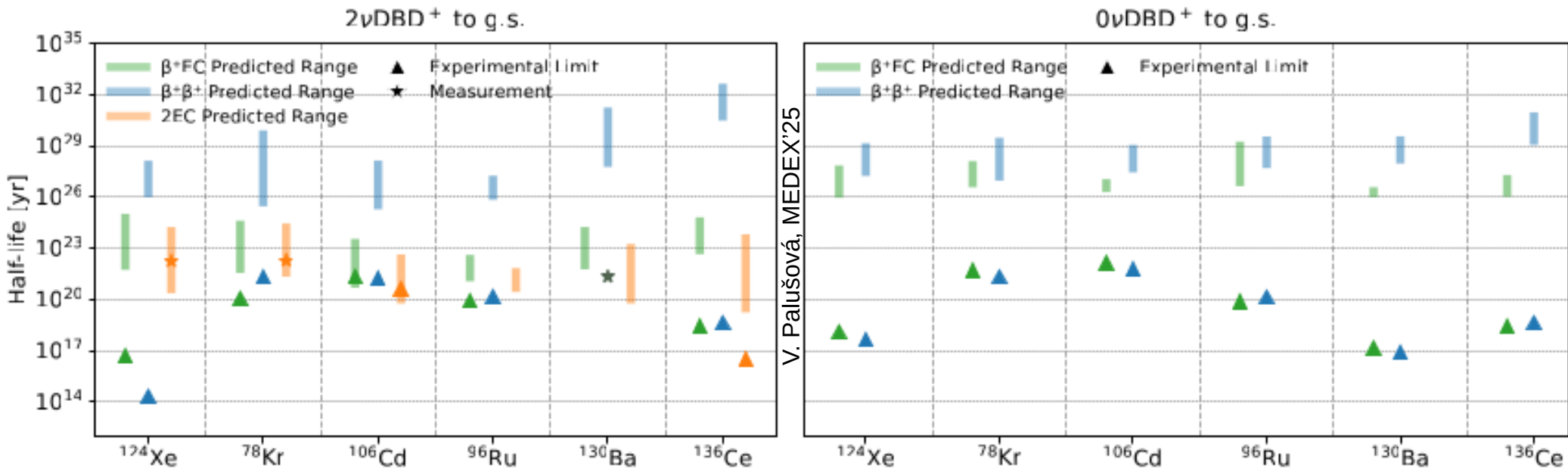
✓ strong background suppression



Patents Pending
EP 25 195 873.2 & EP 25 195 874.0

high signal rate

good energy resolution



Remark:

Combined Ba-130 modes (★) measured indirectly through geochemical analysis of barite samples

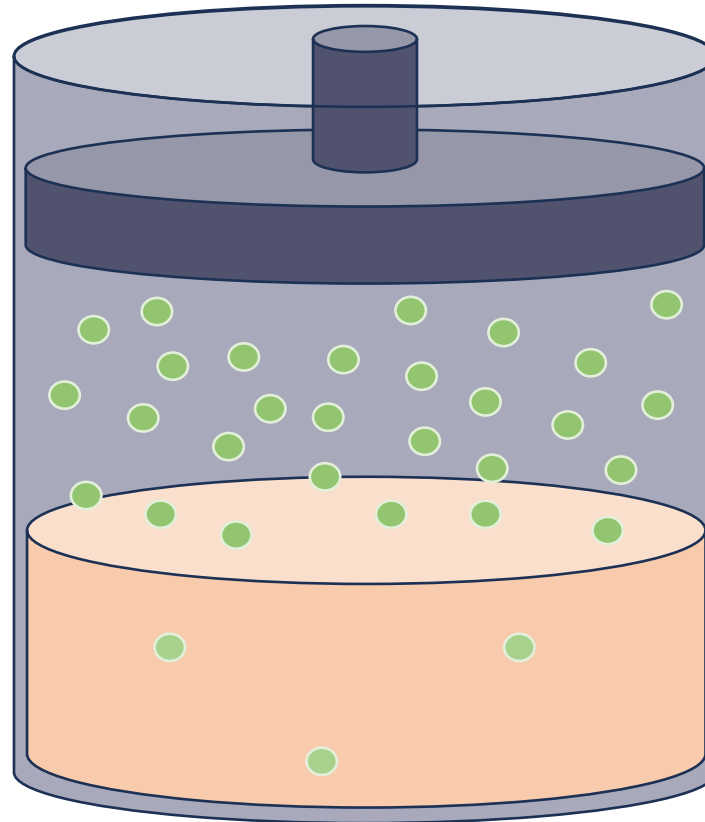
→ Three $2\beta^+$ isotopes have $E_{\max}$ -values above TI-208 background

$E_{\max} \approx Q_{2\beta^+} + 4m_e \approx Q_{EC\beta^+} + 2m_e \approx \Delta M$

	Isotope	$T_{1/2}(2\nu) / \text{years}$			$T_{1/2}(0\nu) / \text{years}$			C.L./ %	$E_{\max}/$ MeV	$a_{\text{nat}}/$ %
		$\beta\beta$	$EC\beta^+$	2EC	$\beta\beta$	$EC\beta^+$	2EC			
β^+	Kr-78	$> 2.0 \cdot 10^{21}$	$> 1.1 \cdot 10^{20}$	$9.2 \cdot 10^{21}$	$> 2.0 \cdot 10^{21}$	$> 5.1 \cdot 10^{21}$		68	2.881	0.4
	Cd-106	$> 1.7 \cdot 10^{21}$	$> 2.1 \cdot 10^{21}$	$> 3.1 \cdot 10^{20}$	$> 4.0 \cdot 10^{21}$	$> 1.2 \cdot 10^{21}$	$> 2.9 \cdot 10^{21}$	90	2.775	1.3
	Xe-124	$> 10^{14}$	$> 10^{17}$	$1.1 \cdot 10^{22}$	$> 10^{18}$	$> 10^{18}$		90	2.857	0.1
β^-	Ge-76	$1.9 \cdot 10^{21}$	—	—	$> 1.8 \cdot 10^{26}$	—	—	90	2.039	7.8
	Te-130	$8.2 \cdot 10^{20}$	—	—	$> 2.2 \cdot 10^{25}$	—	—	90	2.528	34.0
	Xe-136	$2.3 \cdot 10^{21}$	—	—	$> 2.3 \cdot 10^{26}$	—	—	90	2.459	8.9

Krypton-78

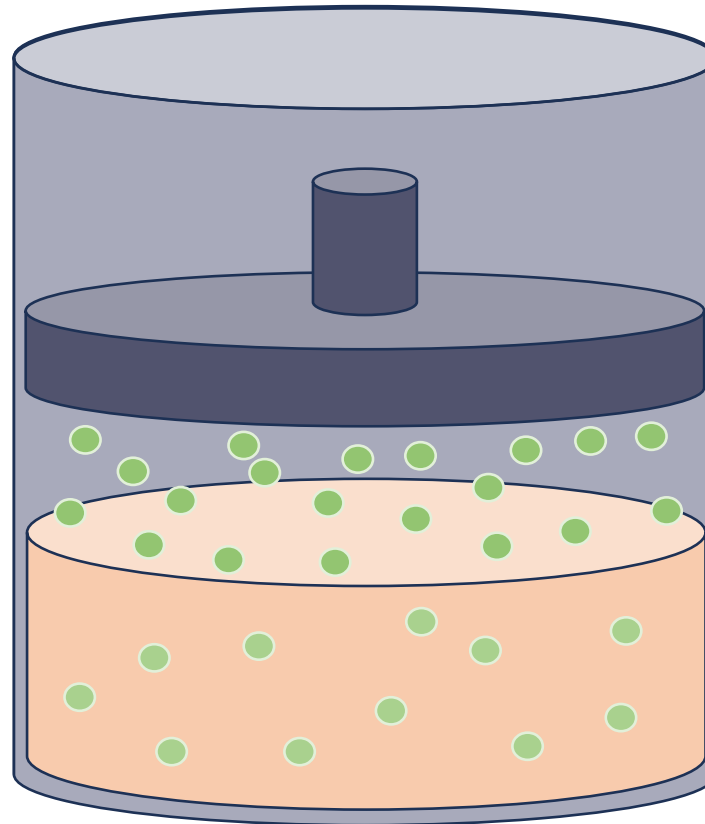
- high $\Delta M = 2.8$ MeV
 - above most backgrounds
- noble gas
 - high enrichment
 - pressure loading



final concentration of krypton: 17g/l

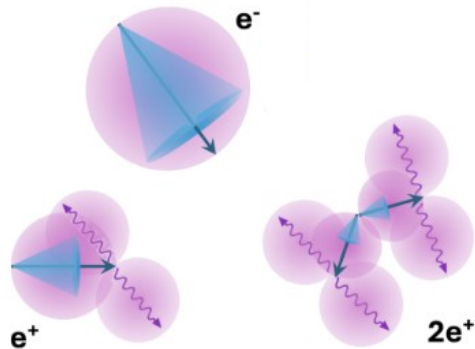
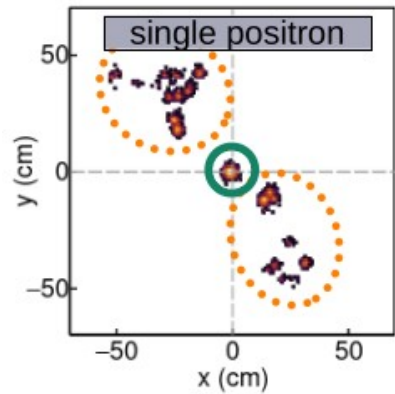
Krypton-78

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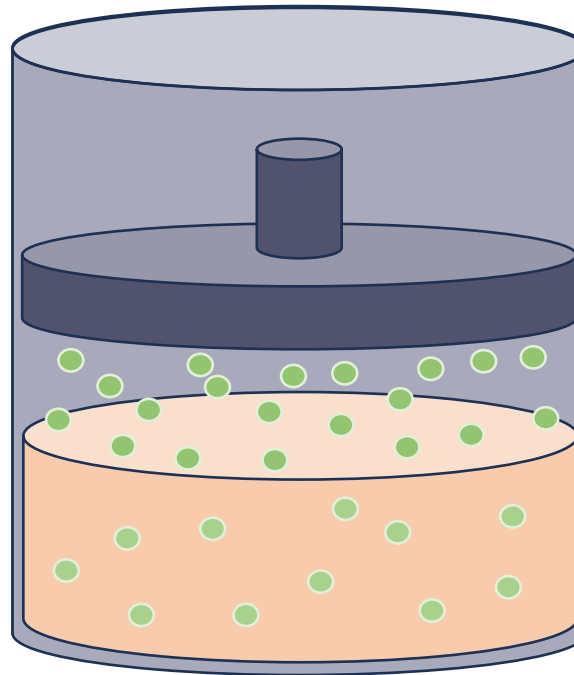
final concentration of krypton: 17g/l

