NuDoubt^{++}
Combining Hybrid and Opaque Scintillation Technology in the Search for Positive Double Weak Decays

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(he/him/his)

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NNN 2025

Sudbury

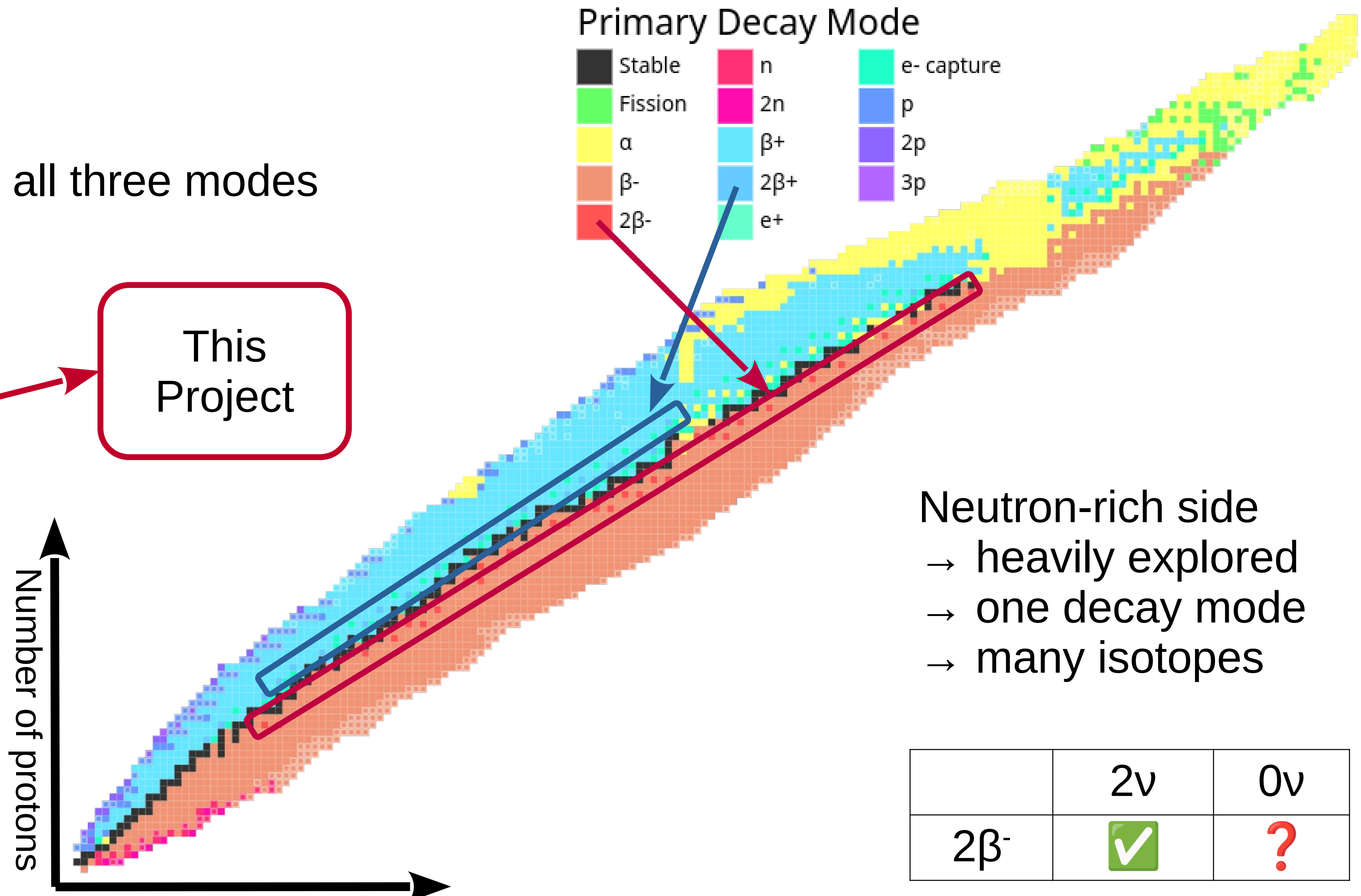
02nd October 2025

Searches for Double Beta Decays

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



Neutron-rich side
→ heavily explored
→ one decay mode
→ many isotopes

	2ν	0ν
$2\beta^-$	✅	❓

How Can We Measure $2\beta^+$ / $EC\beta^+$?

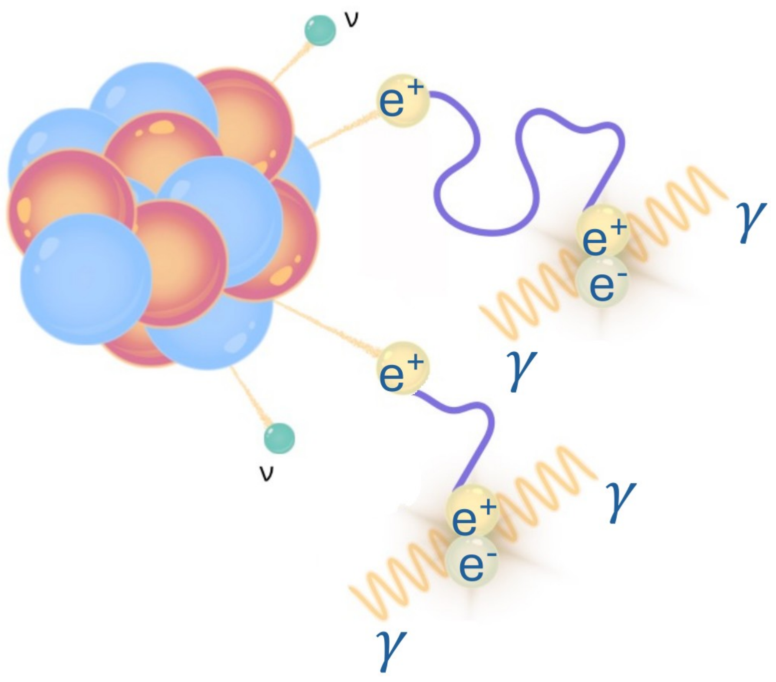
Challenges

→ extremely rare
$T_{1/2} > 10^{22}$ years

→ low natural abundances

Experimental Opportunity

→ unique signature via annihilation gammas



Письма в ЖЭТФ 34 (1981) 148

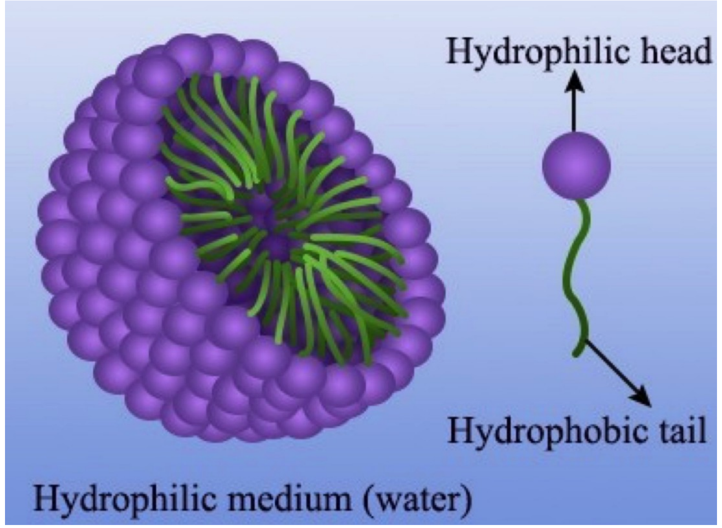
Technology Requirements

→ strong background suppression

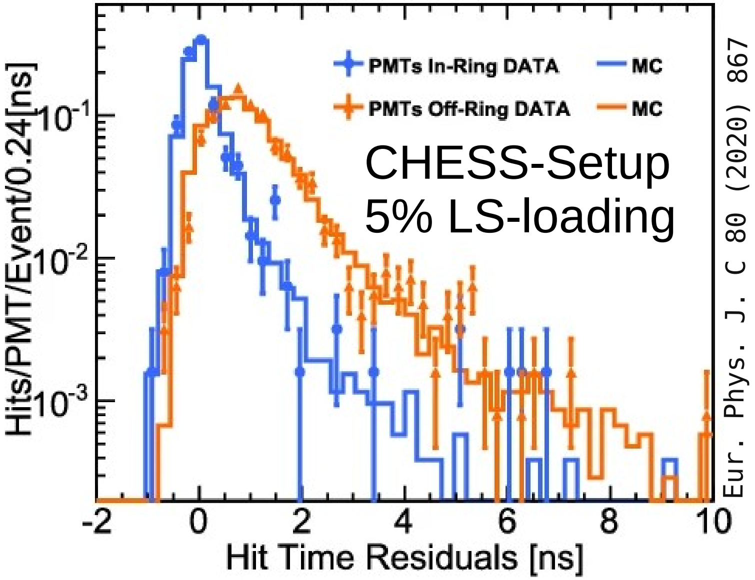
→ high signal rates

→ good energy resolution

Hybrid Scintillator



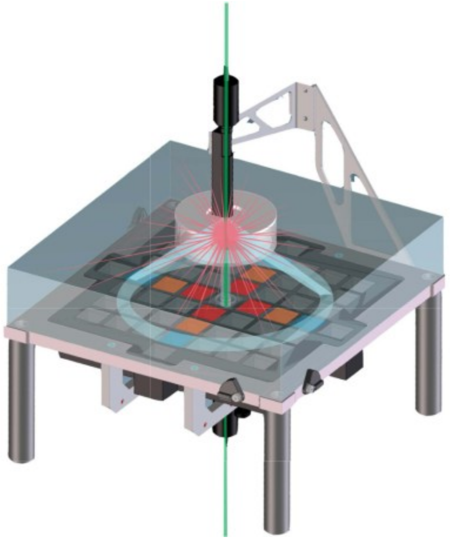
IJAC 13 (2017) 663-672



Eur. Phys. J. C 80 (2020) 867

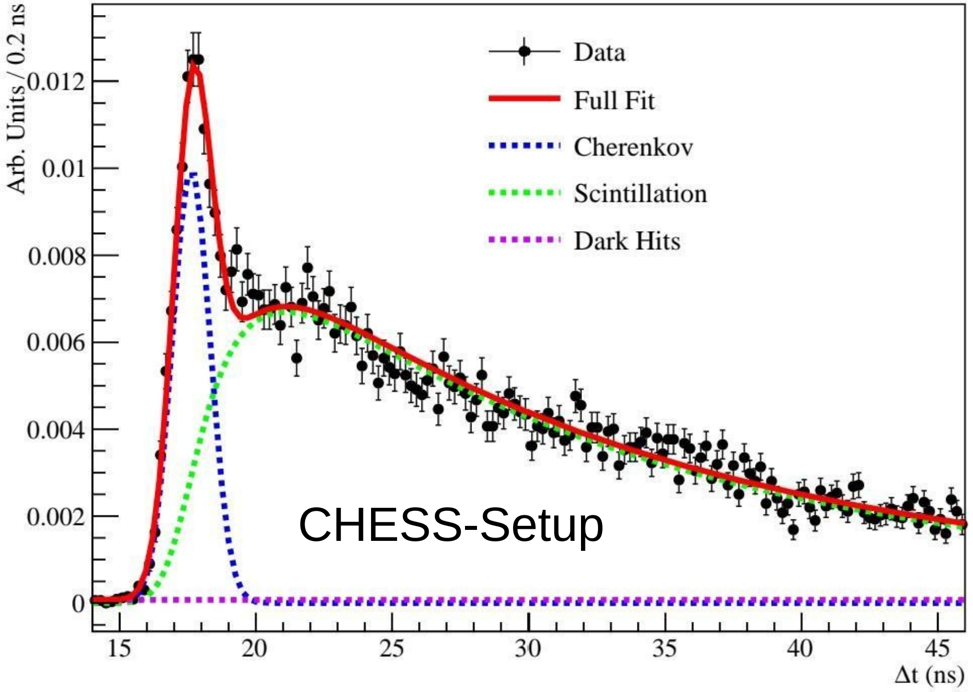
Water-based:
→ organic micelles
suspended in water
with surfactant interface
→ 1 – 10% scintillator loading
→ Theia/Eos collaborations

CHESS
→ spatial separation of Cherenkov and scintillation light



Phys. Rev. C 95 (2017) 055801

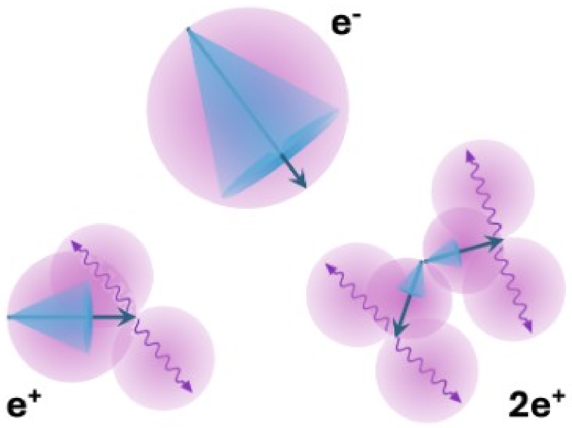
Slow:
→ slow fluorophores / slow solvents
→ intrinsically slow scintillation pulse form
→ τ = >10 ns
→ high light yield scintillators
→ >10000 photons/MeV

