NuDoubt^{++} Report

Stefan Schoppmann for the NuDoubt^{++} Collaboration
(he/him/his)

Johannes Gutenberg University Mainz

SEF 2026

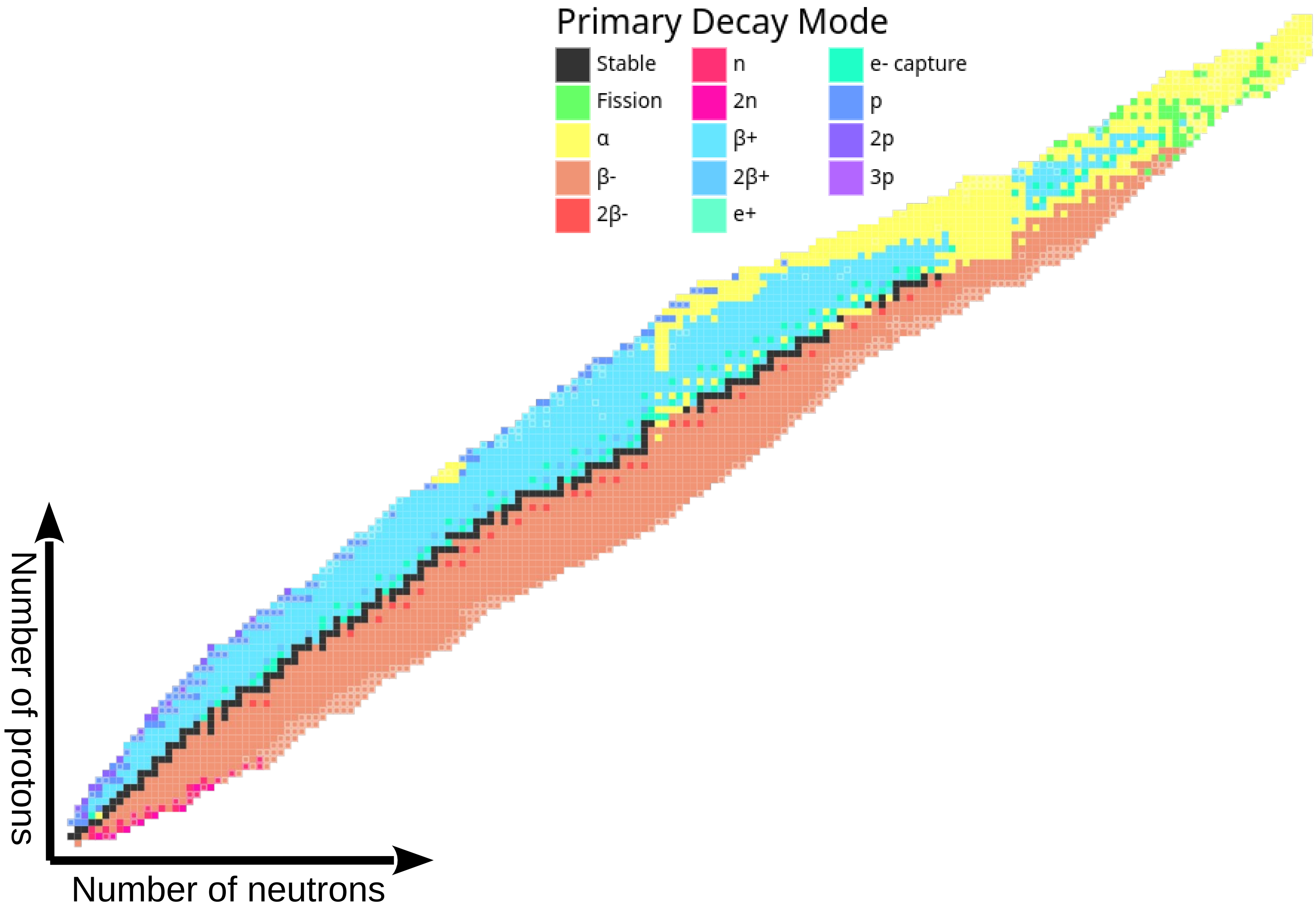
Sudbury

21st July 2026

Funded by the European Union

European Research Council
Established by the European Commission

Searches for Double Beta Decays



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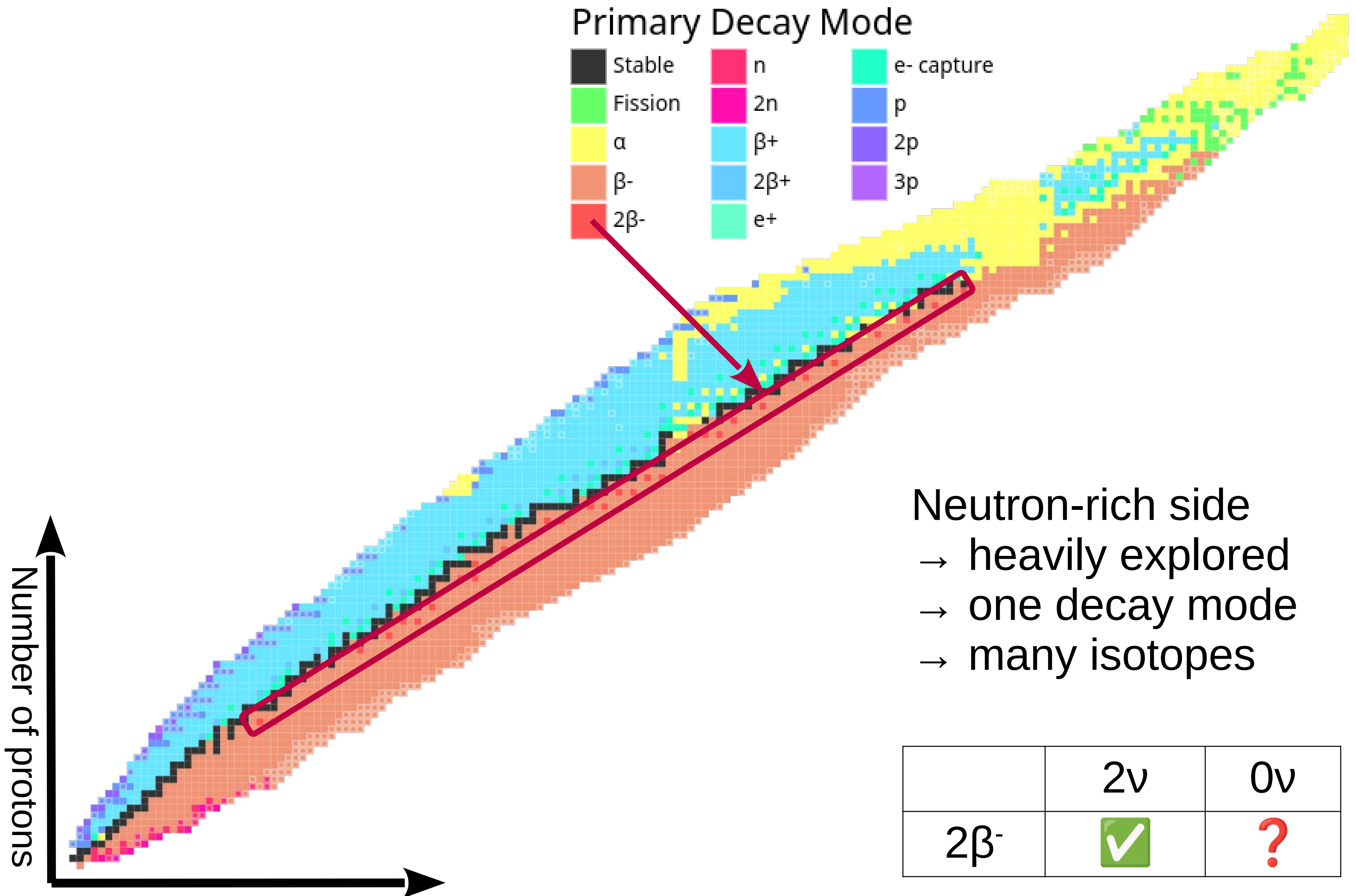


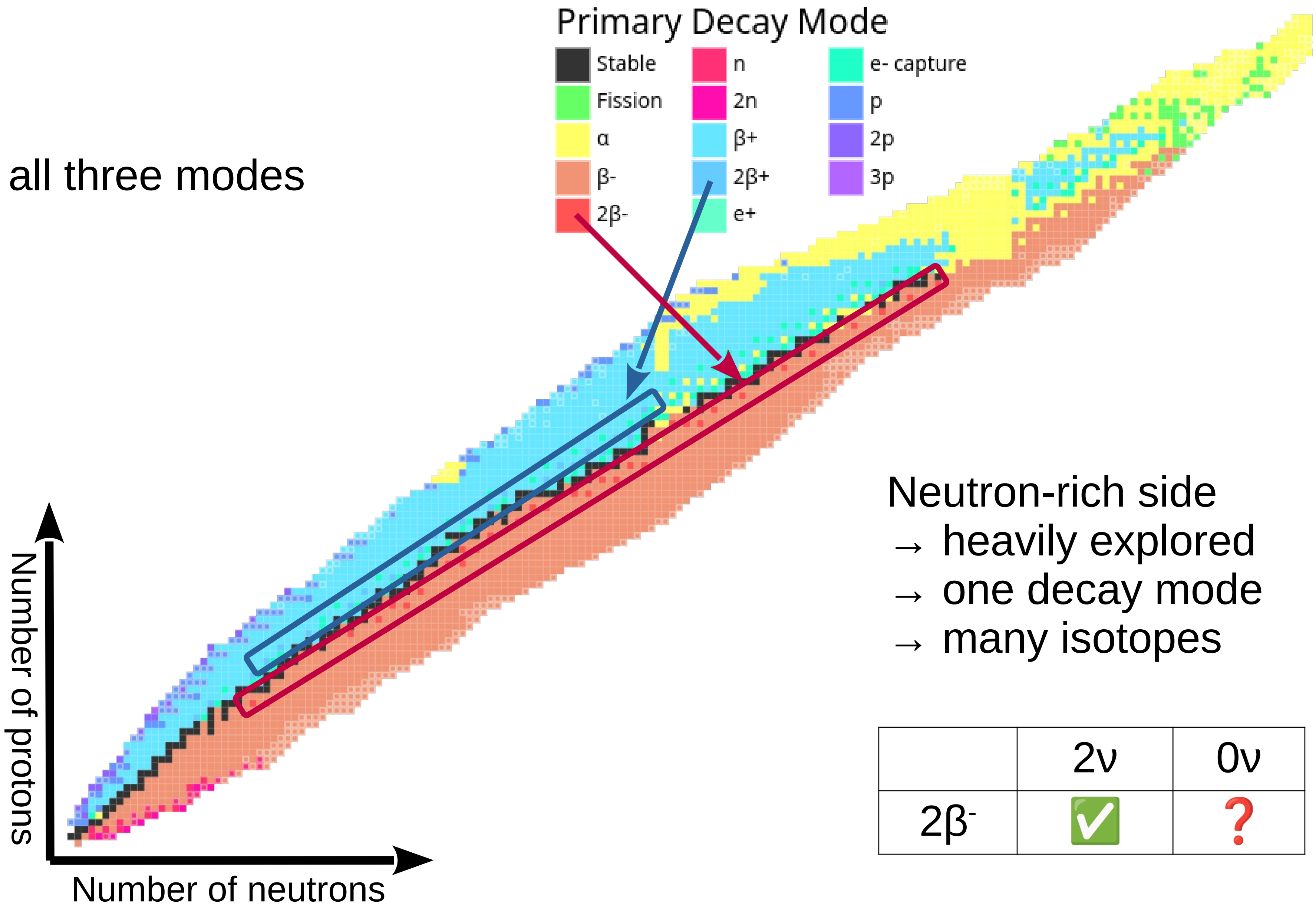
Neutron-rich side
→ heavily explored
→ one decay mode
→ many isotopes

	2ν	0ν
$2\beta^-$	✅	❓

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	✅	❓



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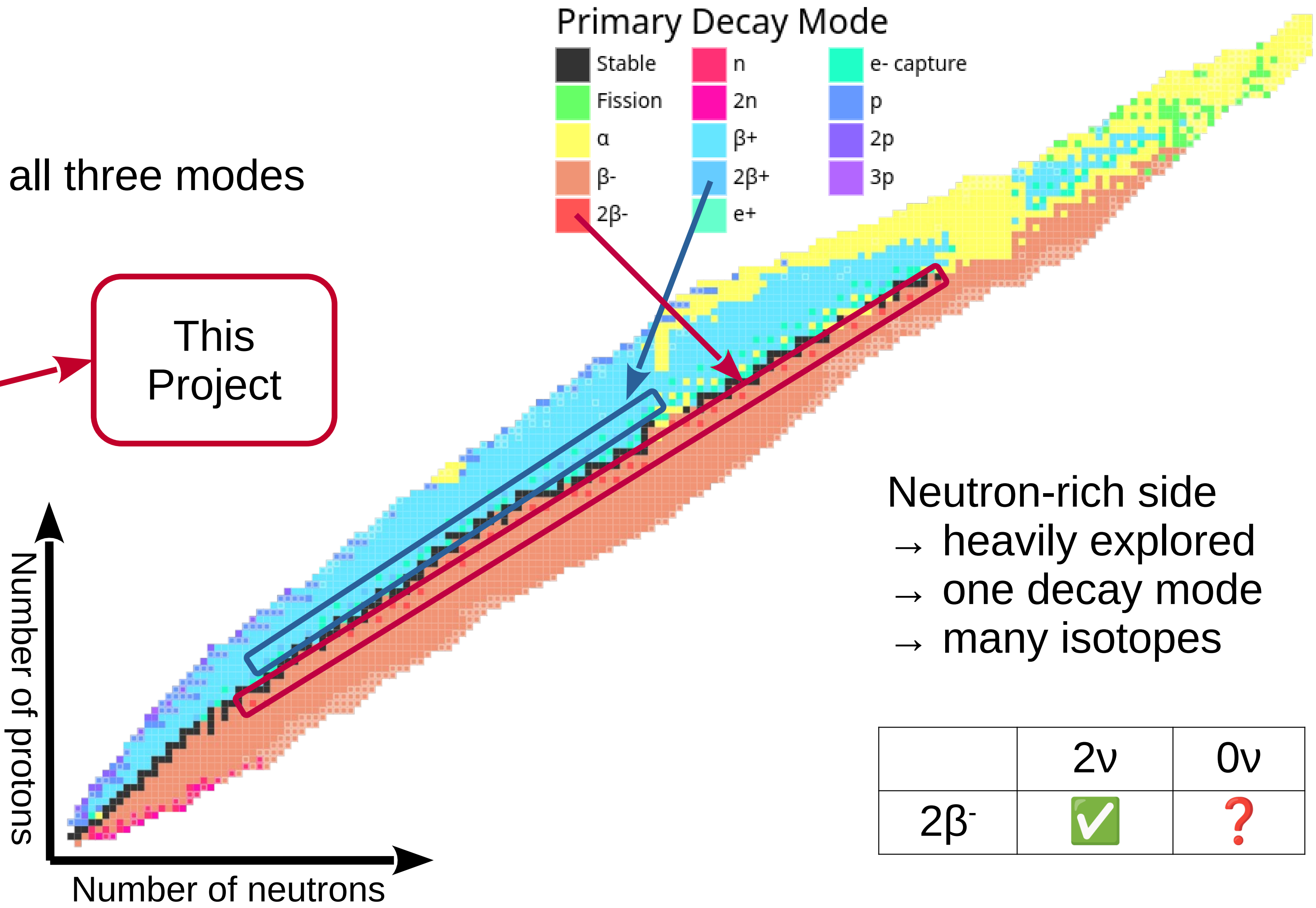
	2ν	0ν
2β+	❌	❓
ECβ+	❌	❓
2EC	✅	❓