✓ strong background suppression



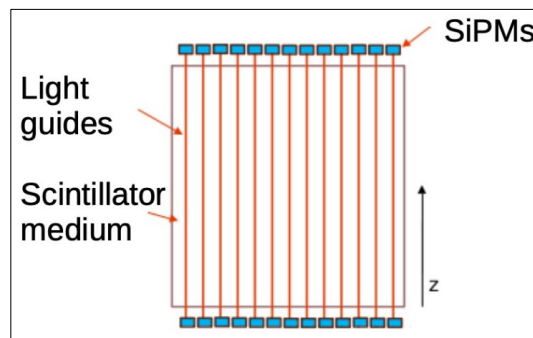
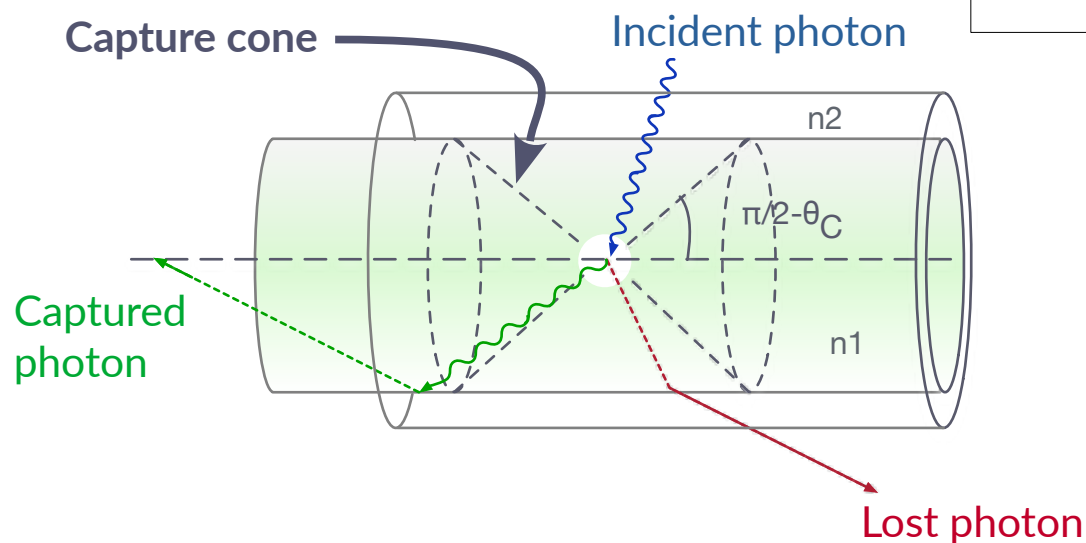
Patents Pending
EP 25 195 873.2 & EP 25 195 874.0

✓ high signal rate

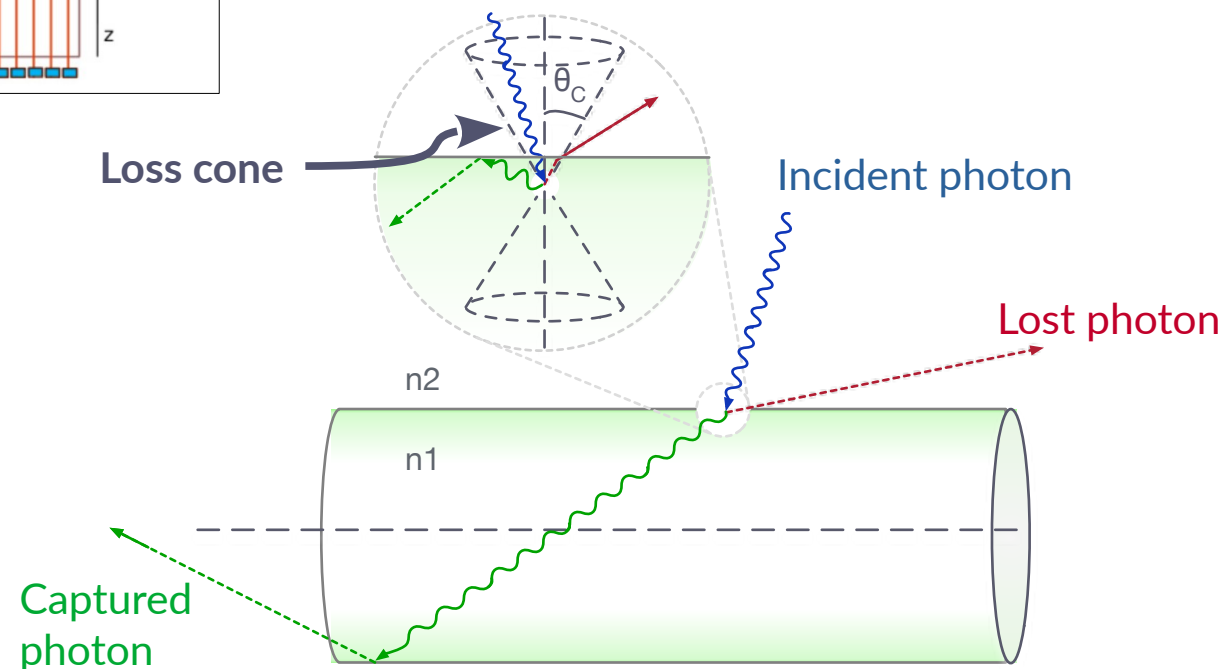


good energy resolution

Traditional Fibre
near centre emission
 $\epsilon_{\text{TIR}} = 8\%$



Coated Fibre
near surface emission
 $\epsilon_{\text{TIR}} = 38\%$

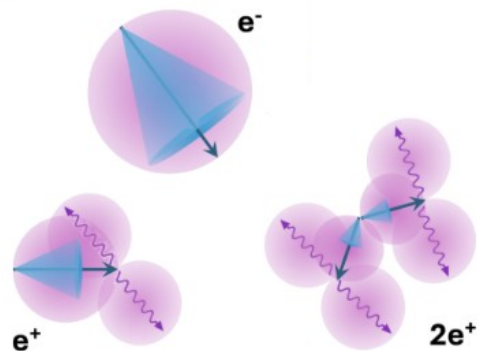
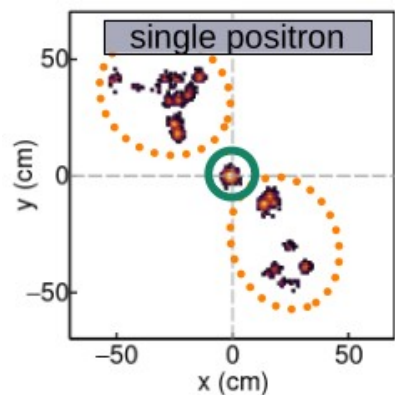


$\sim 800 \text{ PE/MeV}$

energy resolution of 2% in region of interest

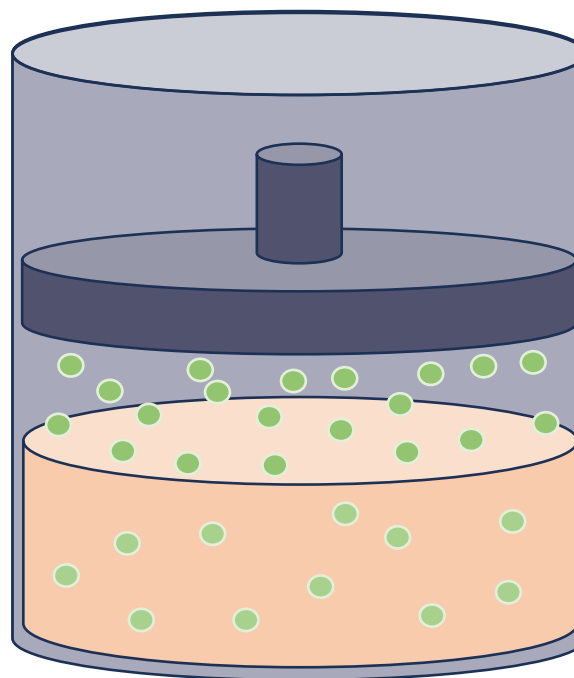


✓ strong background suppression

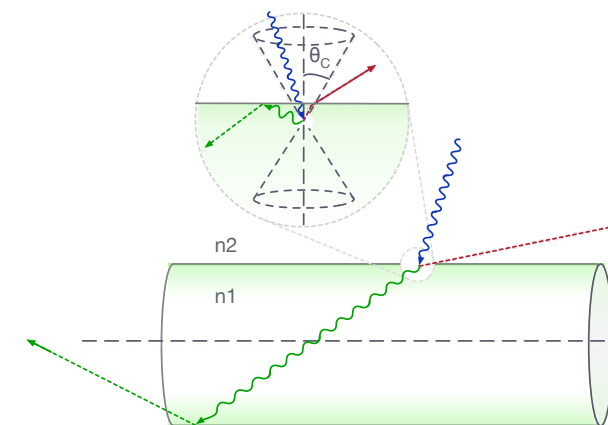


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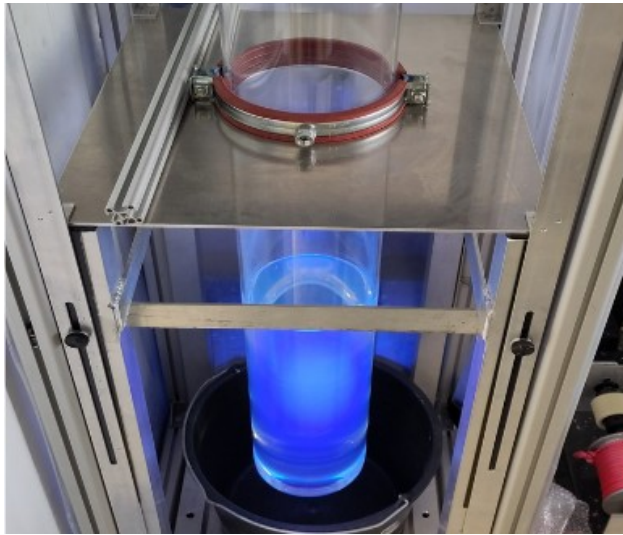
✓ high signal rate