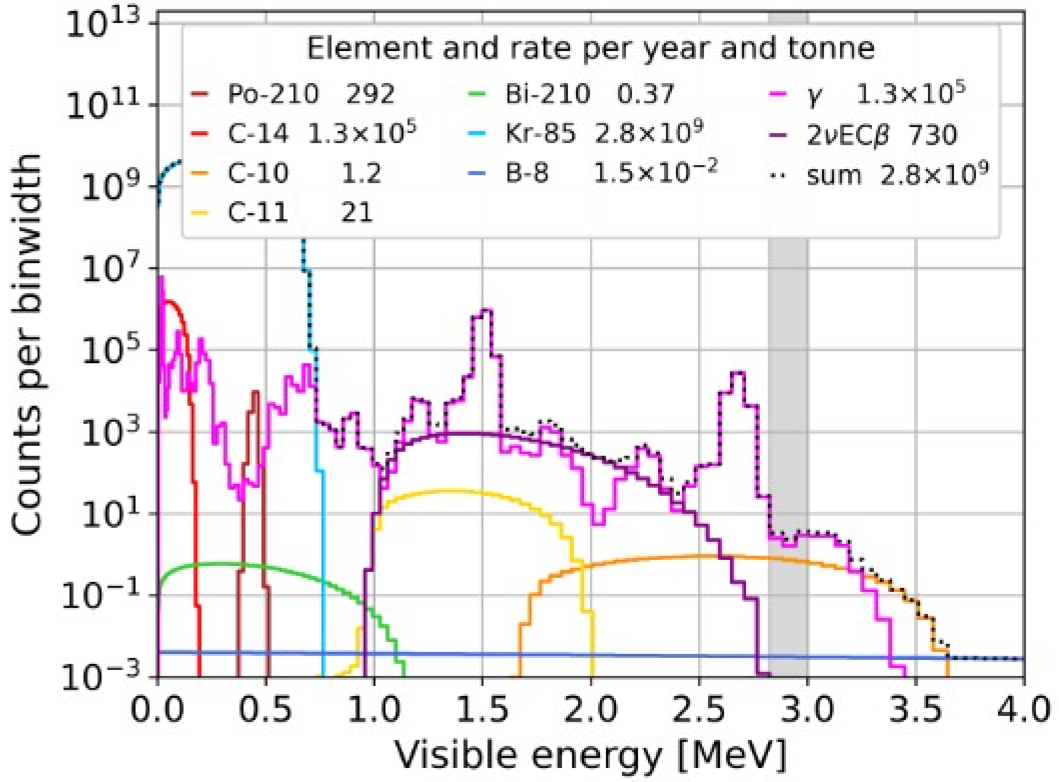


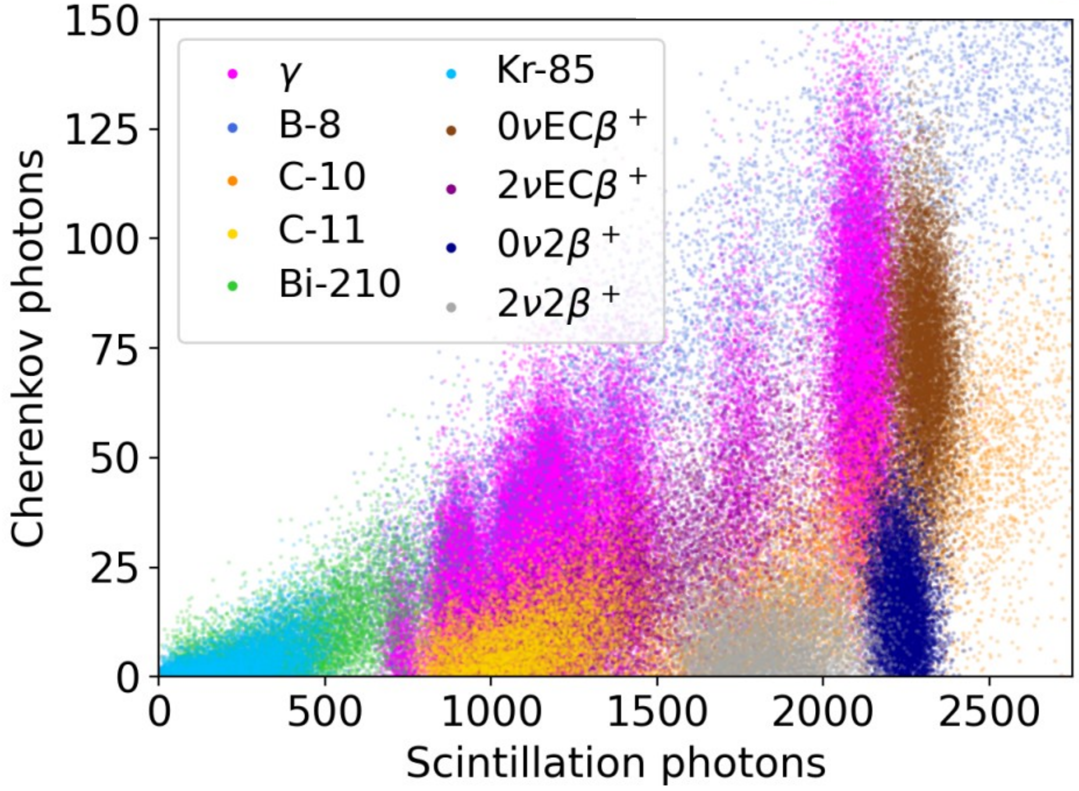
JINST 19 (2024) P09015

Particle ID through C/S Separation

discrimination via ratio of: $\frac{\text{prompt Cherenkov light}}{\text{delayed scintillation light}}$







Opaque Scintillator

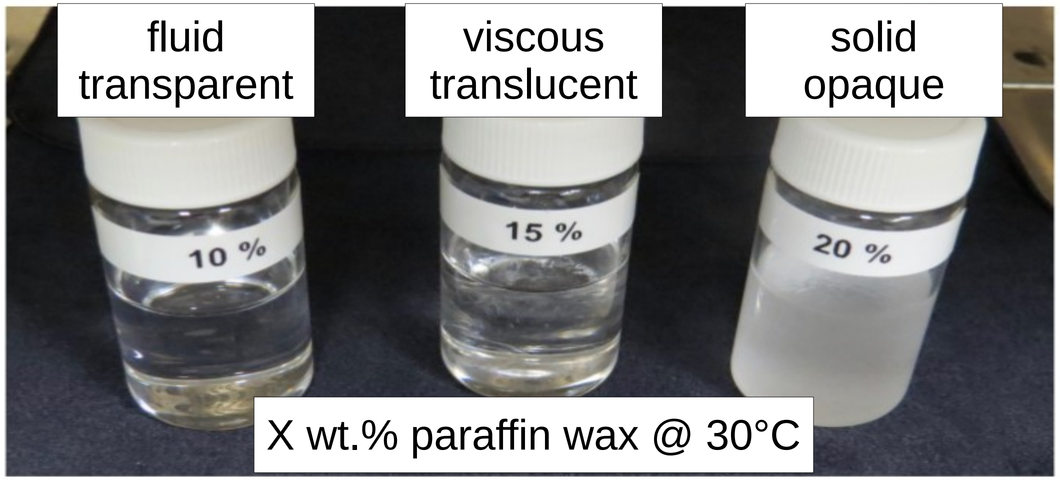
NoWaSH: wax-based opaque scintillator

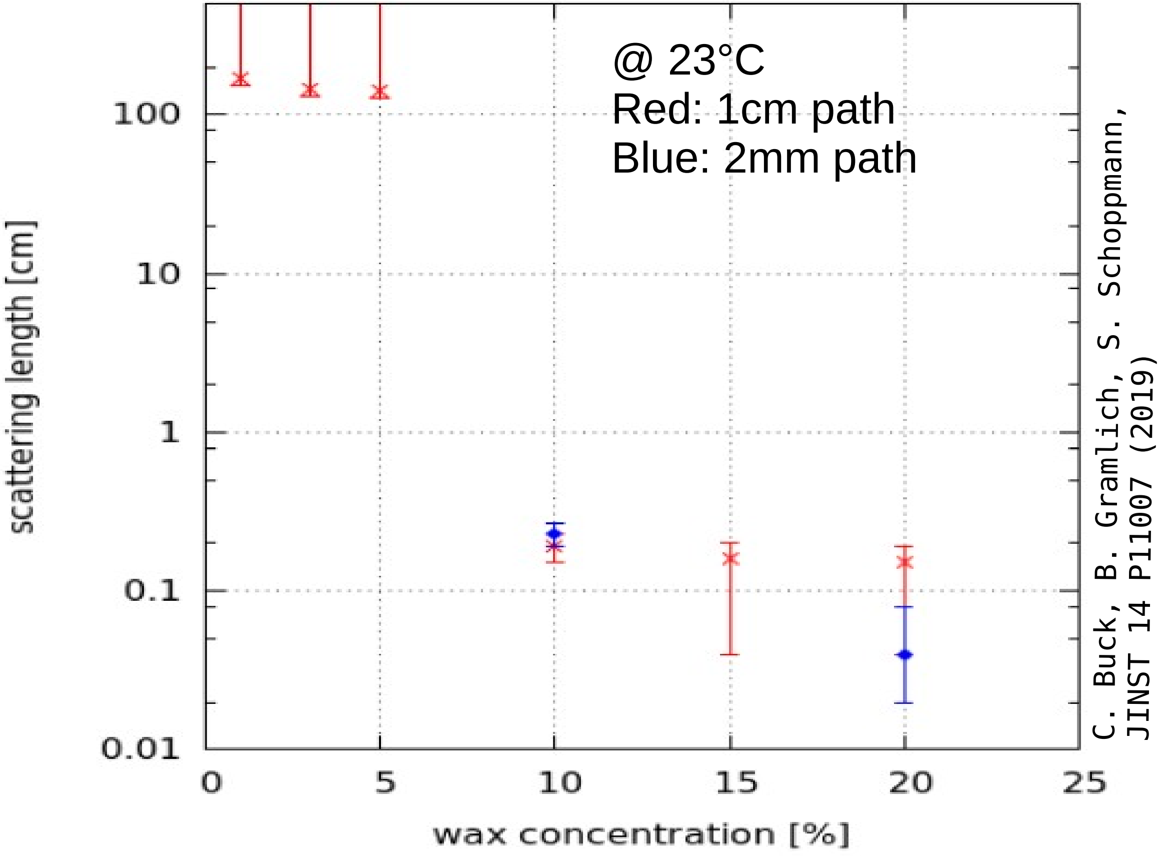
→ transparent solvent + O(1-10 wt.%) wax + fluorophore(s)
JINST 14 (2019) P11007, Patent applications EP 25 195 873.2 & EP 25 195 874.0