This Project



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2β-	✅	❓

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

Positron emission requires more binding energy to be released

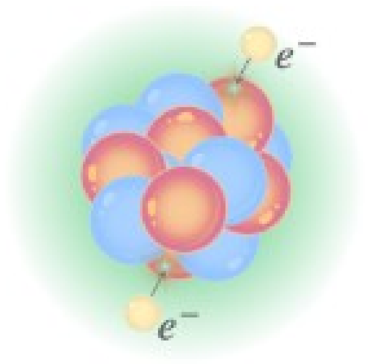
$$K_{\beta^+\beta^+} = M(A,Z) - M(A,Z-2) - 4m_e,$$

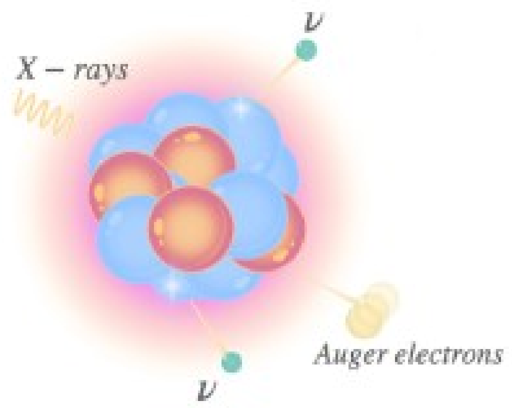
$$K_{\beta^+EC} = M(A,Z) - M(A,Z-2) - 2m_e - \epsilon_b$$

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

$$\epsilon_b \ll m_e$$

Images courtesy of V. Palušová





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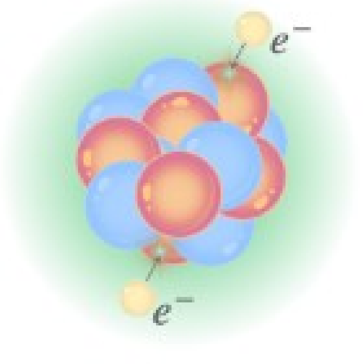
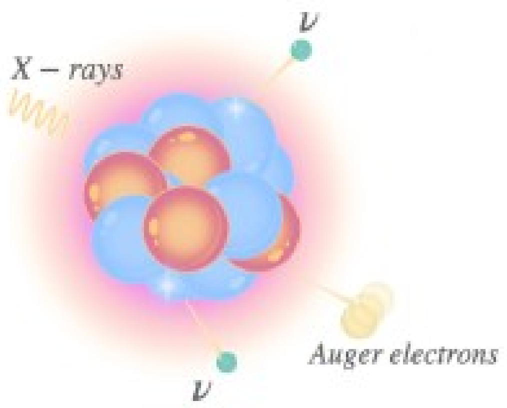




Images courtesy of V. Palušová

Abundant isotopes with dominantly positive double weak decay:

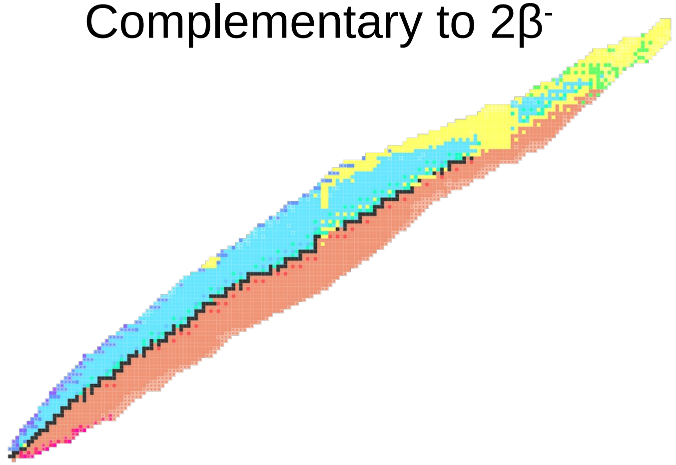
Decay modes	Transition	ΔM (keV)	Natural Abundance (%)
$2\beta^+$, $EC\beta^+$, 2EC	$^{124}Xe \rightarrow ^{124}Te$	2863.9	0.095
	$^{78}Kr \rightarrow ^{78}Se$	2847.67	0.355
	$^{106}Cd \rightarrow ^{106}Pd$	2775.39	1.245
	$^{96}Ru \rightarrow ^{96}Mo$	2714.5	5.54
	$^{130}Ba \rightarrow ^{130}Xe$	2618.9	0.11
	$^{136}Ce \rightarrow ^{136}Ba$	2378.55	0.186
$EC\beta^+$, 2EC	$^{58}Ni \rightarrow ^{58}Fe$	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
2EC	$^{126}Xe \rightarrow ^{126}Te$	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

Tl-208 γ-rays

V. Palušová, MEDEX'25

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

Complementary to $2\beta^-$



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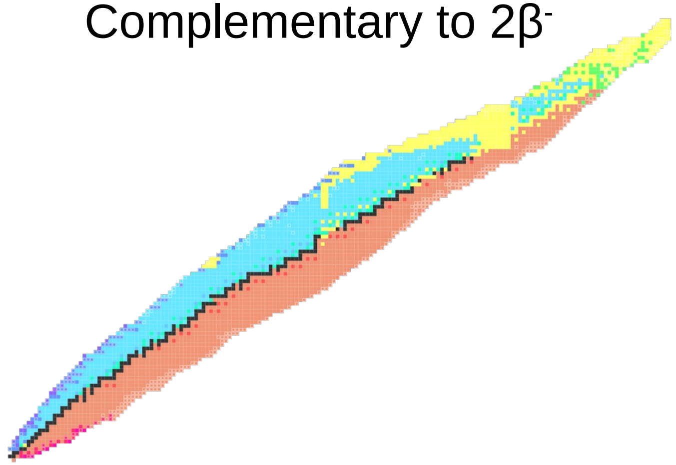
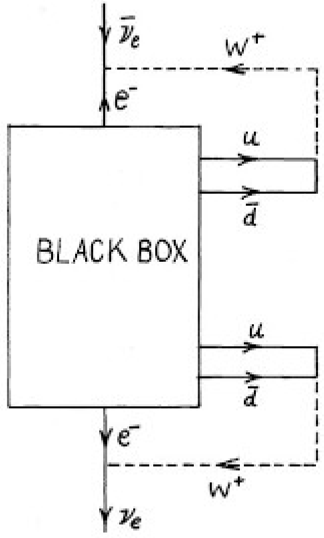


Probe of Majorana Mechanisms



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

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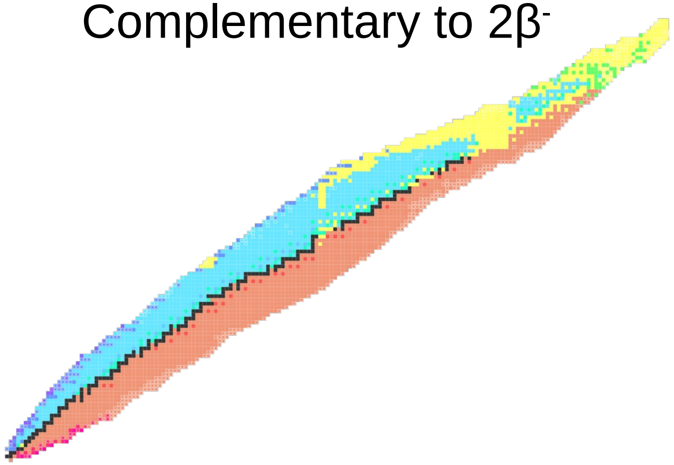

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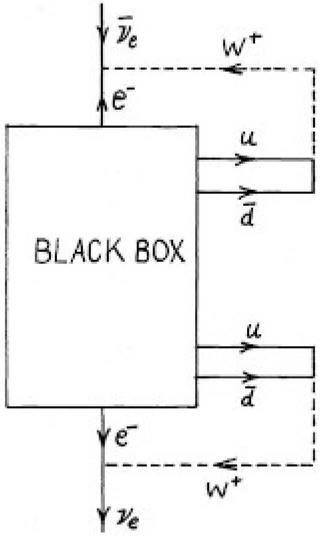

Branching ratio
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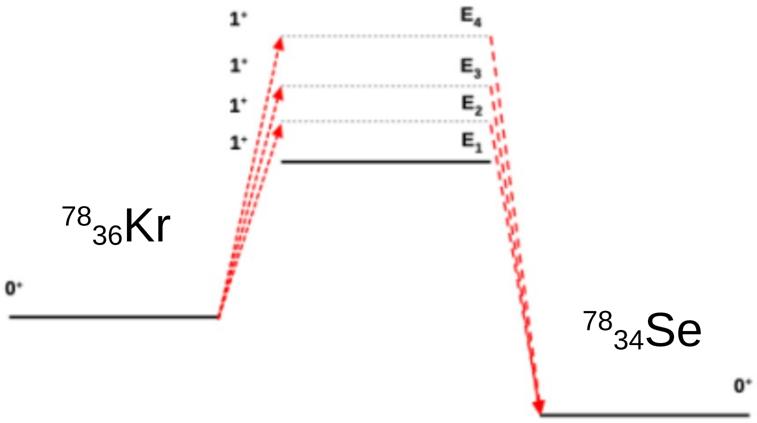
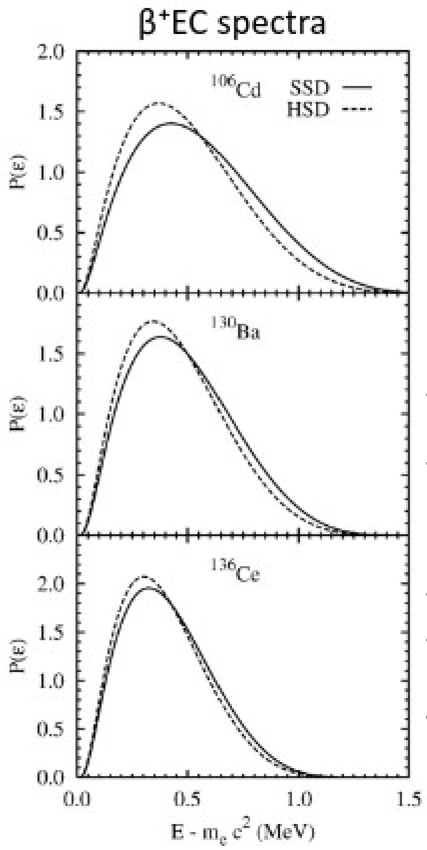
Probe of intermediate state

$(A,Z) \rightarrow (A,Z\pm1) \rightarrow (A,Z\pm2)$





Nuclear Physics A 753 (2005) 337–363

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

Challenges

→ extremely rare
$T^{2\nu}_{1/2} > 10^{22}$ years

→ low natural abundances

How Can We Measure 2β⁺ / ECβ⁺ ?

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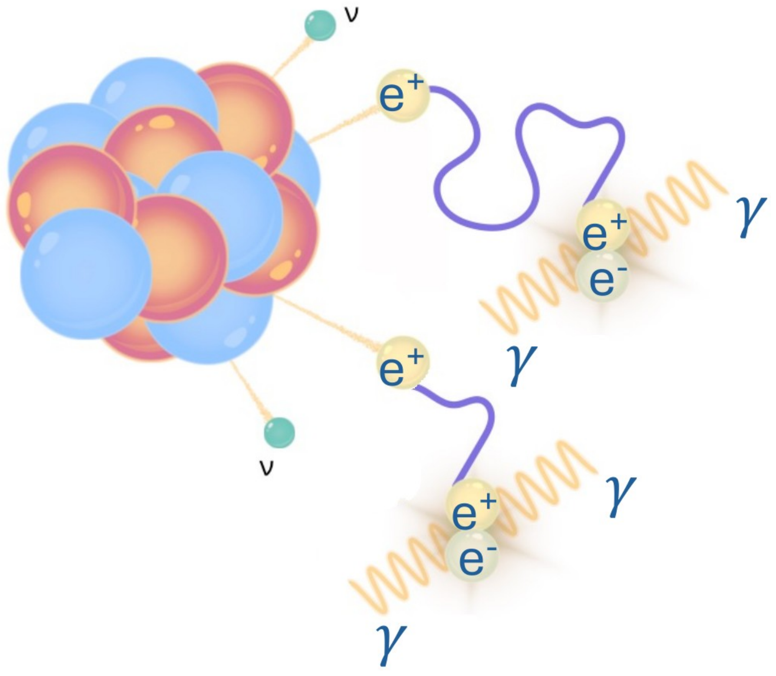
Experimental Opportunity

