WIN 2025

9–13 June 2025
University of Sussex, Brighton, UK

WiN 25

NuDoubt++

NuDoubt++ Experiment

The search for neutrinoless double beta plus decay

Susie Wakely

On behalf of the NuDoubt++ collaboration

NuDoubt++ paper:

Combining Hybrid and Opaque Scintillator Techniques in the Search for Double Beta Plus Decays

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

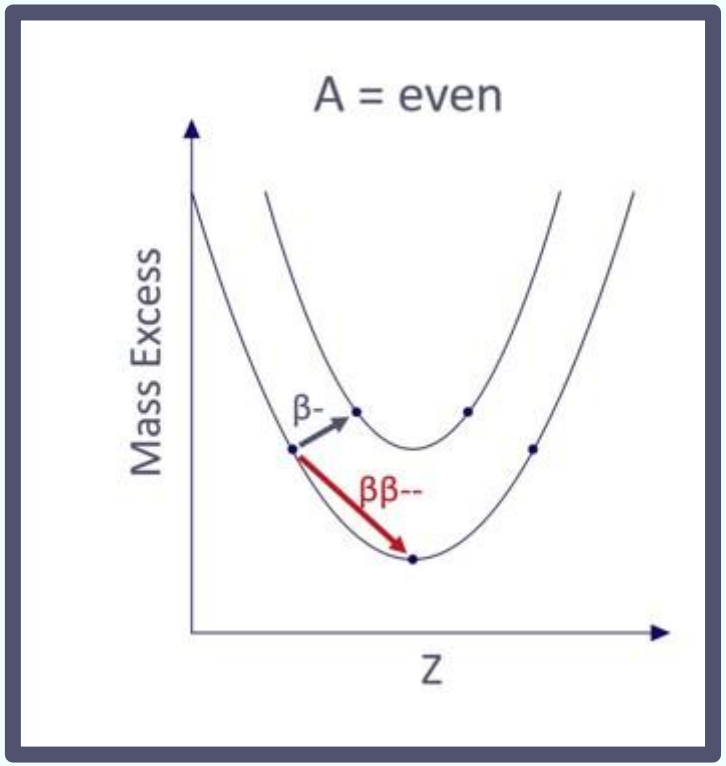
JG|U

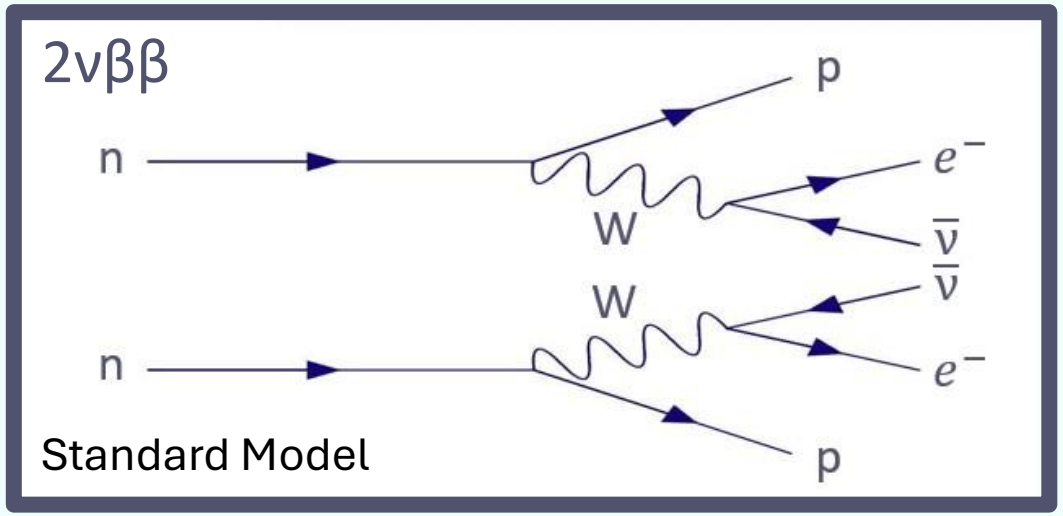
PRISMA+ Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

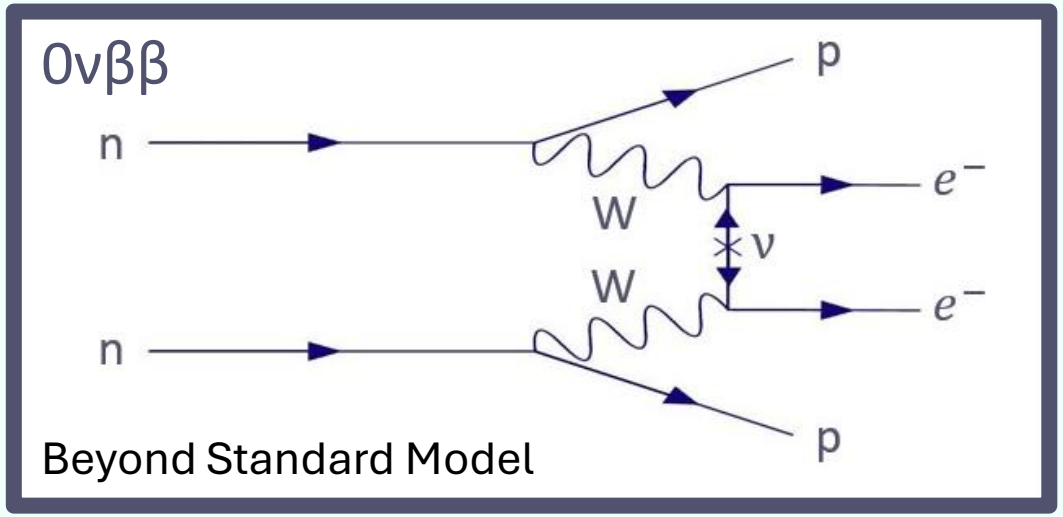
swakely@uni-mainz.de

Double Beta Decay

Occurs when single beta decay is energetically forbidden







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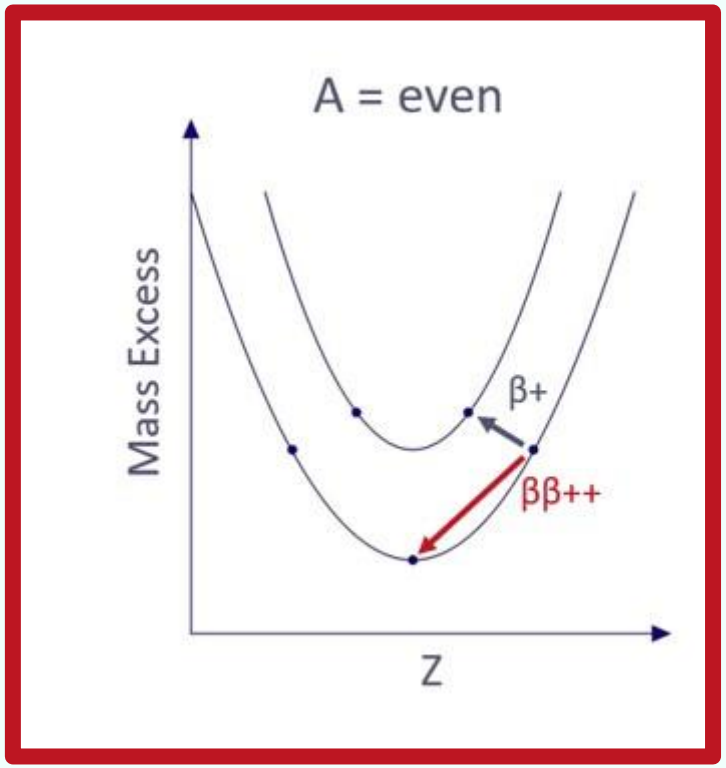
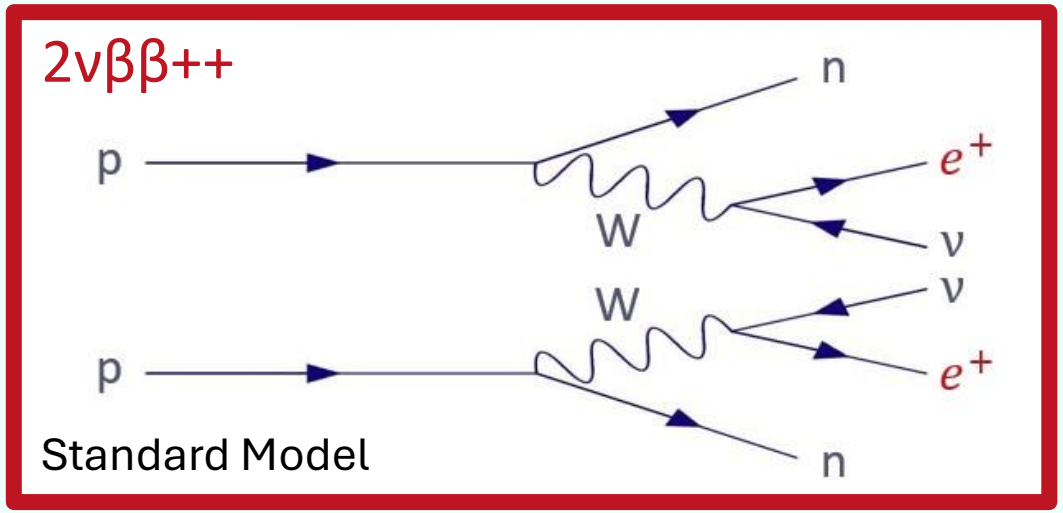
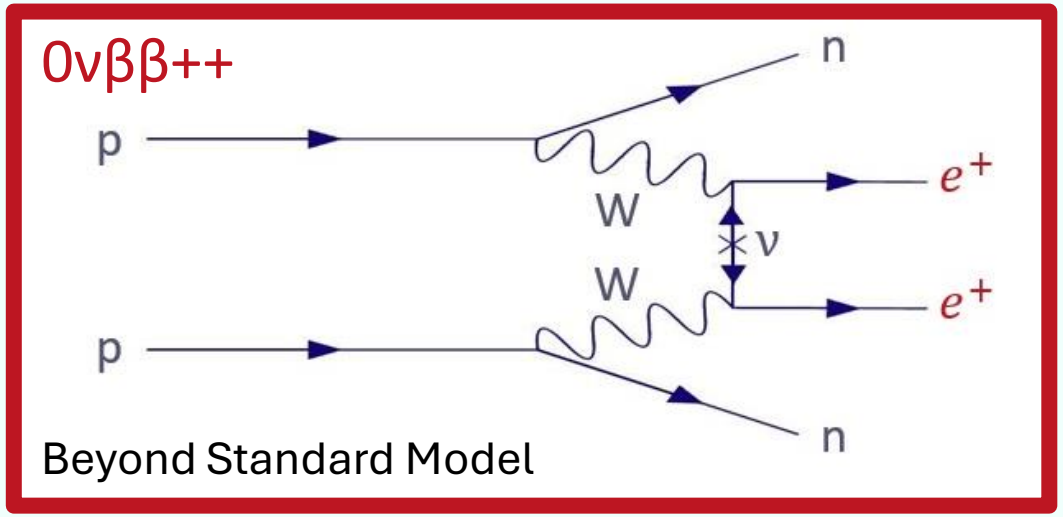
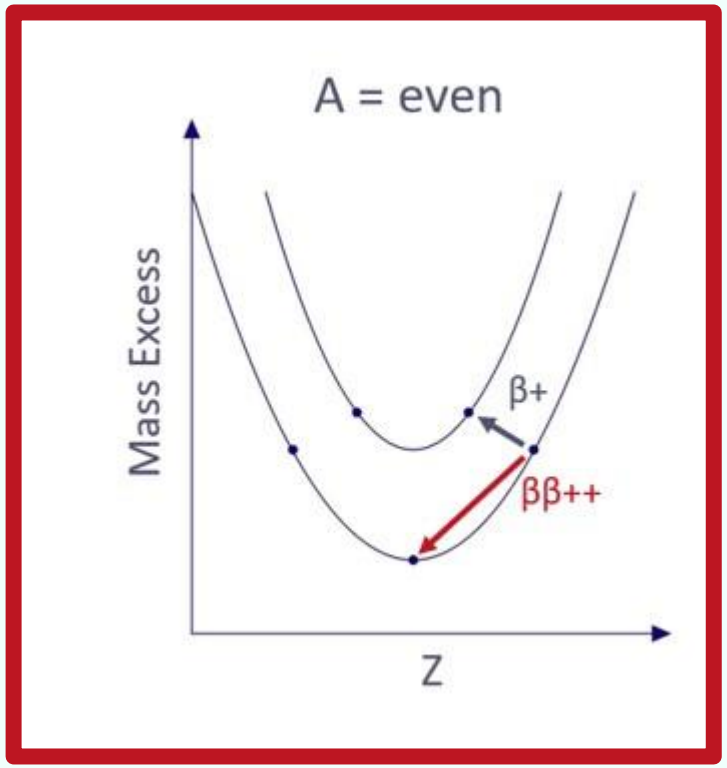