→ 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

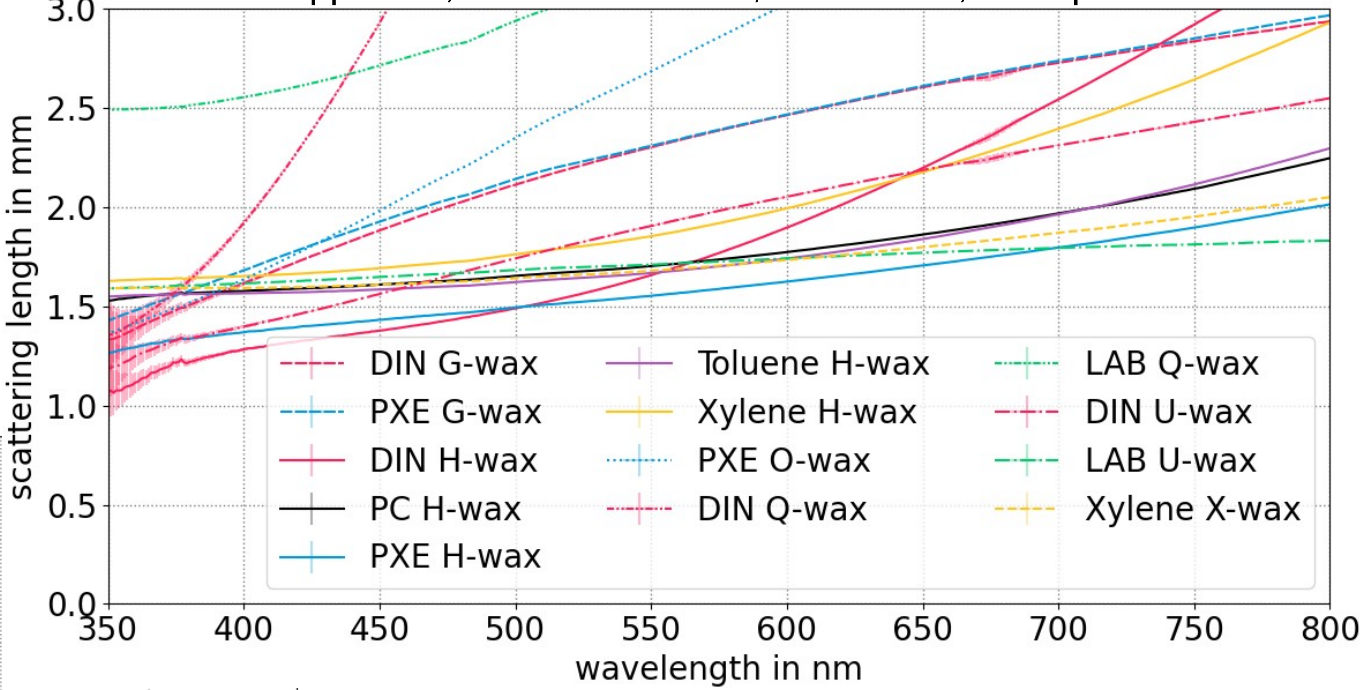


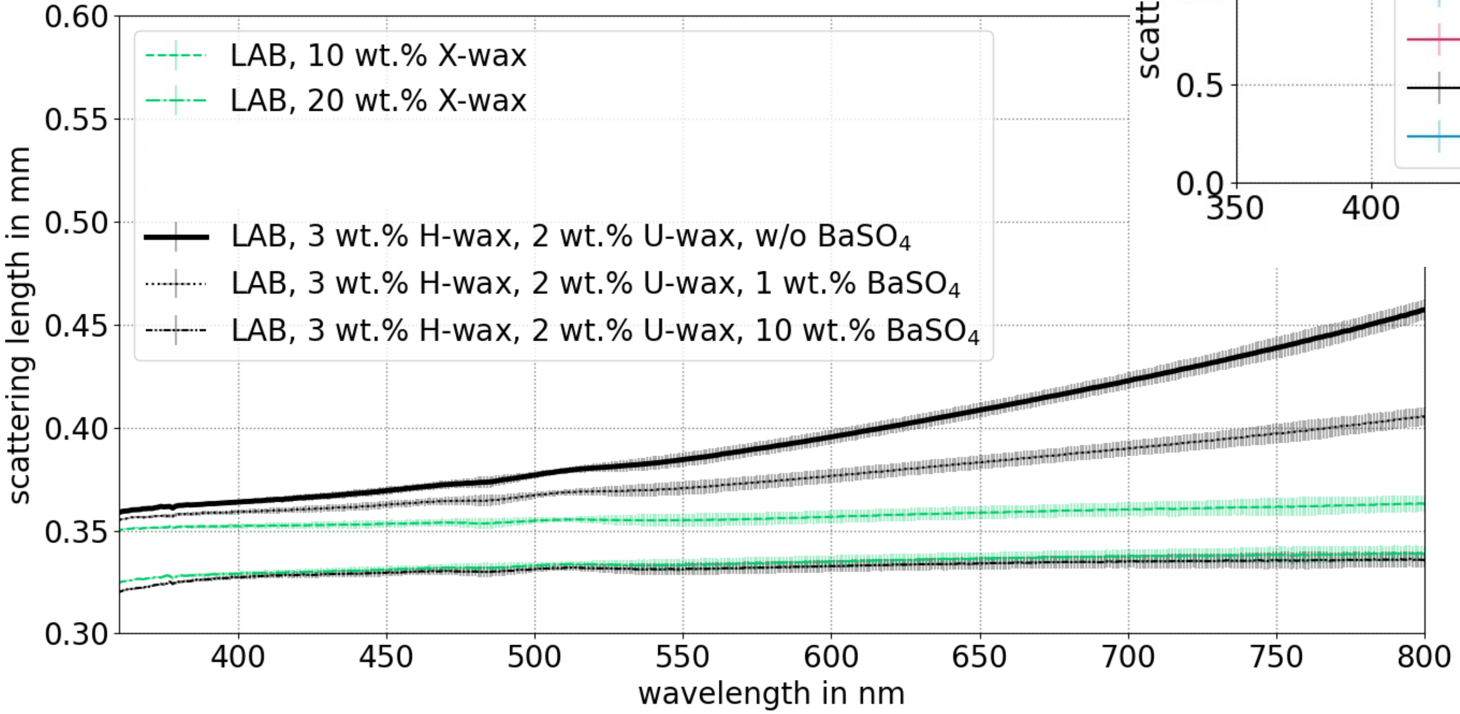


Opaque Scintillators

Scattering length can be adjusted
→ between 300 µm and 3 mm
→ by wax type
→ by blending technique

S. Schoppmann, habilitation thesis, JGU Mainz, to be published 2026

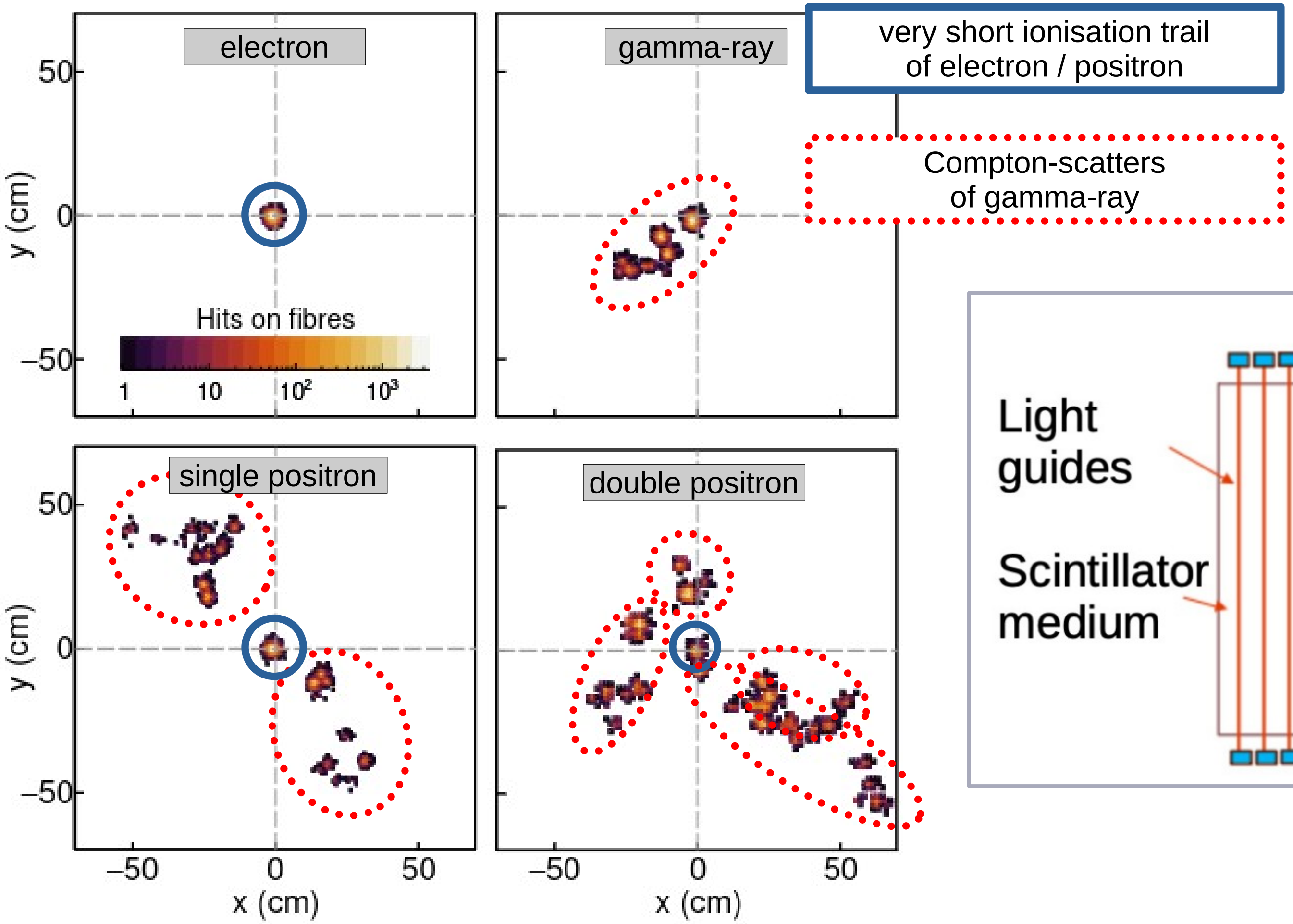




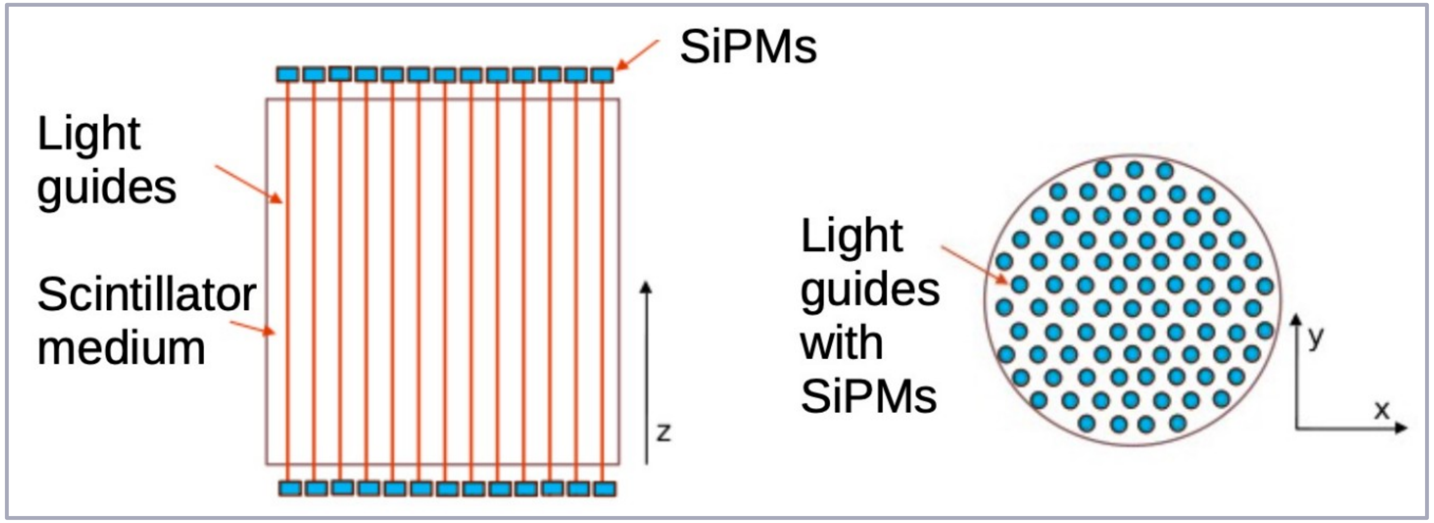
G / O	Polyethylene waxes
H / X	N-N’ Ethylene-bis-steramid waxes
Q	Paraffin wax
U	Fischer-Tropsch wax

Particle ID through Morphology

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

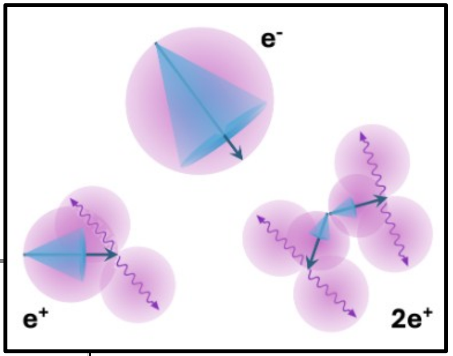


opaque scintillator technology currently explored e.g. by LiquidO / AntiMatter-OTech / CLOUD / L-PET



Combining Hybrid and Opaque

Combination allows insights into morphology of scintillation and Cherenkov light



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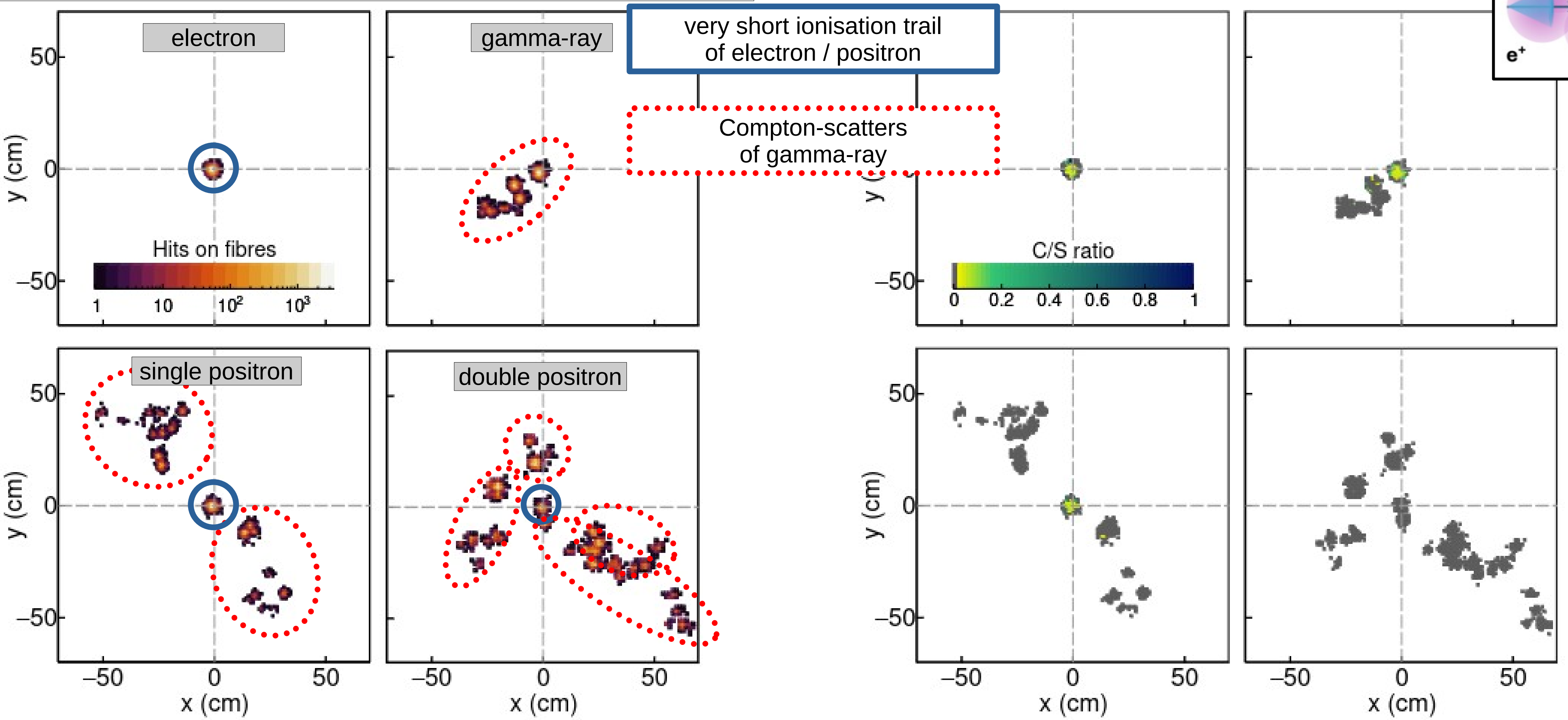
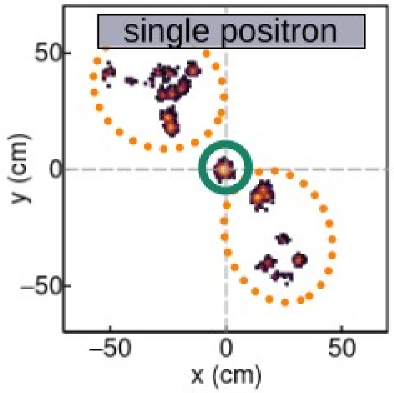
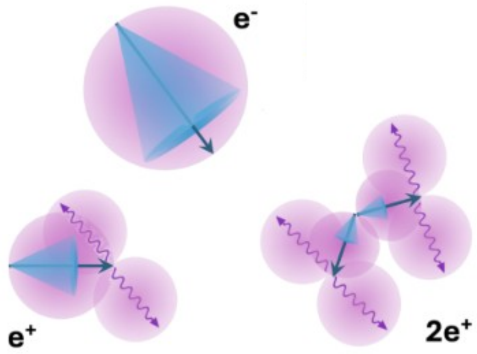
Eur. Phys. J. C 85 (2025) 121