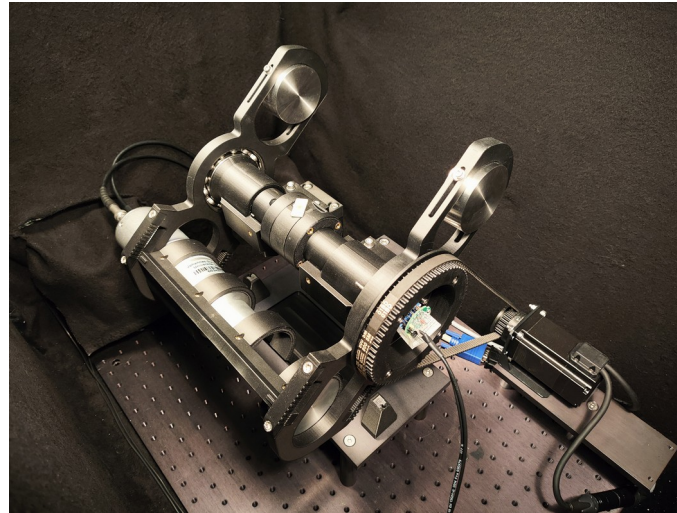
✓ good energy resolution



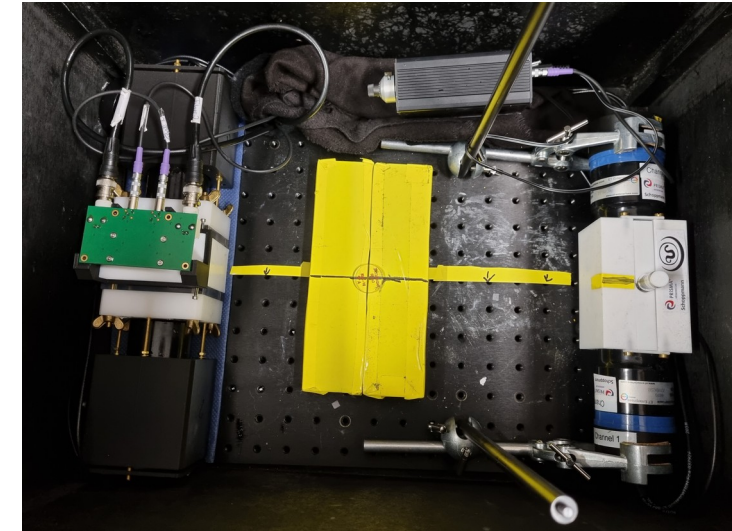
Patent
DE 10 2023 135 496.5



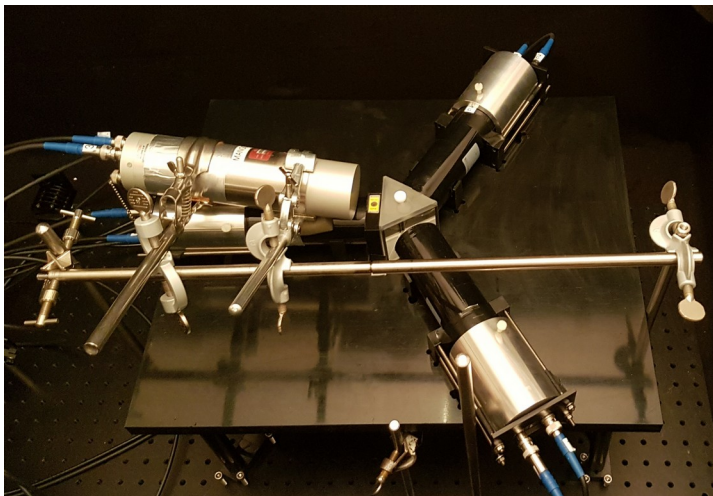
Fibre Coating Station



Scintillator Light Yield



Scintillator-Fibre Coupling



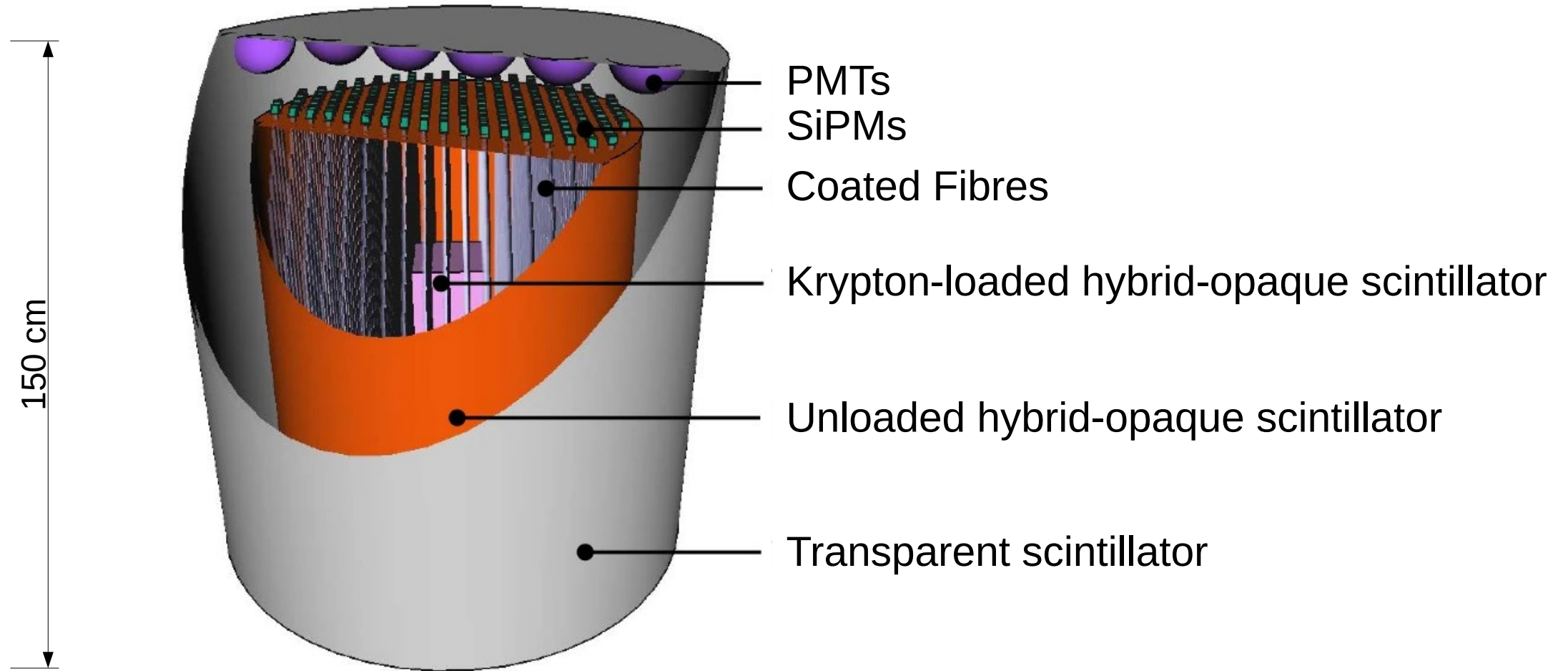
Cherenkov-scintillation separation



Pressure Loading

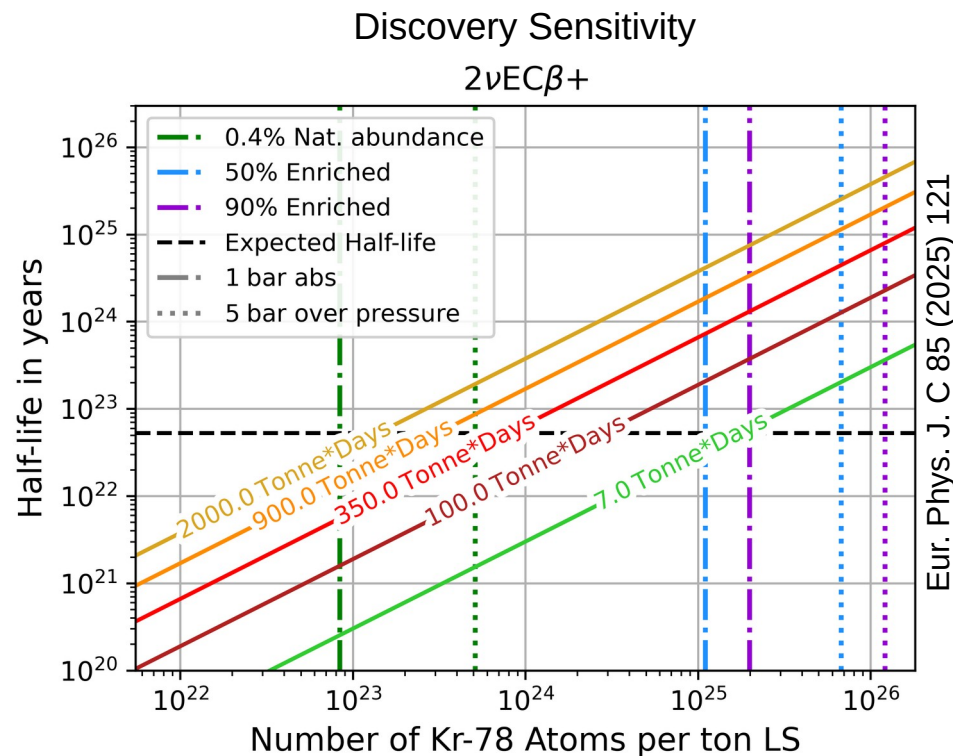


Krypton Purity

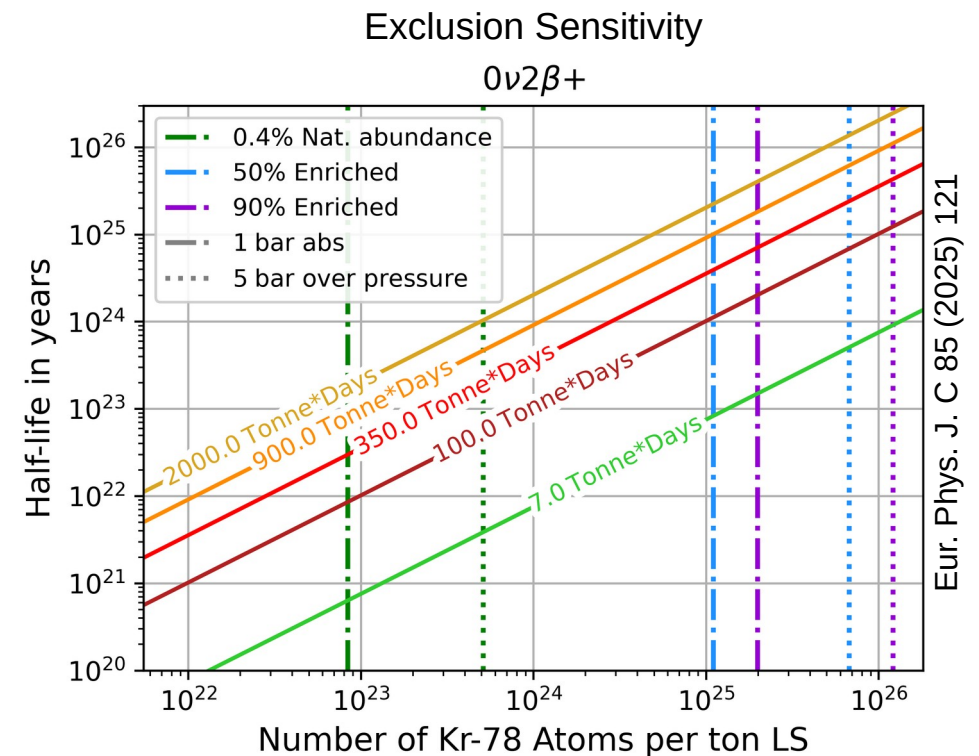


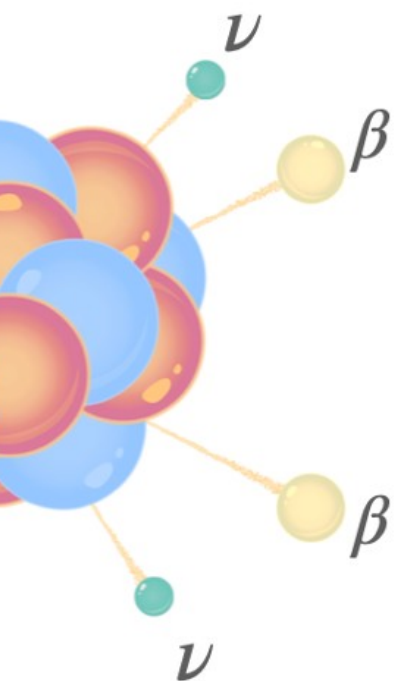
- Suppression factors up to 10^{-4}
- Background-free in region of interest