→ unique signature via annihilation gammas



Письма в ЖЭТФ 34 (1981) 148

Image courtesy of V. Palušová

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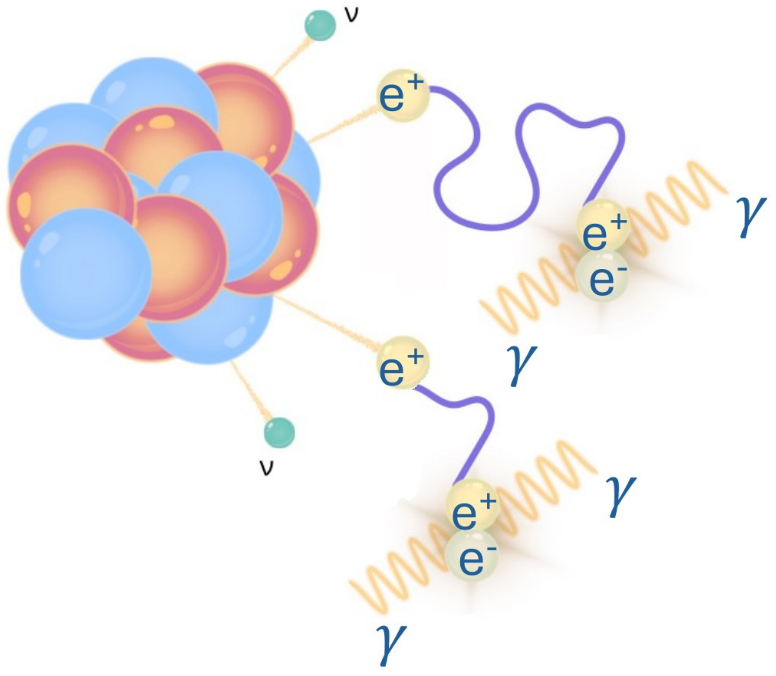


Письма в ЖЭТФ 34 (1981) 148

Technology Requirements

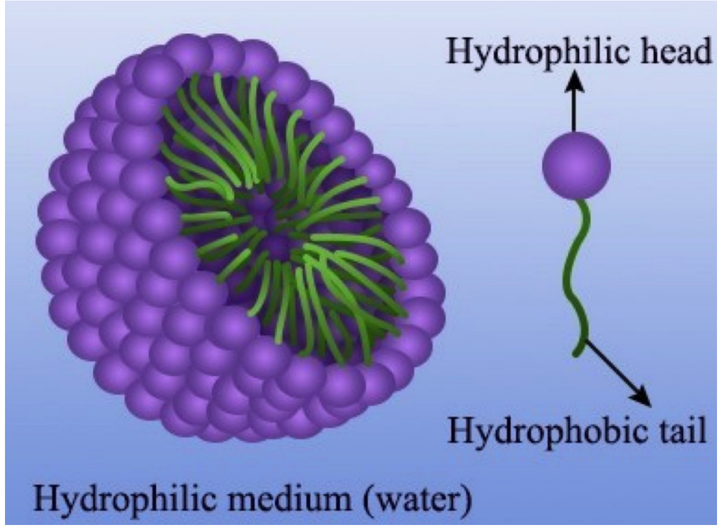
→ strong background suppression

→ high signal rates

→ good energy resolution

Image courtesy of V. Palušová

Hybrid Scintillator

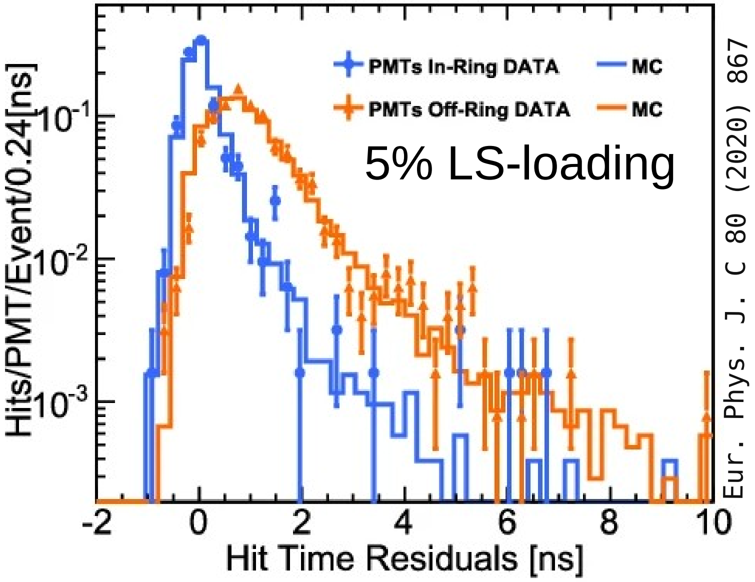


IJAC 13 (2017) 663-672

Water-based:

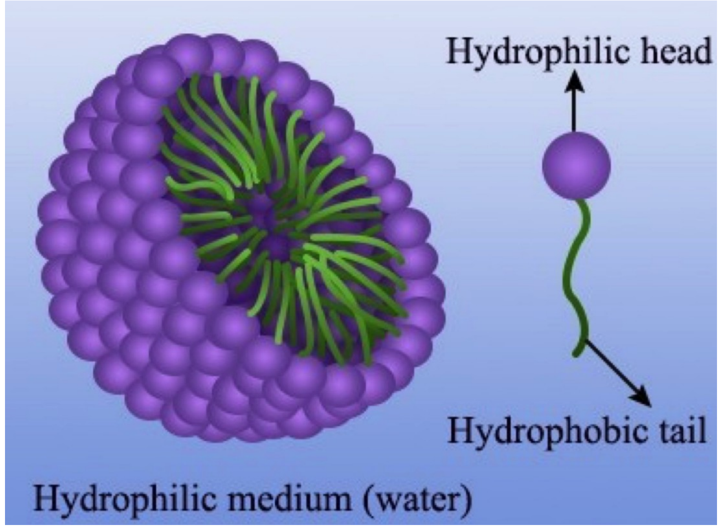
→ organic micelles
 suspended in water
 with surfactant interface

→ 1 – 10% scintillator loading



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

Hybrid Scintillator



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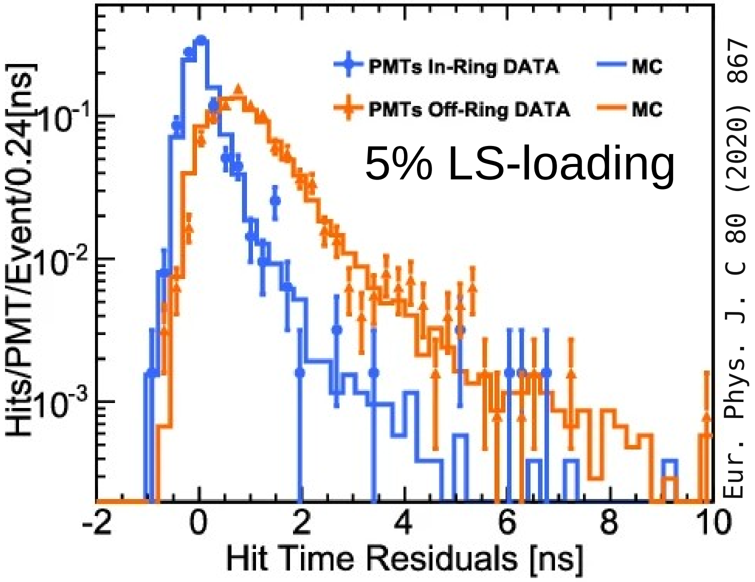

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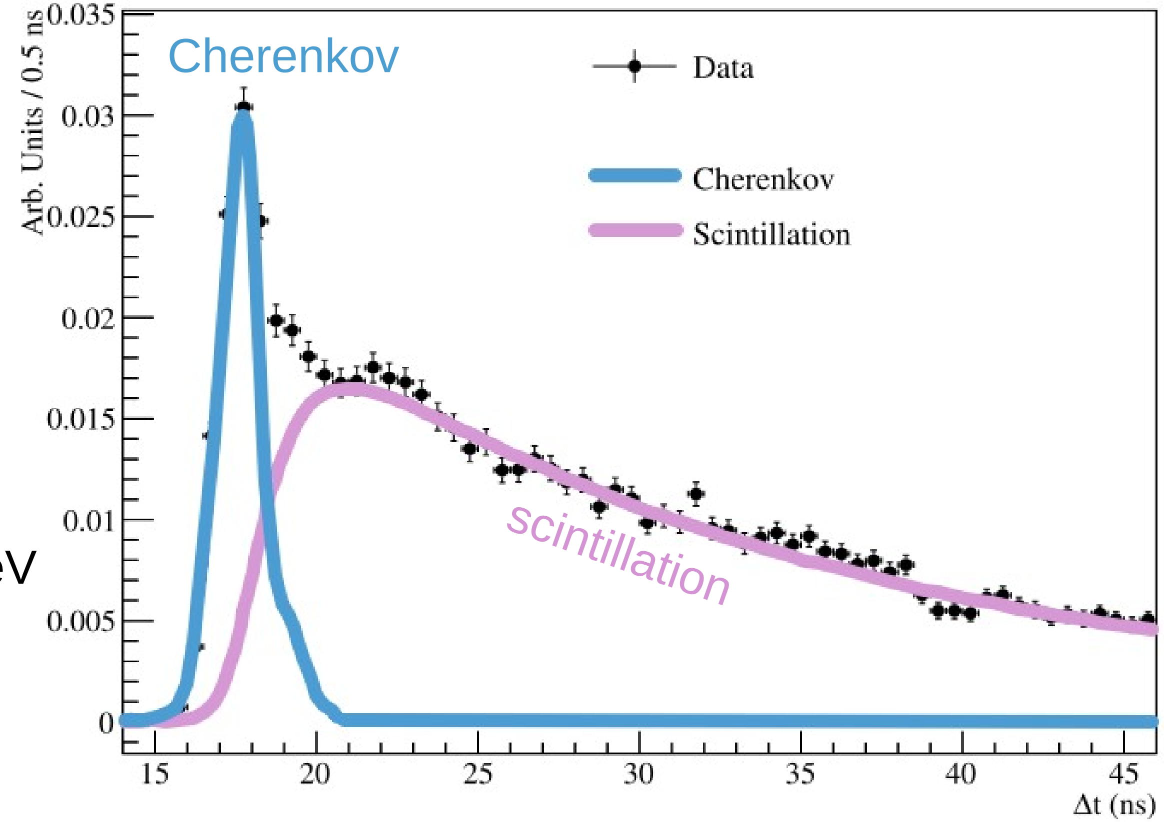
Slow:
→ slow fluorophores / solvents

→ intrinsically slow scintillation pulse form with τ > 10 ns

→ high light yield scintillators of >10000 photons/MeV



JINST 19 (2024) P09015

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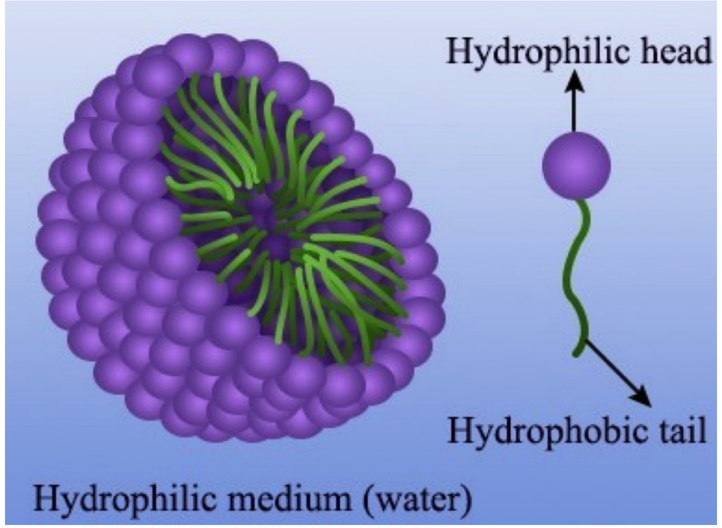

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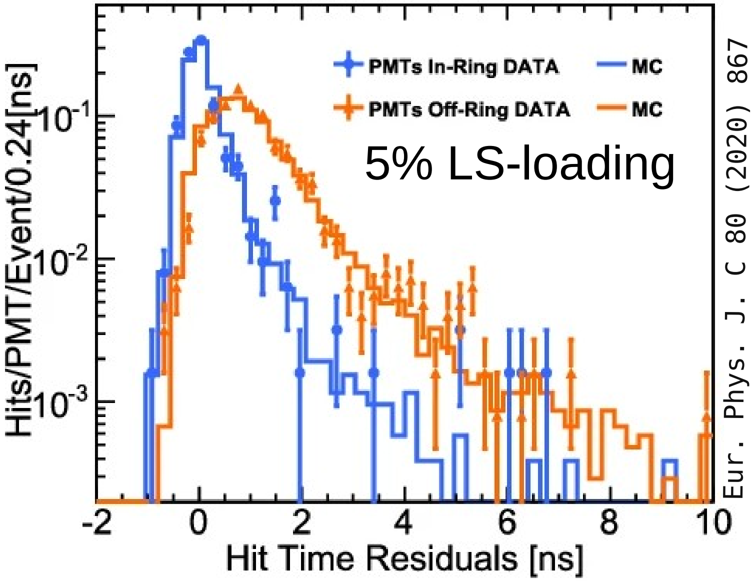