Double Beta Plus Decay

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



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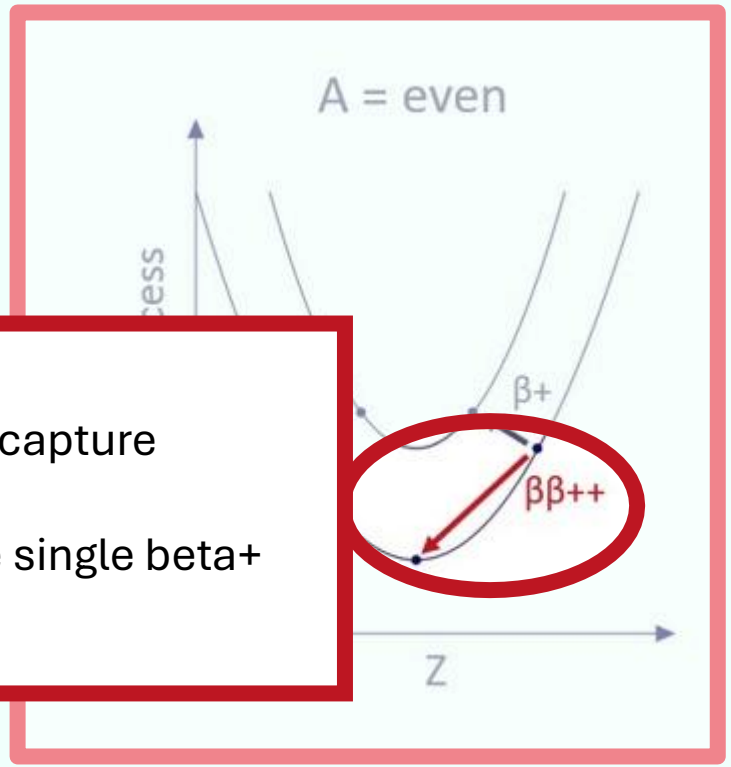

Also possible via:
- double electron capture (ECEC)
- electron capture single beta+ (ECβ+)

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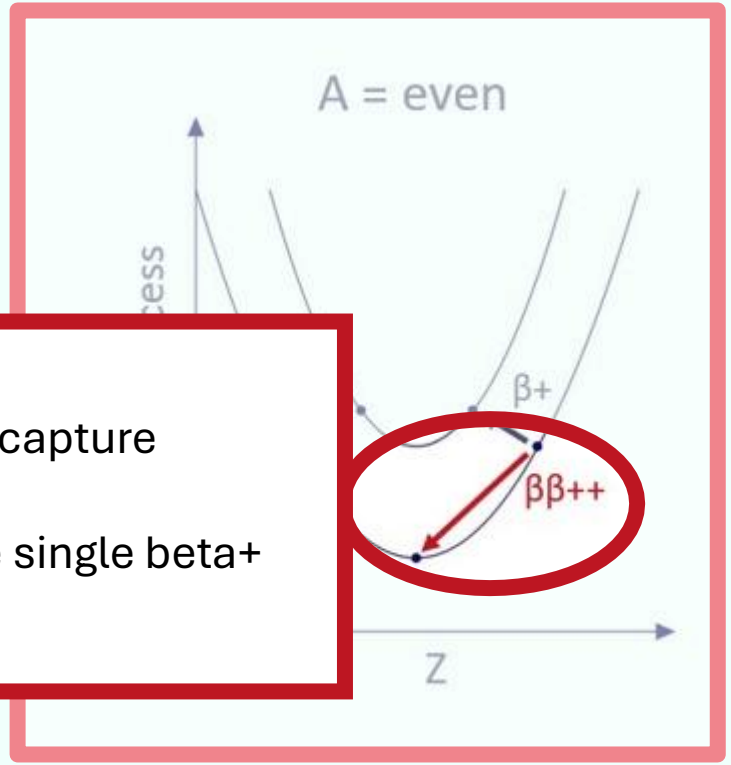

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NuDoubt^{++} will be sensitive to:
- **2νββ++ (0νββ++)**
- **2νECβ+ (0νECβ+)**

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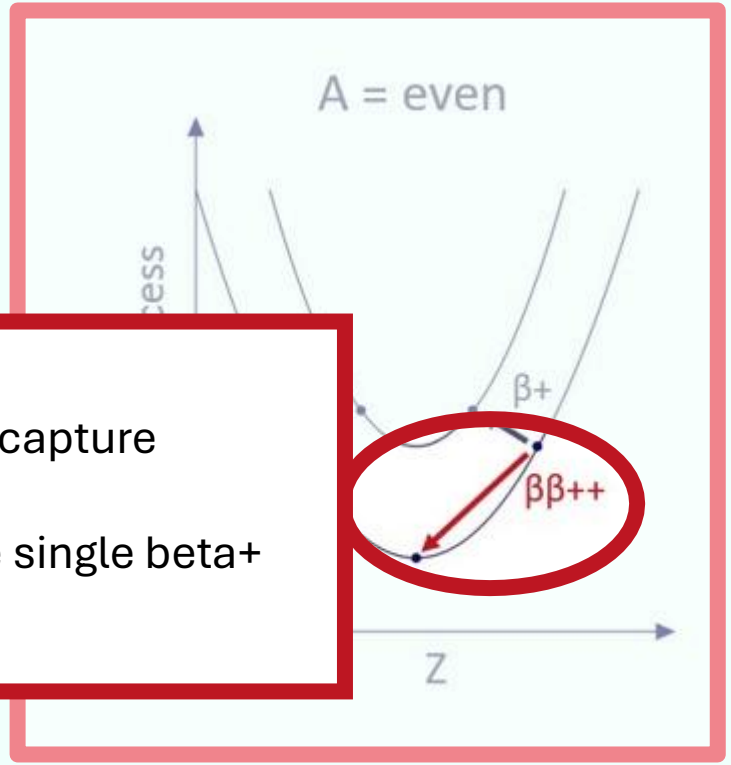

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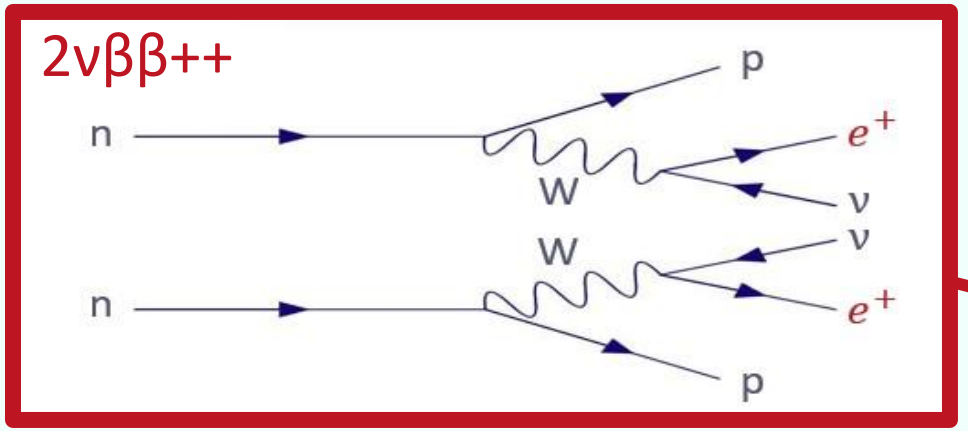
NuDoubt^{++} will be sensitive to:
- **2νββ++ (0νββ++)**
- **2νECβ+ (0νECβ+)**

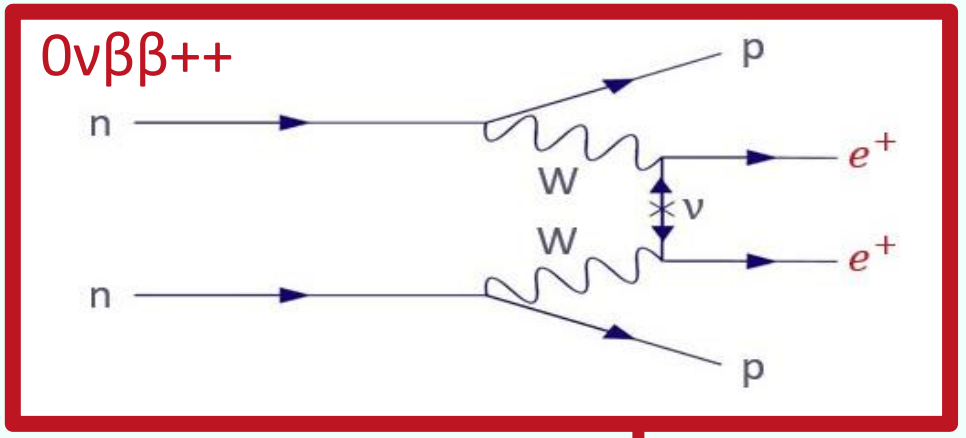
ie. Positron producing processes

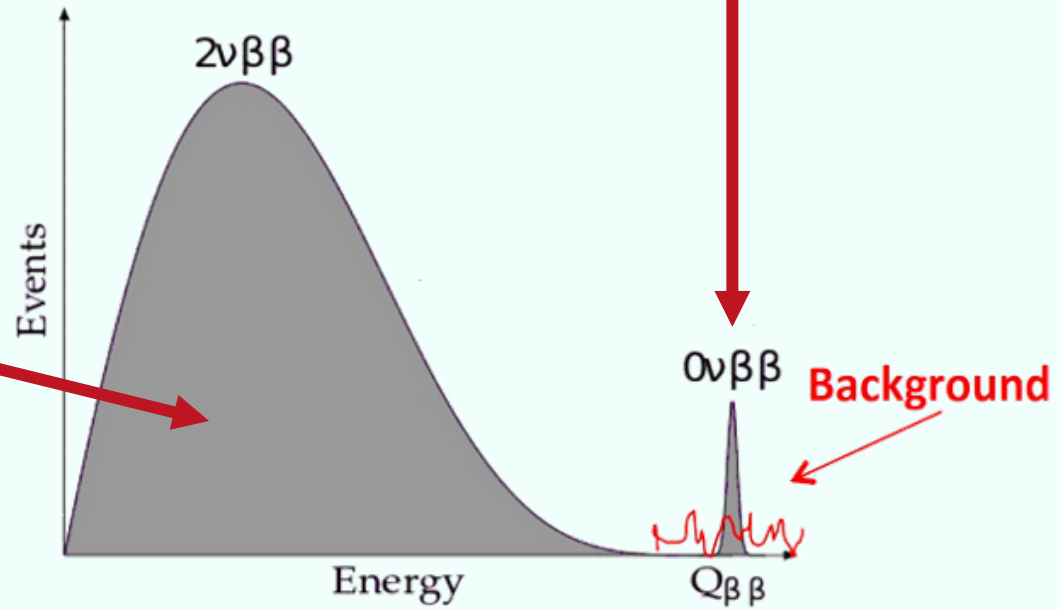
Double Beta Plus Decay

Need to:

- **Identify** positrons
- Reconstruct positron **energy**



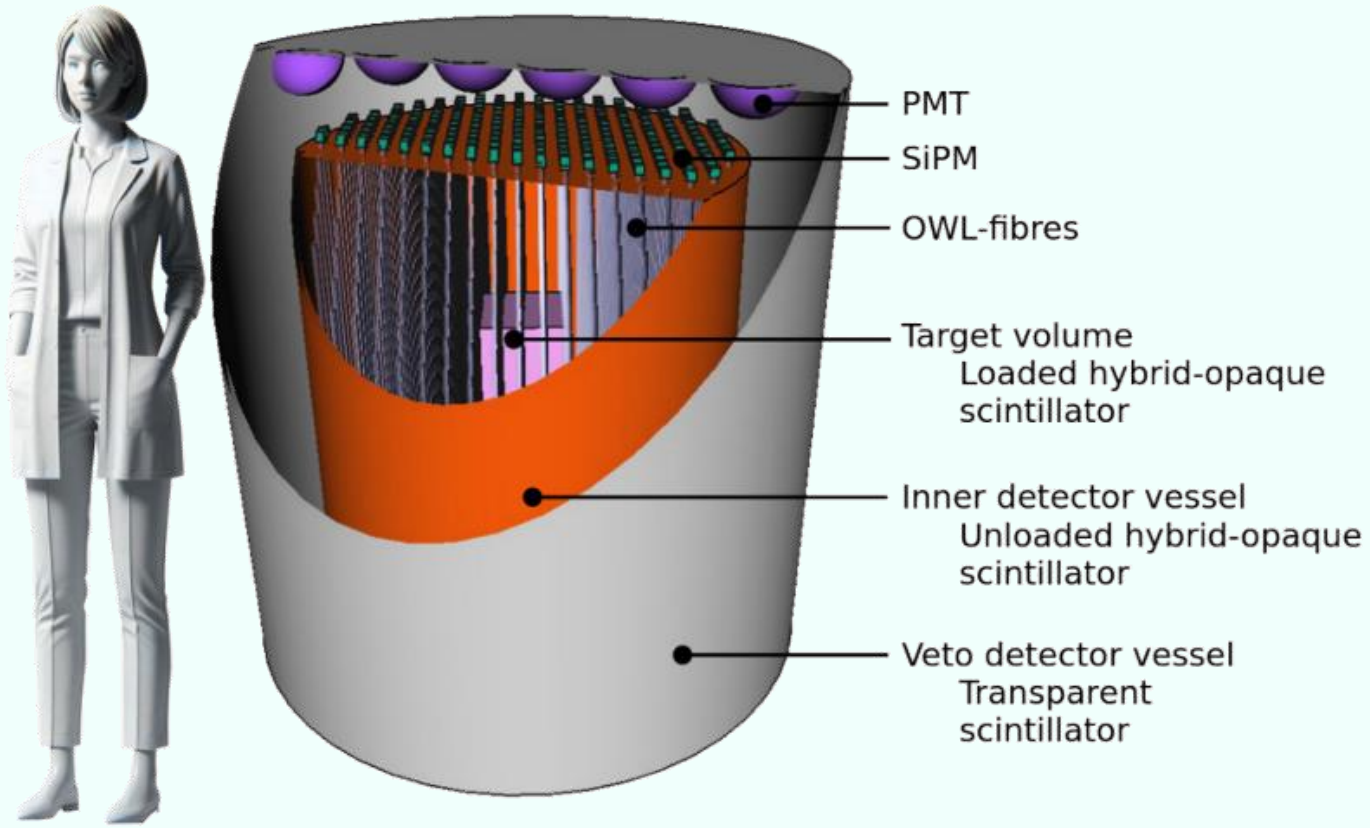




NuDoubt^{++}

First Prototype

- 50% enriched Krypton-78 gas
- 5 bar overpressure
- 10 kg scintillator mass (~1% isotope) in central fiducial vessel



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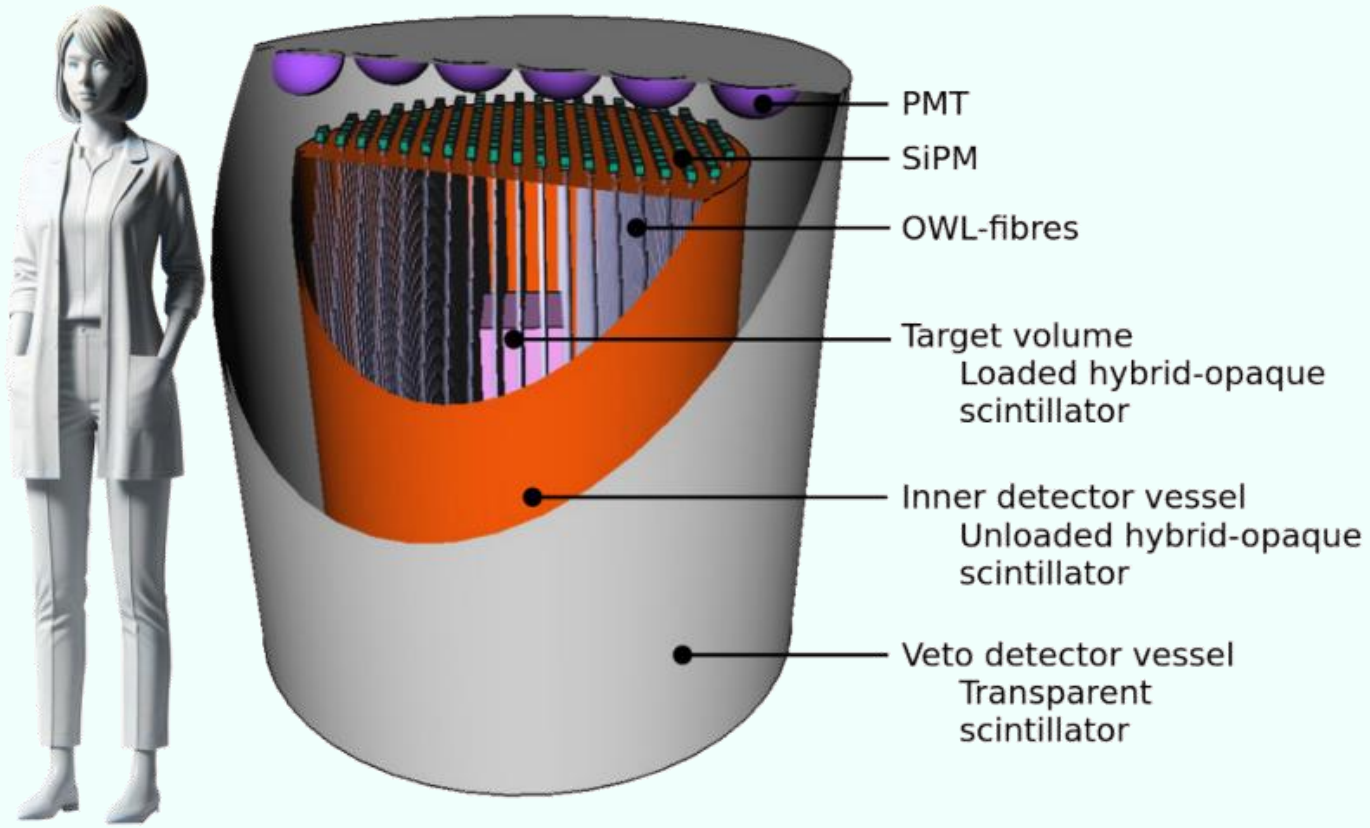
Combining 3 novel technologies



NuDoubt^{++} Prototype

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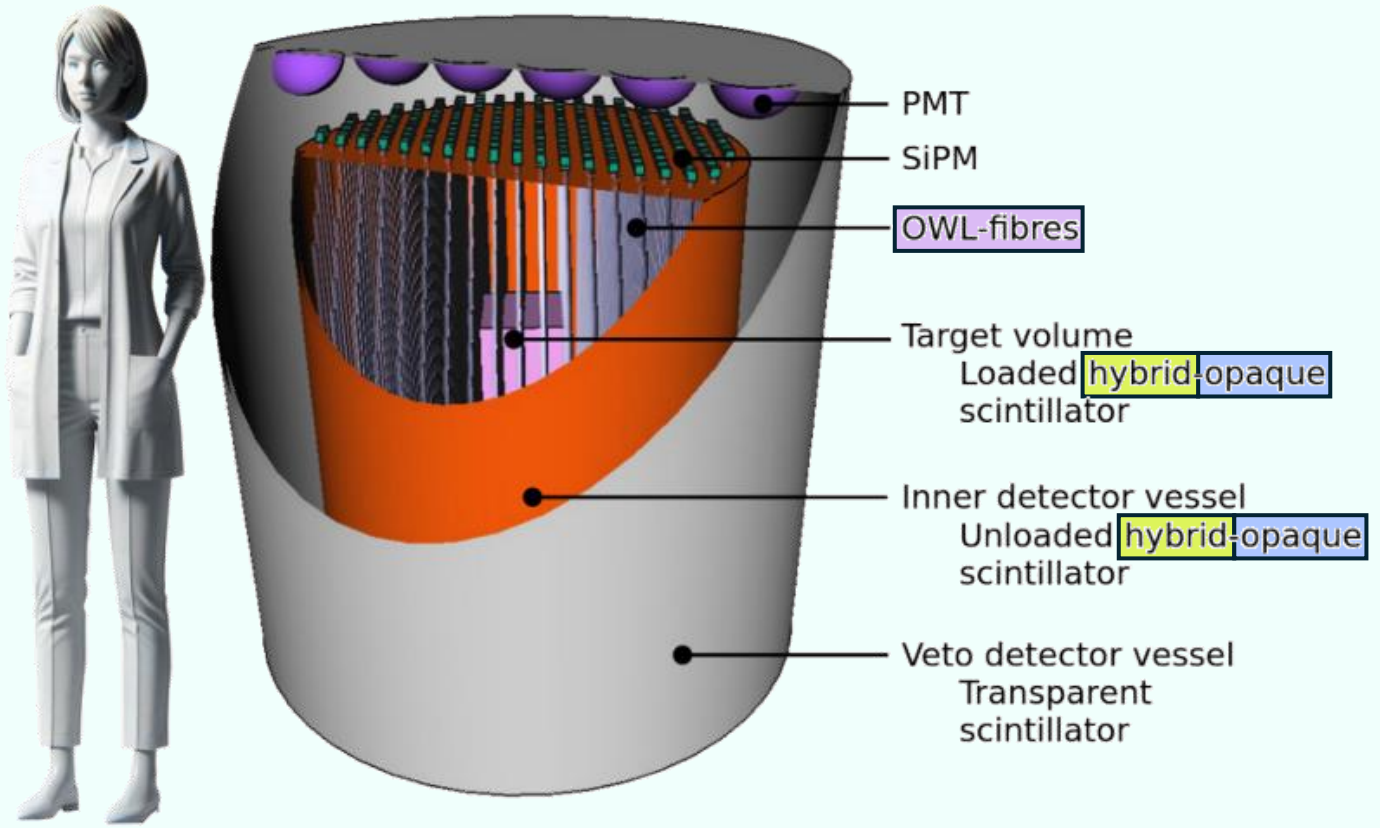