Two-neutrino decay 5σ measurement

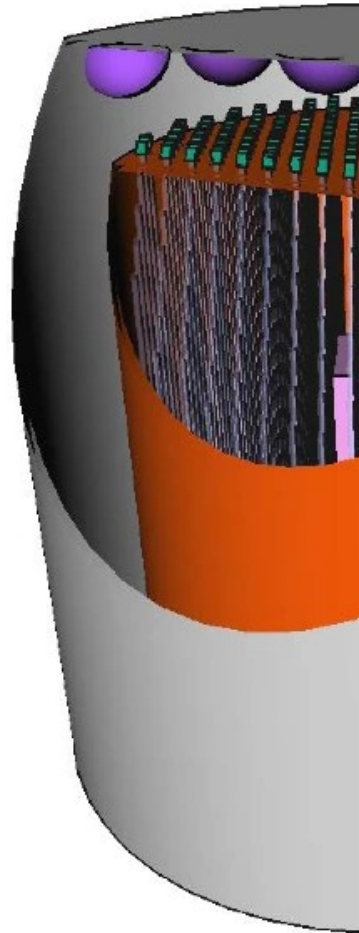


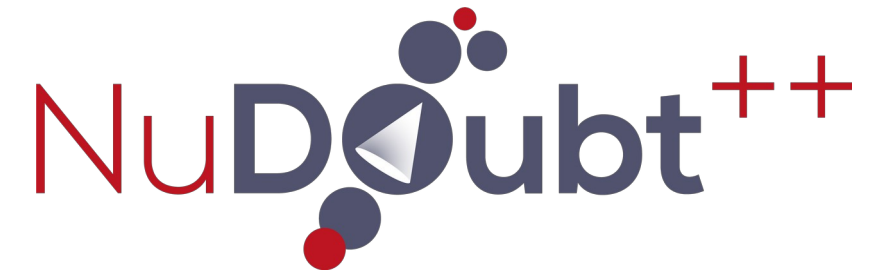
Neutrinoless decay 1000-fold improved limit





- search for double beta plus decays
- coated light guides (OWLs)
 - ~ 800 PE / MeV
 - energy resolution of 2% in ROI
- hybrid-opaque scintillator
 - background discrimination
- pressure loading of krypton-78
- sensitivity
 - measurement of $2\nu\text{EC}\beta^+$
 - 10^3 -fold improved limits on neutrinoless decay
- more details: [Eur. Phys. J. C 85 \(2025\) 121](#)





Contact:

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Webpage:

<https://nudoubt.uni-mainz.de>

Appendix

Transition	ΔM (MeV)	Abundance (%)	PSFs (yr^{-1})
$^{124}\text{Xe} \rightarrow ^{124}\text{Te}$	2.86	0.095	$G_{\beta^+\beta^+}^{2\nu} = (4, 261 - 4, 850) \times 10^{-29}$, $G_{\beta^+\beta^+}^{0\nu} = (107.8 - 123) \times 10^{-20}$ $G_{\beta^+\text{EC}}^{2\nu} = (1, 235 - 1, 720) \times 10^{-24}$, $G_{\beta^+\text{EC}}^{0\nu} = (17.1 - 22.9) \times 10^{-18}$ $G_{2\text{EC}}^{2\nu} = (15, 096 - 20, 200) \times 10^{-24}$
$^{78}\text{Kr} \rightarrow ^{78}\text{Se}$	2.85	0.355	$G_{\beta^+\beta^+}^{2\nu} = (9, 159 - 13, 600) \times 10^{-29}$, $G_{\beta^+\beta^+}^{0\nu} = (243.2 - 293) \times 10^{-20}$ $G_{\beta^+\text{EC}}^{2\nu} = (338 - 464) \times 10^{-24}$, $G_{\beta^+\text{EC}}^{0\nu} = (6.34 - 7.11) \times 10^{-18}$ $G_{2\text{EC}}^{2\nu} = (410 - 774) \times 10^{-24}$
$^{106}\text{Cd} \rightarrow ^{106}\text{Pd}$	2.78	1.245	$G_{\beta^+\beta^+}^{2\nu} = (1, 794 - 2, 000) \times 10^{-29}$, $G_{\beta^+\beta^+}^{0\nu} = (91.75 - 102) \times 10^{-20}$ $G_{\beta^+\text{EC}}^{2\nu} = (702 - 779) \times 10^{-24}$, $G_{\beta^+\text{EC}}^{0\nu} = (13 - 15.4) \times 10^{-18}$ $G_{2\text{EC}}^{2\nu} = (4, 299 - 6, 220) \times 10^{-24}$
$^{96}\text{Ru} \rightarrow ^{96}\text{Mo}$	2.71	5.54	$G_{\beta^+\beta^+}^{2\nu} = (942.3 - 1, 080) \times 10^{-29}$, $G_{\beta^+\beta^+}^{0\nu} = (80.98 - 90.7) \times 10^{-20}$ $G_{\beta^+\text{EC}}^{2\nu} = (372 - 454) \times 10^{-24}$, $G_{\beta^+\text{EC}}^{0\nu} = (9.62 - 11.3) \times 10^{-18}$ $G_{2\text{EC}}^{2\nu} = (1, 450 - 2, 740) \times 10^{-24}$
$^{130}\text{Ba} \rightarrow ^{130}\text{Xe}$	2.62	0.11	$G_{\beta^+\beta^+}^{2\nu} = (47.9 - 110) \times 10^{-29}$, $G_{\beta^+\beta^+}^{0\nu} = (21 - 25.7) \times 10^{-20}$ $G_{\beta^+\text{EC}}^{2\nu} = (549 - 740) \times 10^{-24}$, $G_{\beta^+\text{EC}}^{0\nu} = (17.6 - 22.9) \times 10^{-18}$ $G_{2\text{EC}}^{2\nu} = (14, 773 - 16, 300) \times 10^{-24}$
$^{136}\text{Ce} \rightarrow ^{136}\text{Ba}$	2.38	0.186	$G_{\beta^+\beta^+}^{2\nu} = (0.205 - 0.559) \times 10^{-29}$, $G_{\beta^+\beta^+}^{0\nu} = (2.13 - 3.55) \times 10^{-20}$ $G_{\beta^+\text{EC}}^{2\nu} = (190 - 253) \times 10^{-24}$, $G_{\beta^+\text{EC}}^{0\nu} = (15.3 - 21.5) \times 10^{-18}$ $G_{2\text{EC}}^{2\nu} = (12, 223 - 15, 800) \times 10^{-24}$

V. Palušová, MEDEX'25

Remark:

There are more than six isotopes that can undergo 2EC, because it requires less energy:

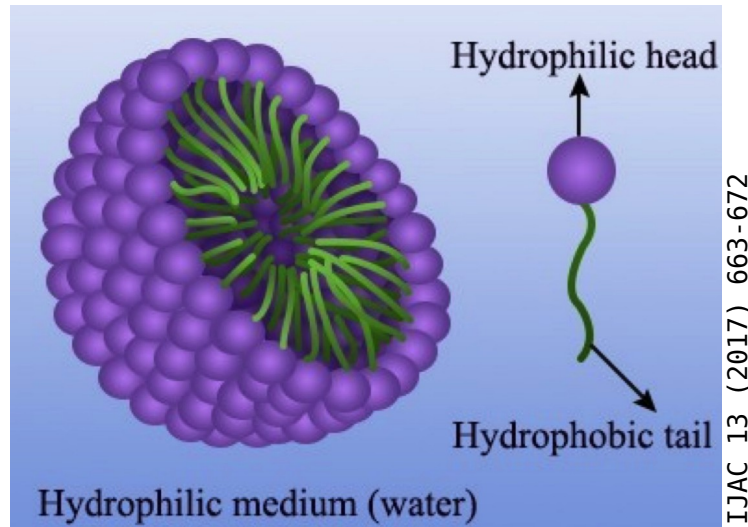
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with $\epsilon_b \ll m_e$

Transition	ΔM (keV)	Natural Abundance (%)
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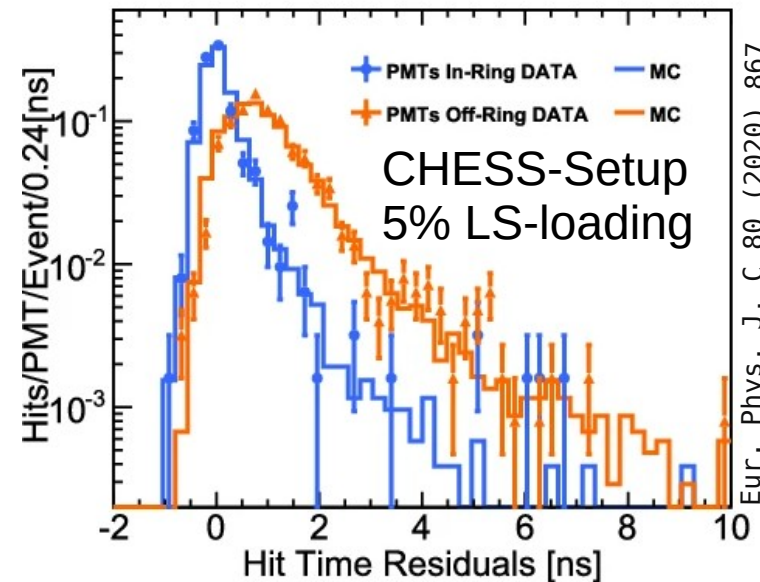
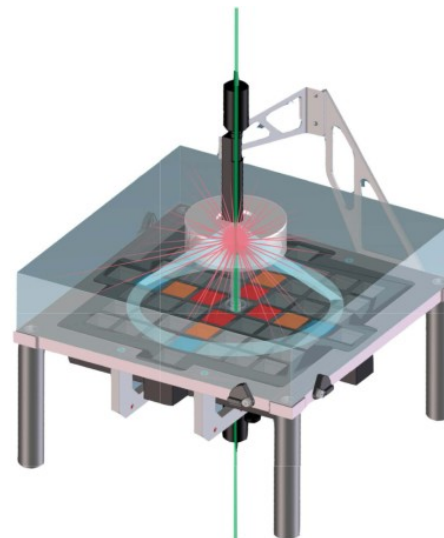


Water-based:

- organic micelles suspended in water with surfactant interface
- 1 – 10% scintillator loading
- Theia/Eos collaborations