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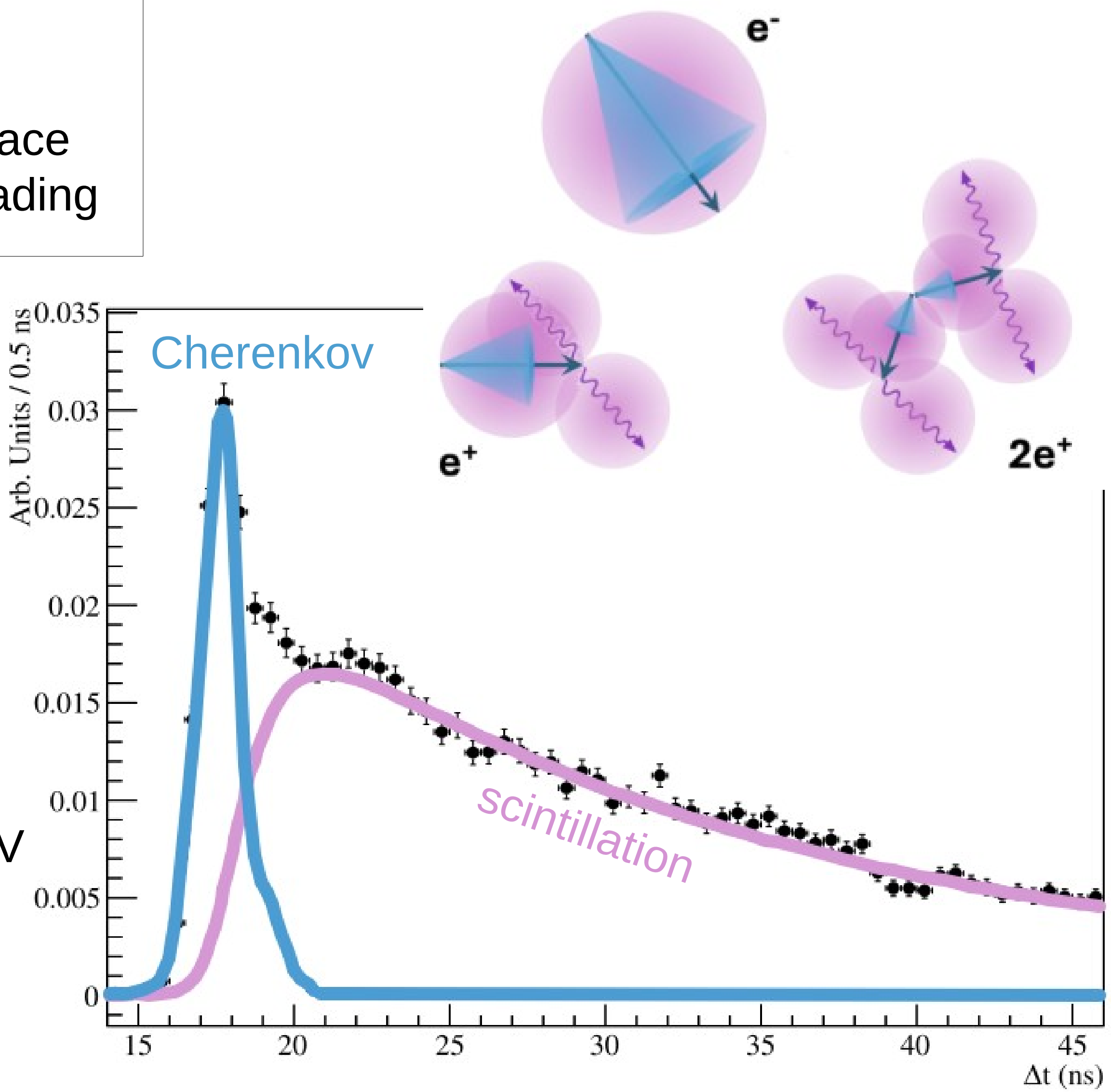


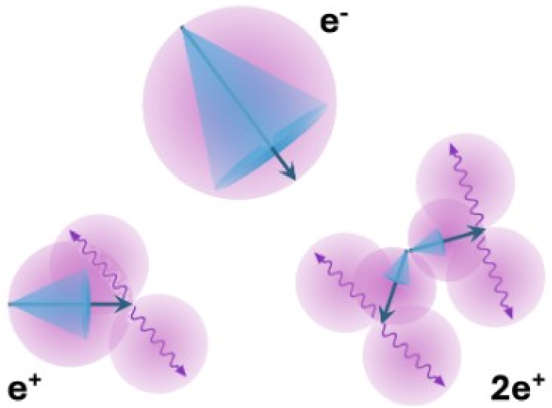
Image courtesy of M. Wurm

JINST 19 (2024) P09015

Particle ID through C/S Separation

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

→ hybrid-slow scintillator: 90 wt.% LAB + 10 wt.% DIN + fluorophore(s)
JINST 19 (2024) P09015



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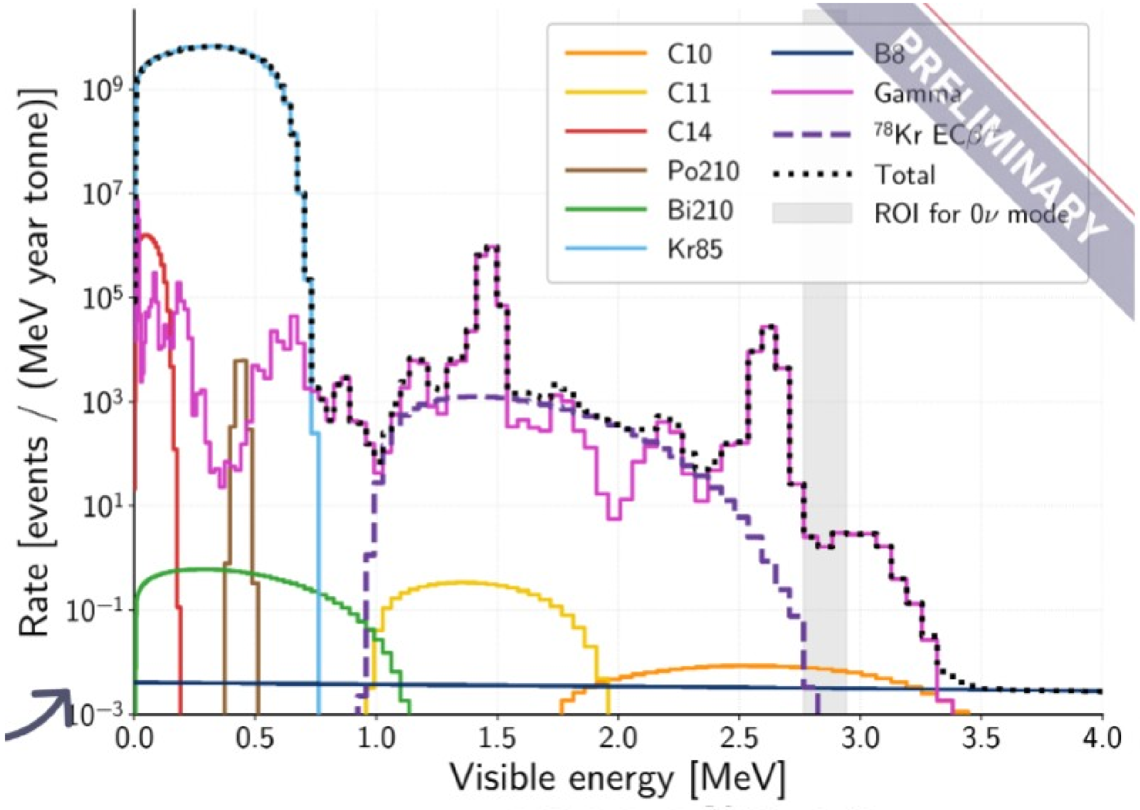
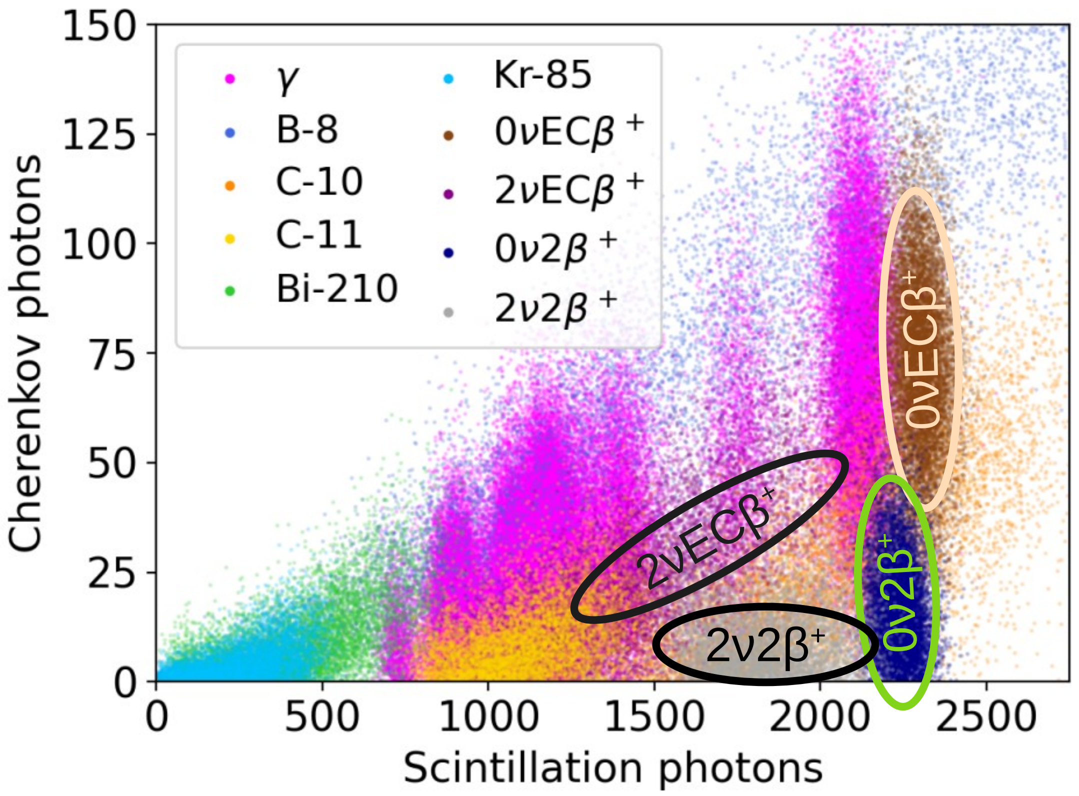


V. Palušová, NEUTRINO2026



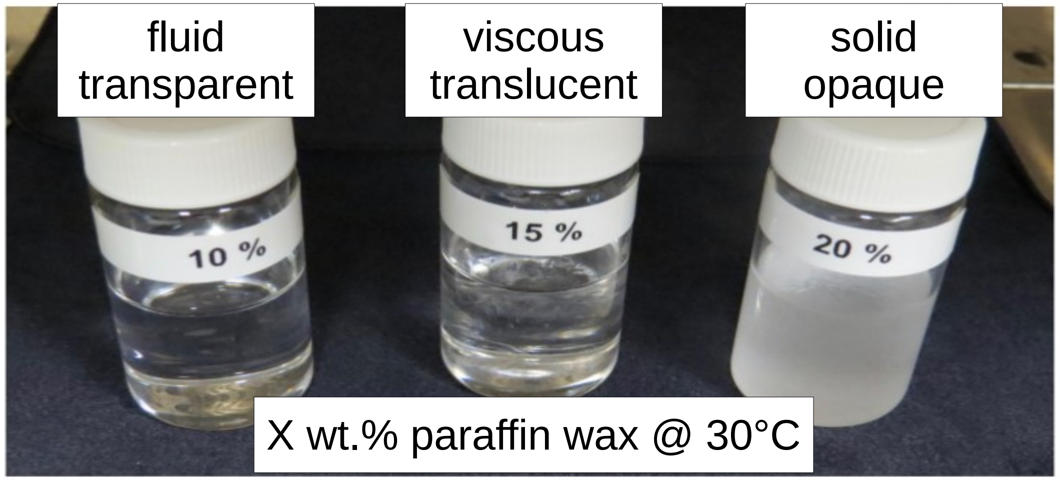
Eur. Phys. J. C 85 (2025) 121

Opaque Scintillator

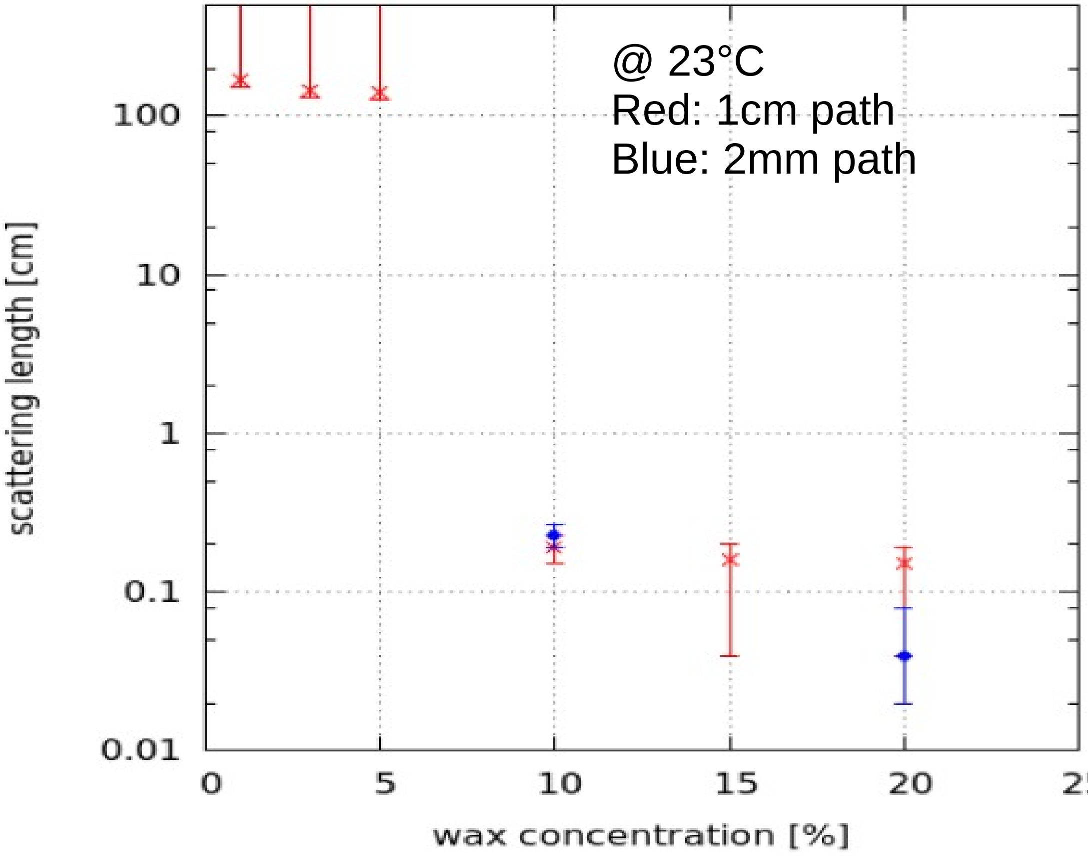
NoWaSH: wax-based opaque scintillator

→ 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 scattering, scattering length of millimetres)