Technology Requirements

✅ strong background suppression





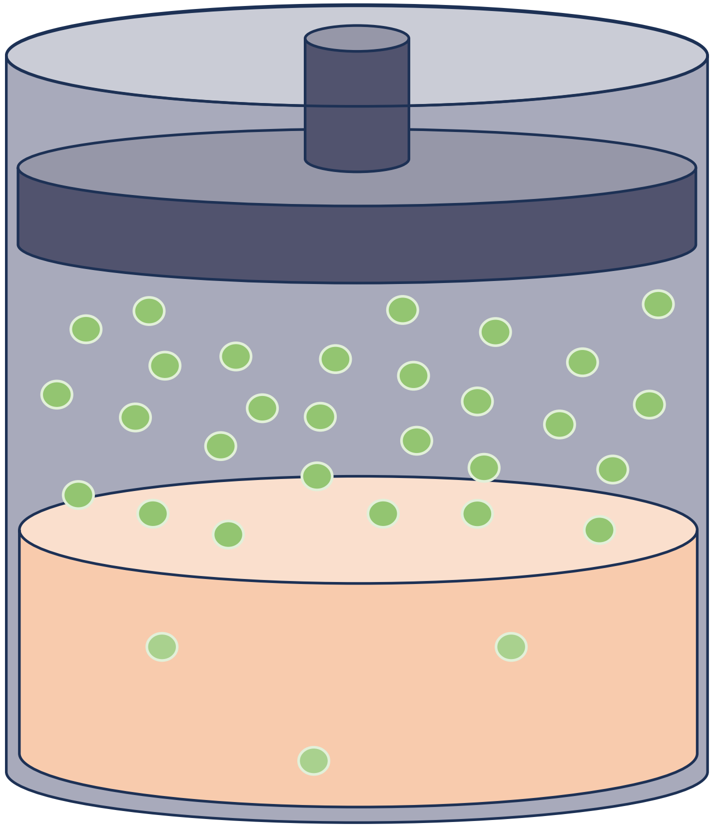
Patents Pending
EP 25 195 873.2 & EP 25 195 874.0

high signal rate

good energy resolution

Isotope Loading

Krypton-78
→ high $\Delta M = 2.8$ MeV
  → above most backgrounds
→ nobel gas
  → high enrichment
  → pressure loading



final concentration of krypton: 17g/l

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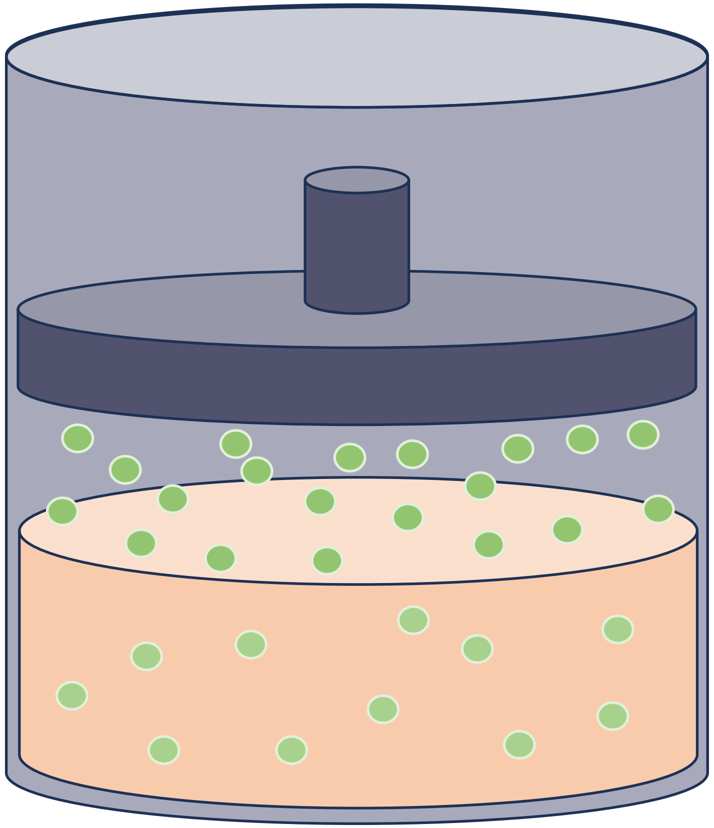

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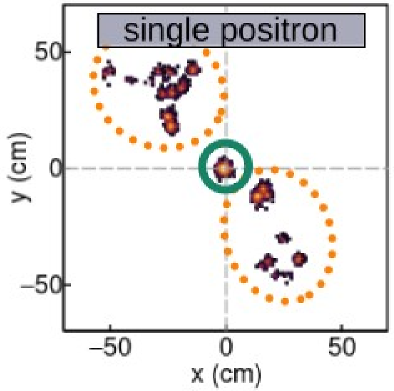

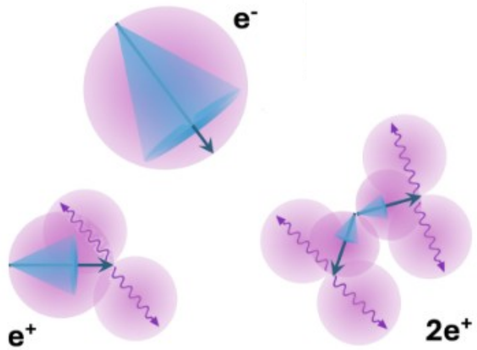

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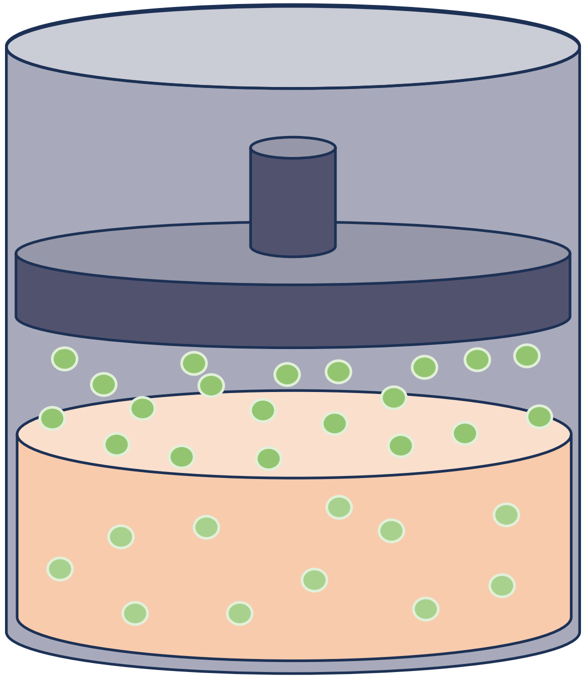