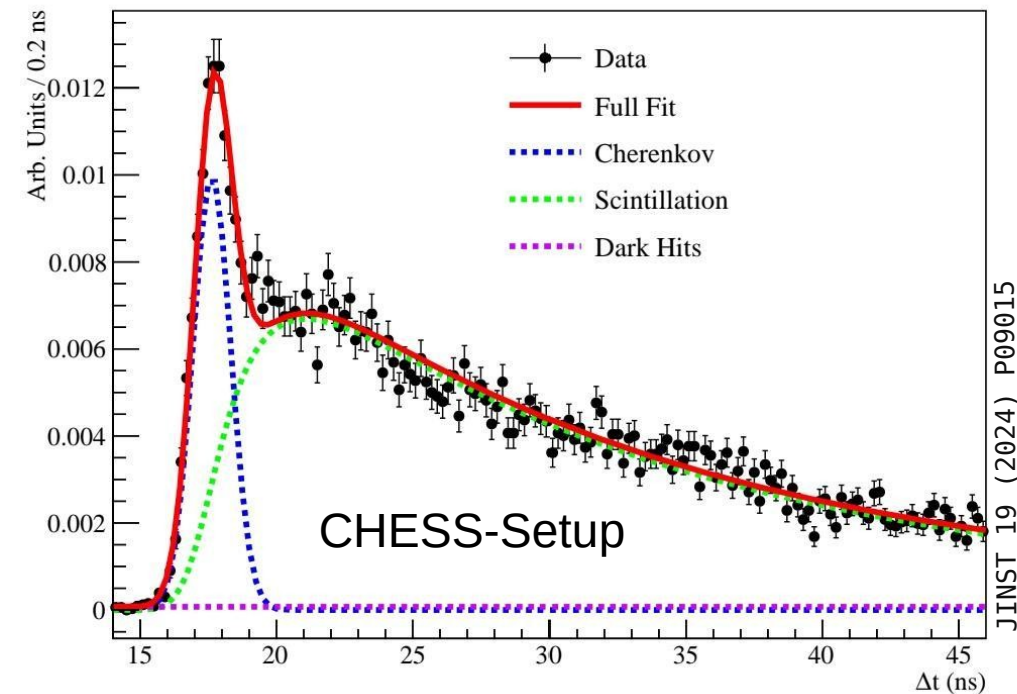
CHES

- spatial separation of Cherenkov and scintillation light



Slow:

- slow fluorophores / slow solvents
- intrinsically slow scintillation pulse form
 - $\tau = >10$ ns
- high light yield scintillators
 - >10000 photons/MeV



NoWaSH: wax-based opaque scintillator

→ transparent solvent + O(1-10 wt.%) wax + fluorophore(s)

JINST 14 (2019) P11007, Patent applications EP 25 195 873.2 & EP 25 195 874.0

→ opaqueness through scattering without absorption (Mie-Lorentz scattering, scattering length of millimetres)

→ scattering length tunable via

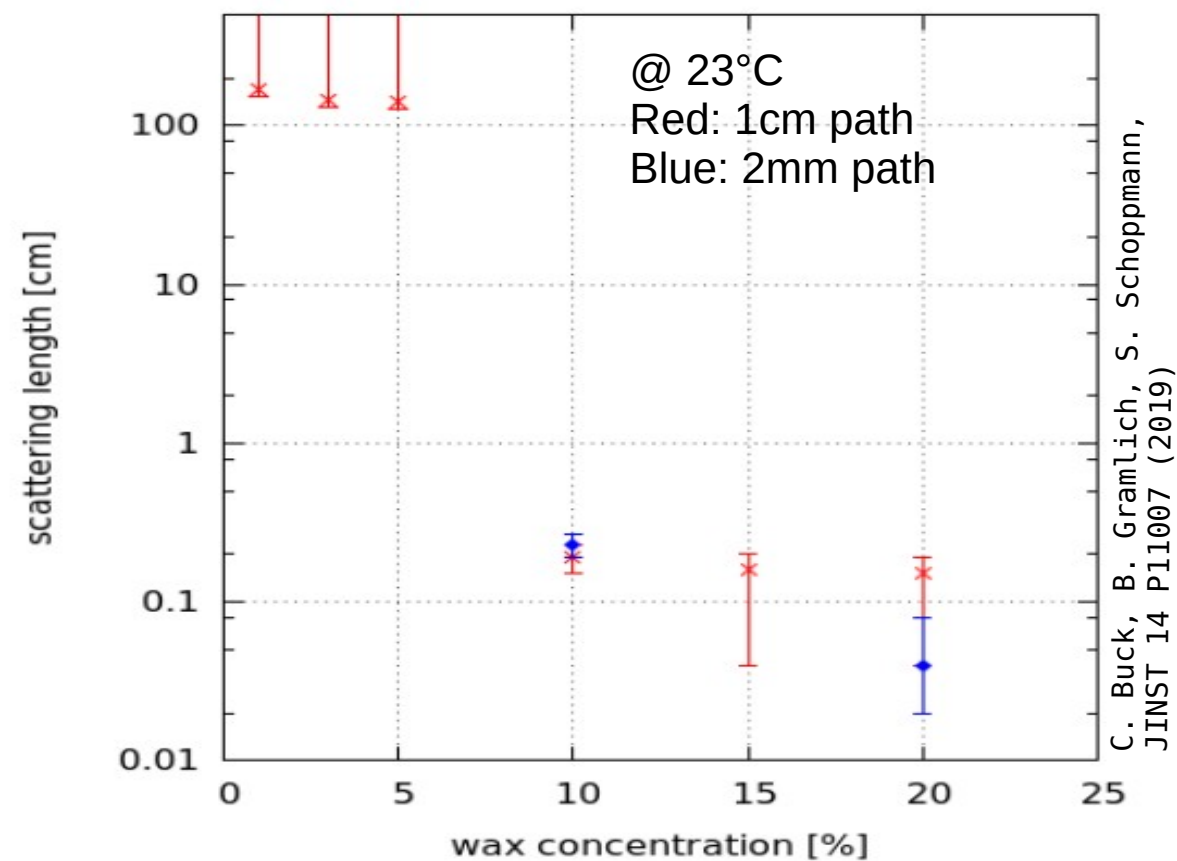
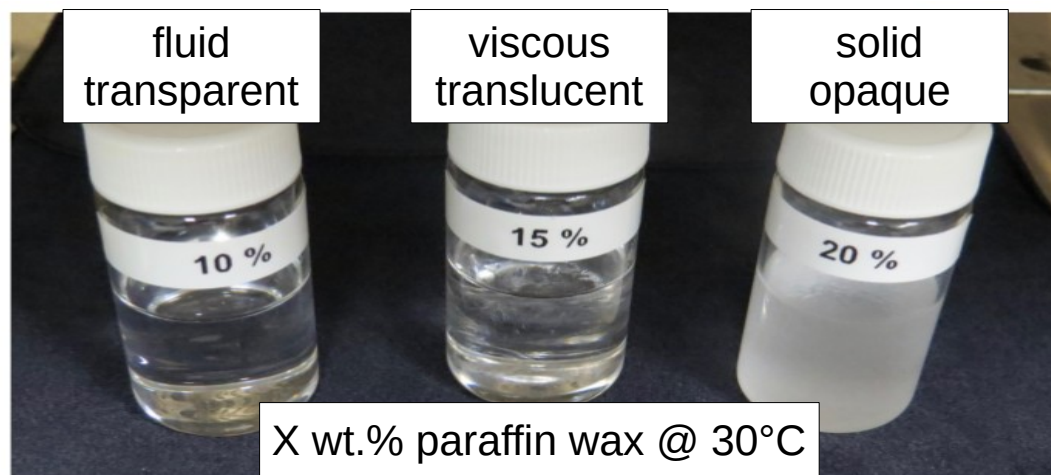
→ wax type

→ wax concentration

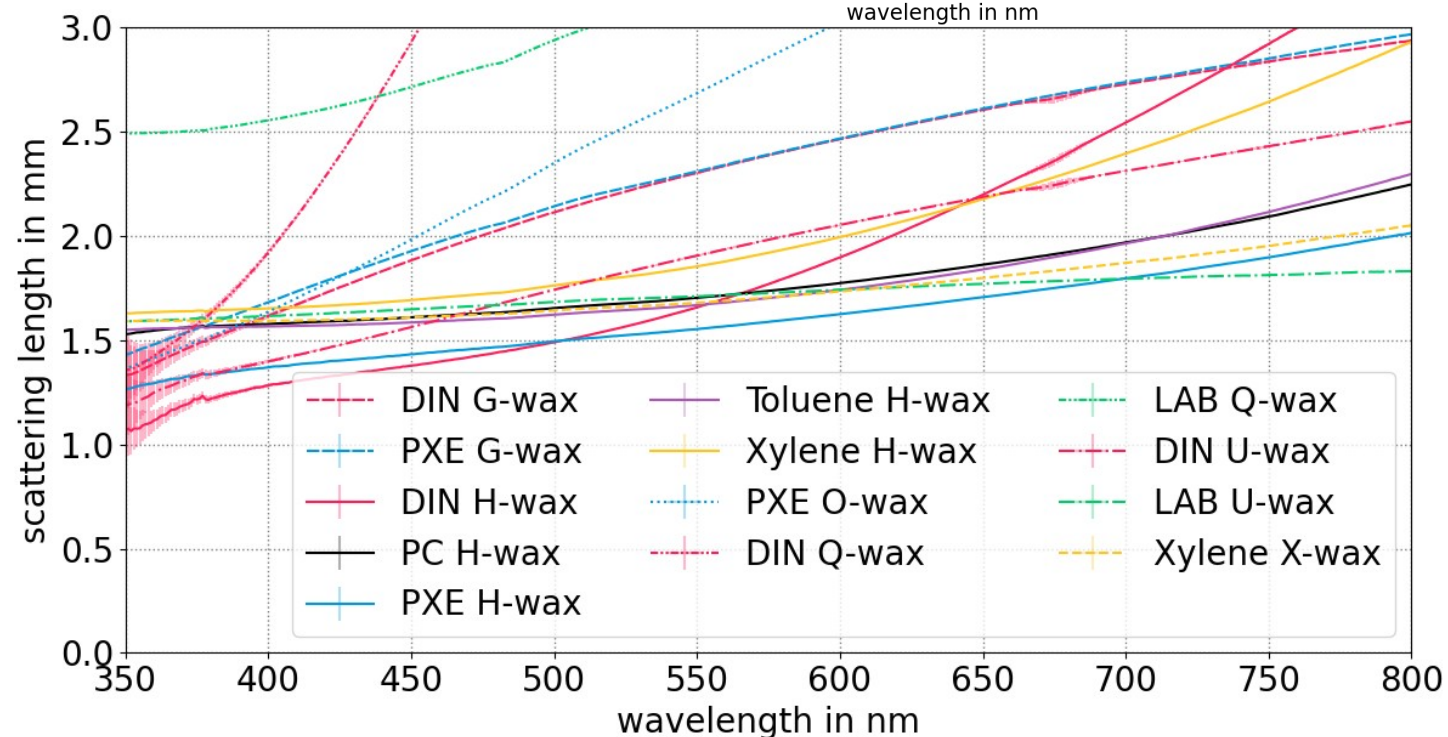
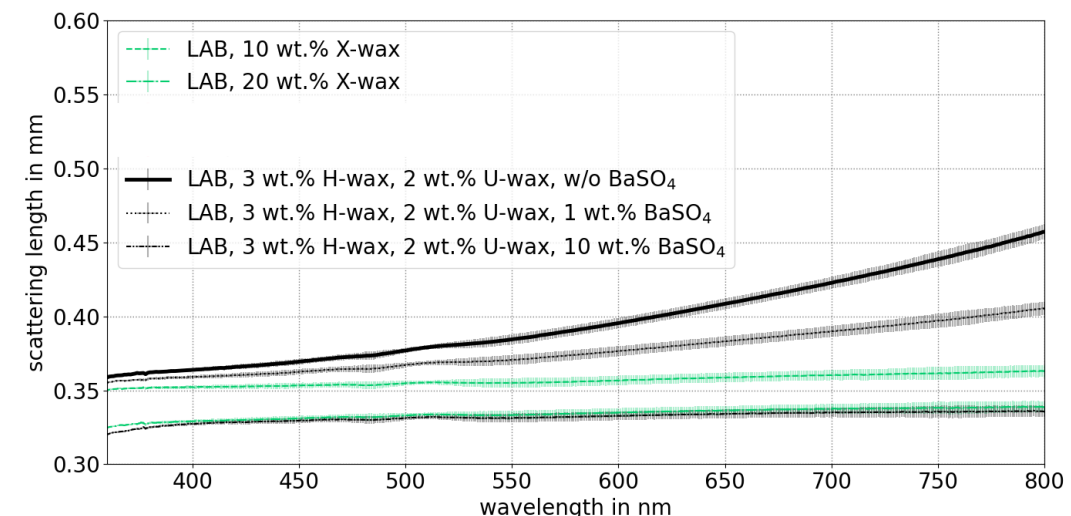
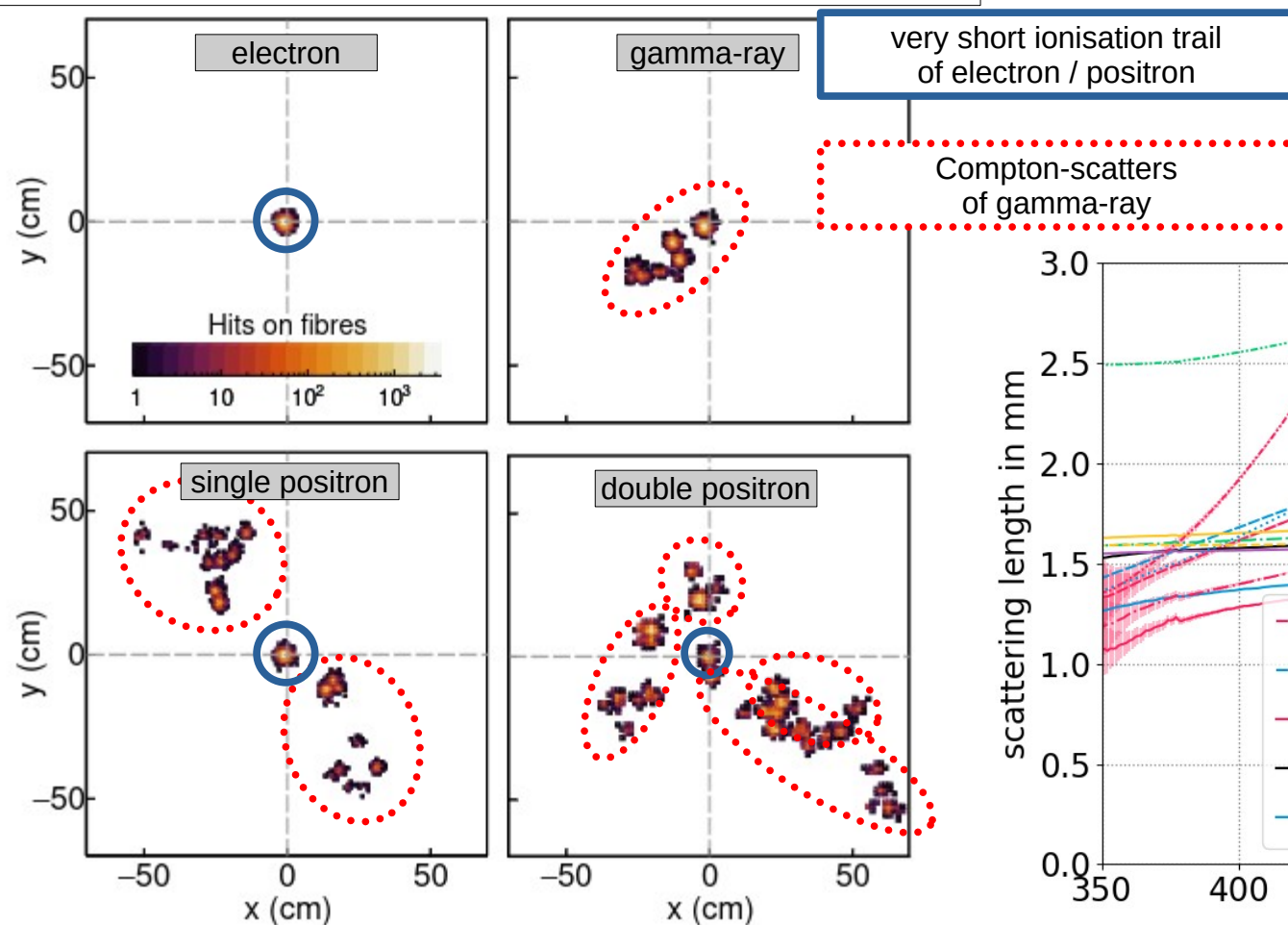
→ temperature (in some formulations)