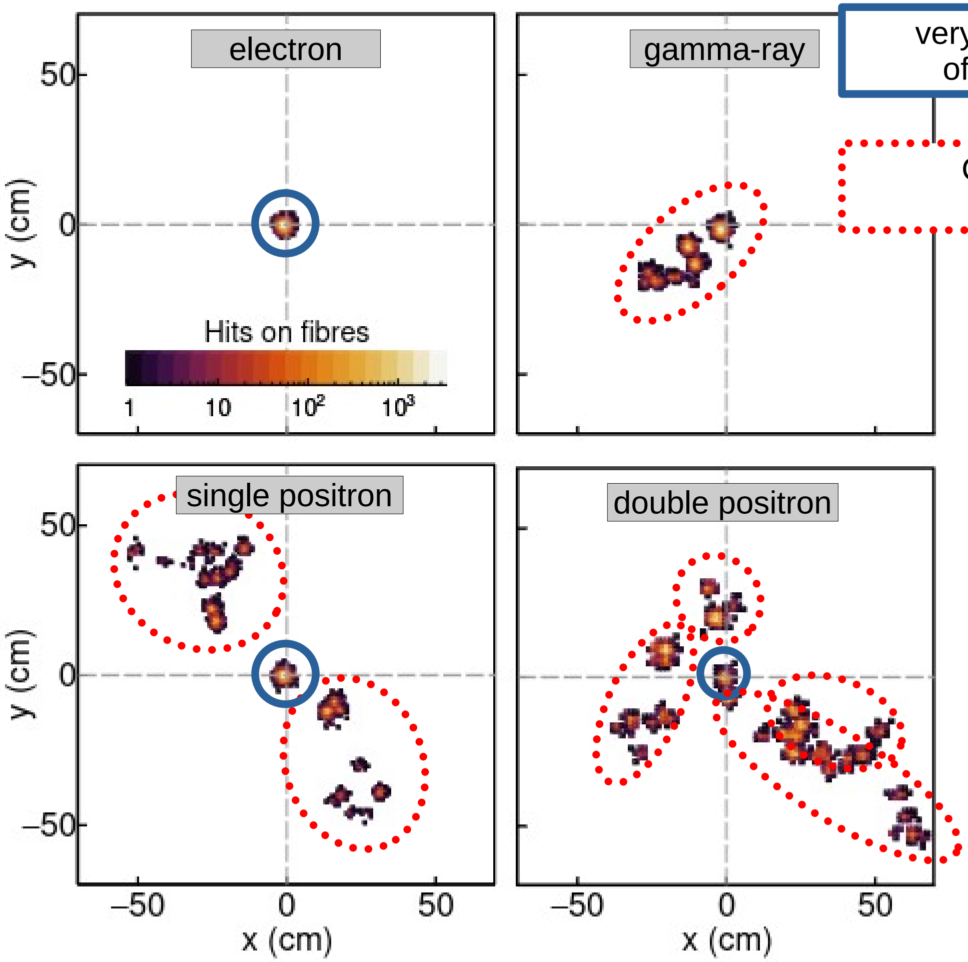
JINST 14 P11007 (2019)



JINST 14 P11007 (2019)

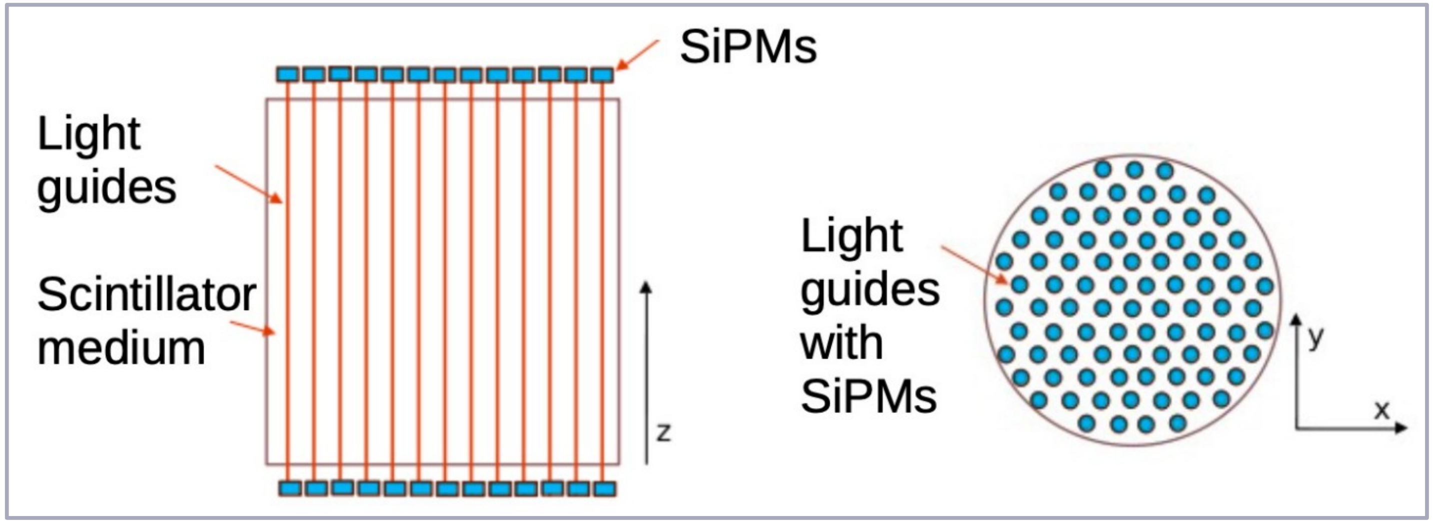
Particle ID through Morphology

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



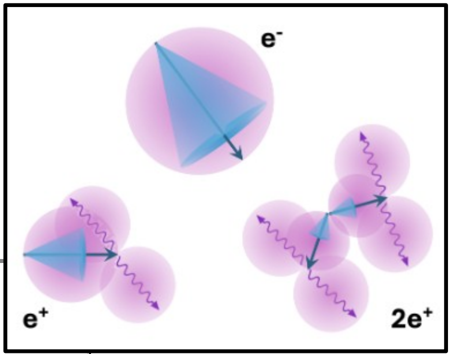
very short ionisation trail
of electron / positron

Compton-scatters
of gamma-ray



Combining Hybrid and Opaque

Combination allows insights into morphology of scintillation and Cherenkov light



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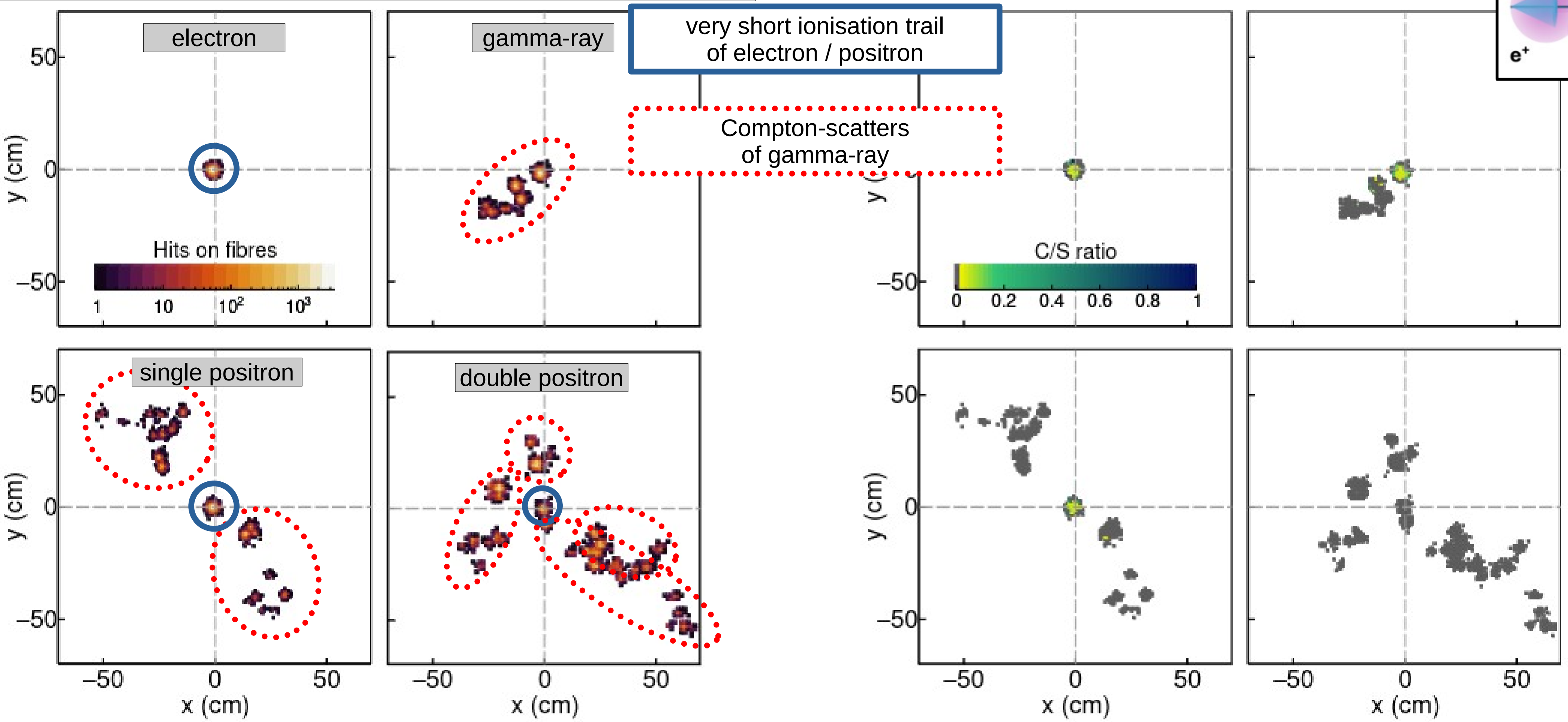

Technology Requirements

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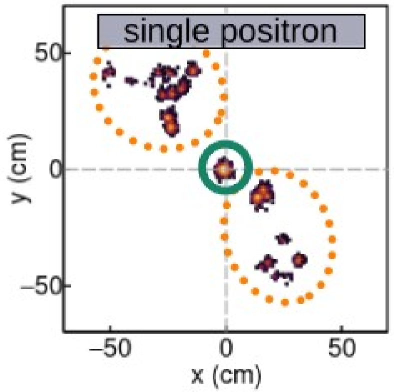
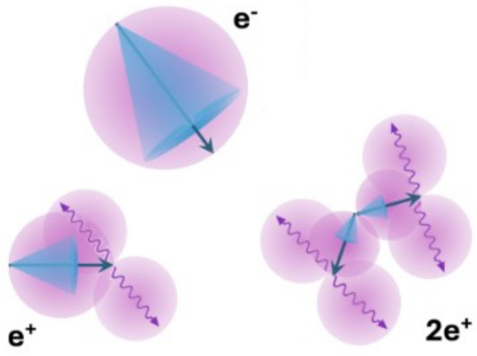


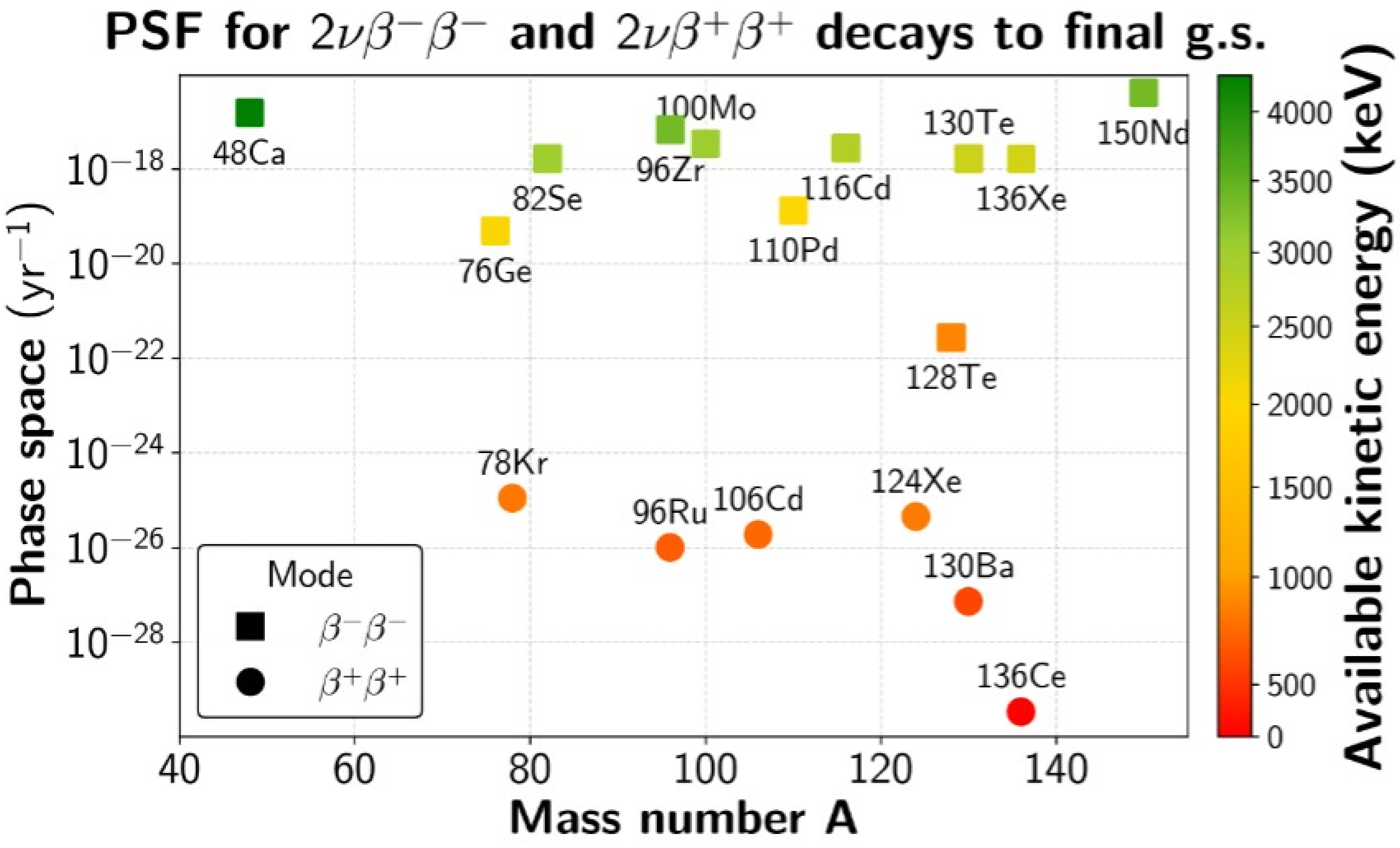


Patents Pending
EP 25 195 873.2 & EP 25 195 874.0

high signal rate

good energy resolution

Choice of Isotope



Data from: S. Stoica and M. Mirea, Front. Phys. 7 (2019) 12

V. Palušová, NEUTRINO2026

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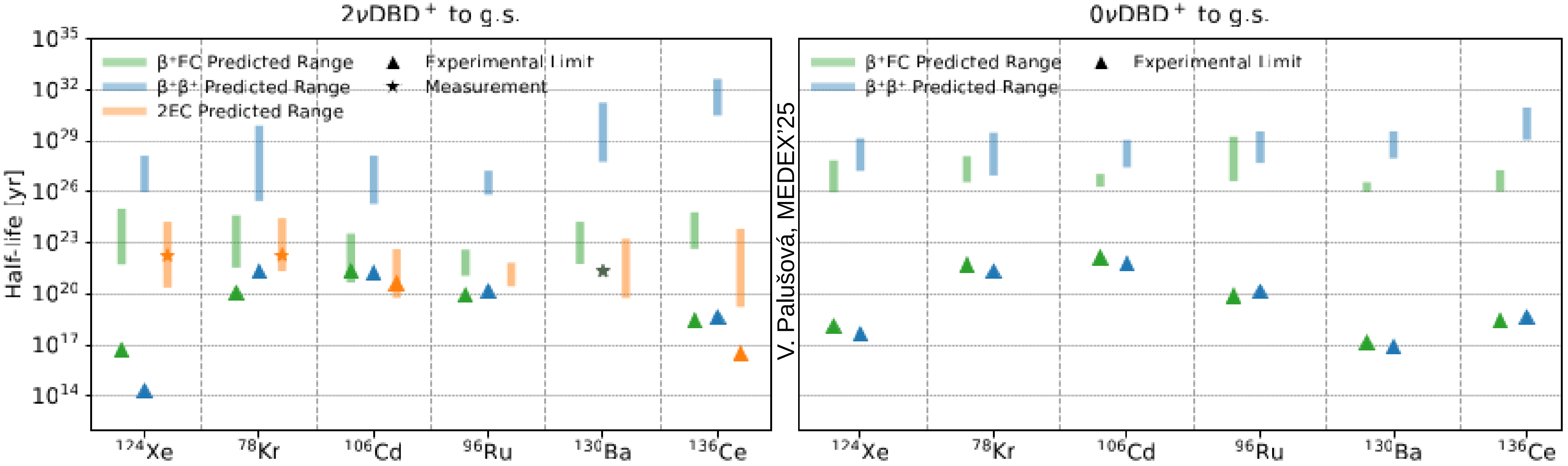