NuDoubt^{++} Prototype

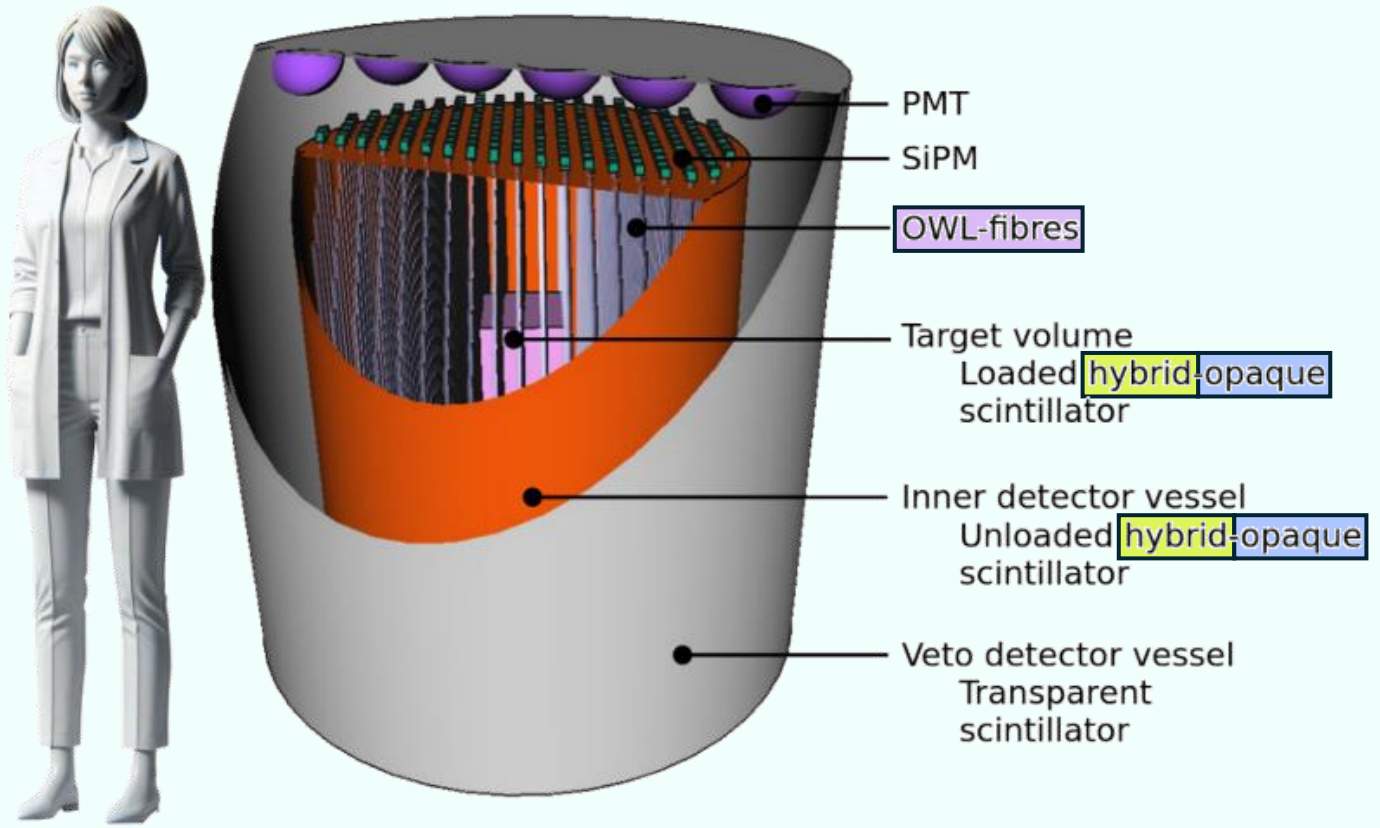
Combining 3 novel technologies

OWL-fibres

- Based on WOMs (IceCube)
- Wavelength shifter coated on fibre to maximise photon capture

Hybrid-Slow Opaque Scintillator

- Separate Cherenkov and scintillation light in time
- Stochastic confinement of light for improved PID



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Opaque Scintillator

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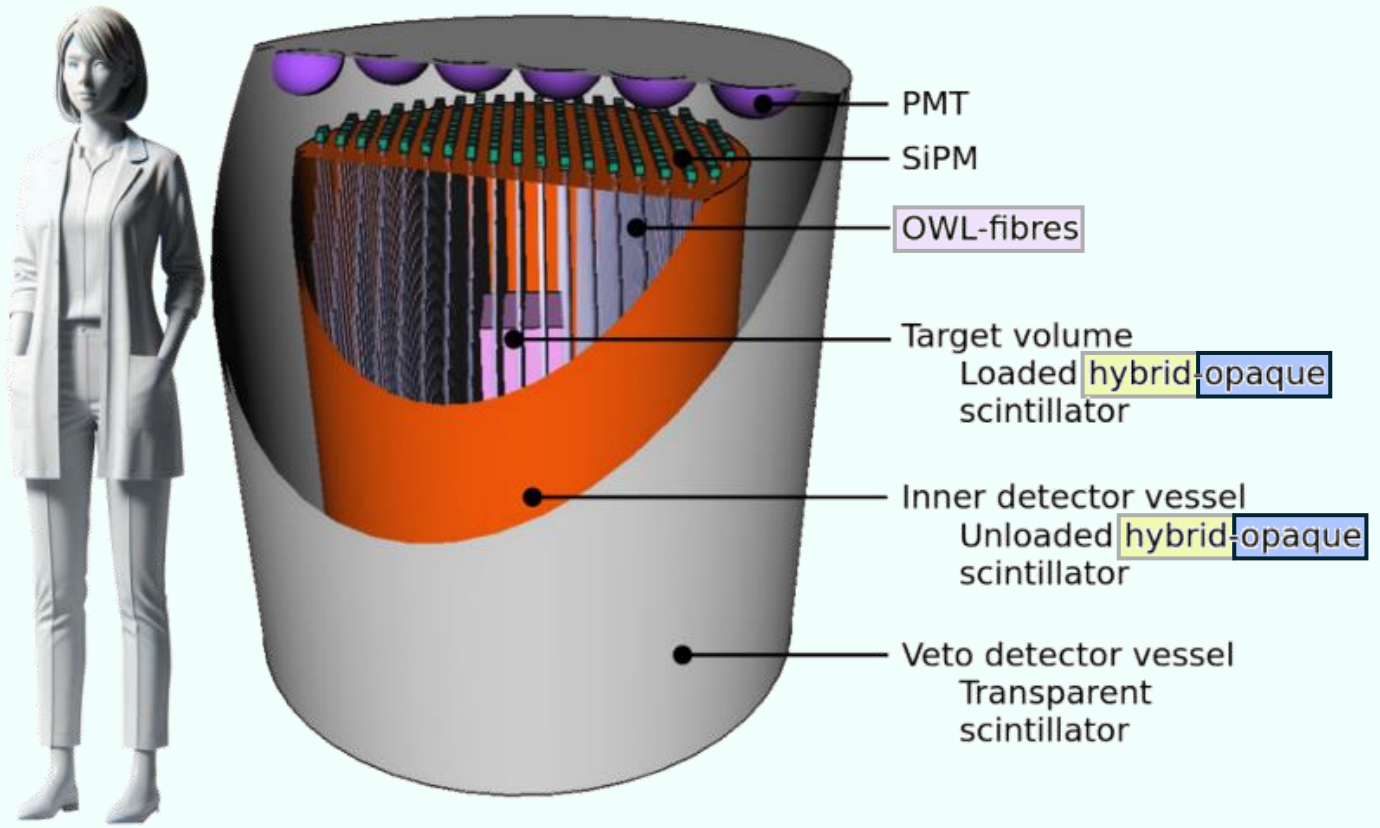
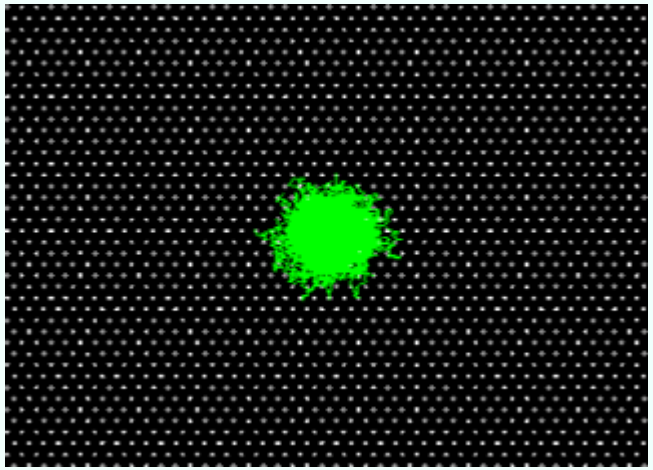


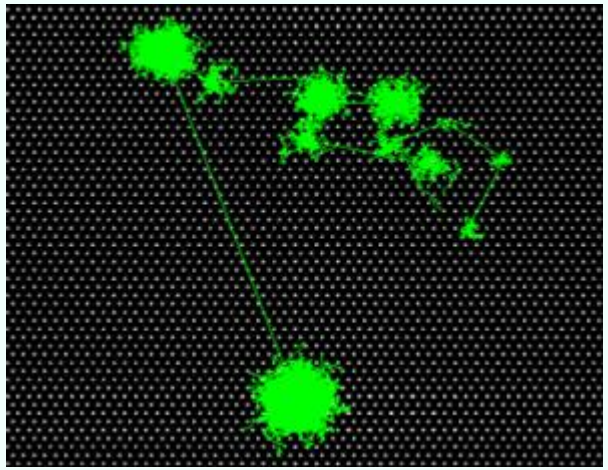
Opaque Scintillator

Short scattering length + Long absorption length = Stochastic light confinement

Particle ID from event topology (pattern of energy deposits)

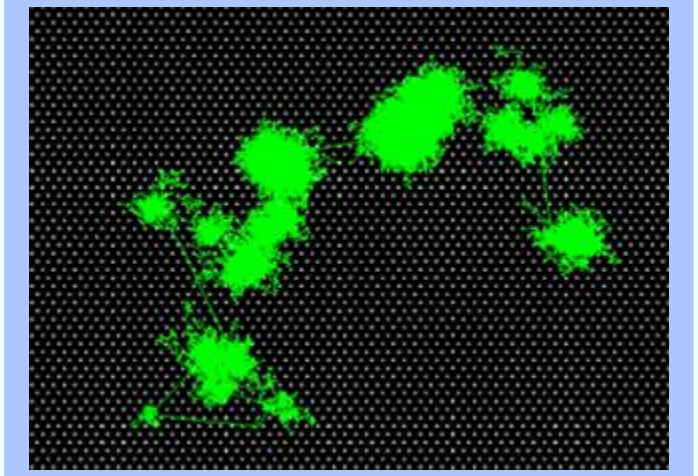


Electron



Gamma

(Compton Scattering)



Positron

(electron-like + 2 x 511keV gammas)

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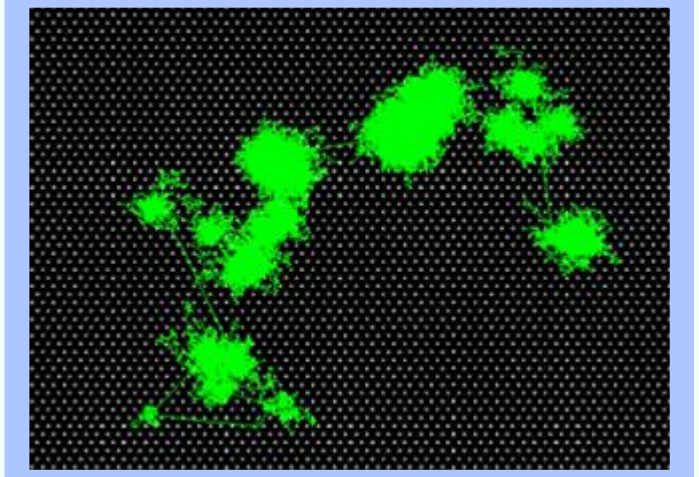

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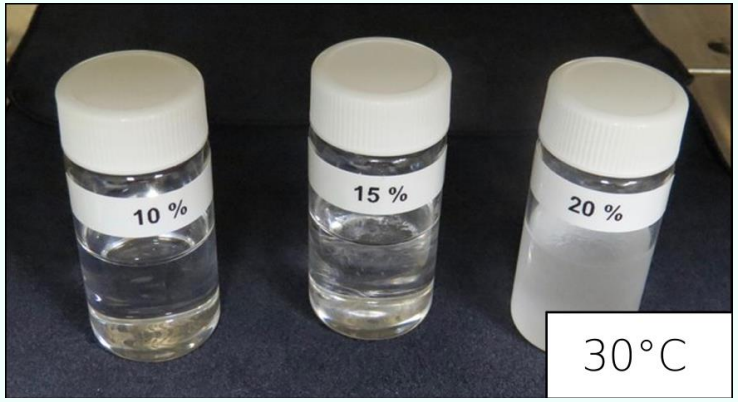
First implementation of opaque scintillator: adding wax to LS (NoWaSH)