→ high isotope loading possible

→ relaxed requirement on absorption length

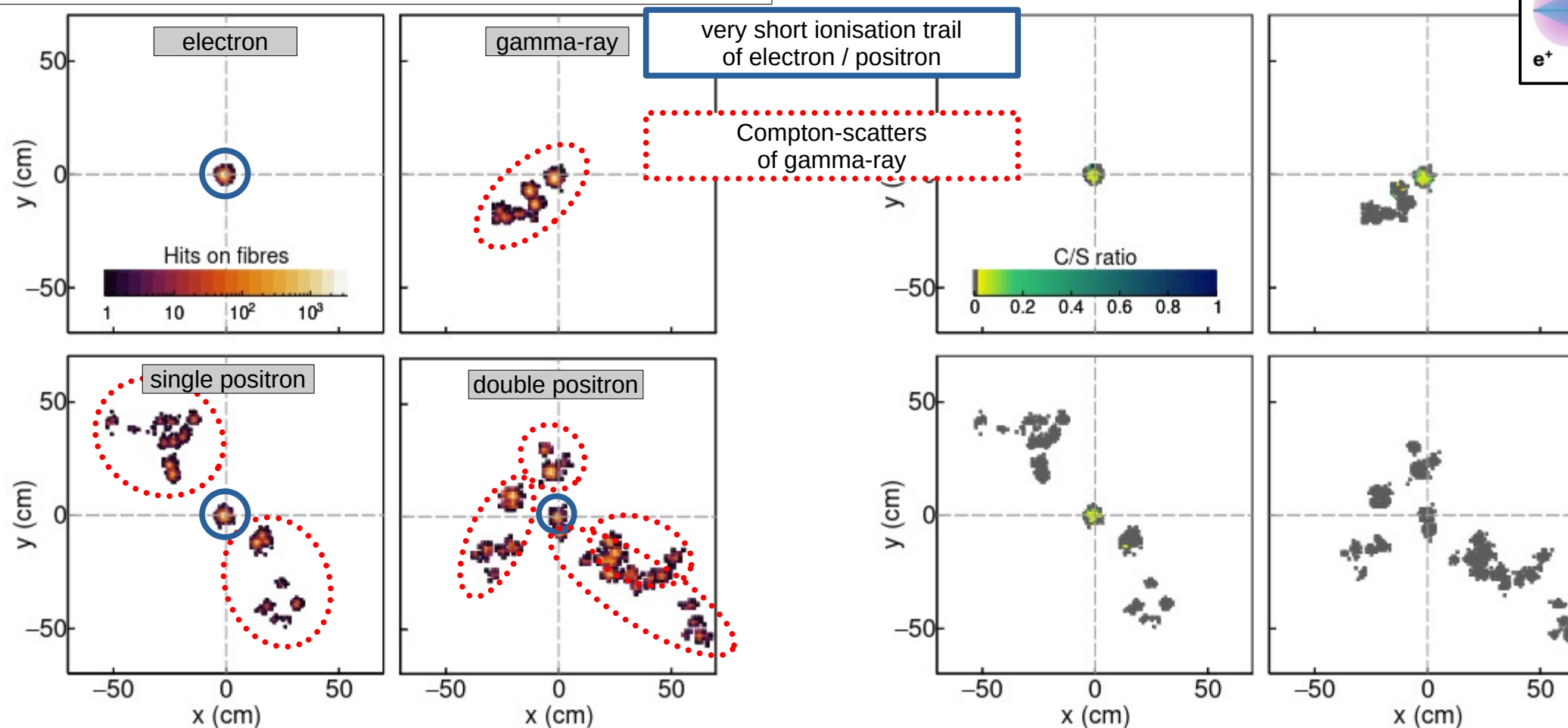


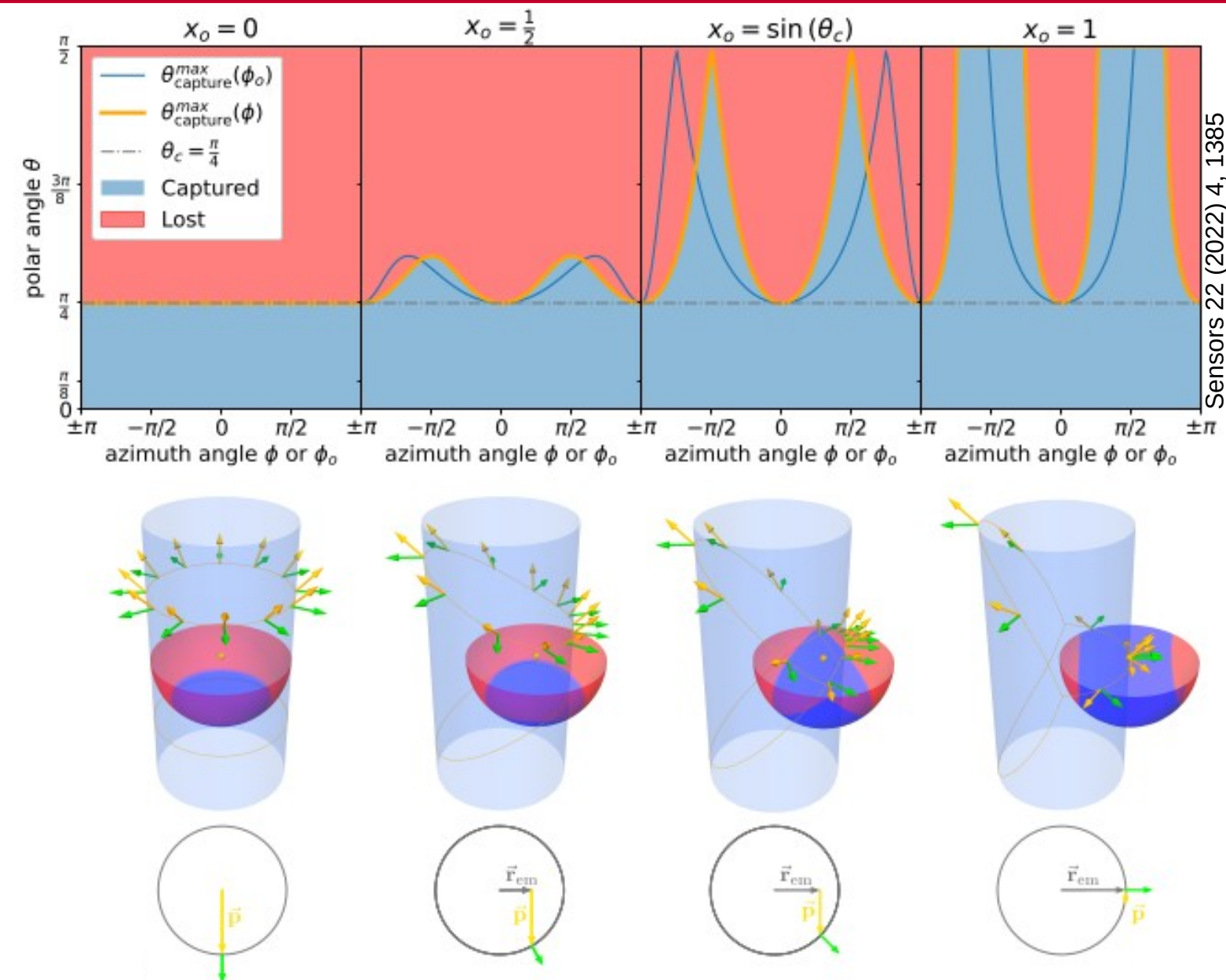
Simulation, 2.8 MeV total energy, 1 cm fibre pitch, 2 mm scattering length,
Eur. Phys. J. C 85 (2025) 121