Remark:

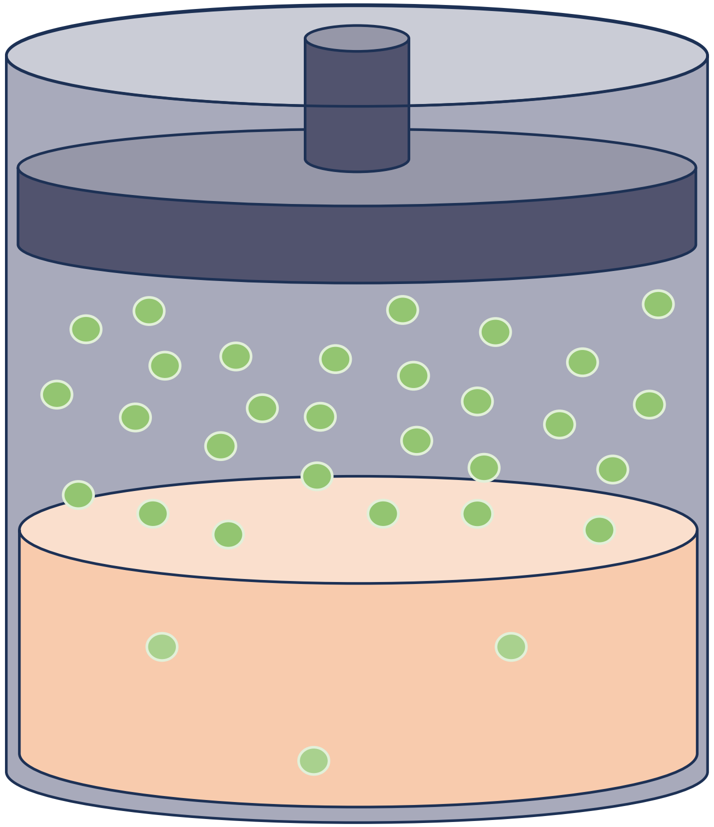
Combined Ba-130 modes (★) measured indirectly through geochemical analysis of barite samples

→ Three $2\beta^+$ isotopes have E_{max}-values well above Tl-208 γ-ray background (2614 keV)

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

Isotope Loading

Krypton-78
→ high ΔM = 2.8 MeV
  → above most backgrounds
→ nobel gas
  → high enrichment
  → pressure loading



final concentration of krypton: ~17g/l

Images courtesy of M. Eisenhuth

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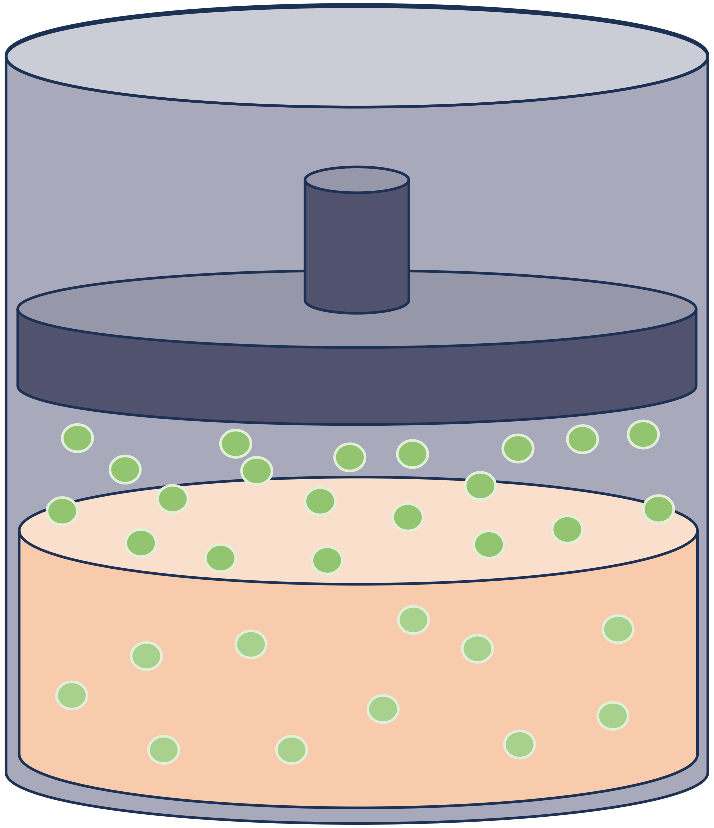

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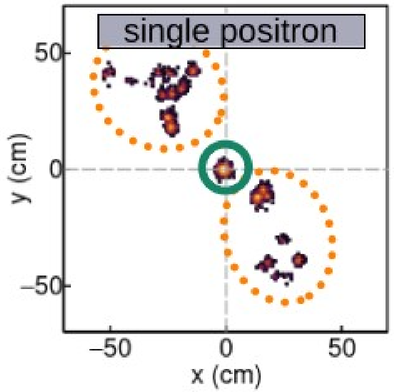

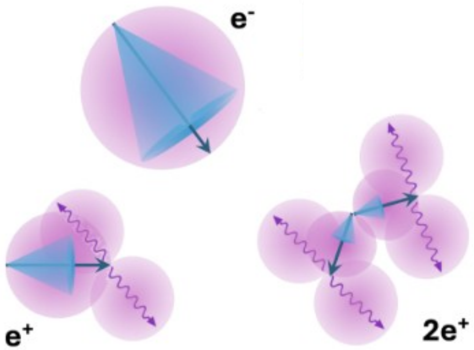

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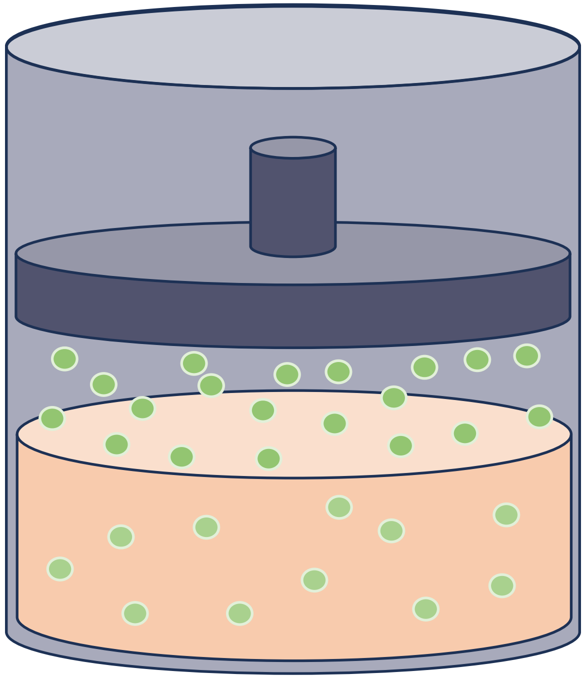
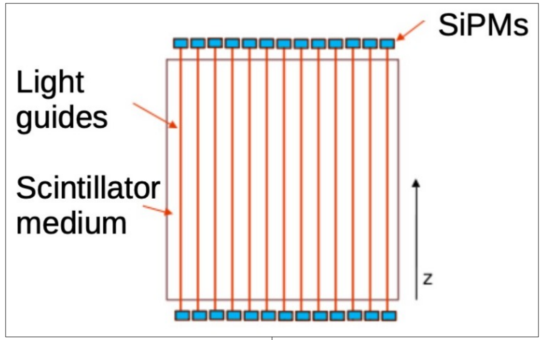
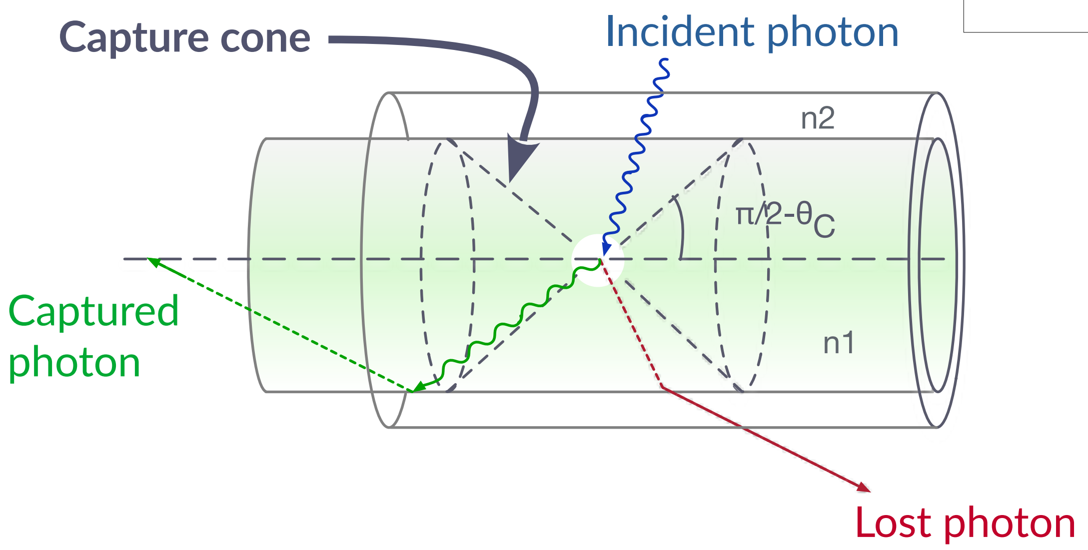


good energy resolution

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





Images courtesy of B. Keßler

Optimised Light Collection

Traditional Fibre

near centre emission

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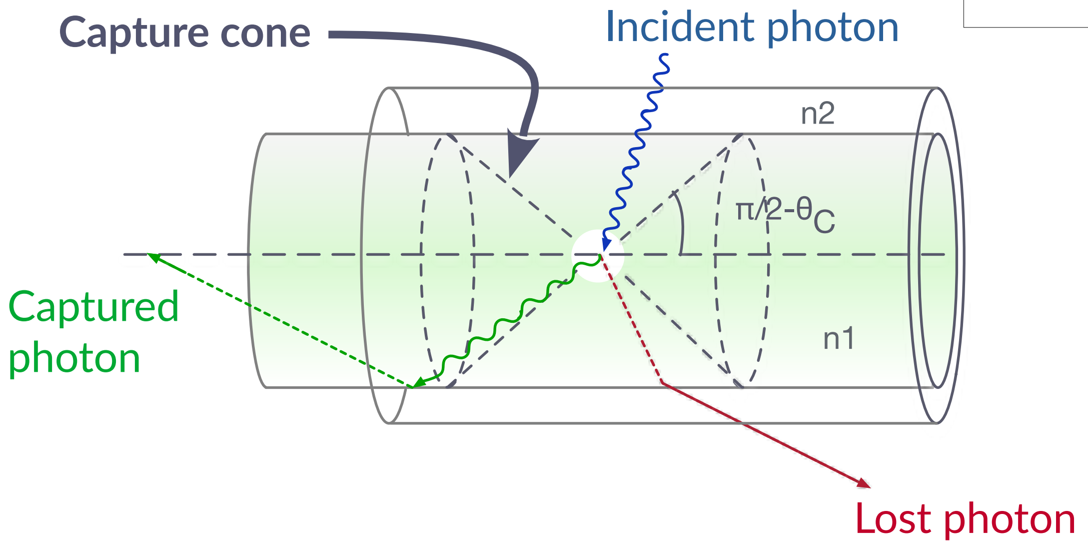
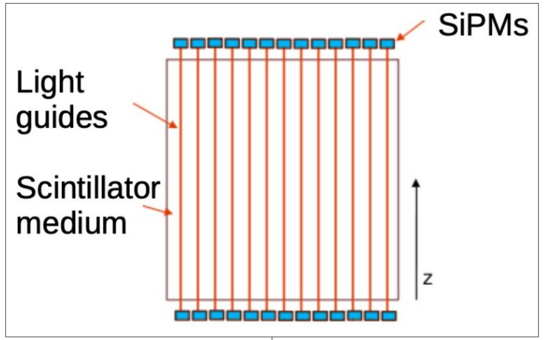
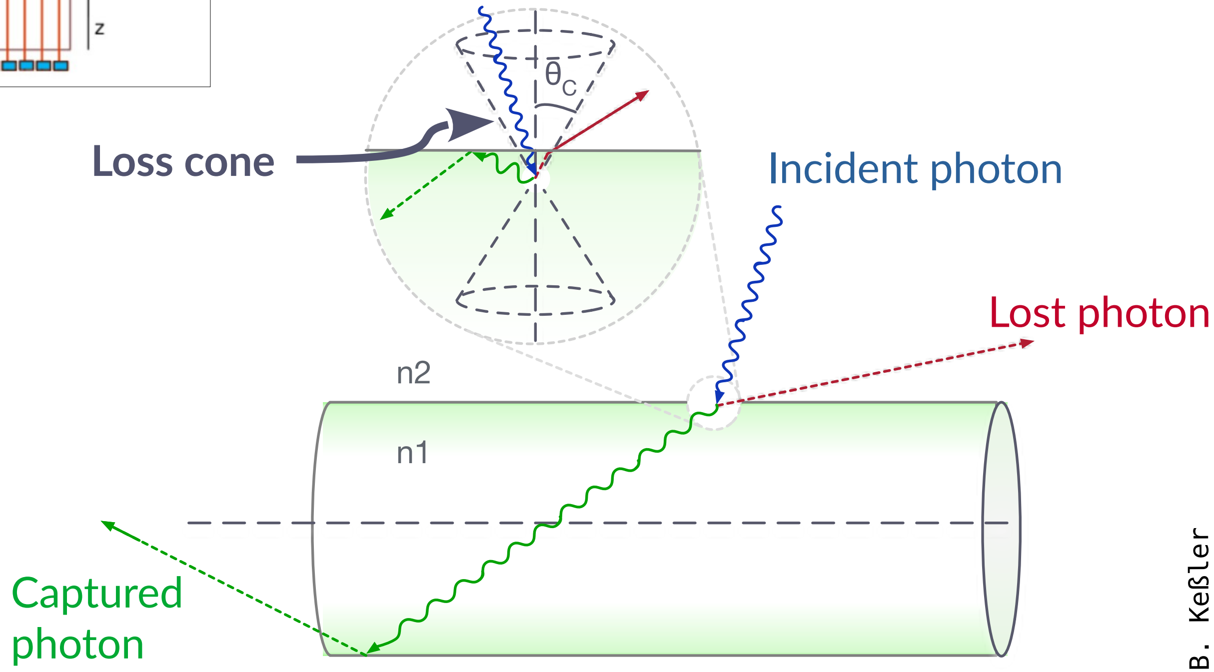