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

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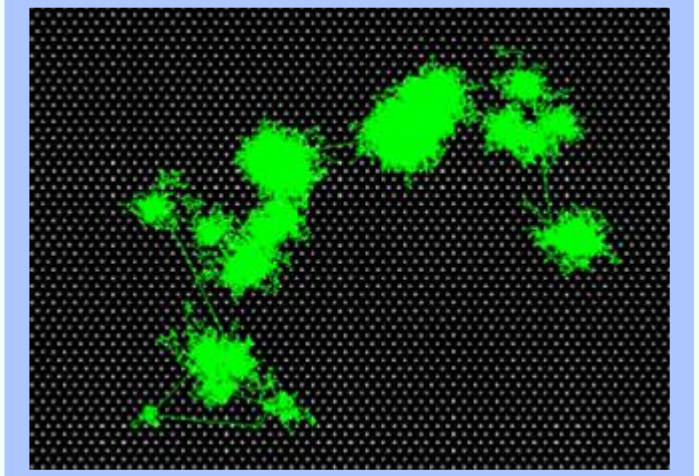

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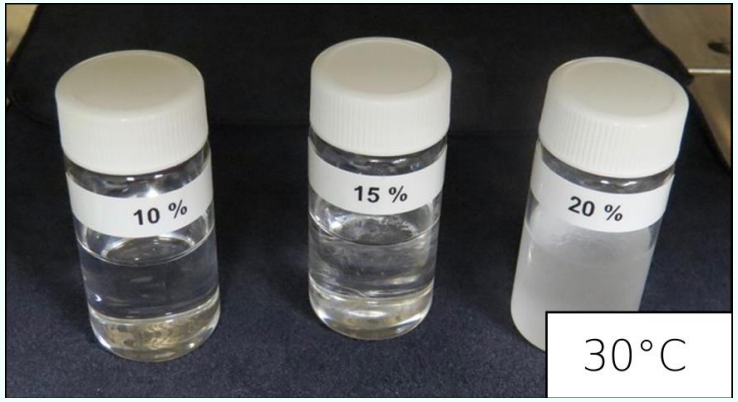

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Additional properties:

- Tuneable opacity
- High fluor/isotope concentration is possible
- Comparable light yield to transparent scintillators

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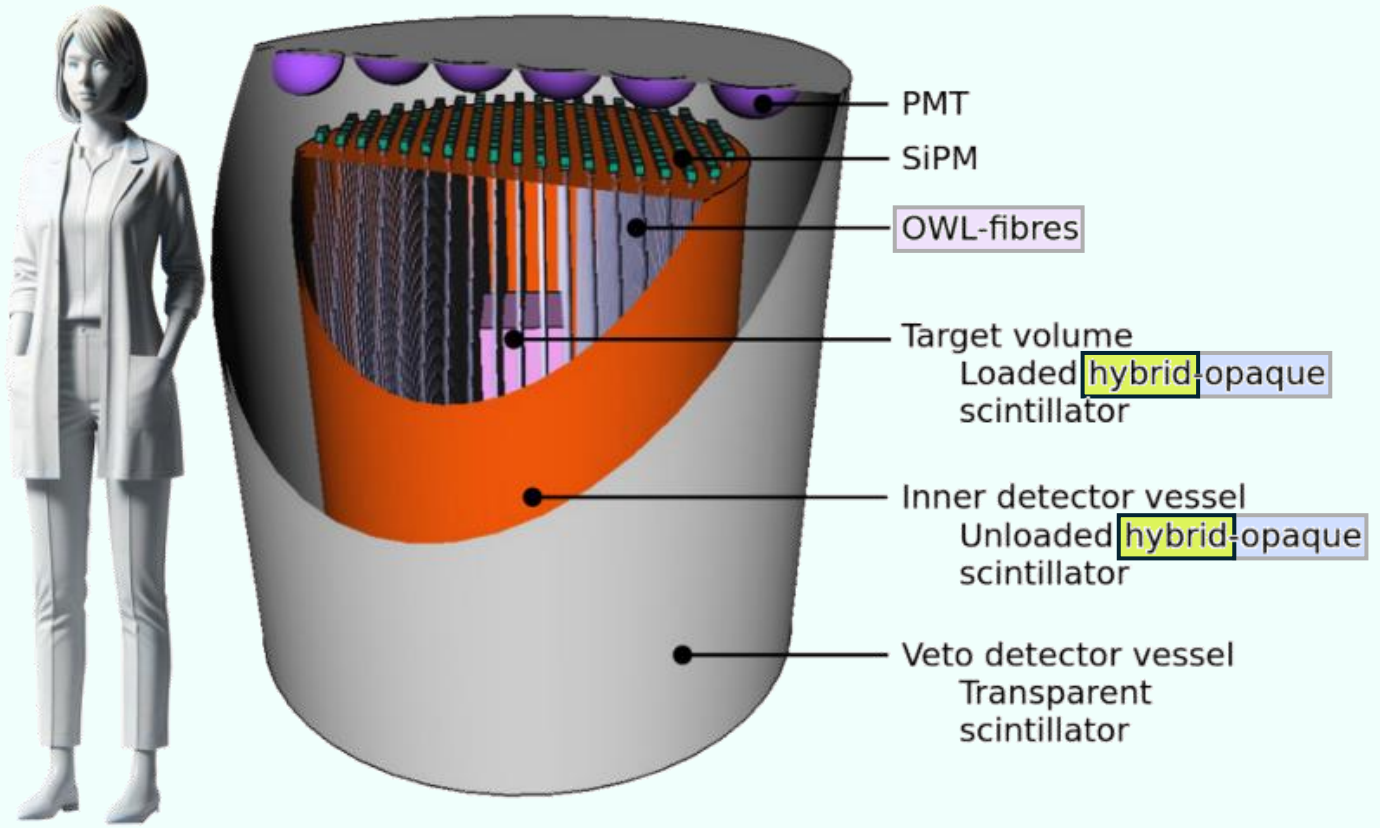
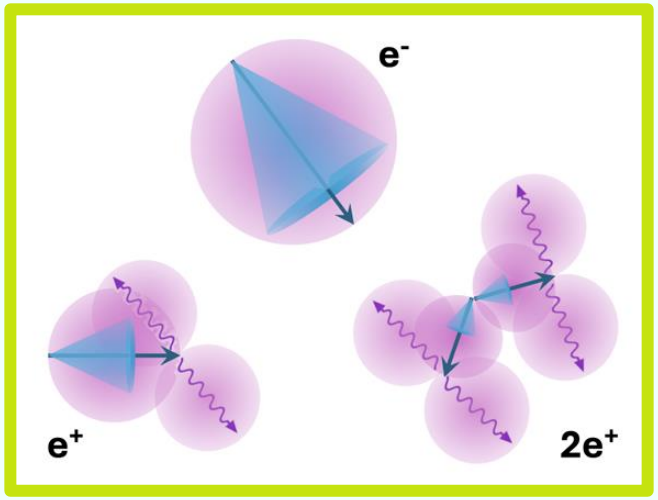
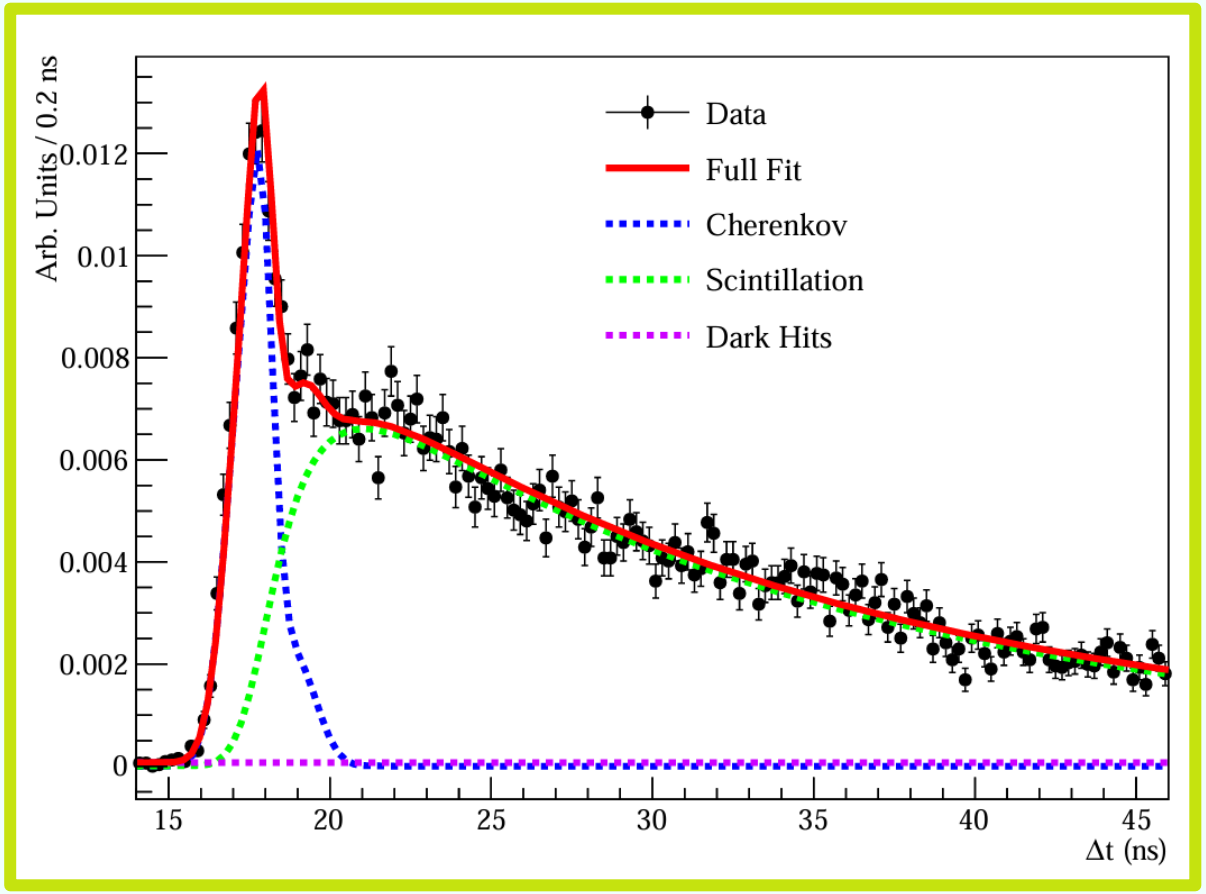