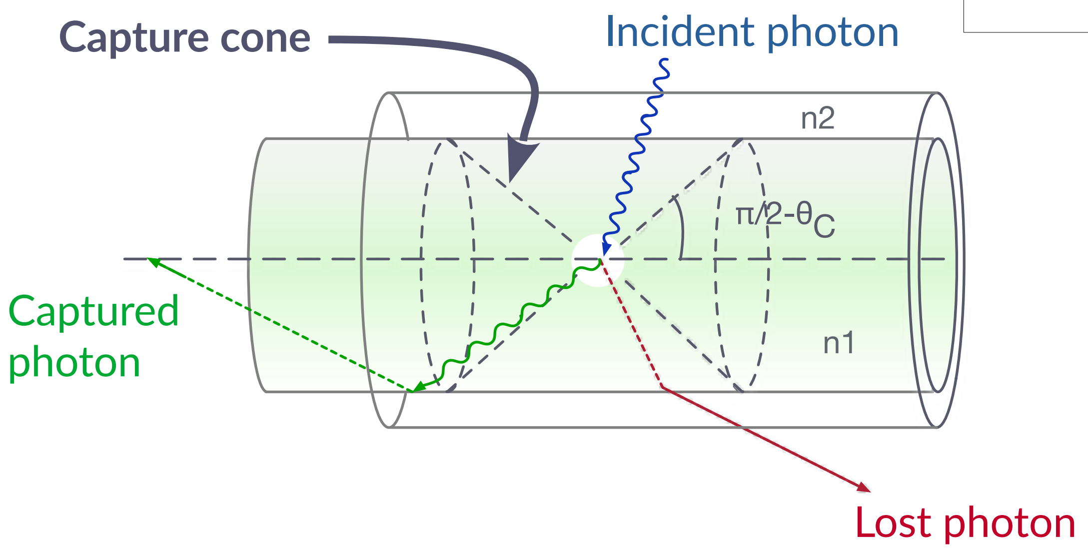
good energy resolution

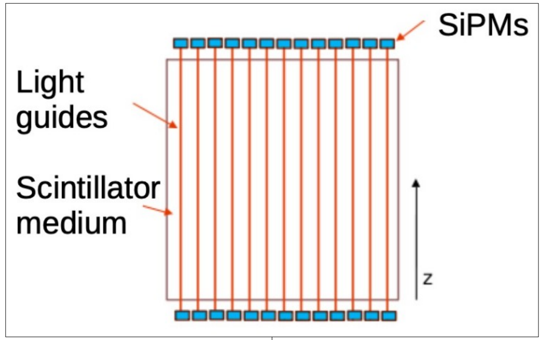
Optimised Light Collection

Traditional Fibre

near centre emission

ε_{TIR} = 8%

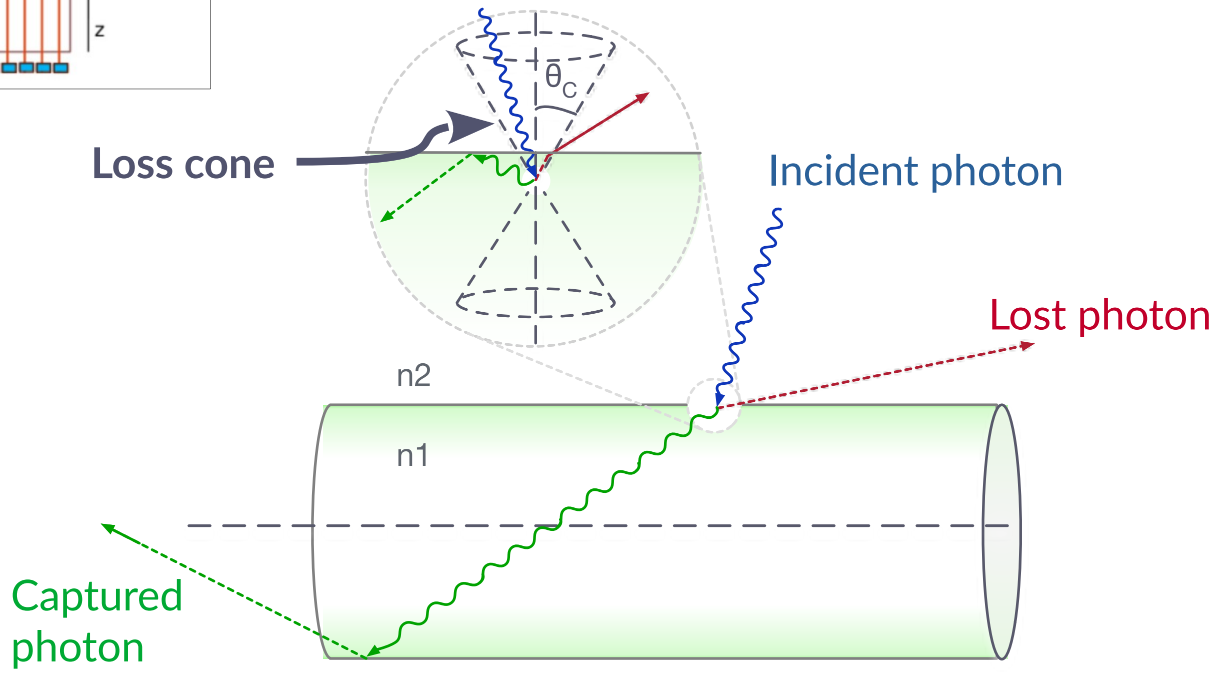




Coated Fibre

near surface emission

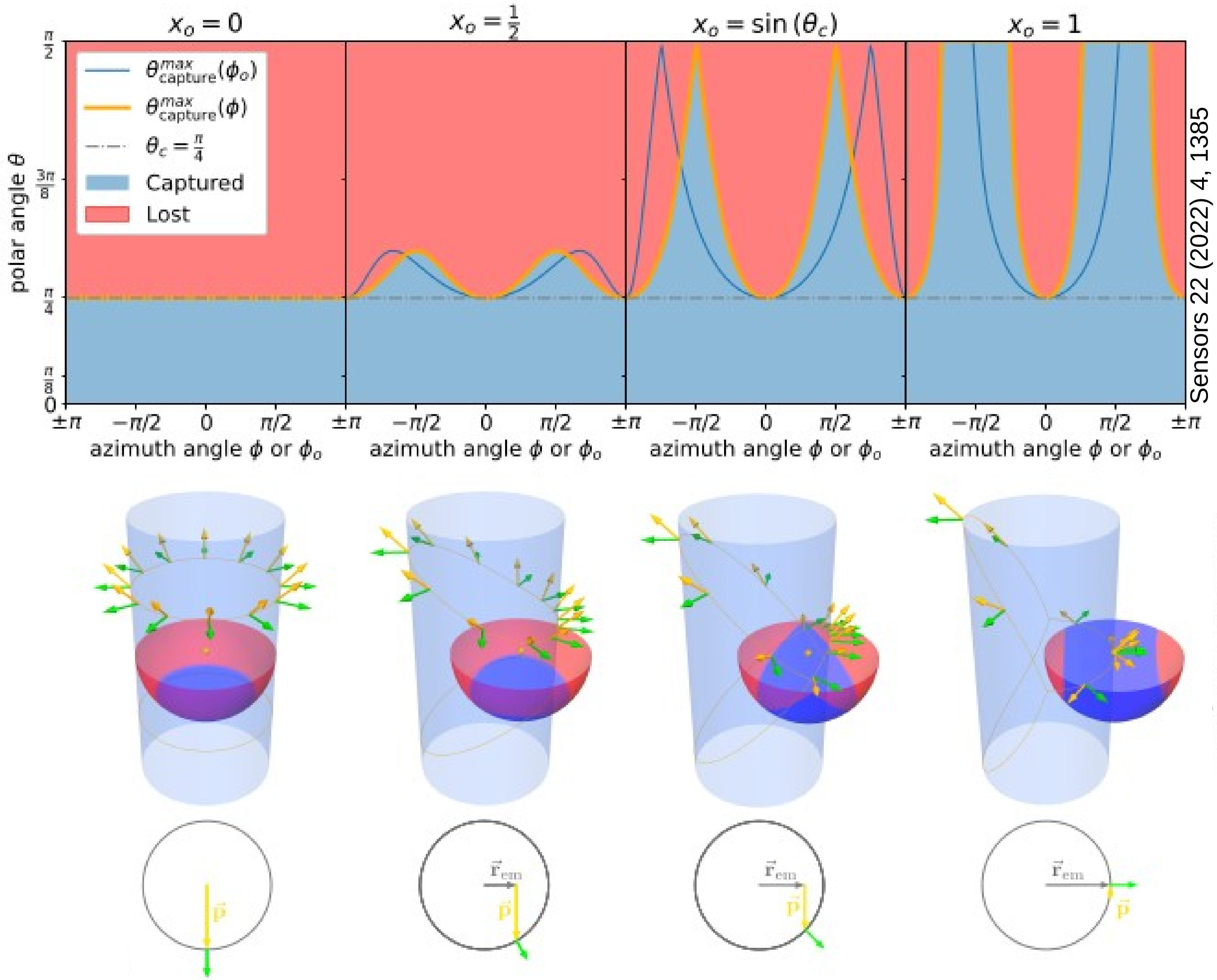
ε_{TIR} =38%



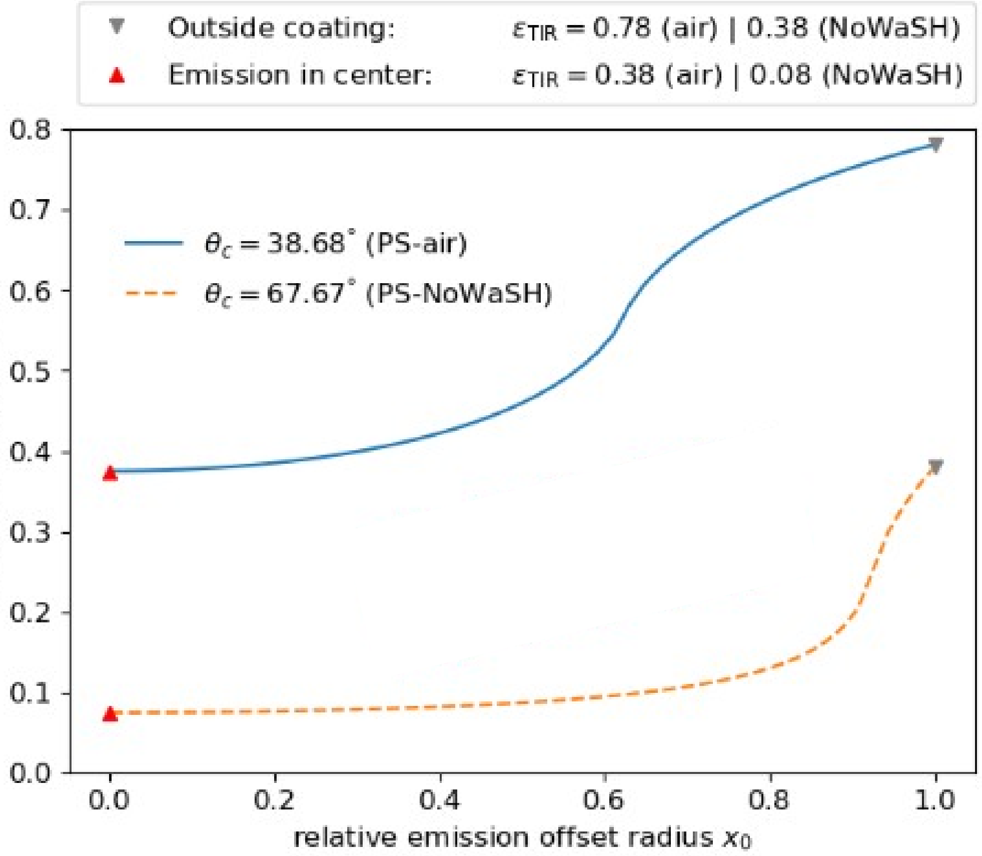
~800 PE/MeV

energy resolution of 2% in region of interest

Moving the Emission Point



Sensors 22 (2022) 4, 1385



Technology Requirements

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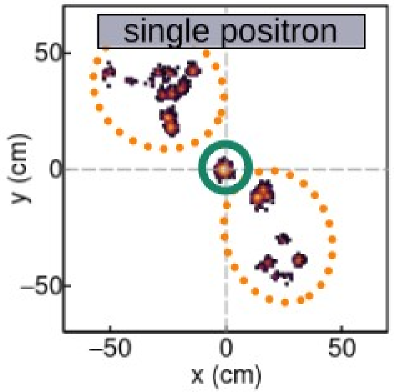

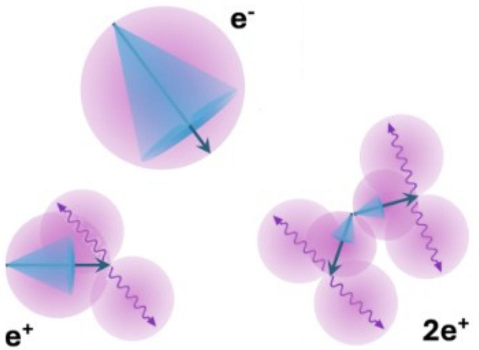

Patents Pending
EP 25 195 873.2 & EP 25 195 874.0

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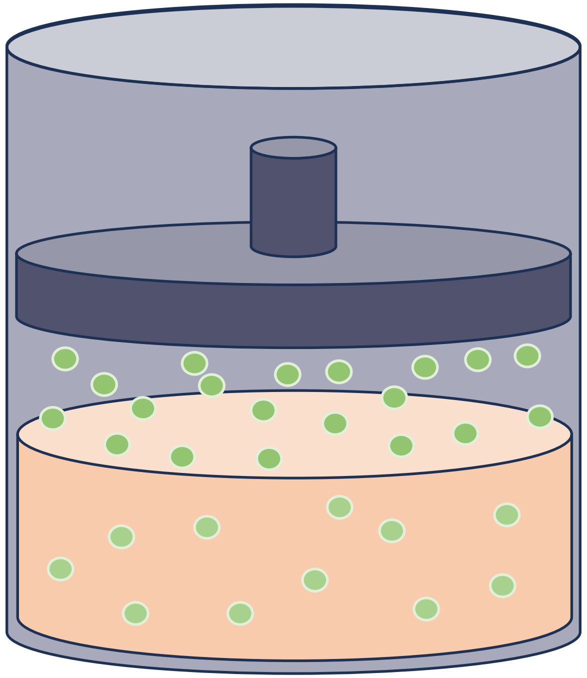

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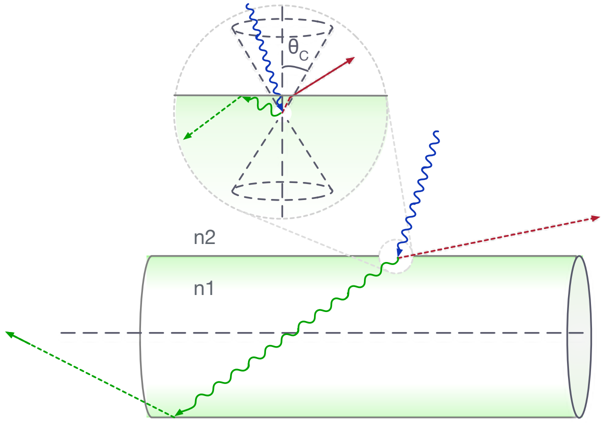
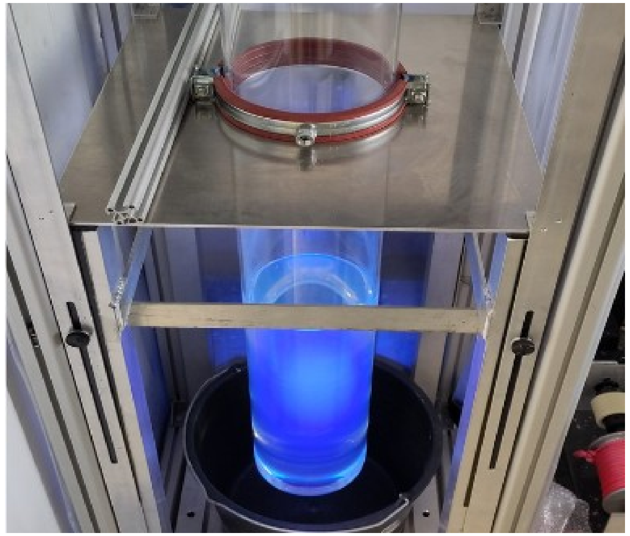
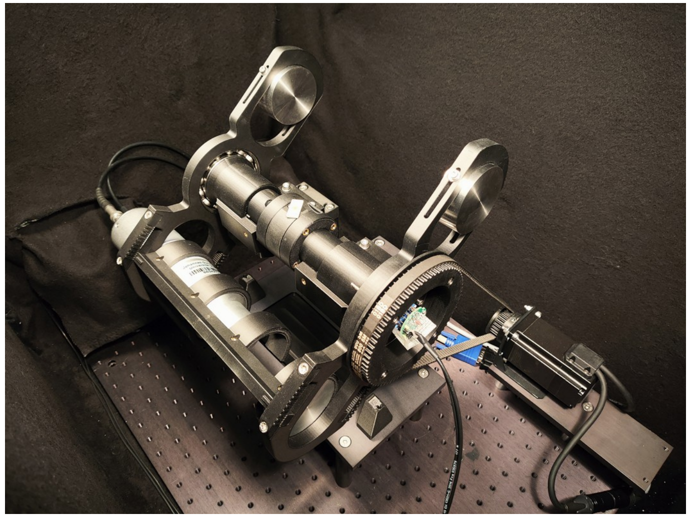