Coated Fibre

near surface emission

$\varepsilon_{TIR} = 38\%$



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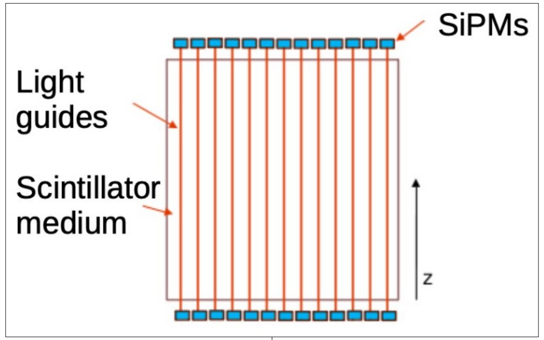

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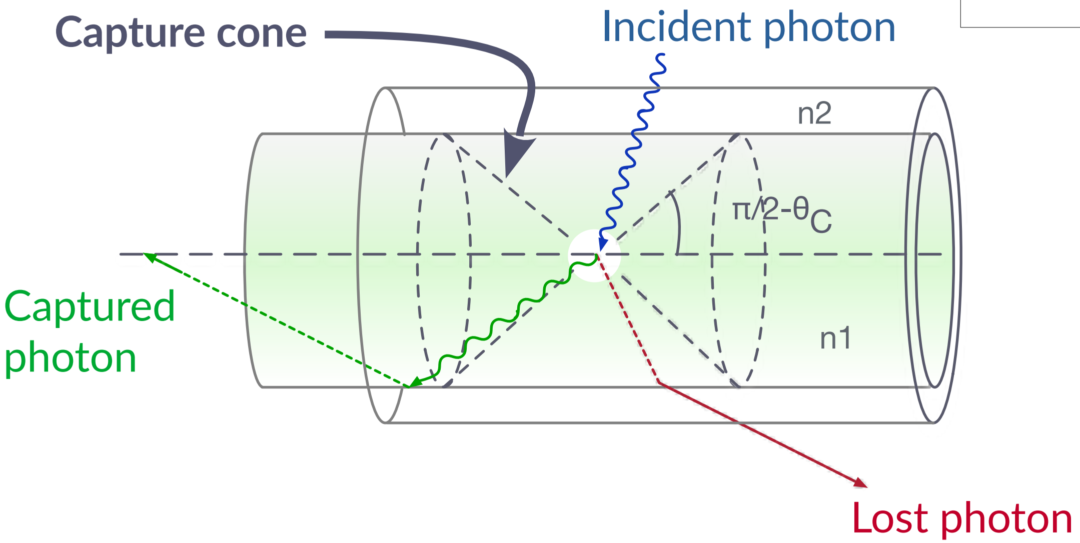
near centre emission

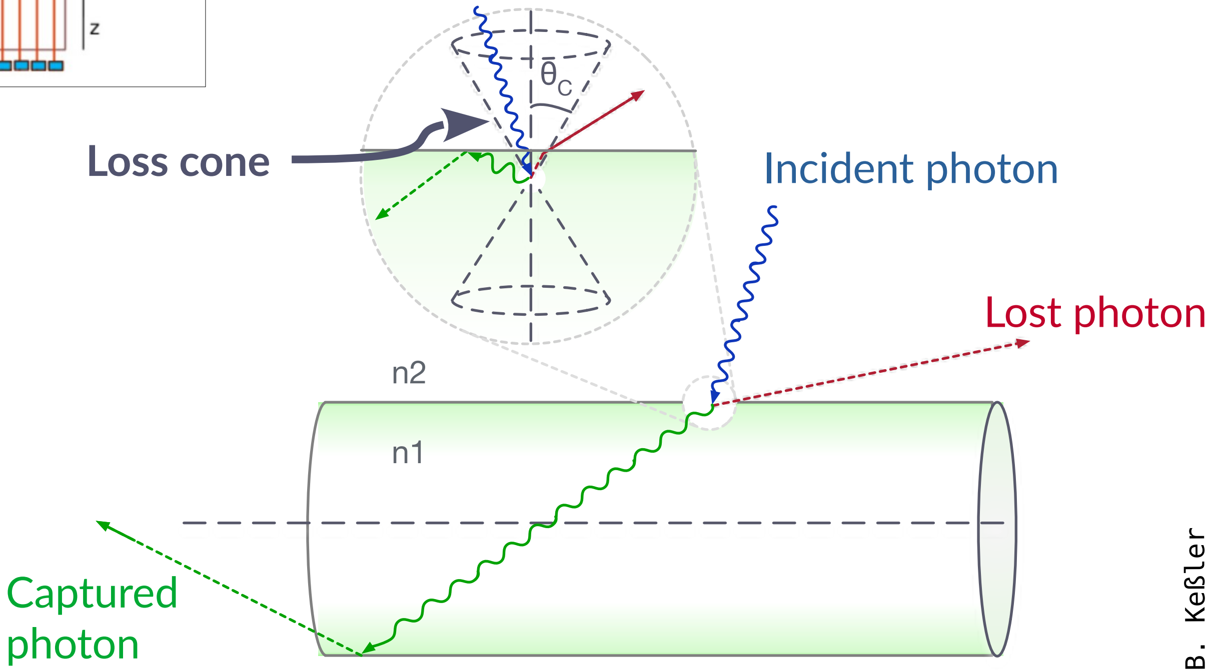
ε_{TIR} = 8%



Coated Fibre

near surface emission

ε_{TIR} =38%

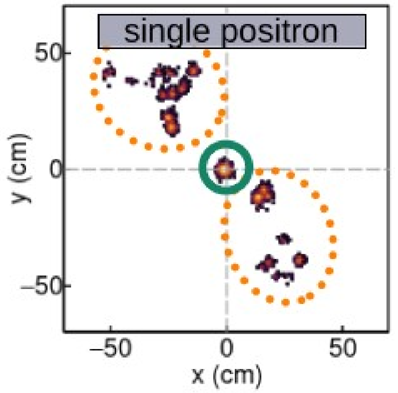


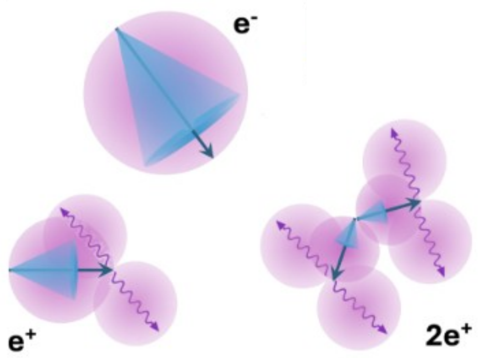
~800 PE/MeV
energy resolution of 2% @ 2.8 MeV (region of interest for neutrinoless decay modes)