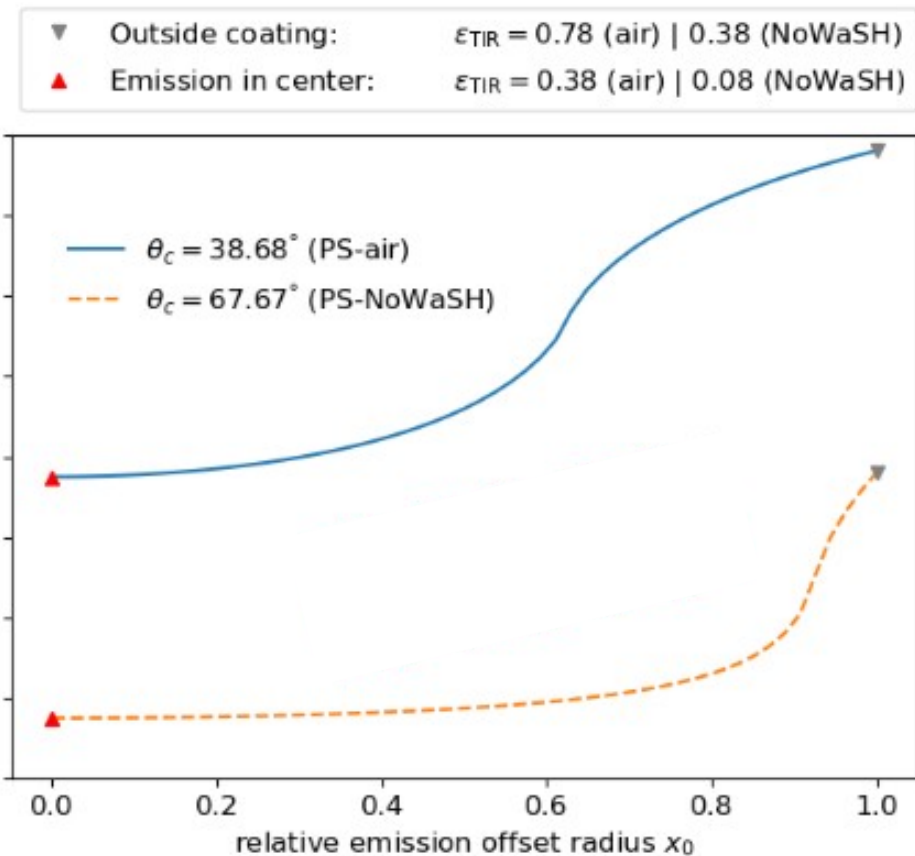
Combination allows insights into morphology of scintillation and Cherenkov light

Simulation, 2.8 MeV total energy, 1 cm fibre pitch, 2 mm scattering length,
Eur. Phys. J. C 85 (2025) 121

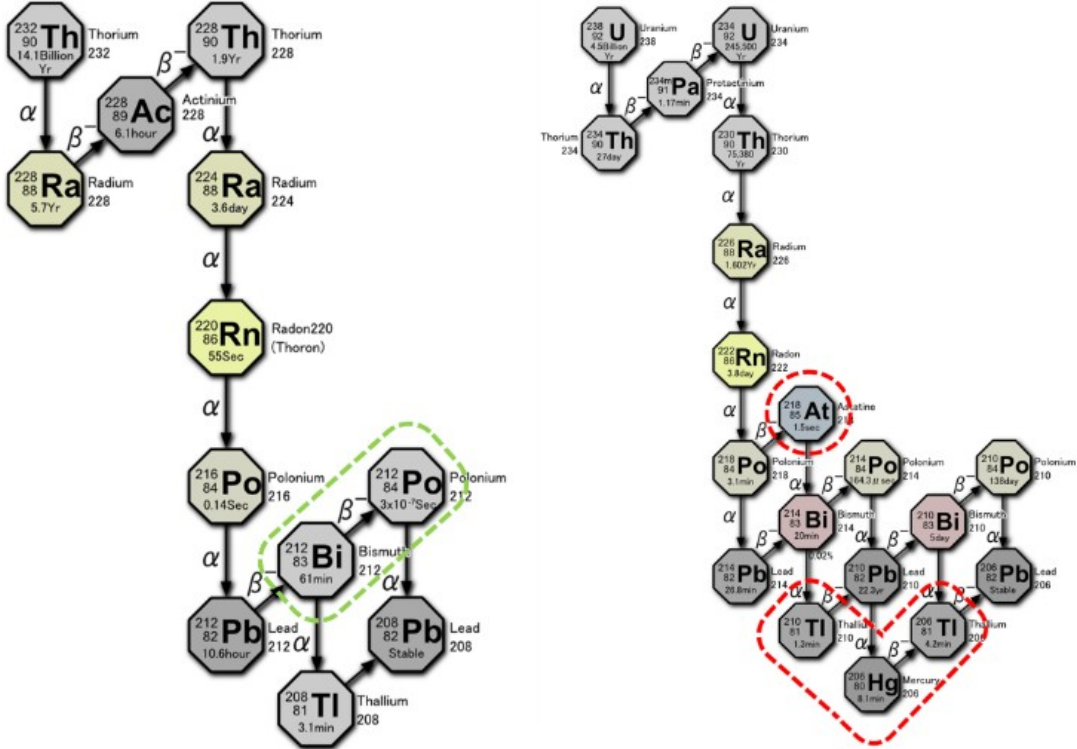




Sensors 22 (2022) 4, 1385



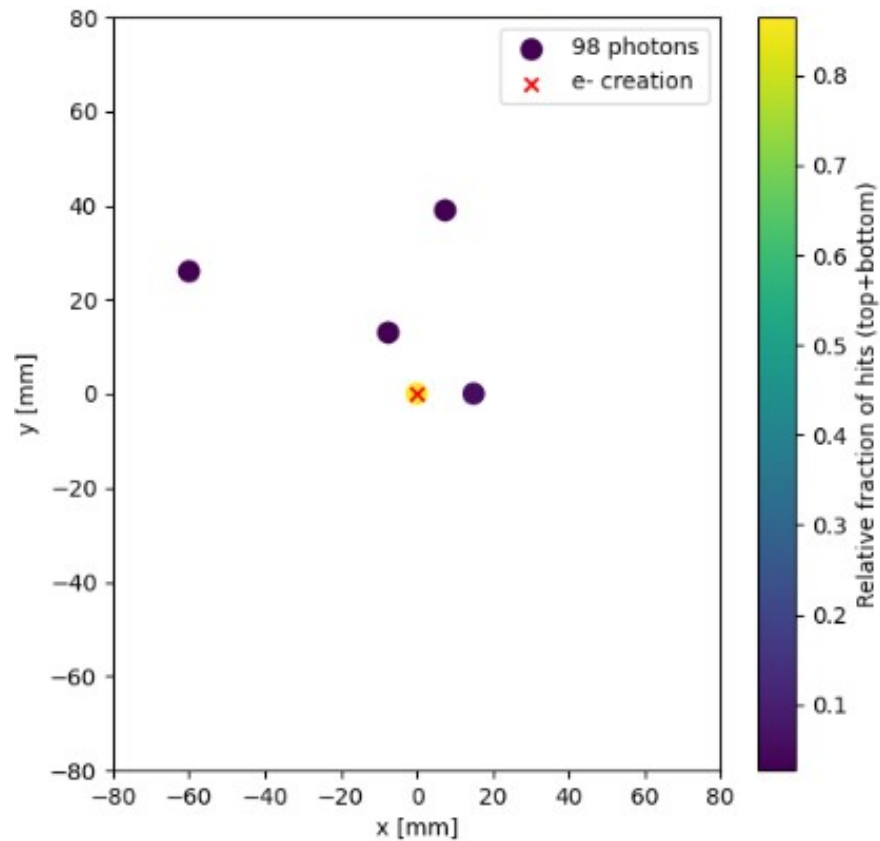
Scintillator		wavelength-shifter		Dust on fibres	fibres
<10 ⁻¹² g/g (U/Th)	< 5 μBq/m ³ (Rn)	< 1 ppb (K/U/Th)	Low energy (C-14/Bi-210)	<5 μg/m ²	1 ppb (U/Th/K)
→ Column purification → Fractional distillation	→ active charcoal filtering of nitrogen blanket	→ Water extraction		→ rinsing of surfaces	→ material selection



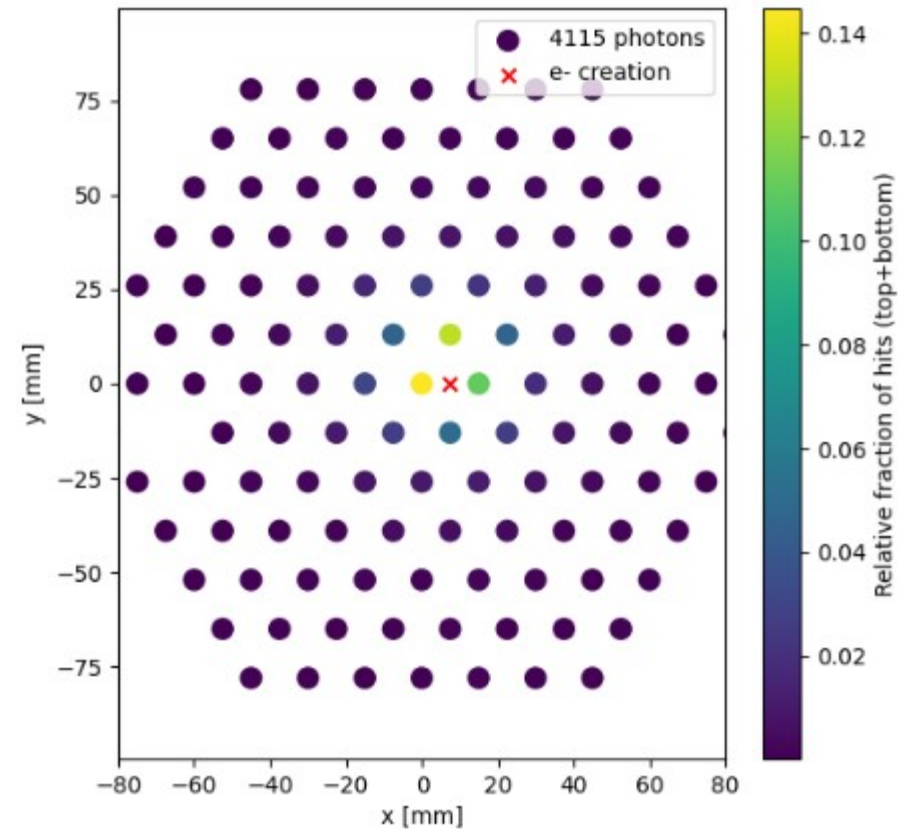
Backgrounds from fibres (10mm spacing):

location	isotope	rate / mBq/m ³	
		baseline	optimistic
OWL-fibre bulk (γ only)	U-238	103	1.03
	Th-232	33.7	0.34
	K-40	225	2.25
	Tl-208	12.1	0.12
OWL-fibre surface+dust (β+γ)	Bi-214	2.1	0.028
	Bi-212	0.48	0.014
	K-40	0.5	0.005