Patent
DE 10 2023 135 496.5

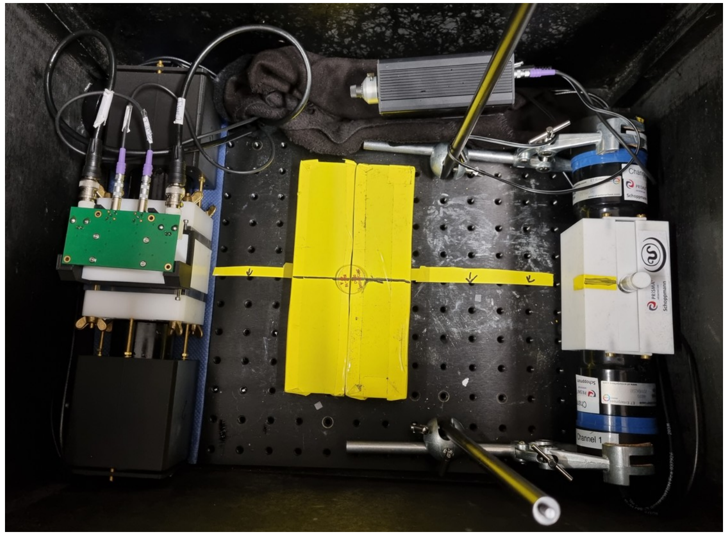
Prototype Verification



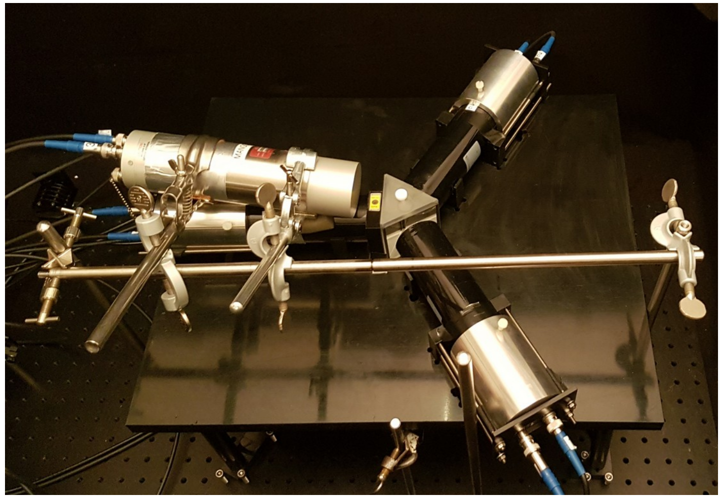
Fibre Coating Station



Scintillator Light Yield



Scintillator-Fibre Coupling

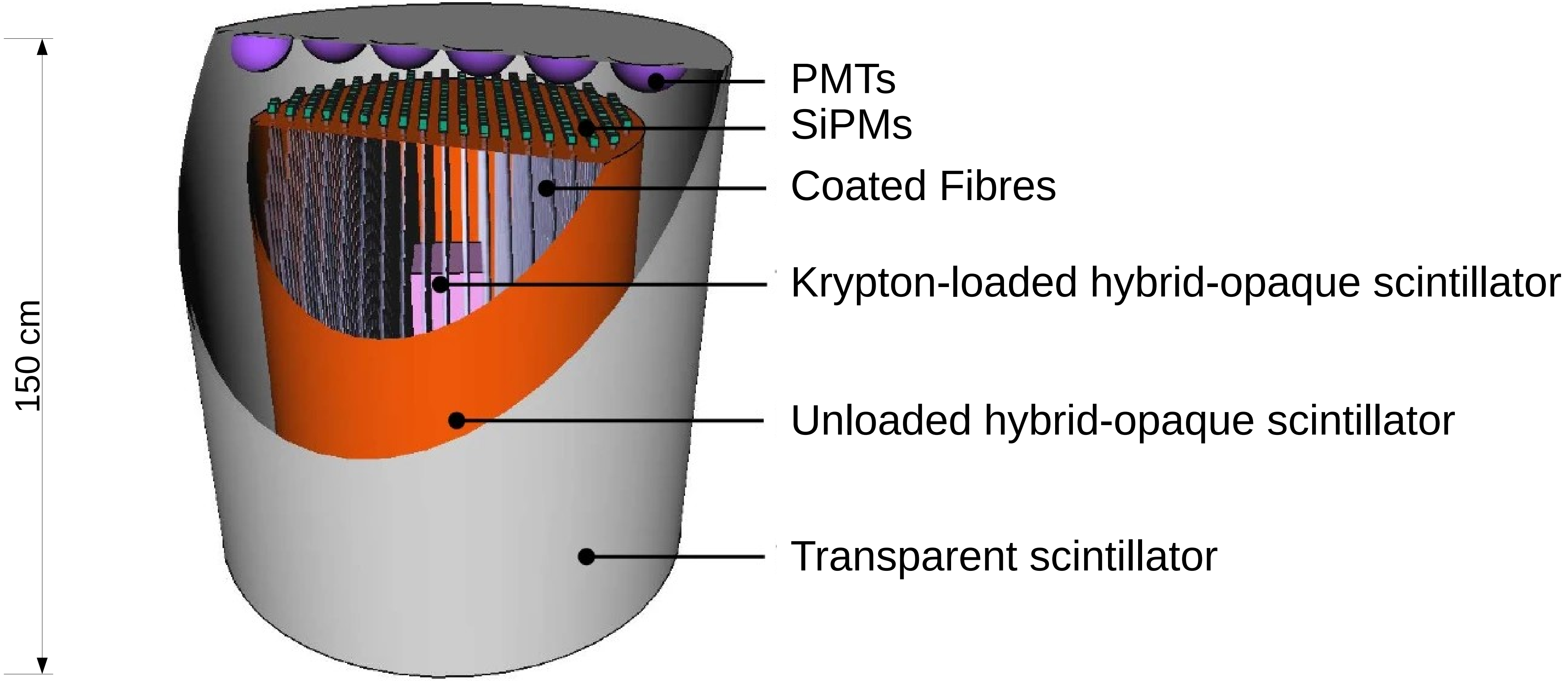


Cherenkov-scintillation separation

Pressure Loading

Krypton Purity

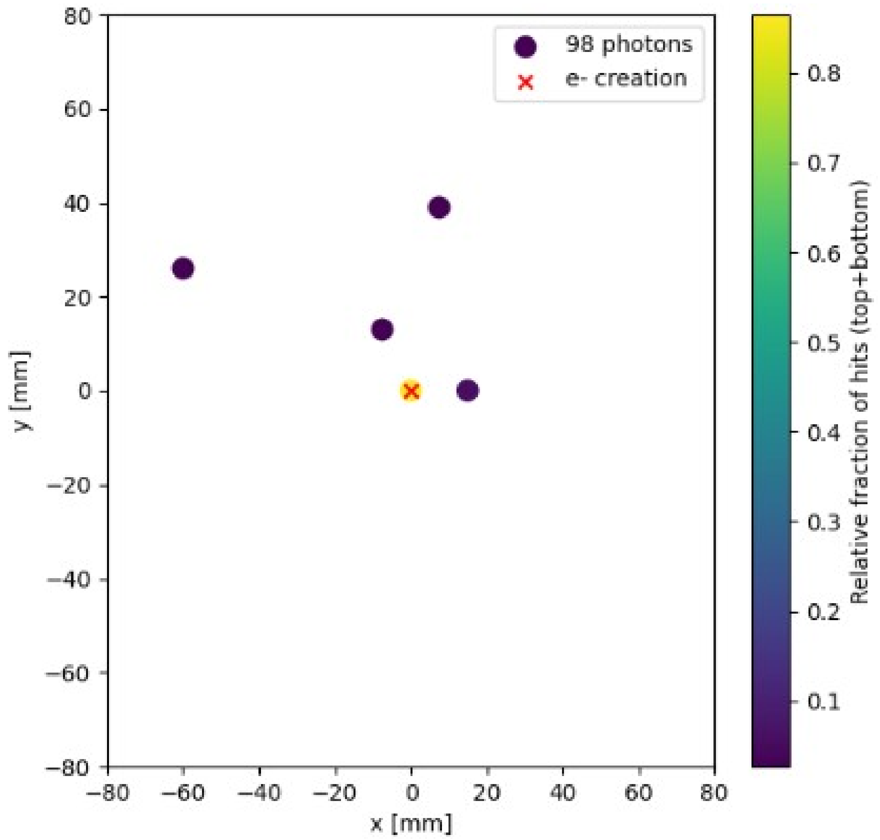
The NuDoubt^{++} Detector Concept



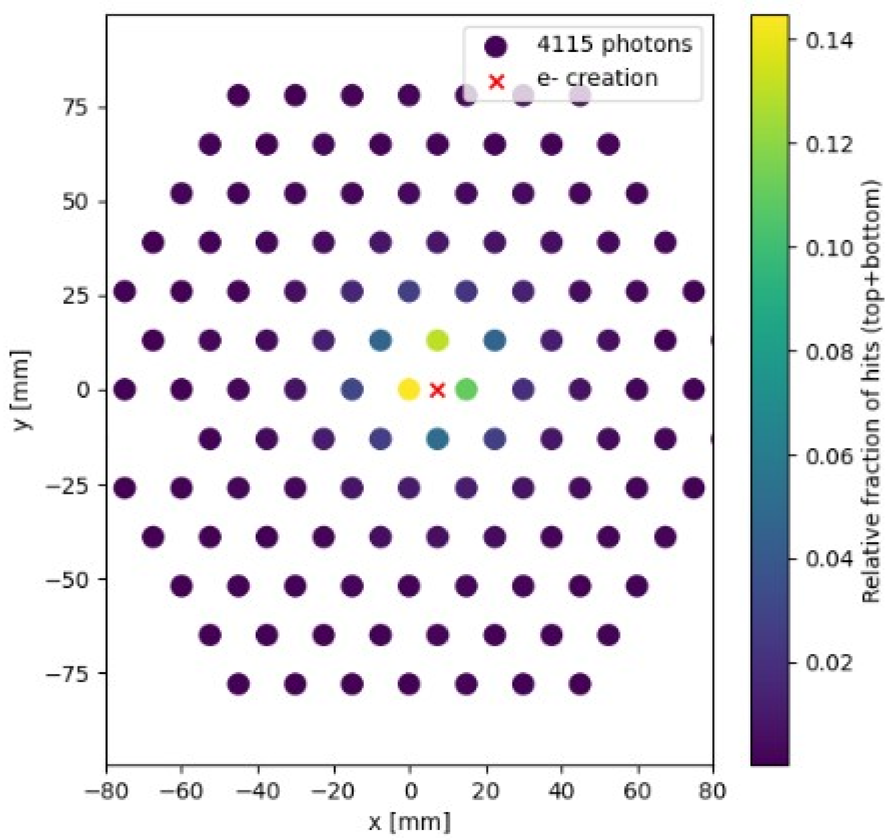
Fibre Background Rejection

Simulation of a background decay inside:

Fibre



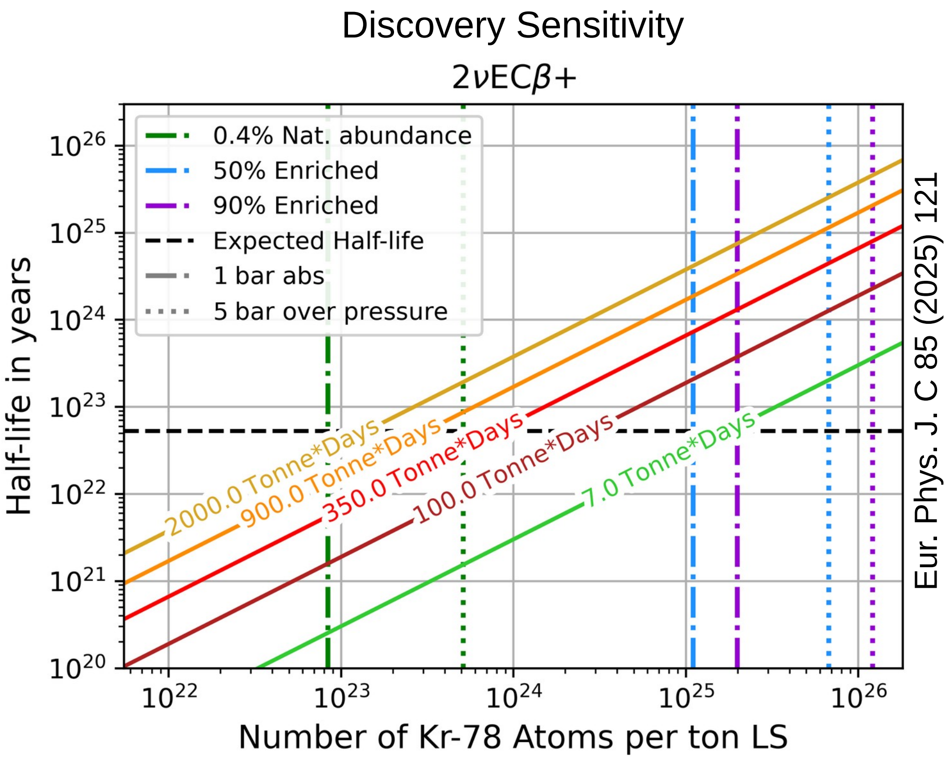
Scintillator



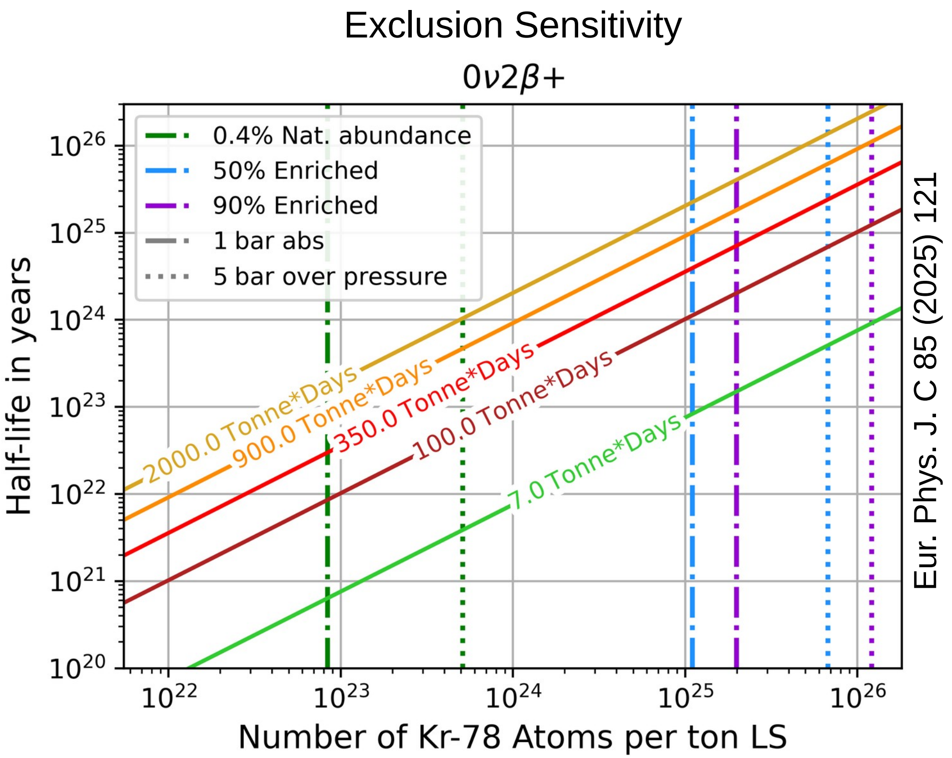
Expected Sensitivity

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

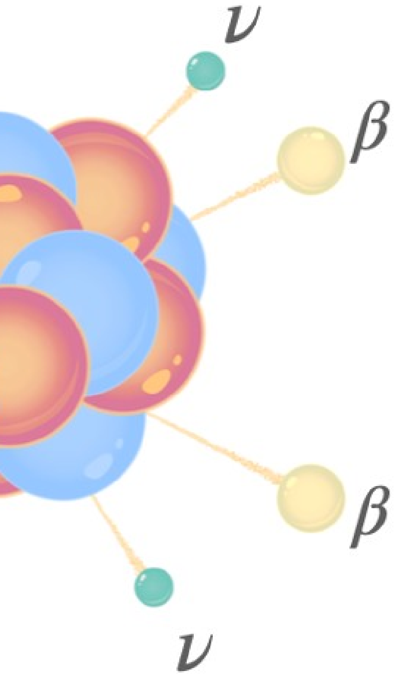
Two-neutrino decay
5σ measurement



Neutrinoless decay
1000-fold improved limit



Conclusion



- → 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
  - → first measurement of standard model mode
  - → 10^3-fold improved limits on neutrinoless mode
- → more details: Eur. Phys. J. C 85 (2025) 121