Images courtesy of B. Keßler

Technology Requirements

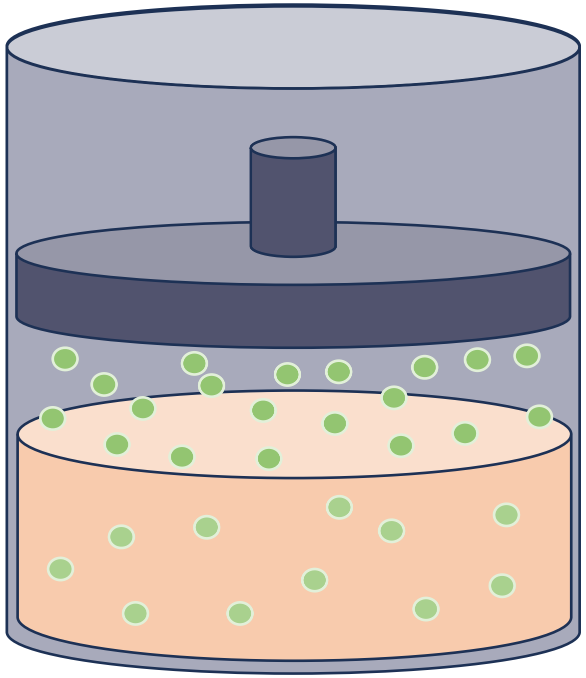
✅ **strong background suppression**



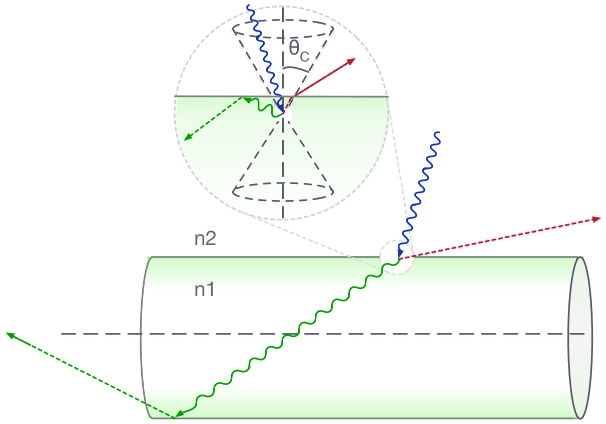


Patents Pending
EP 25 195 873.2 & EP 25 195 874.0

✅ **high signal rate**

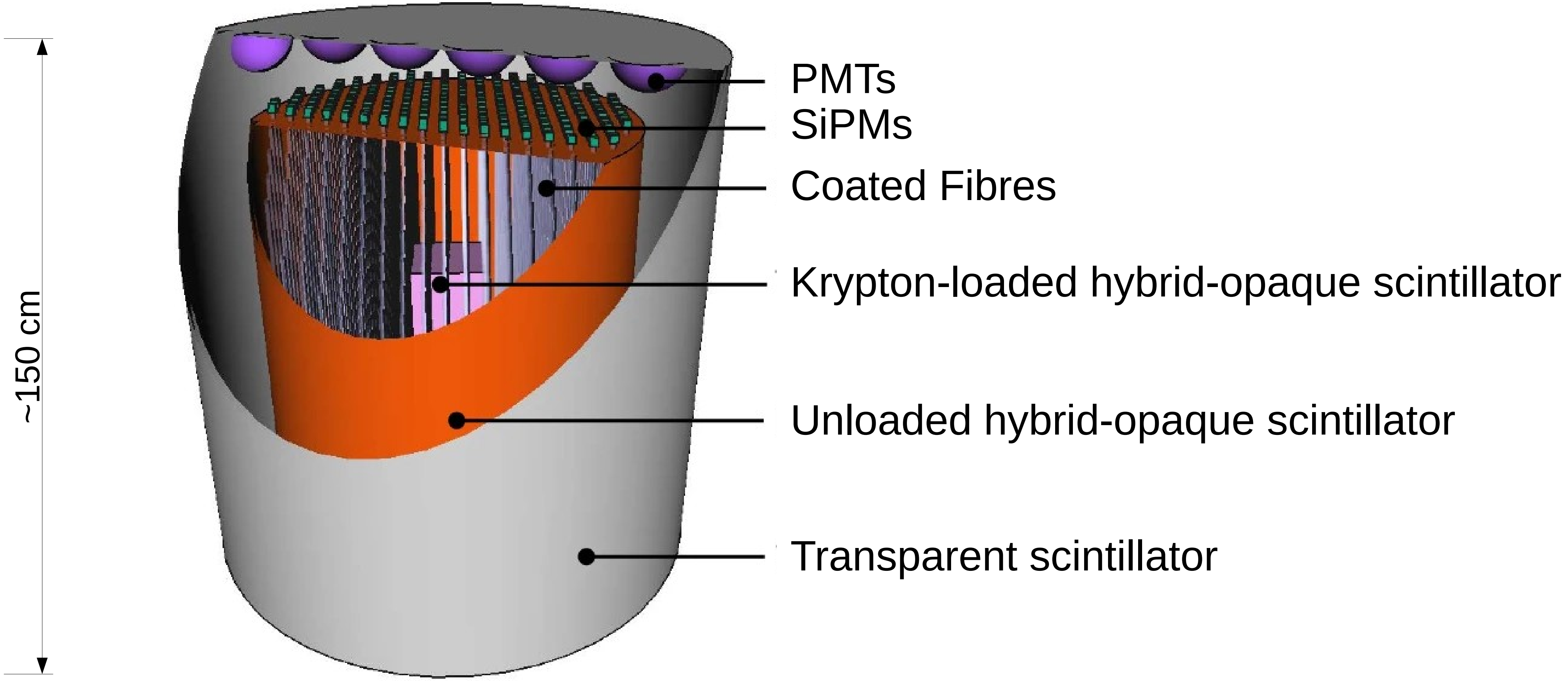


✅ **good energy resolution**



Patent
DE 10 2023 135 496.5

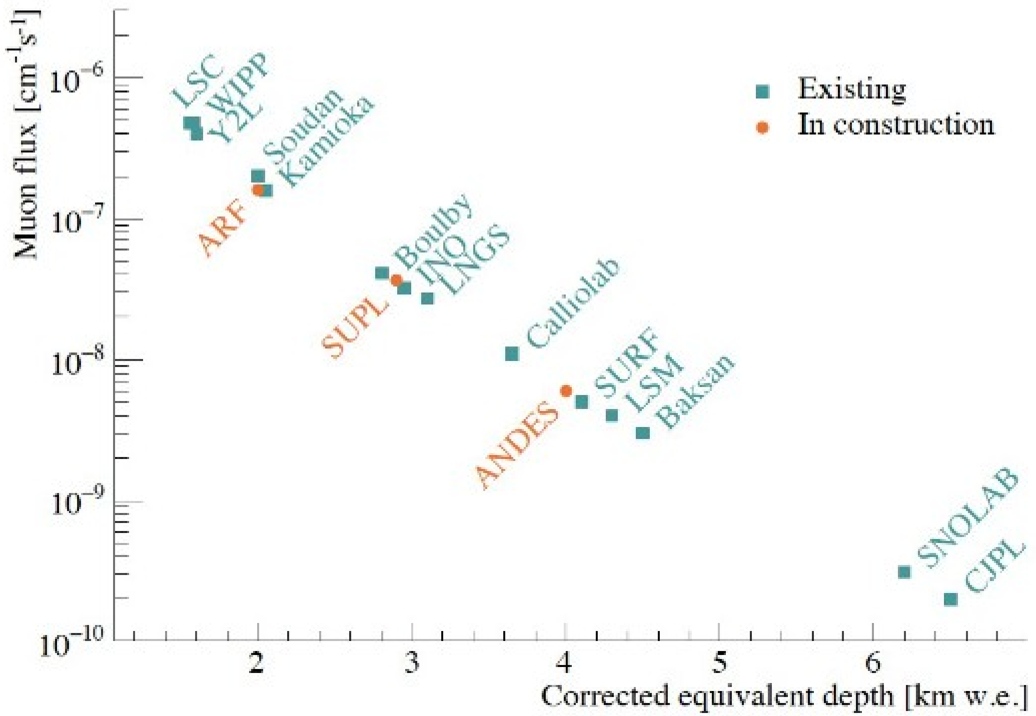
The NuDoubt^{++} Detector Concept

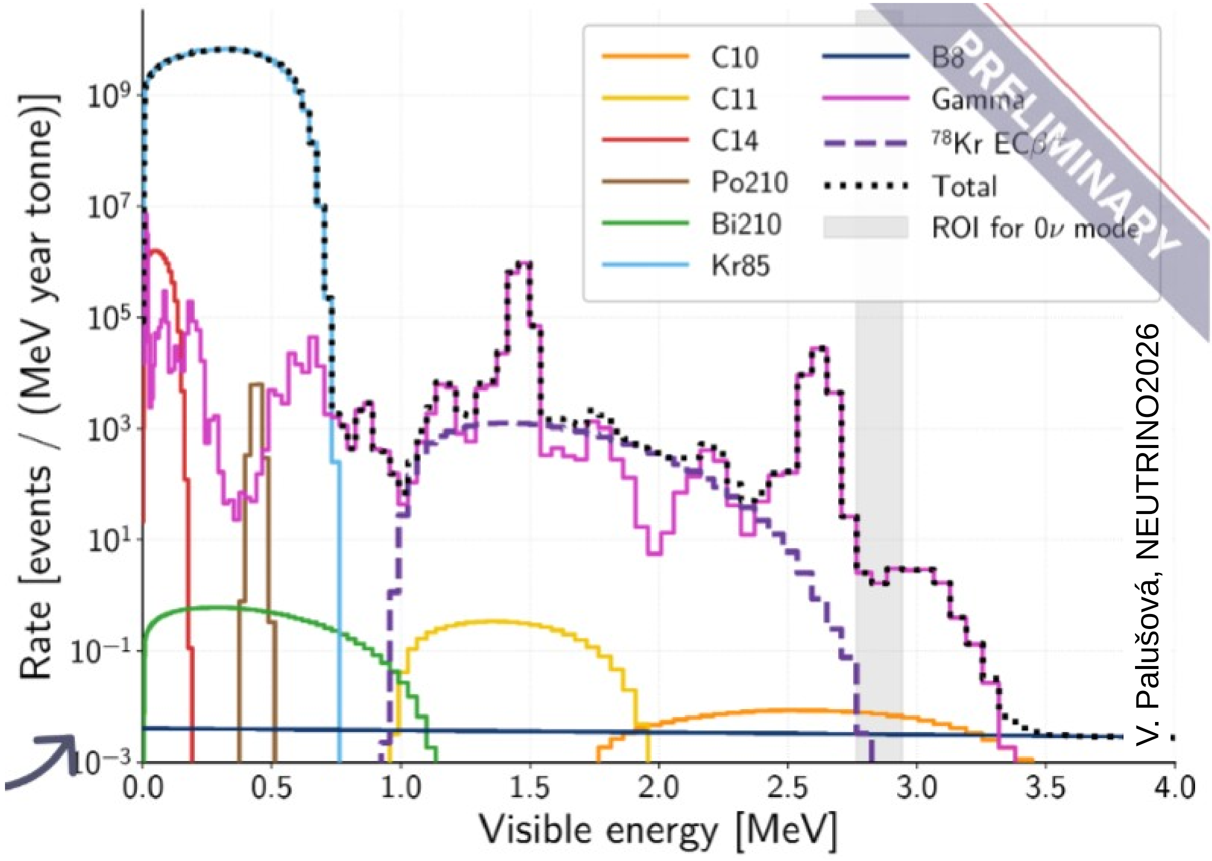


Underground Deployment

Most critical background:
→ muon-induced β+ emitters
→ C-10 and C-11

Mitigation strategy:
→ overburden
→ triple coincidence / after muon veto



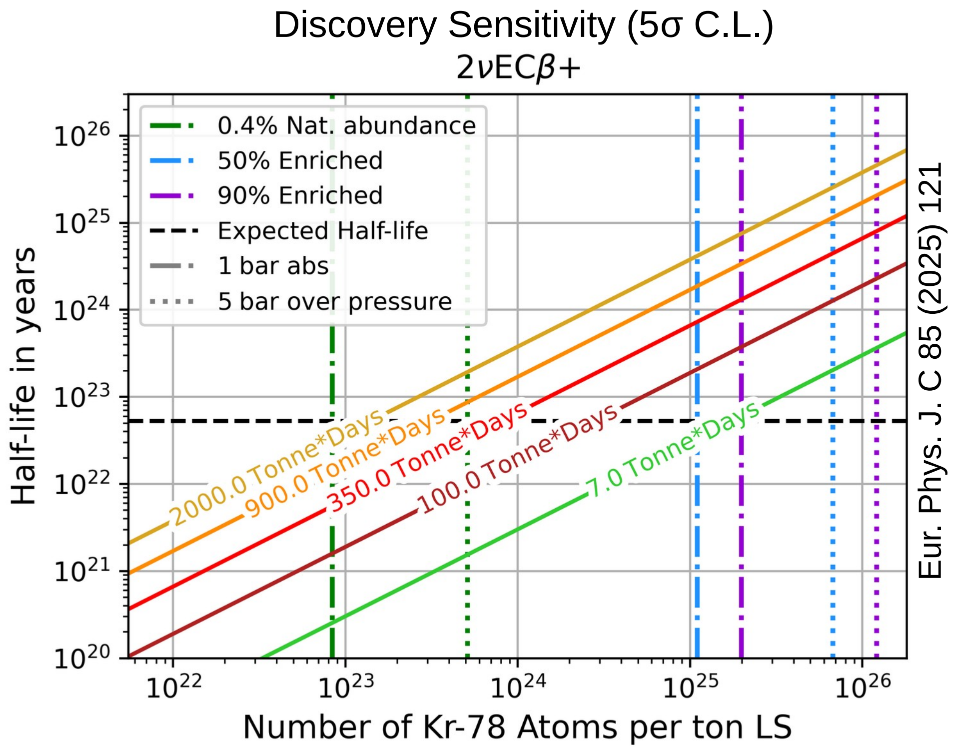


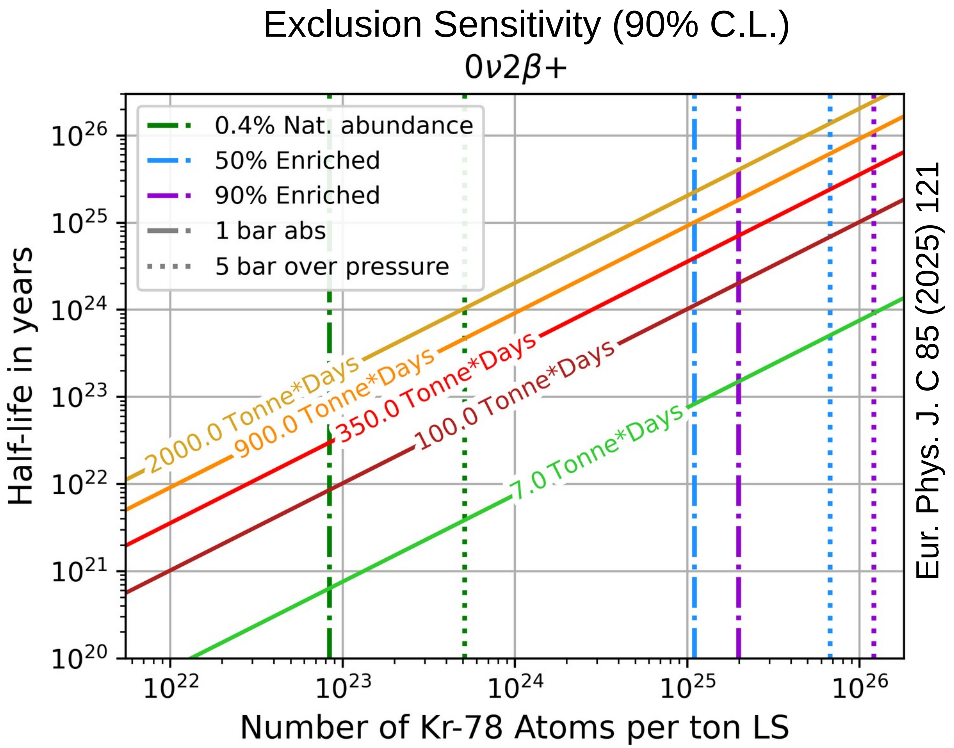
Expected Sensitivity

→ background index 10^{-9} counts/(keV kg year) in region of interest for neutrinoless decays
→ background-free

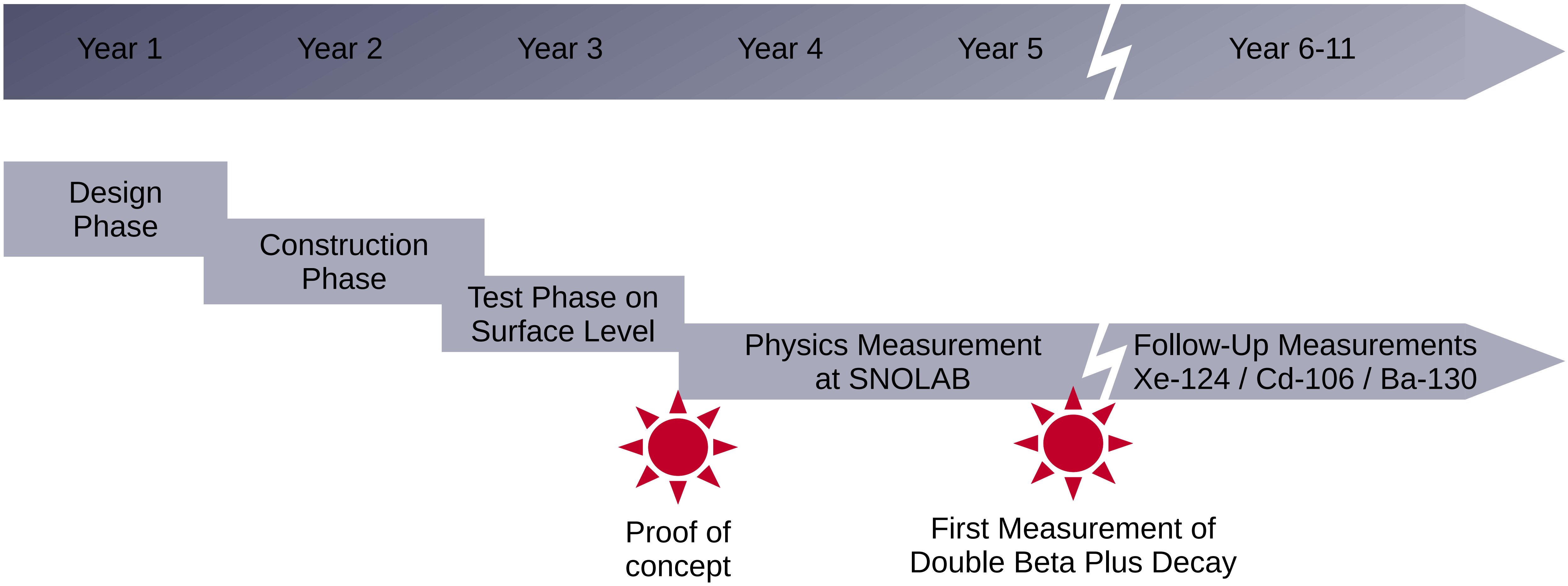
Two-neutrino decay
first measurement

Neutrinoless decay
1000-fold improved limit

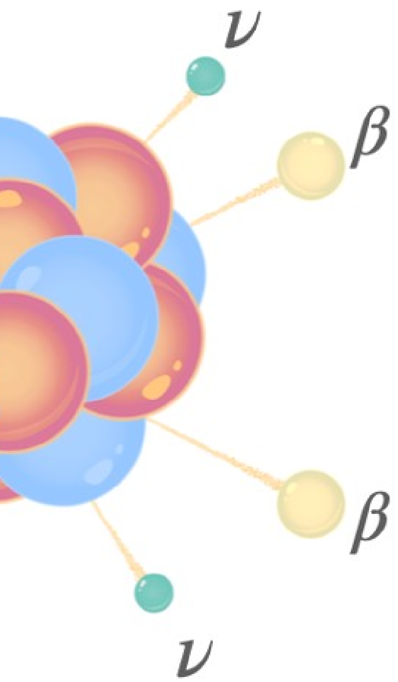




Project Timeline



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 NuDoubt^{++} Collaboration

UC Berkeley

BERKELEY LAB

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

JG|U

Queen's UNIVERSITY

SNOLAB

Photo: C. Girard-Carillo

Contact:
nudoubt@lists.uni-mainz.de

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

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