Fibre



Scintillator



Main features:

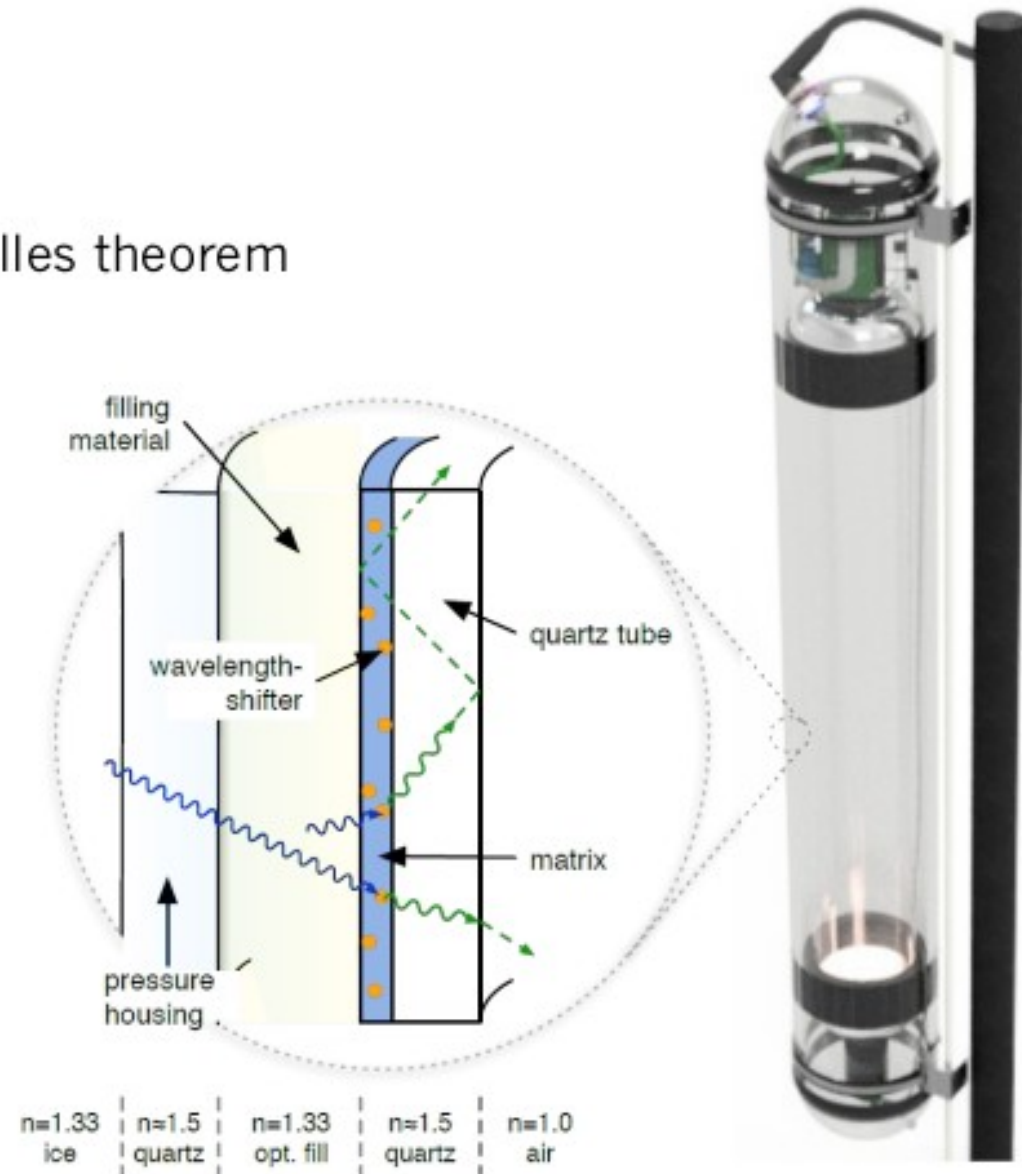
- Large light collection area
 - ▶ WLS allows circumventing Liouville's theorem
- Enhanced UV sensitivity
 - ▶ better matched to Cherenkov
- Low noise rate
 - ▶ for supernova detection

Target:

- build and deploy 12 modules in the IceCube Upgrade

Publication:

→ B. Bastian-Querner et al.
Sensors 22 (2022) 4, 1385



B. Bastian-Querner et al., Sensors 22 (2022) 4, 1385

		Cut efficiencies ε_x				
Scenario		Baseline	Optimistic			
Signal type		$2\nu 2\beta^+$ and $2\nu\text{EC}\beta^+$	$0\nu 2\beta^+$	$0\nu\text{EC}\beta^+$		
Discrimination technique		All	Hybrid	Opaque	Hybrid	Opaque
Event type	Kr-85	0.010	$-\dagger$	$-\dagger$	$-\dagger$	$-\dagger$
	Po-210	0.010	$-\dagger$	$-\dagger$	$-\dagger$	$-\dagger$
	Bi-210	0.010	$-\dagger$	$-\dagger$	$-\dagger$	$-\dagger$
	B-8	0.010	0.001	$< 10^{-4}$	0.296	0.016
	Gamma-rays	0.010	0.030	0.016	0.676	0.477
	C-10	0.050*	0.278	0.237	0.439	0.823
	C-11	0.100*	$< 10^{-4}$	0.237	$< 10^{-4}$	0.823
	C-14	0.010	$-\dagger$	$-\dagger$	$-\dagger$	$-\dagger$
	$0\nu 2\beta^+$	0.900	0.900	0.920	0.001	0.187
	$2\nu 2\beta^+$	0.900	0.900	0.920	$< 10^{-4}$	0.187
	$0\nu\text{EC}\beta^+$	0.900	0.001	0.237	0.900	0.823
	$2\nu\text{EC}\beta^+$	0.900	0.001	0.237	0.900	0.823

Experiment	Atomic phys.		Nuclear phys.	Particle phys.
$(T_{1/2})^{-1}$	$G(Q_{\beta\beta}, Z)$	g_A^4	$ M_{\text{nuc}} ^2$	$m_{\beta\beta}^2$
Measured half-life	Phase space factor	Axial coupling	Nuclear matrix elements	Effective Majorana neutrino mass

$$m_{\beta\beta} \equiv \left| \sum_k m_k U_{ek}^2 \right| = \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i(\alpha_2 - \alpha_1)} + m_3 |U_{e3}|^2 e^{-i(\alpha_1 + 2\delta)} \right|$$

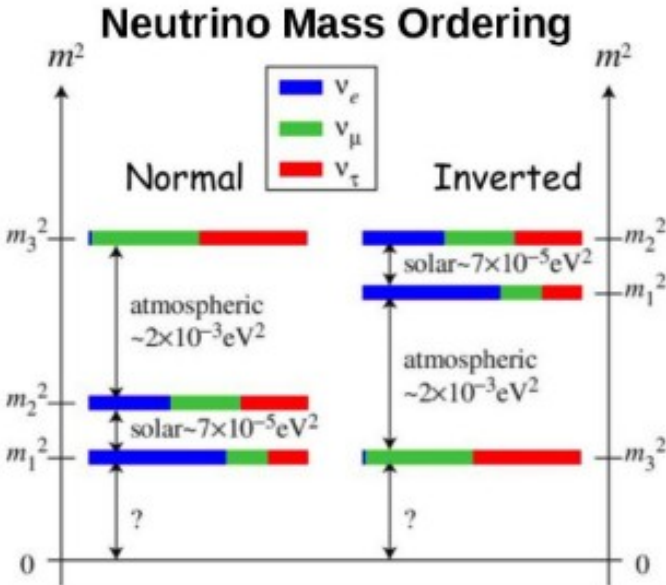
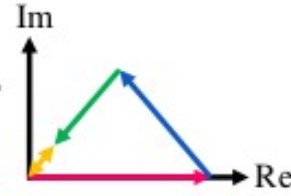
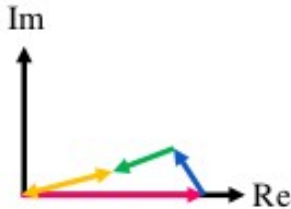
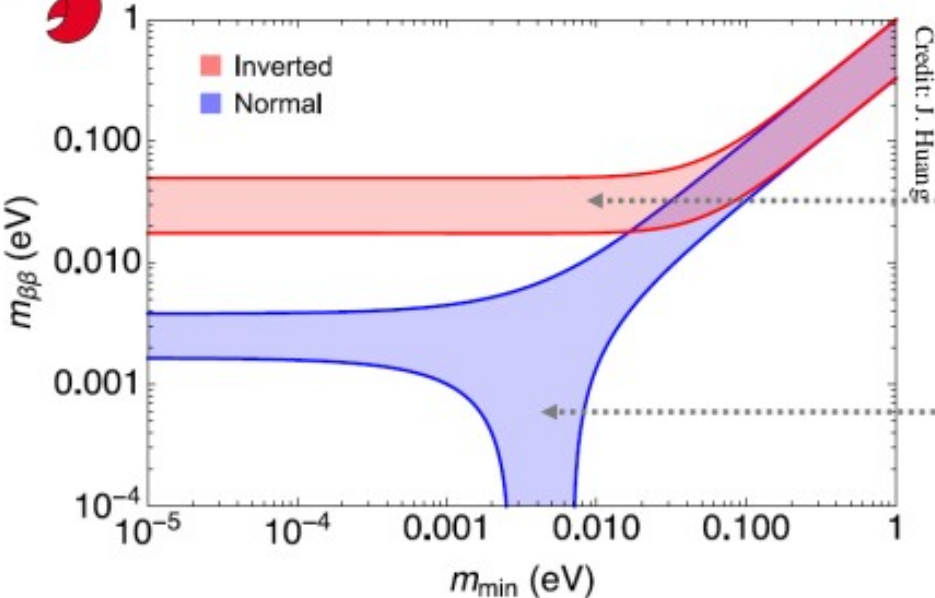
α_1, α_2 : Majorana phases

δ : Dirac phase

Effective Majorana neutrino mass

α_1, α_2 : Majorana phases
 δ : Dirac phase

$$m_{\beta\beta} \equiv \left| \sum_k m_k U_{ek}^2 \right| = \left| \underbrace{m_1}_{\text{yellow}} \underbrace{|U_{e1}|^2}_{\text{pink}} + \underbrace{m_2}_{\text{blue}} \underbrace{|U_{e2}|^2}_{\text{blue}} e^{i(\alpha_2 - \alpha_1)} + \underbrace{m_3}_{\text{green}} \underbrace{|U_{e3}|^2}_{\text{green}} e^{-i(\alpha_1 + 2\delta)} \right|$$



Credit: P. Fernández, *SciPost Phys. Proc.* 1, 029 (2019)