Hybrid-Slow Scintillator

Cherenkov/Scintillator ratio

- Slow scintillator separates Cherenkov and scintillation signals





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

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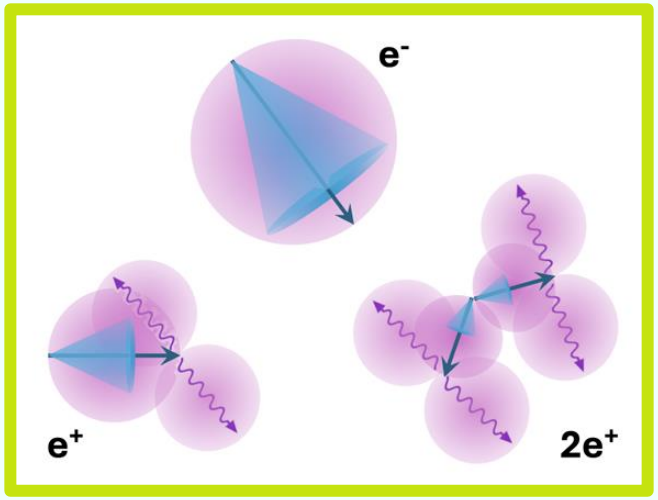
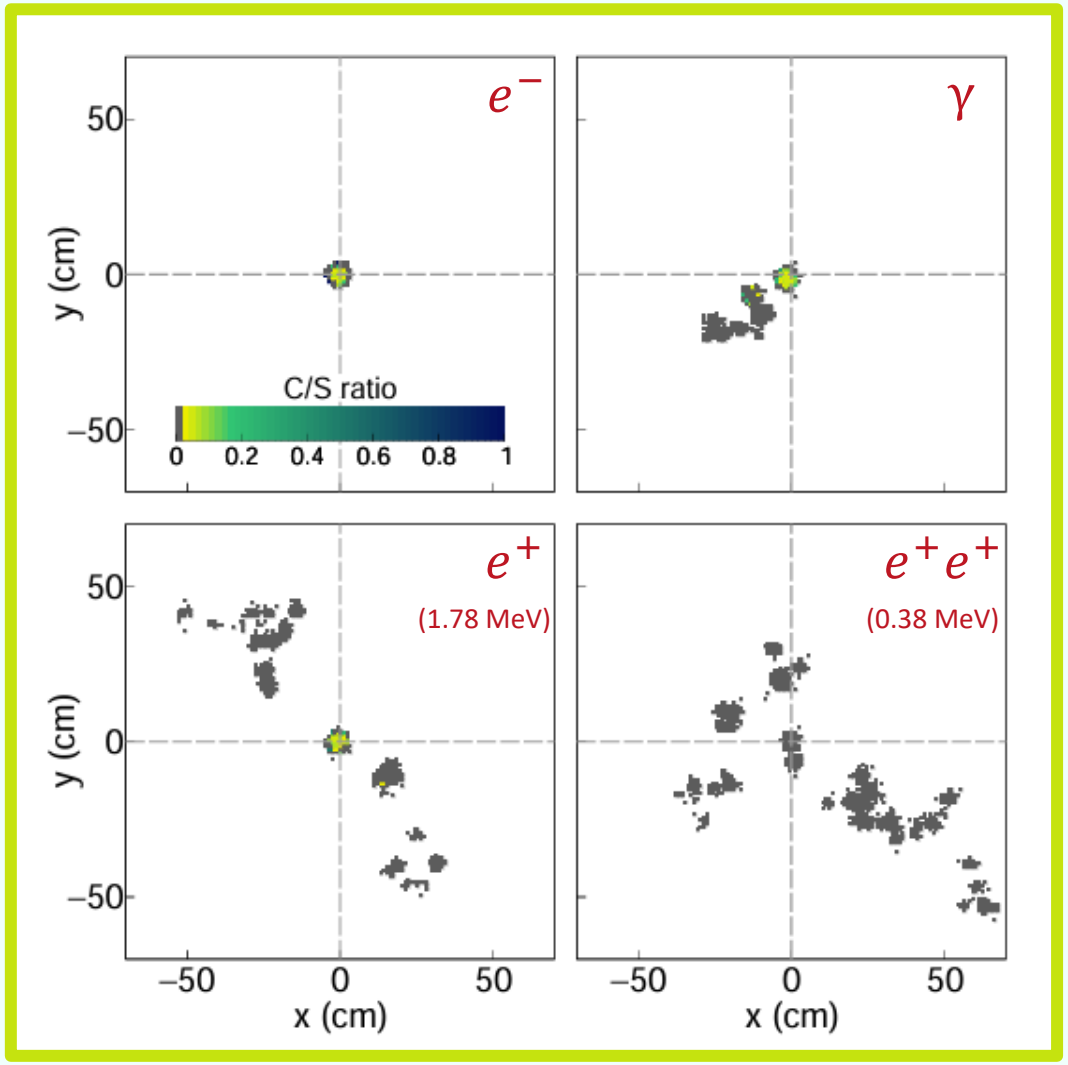


C/S for 2.8 MeV deposited in detector

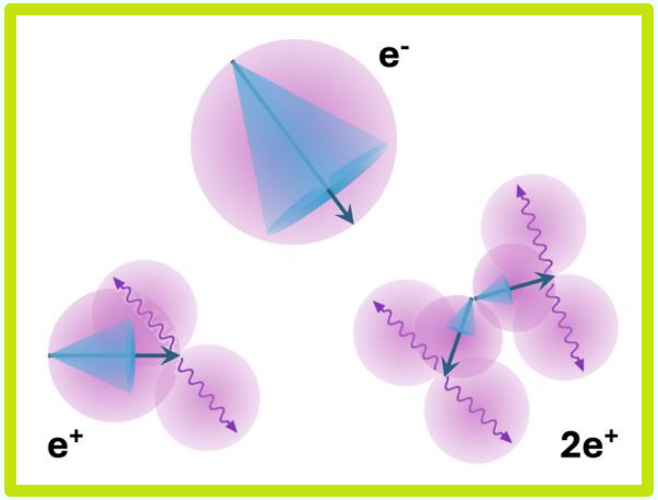


Hybrid-Slow Scintillator

Cherenkov/Scintillator ratio

- Slow scintillator separates Cherenkov and scintillation signals
- Ratio of Cherenkov to scintillation light depends on particle

=> Particle ID from C/S ratio



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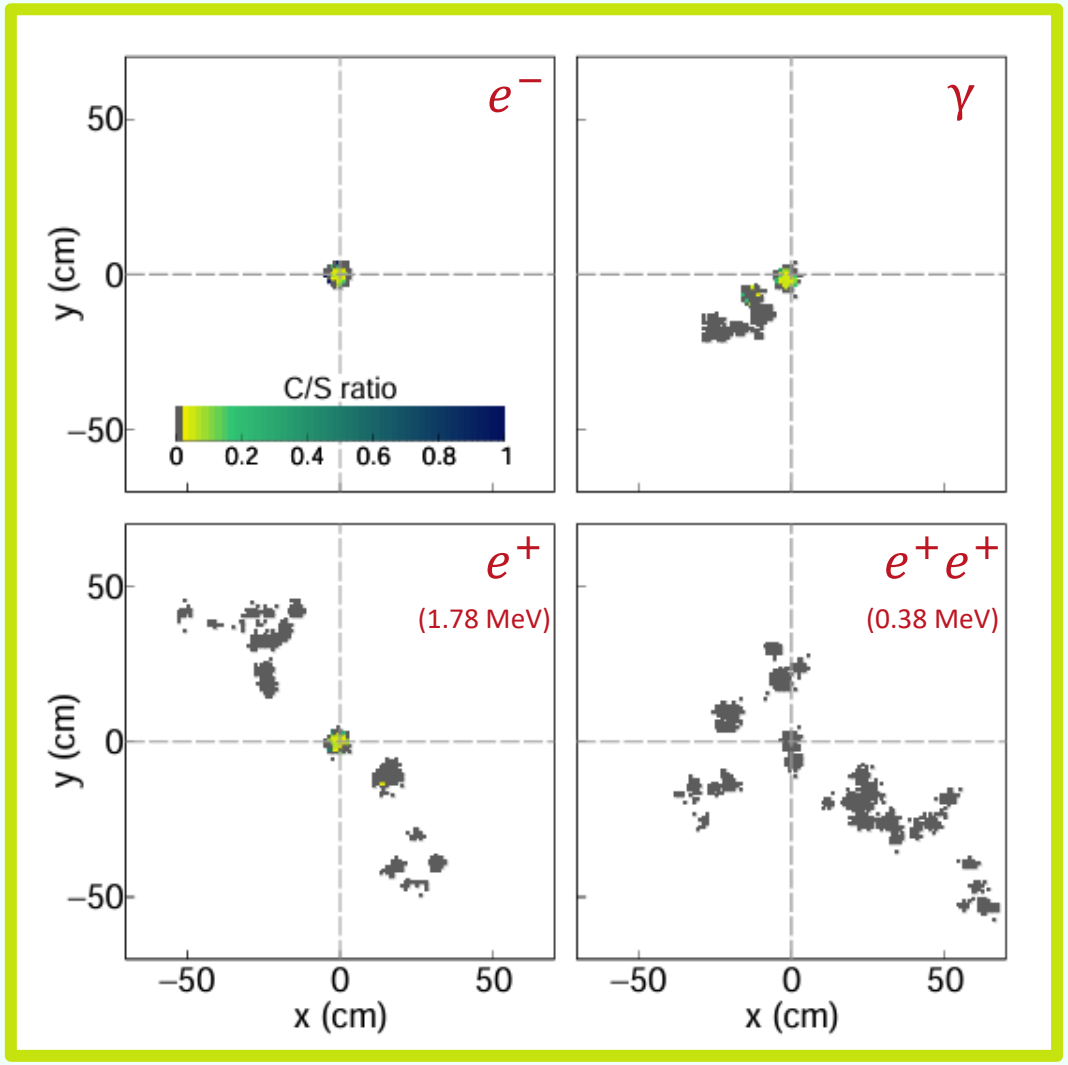

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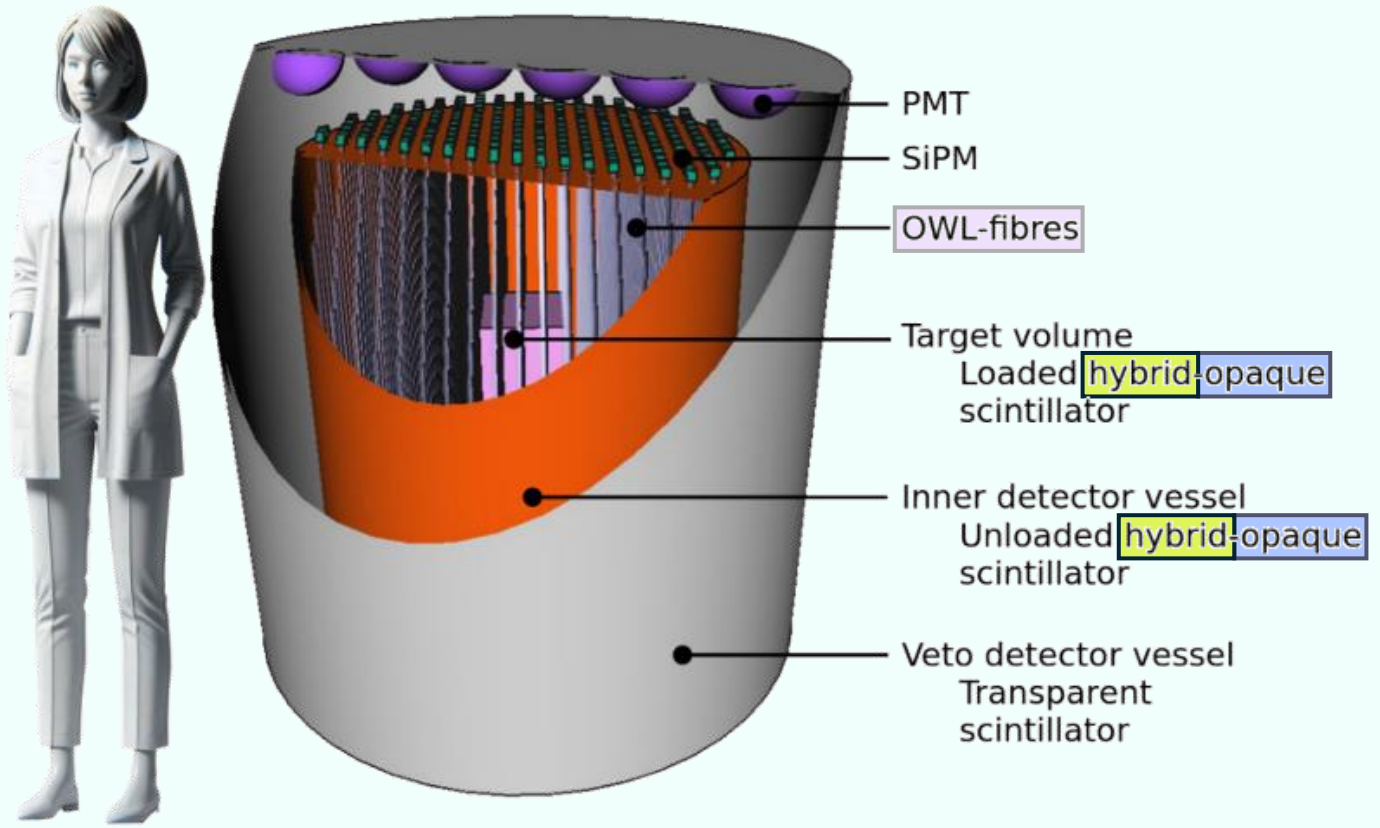

Hybrid-Opaque Scintillator

PID & Positron Energy

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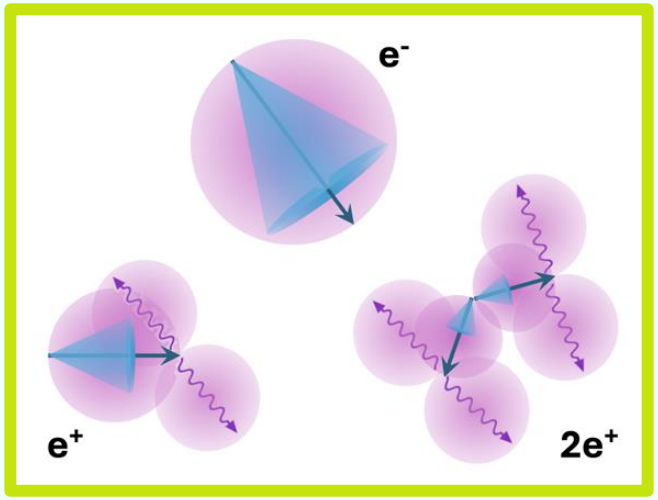