The Collaboration

NuDoubt++

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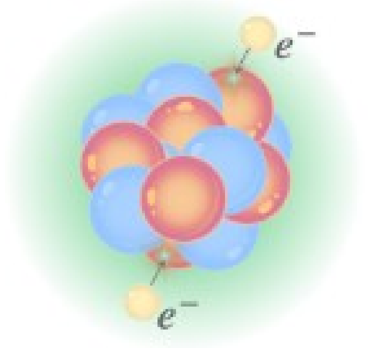
Webpage:
https://nudoubt.uni-mainz.de

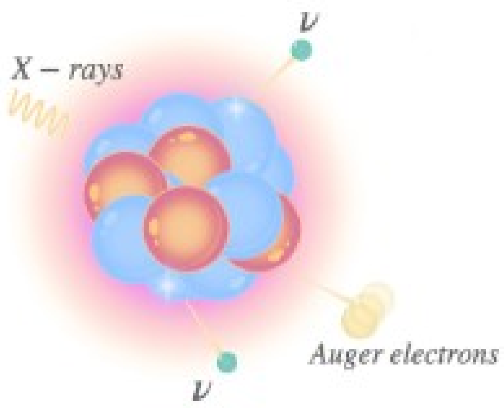
Appendix

$2\beta^+$ / $EC\beta^+$ versus 2EC

Positron emission requires more binding energy to be released

$$K_{\beta^+\beta^+} = M(A,Z) - M(A,Z-2) - 4m_e,$$
$$K_{\beta^+EC} = M(A,Z) - M(A,Z-2) - 2m_e - \epsilon_b$$
$$K_{2EC} = M(A,Z) - M(A,Z-2) - \epsilon_{b_1} - \epsilon_{b_2}$$
$$\epsilon_b \ll m_e$$





Decay modes	Transition	ΔM (keV)	Natural Abundance (%)
$2\beta^+$, $EC\beta^+$, 2EC	$^{124}Xe \to ^{124}Te$	2863.9	0.095
	$^{78}Kr \to ^{78}Se$	2847.67	0.355
	$^{106}Cd \to ^{106}Pd$	2775.39	1.245
	$^{96}Ru \to ^{96}Mo$	2714.5	5.54
	$^{130}Ba \to ^{130}Xe$	2618.9	0.11
	$^{136}Ce \to ^{136}Ba$	2378.55	0.186
$EC\beta^+$, 2EC	$^{58}Ni \to ^{58}Fe$	1926.4	68.07
	$^{112}Sn \to ^{112}Cd$	1919.8	0.97
	$^{84}Sr \to ^{84}Kr$	1789.8	0.355
	$^{144}Sm \to ^{144}Nd$	1782.4	3.08
	$^{120}Te \to ^{120}Sn$	1730	0.09
	$^{92}Mo \to ^{92}Zr$	1650.45	14.64
	$^{74}Se \to ^{74}Ge$	1209.24	0.86
	$^{102}Pd \to ^{102}Ru$	1203.3	1.02
	$^{50}Cr \to ^{50}Ti$	1169.6	4.34
	$^{64}Zn \to ^{64}Ni$	1094.9	49.17
2EC	$^{126}Xe \to ^{126}Te$	918	0.089
	$^{132}Ba \to ^{132}Xe$	843.9	0.1
	$^{138}Ce \to ^{138}Ba$	691	0.25
	$^{54}Fe \to ^{54}Cr$	680.3	5.84
	$^{108}Cd \to ^{108}Pd$	271.8	0.88
	$^{40}Ca \to ^{40}Ar$	193.51	96.94

Overview of All Six Double Beta Plus Isotopes

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

V. Palušová, MEDEX'25

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

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

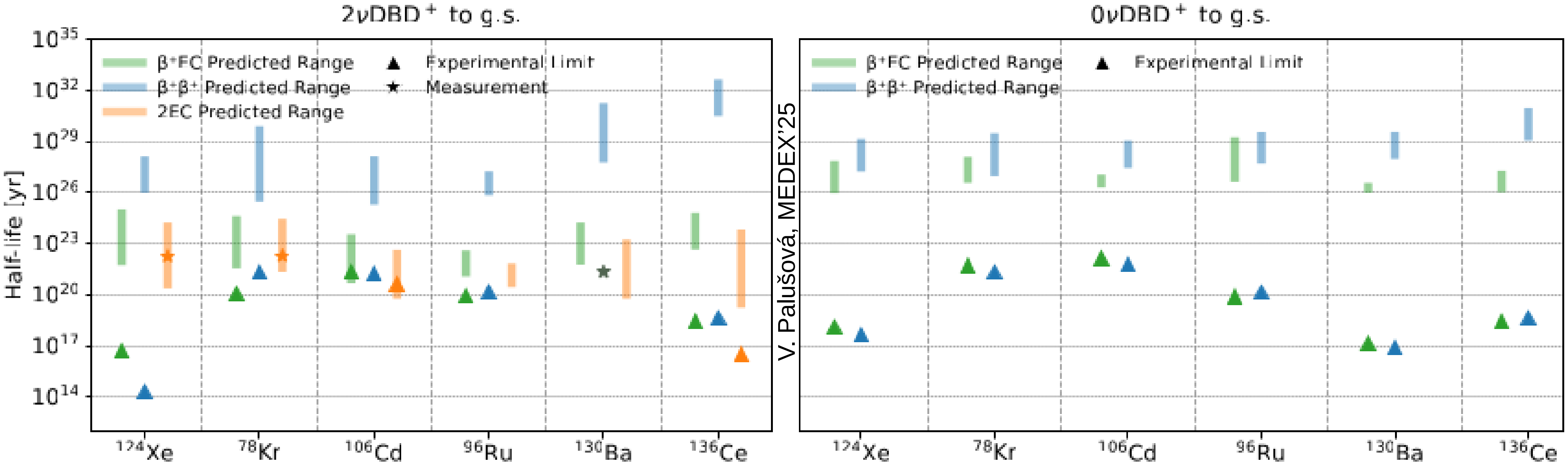
$$K_{\beta^+EC} = M(A,Z) - M(A,Z-2) - 2m_e - \epsilon_b$$

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

with $\epsilon_b \ll m_e$

Transition	ΔM (keV)	Natural Abundance (%)
$^{124}Xe \rightarrow {}^{124}Te$	2863.9	0.095
$^{78}Kr \rightarrow {}^{78}Se$	2847.67	0.355
$^{106}Cd \rightarrow {}^{106}Pd$	2775.39	1.245
$^{96}Ru \rightarrow {}^{96}Mo$	2714.5	5.54
$^{130}Ba \rightarrow {}^{130}Xe$	2618.9	0.11
$^{136}Ce \rightarrow {}^{136}Ba$	2378.55	0.186
$^{58}Ni \rightarrow {}^{58}Fe$	1926.4	68.07
$^{112}Sn \rightarrow {}^{112}Cd$	1919.8	0.97
$^{84}Sr \rightarrow {}^{84}Kr$	1789.8	0.355
$^{144}Sm \rightarrow {}^{144}Nd$	1782.4	3.08
$^{120}Te \rightarrow {}^{120}Sn$	1730	0.09
$^{92}Mo \rightarrow {}^{92}Zr$	1650.45	14.64
$^{74}Se \rightarrow {}^{74}Ge$	1209.24	0.86
$^{102}Pd \rightarrow {}^{102}Ru$	1203.3	1.02
$^{50}Cr \rightarrow {}^{50}Ti$	1169.6	4.34
$^{64}Zn \rightarrow {}^{64}Ni$	1094.9	49.17
$^{126}Xe \rightarrow {}^{126}Te$	918	0.089
$^{132}Ba \rightarrow {}^{132}Xe$	843.9	0.1
$^{138}Ce \rightarrow {}^{138}Ba$	691	0.25
$^{54}Fe \rightarrow {}^{54}Cr$	680.3	5.84
$^{108}Cd \rightarrow {}^{108}Pd$	271.8	0.88
$^{40}Ca \rightarrow {}^{40}Ar$	193.51	96.94

Choice of Isotope



Remark:

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

→ Three 2β⁺ isotopes have E_{max}-values above Tl-208 background

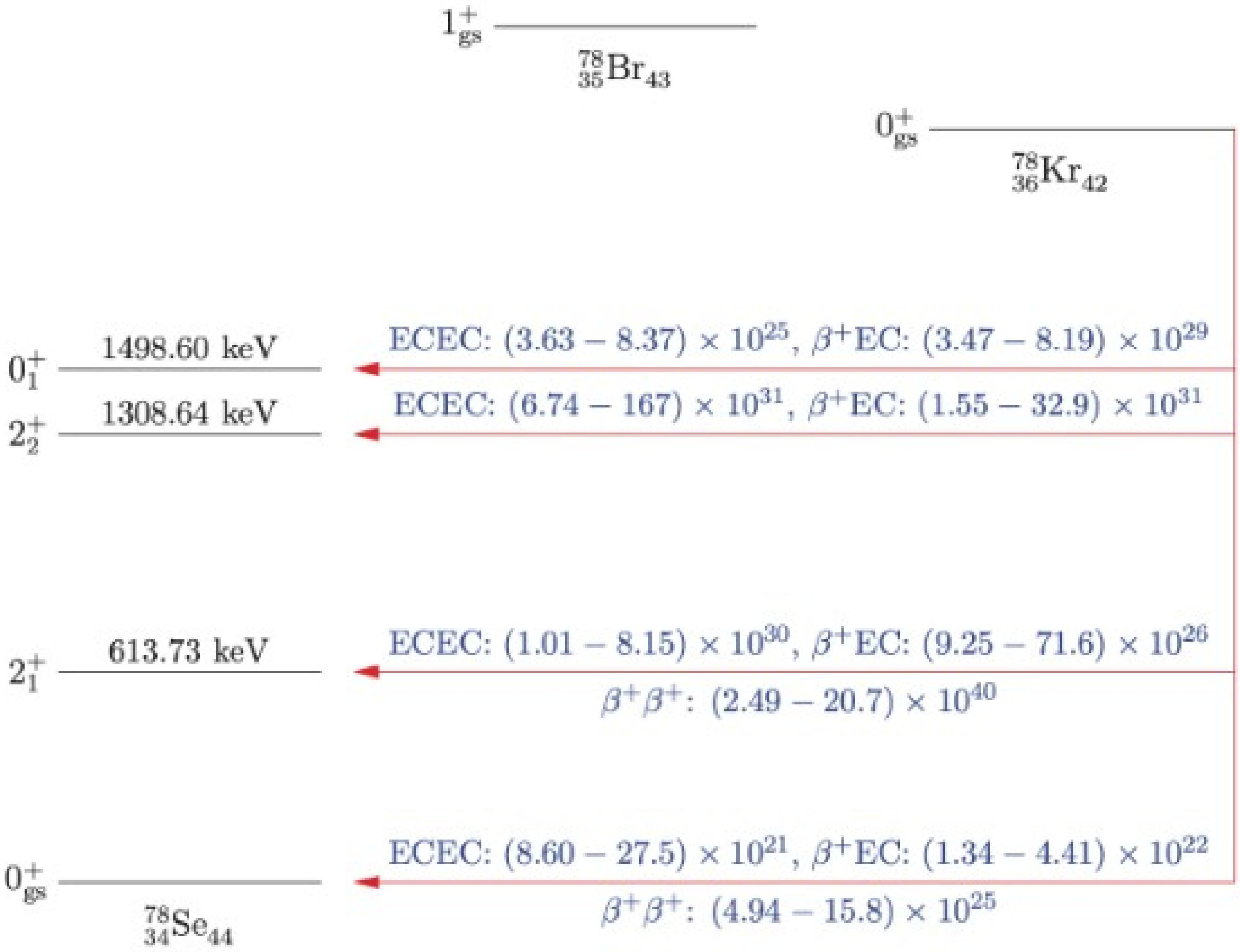
$$E_{\rm max} :\approx Q_{2\beta^+} + 4m_e \approx Q_{{\rm EC}\beta^+} + 2m_e \approx \Delta M$$

	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	%
β+	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	$> 10^{14}$	$> 10^{17}$	$1.1\ 10^{22}$	$> 10^{18}$	$> 10^{18}$		90	2.857	0.1
β-	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

Decays to Excited States

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



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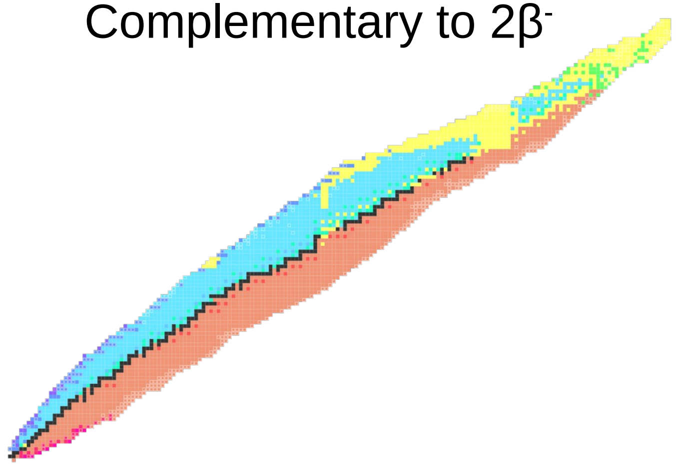
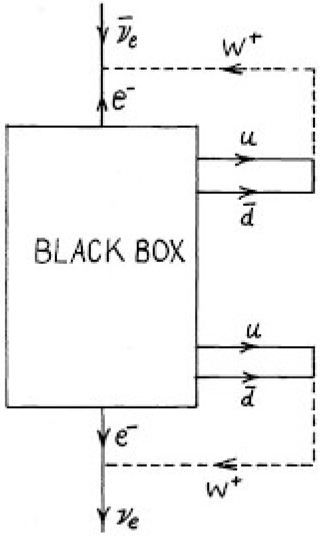
Why Measuring $2\beta^+$ / $EC\beta^+$?