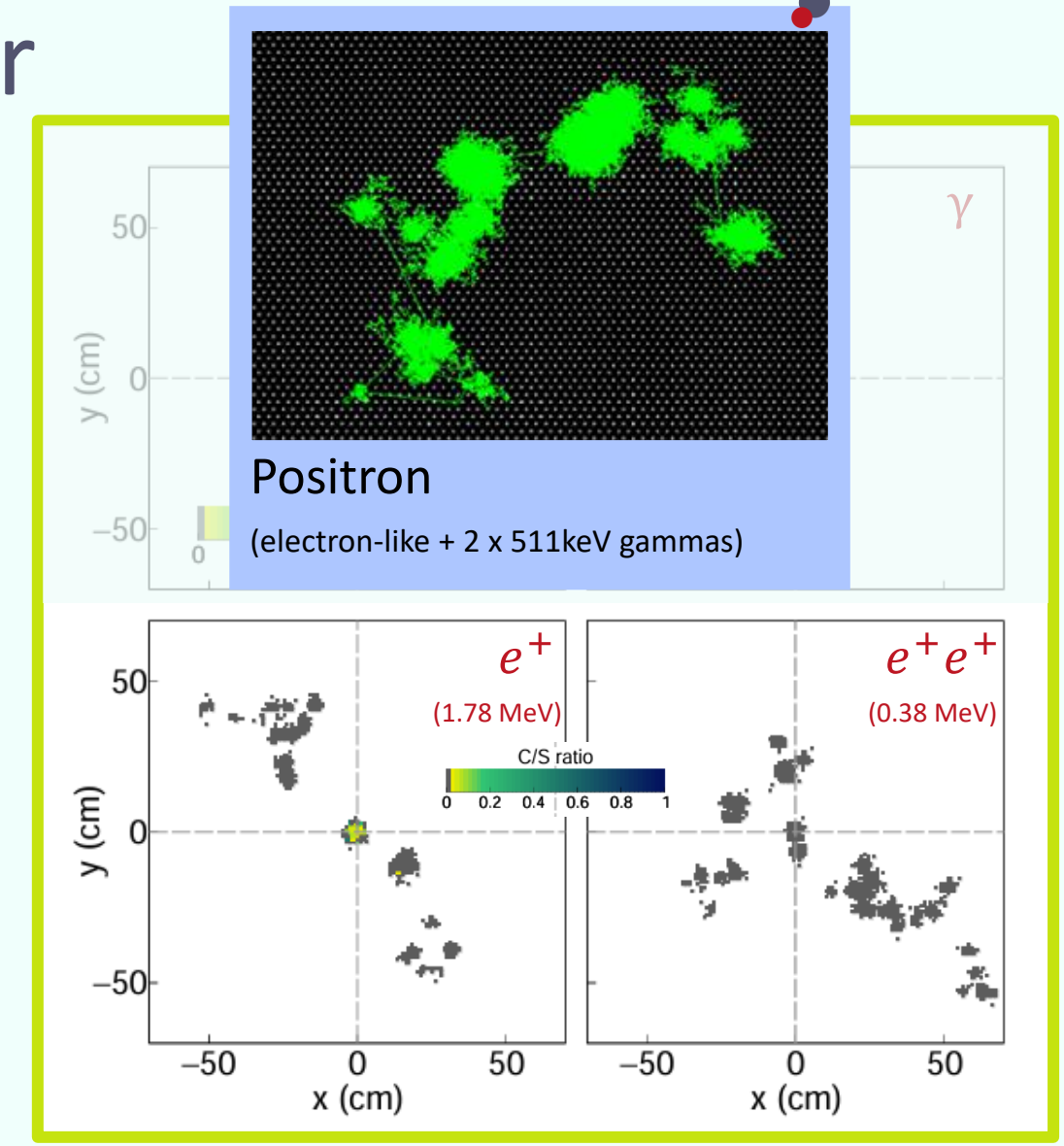

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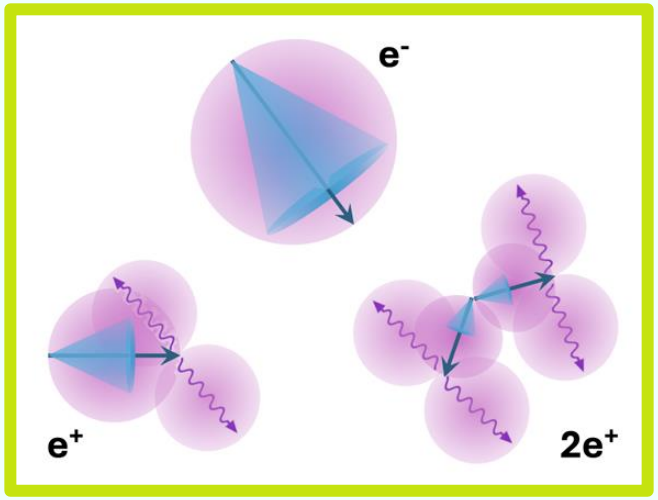