Complementary to $2\beta^-$



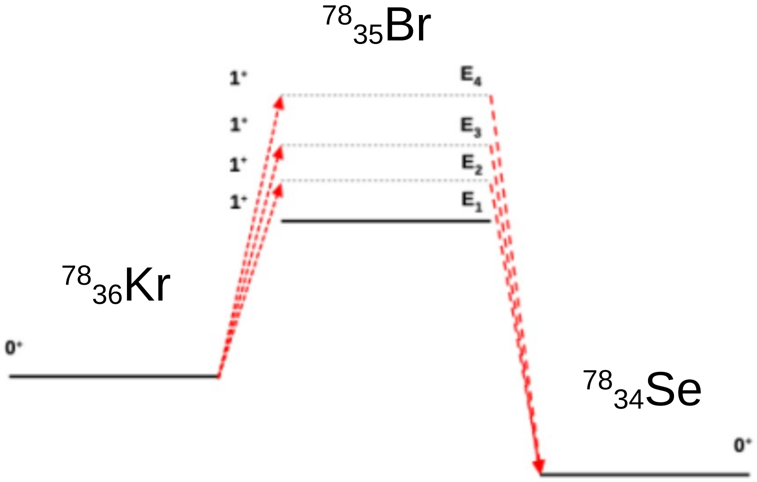
Probe of Majorana Mechanisms

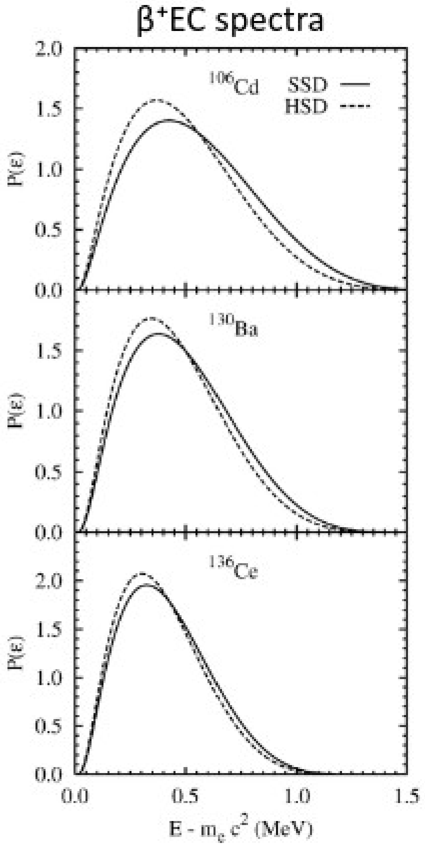


Branching ratio
$2\beta^+$ / $EC\beta^+$

Probe of intermediate state

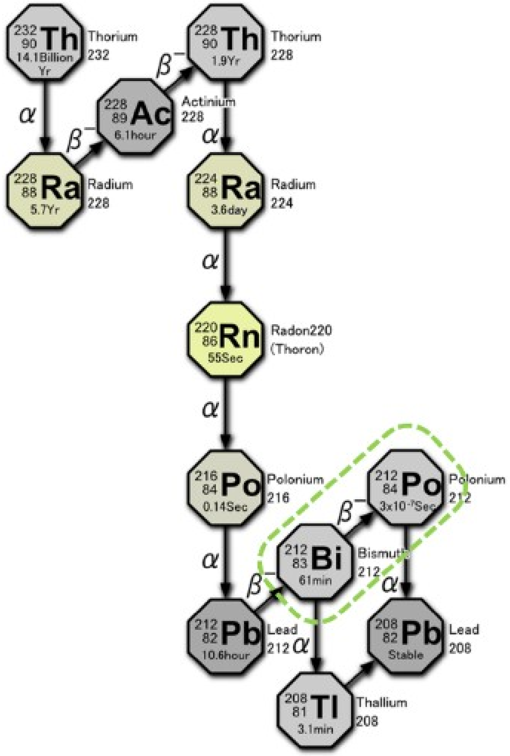
$$(A, Z) \rightarrow (A, Z \pm 1) \rightarrow (A, Z \pm 2)$$

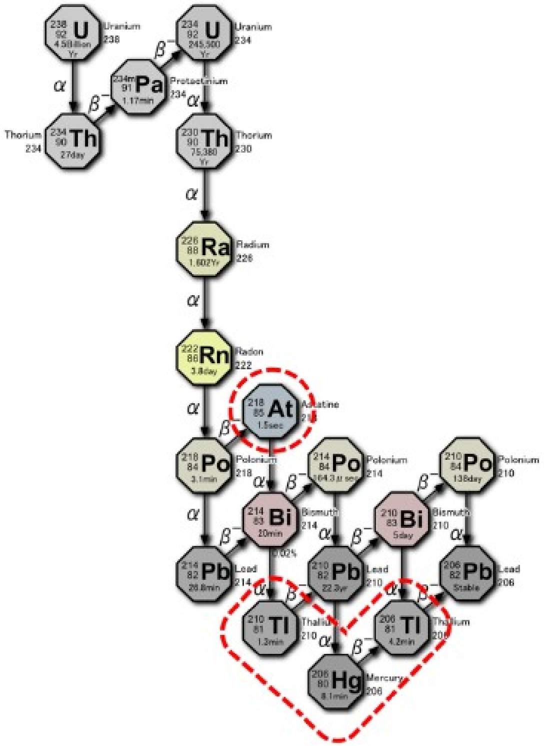




Radioactivity Levels

Scintillator		wavelength-shifter		Dust on fibres	fibres
<10^{-12}g/g (U/Th)	< 5 µBq/m³ (Rn)	< 1 ppb (K/U/Th)	Low energy (C-14/Bi-210)	<5 µg/m²	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/m³ baseline	optimistic
OWL-fibre	U-238	103	1.03
bulk	Th-232	33.7	0.34
(γ only)	K-40	225	2.25
	Tl-208	12.1	0.12
OWL-fibre	Bi-214	2.1	0.028
surface+dust	Bi-212	0.48	0.014
(β+γ)	K-40	0.5	0.005

The Wavelength-Shifting Optical Module (WOM)

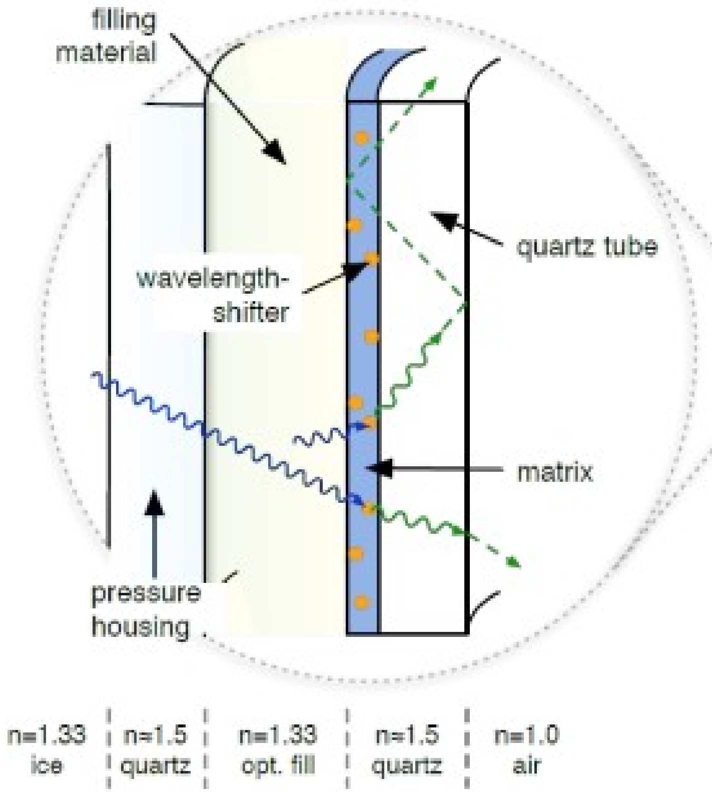
Main features:

- Large light collection area
  - WLS allows circumventing Liouvilles 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

		Cut efficiencies ε_x				
Scenario		Baseline	Optimistic			
Signal type		$2\nu2\beta^+$ and $2\nu EC\beta^+$	$0\nu2\beta^+$		$0\nu EC\beta^+$	
Discrimination technique		All	Hybrid	Opaque	Hybrid	Opaque
Event type	Kr-85	0.010	–†	–†	–†	–†
	Po-210	0.010	–†	–†	–†	–†
	Bi-210	0.010	–†	–†	–†	–†
	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	–†	–†	–†	–†
	$0\nu2\beta^+$	0.900	0.900	0.920	0.001	0.187
	$2\nu2\beta^+$	0.900	0.900	0.920	$< 10^{-4}$	0.187
	$0\nu EC\beta^+$	0.900	0.001	0.237	0.900	0.823
	$2\nu EC\beta^+$	0.900	0.001	0.237	0.900	0.823

Half-life Measurement and Theory

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

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

$\alpha_1,\ \alpha_2$: Majorana phases

δ: Dirac phase

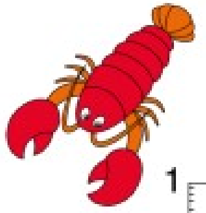
Lobster Plot

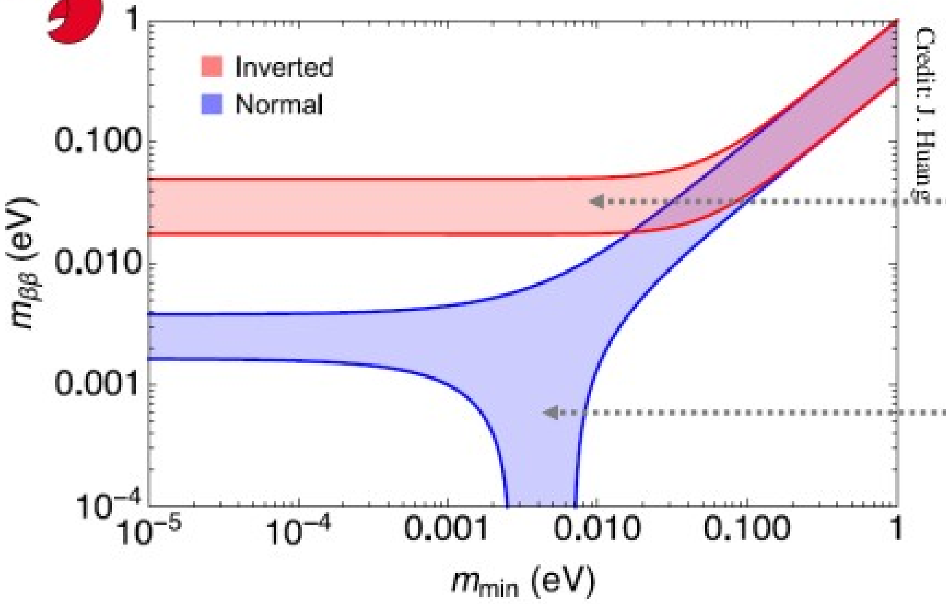
α_1, α_2: Majorana phases

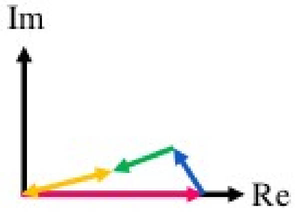
δ: Dirac phase

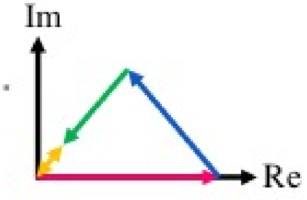
Effective Majorana neutrino mass

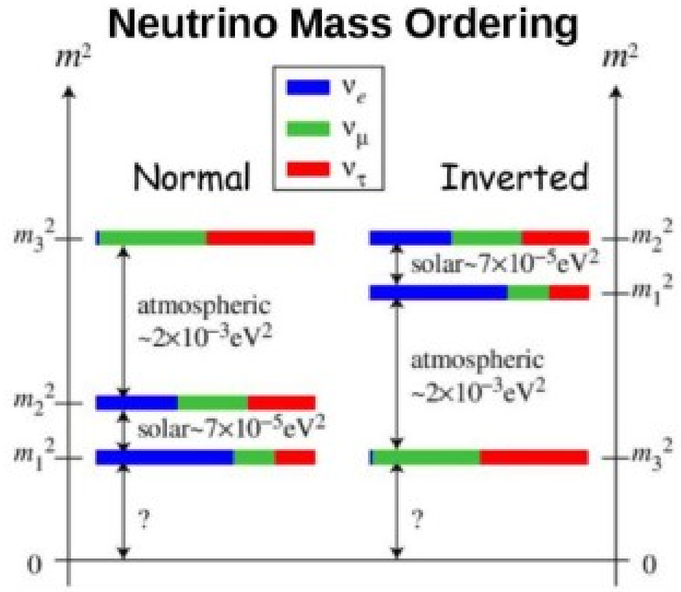
$$m_{\beta\beta} \equiv \left|\sum_k m_k U_{ek}^2\right| = \left|m_1 \left|U_{e1}\right|^2 + m_2 \left|U_{e2}\right|^2 e^{i(\alpha_2-\alpha_1)} + m_3 \left|U_{e3}\right|^2 e^{-i(\alpha_1+2\delta)}\right|$$











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