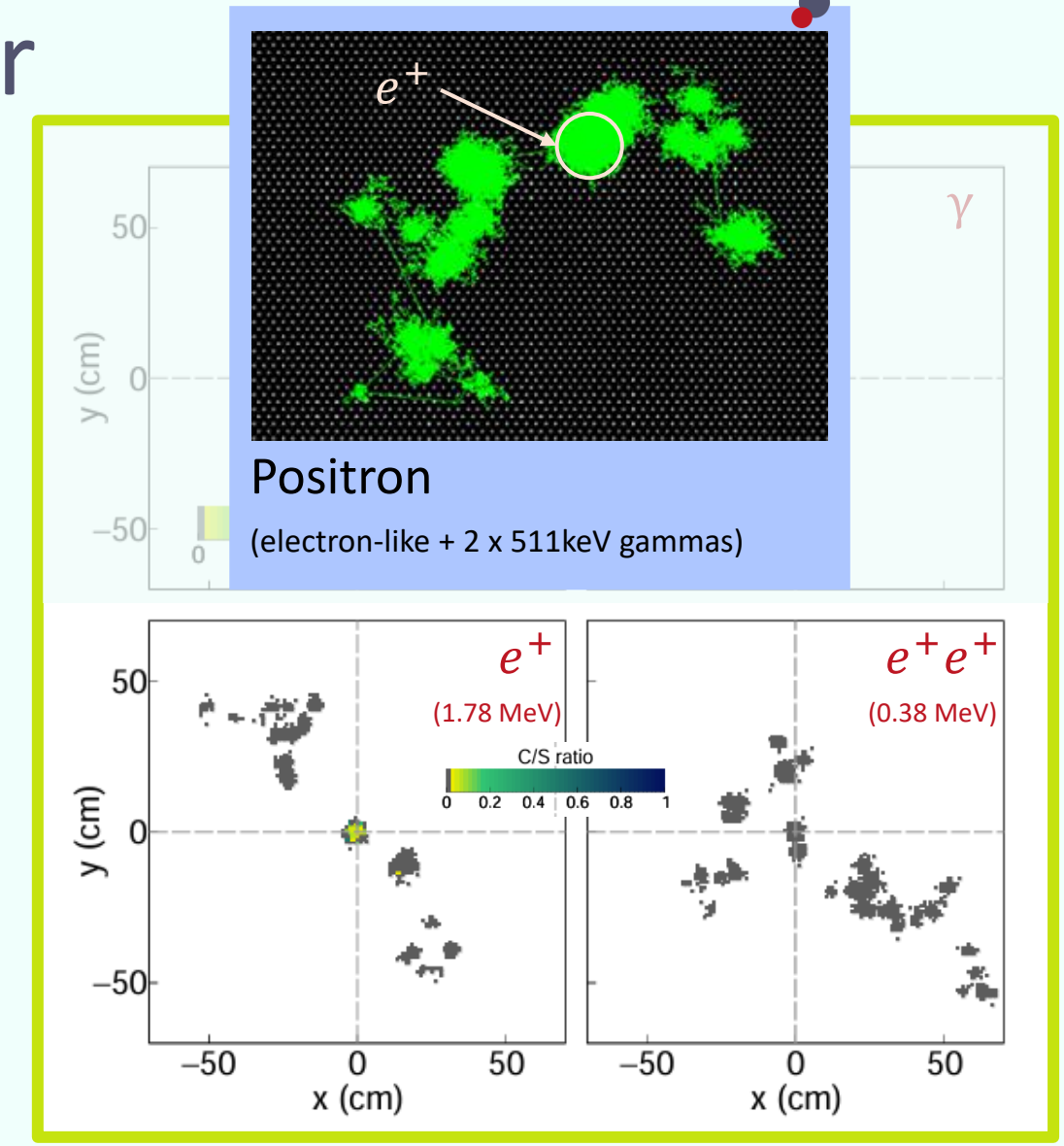

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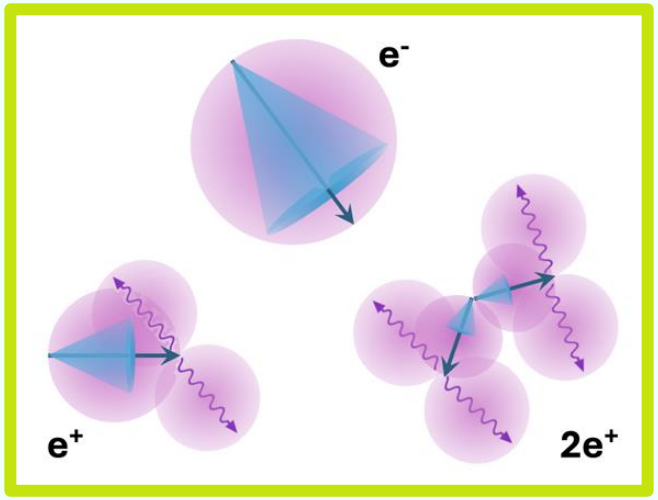
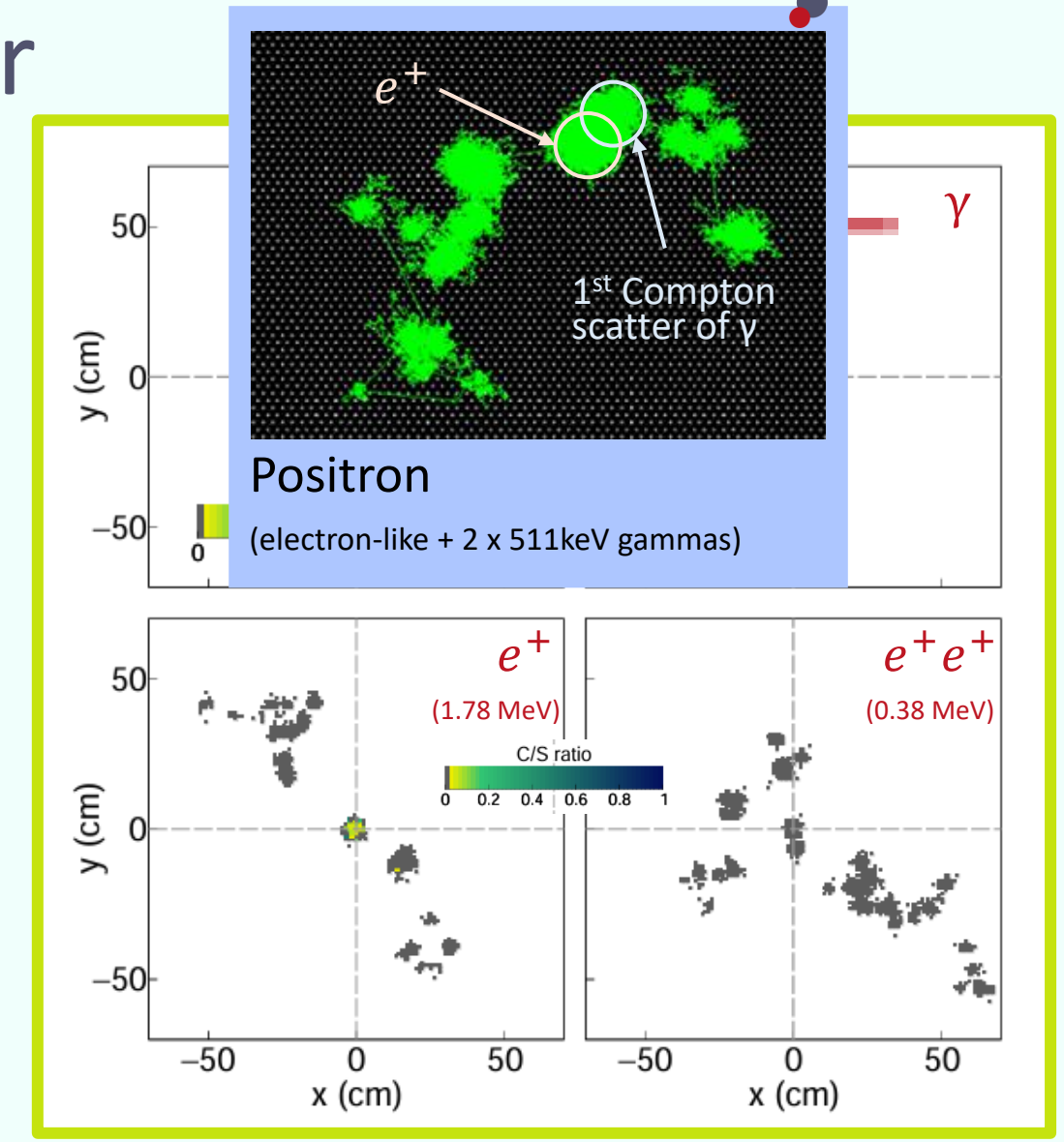
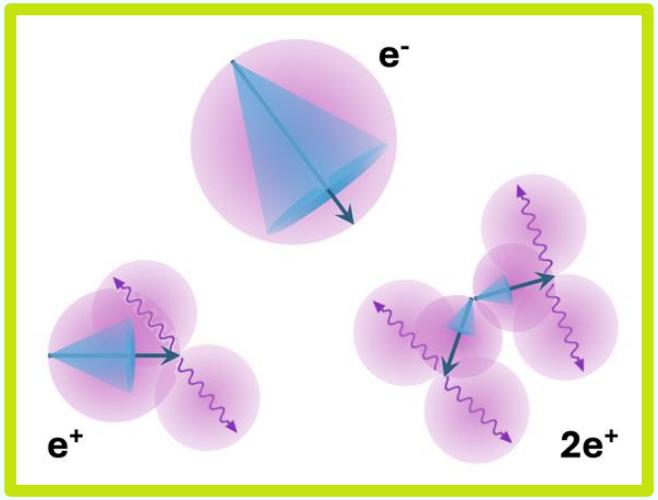


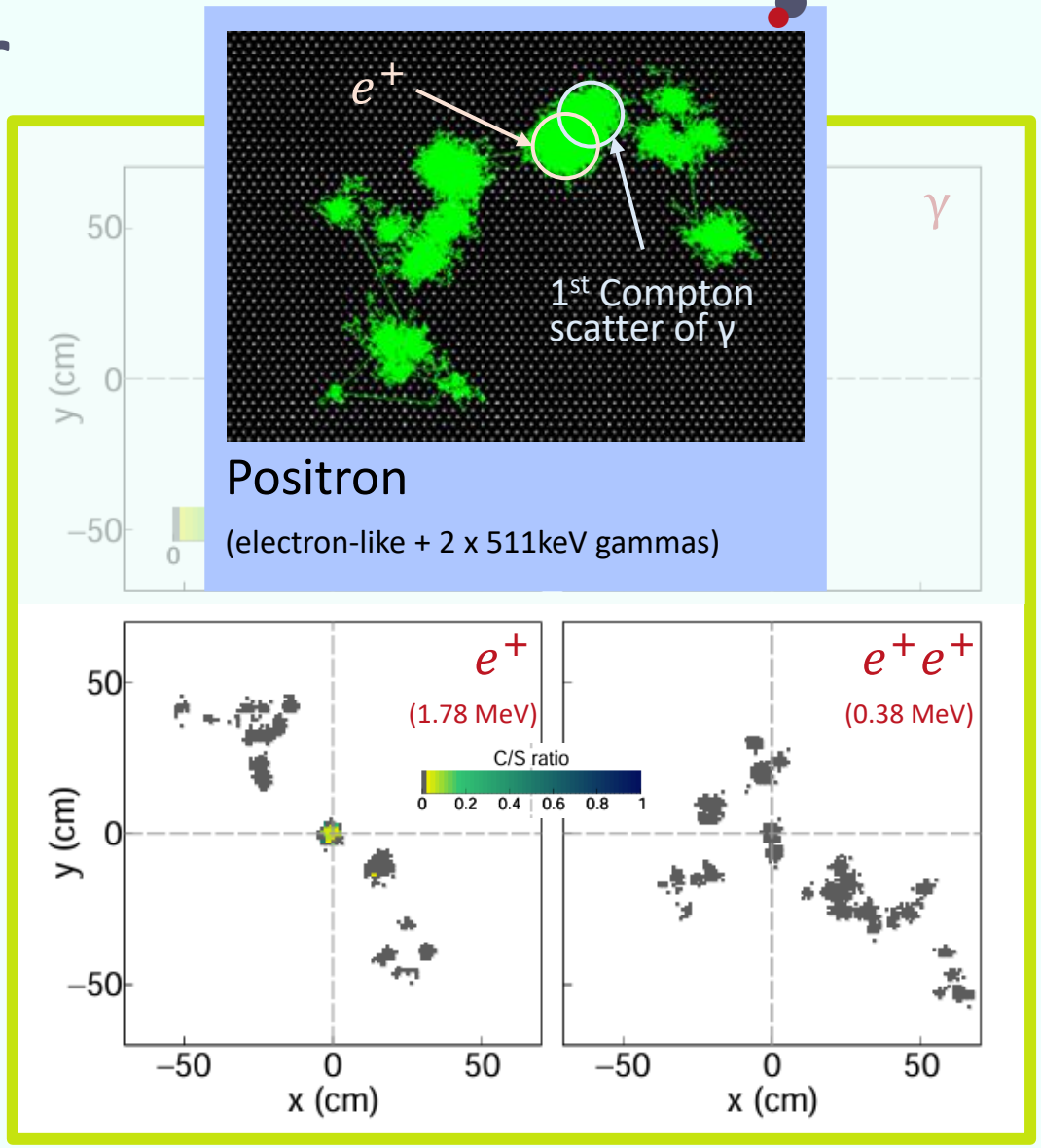


Hybrid-Opaque Scintillator

PID & Positron Energy

- Both Hybrid and Opaque Scintillator give PID.
- Compton scatters from annihilation gammas (511keV) don't produce Cherenkov light.





Hybrid-Opaque Scintillator

PID & Positron Energy

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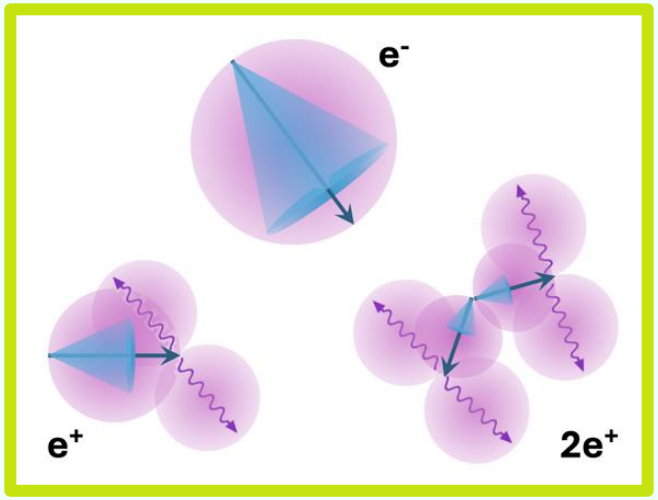
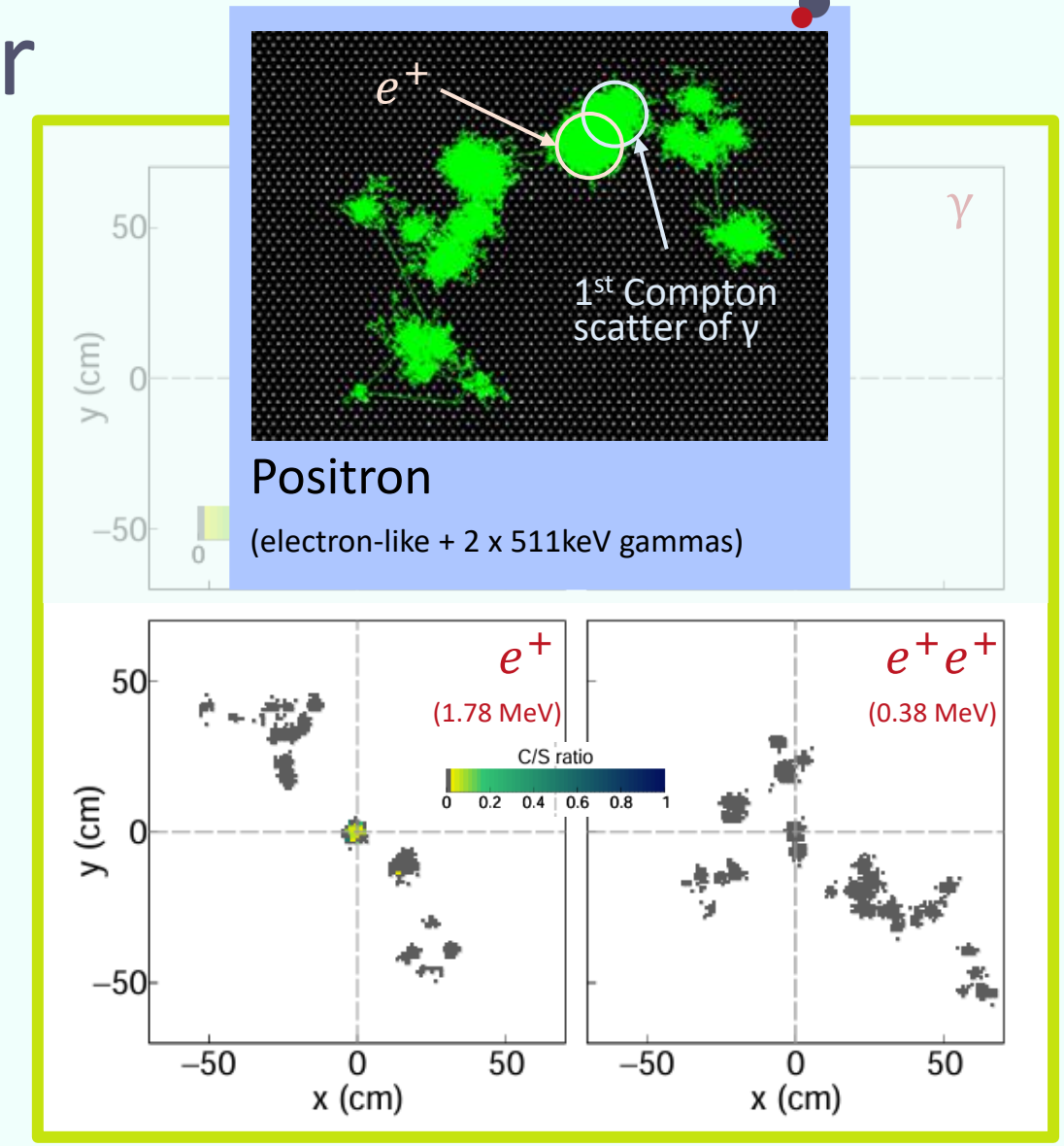
- Positron energy from Cherenkov signal





NuDoubt^{++} Prototype

Combining 3 novel technologies

OWL-fibres

- Based on WOMs (IceCube)
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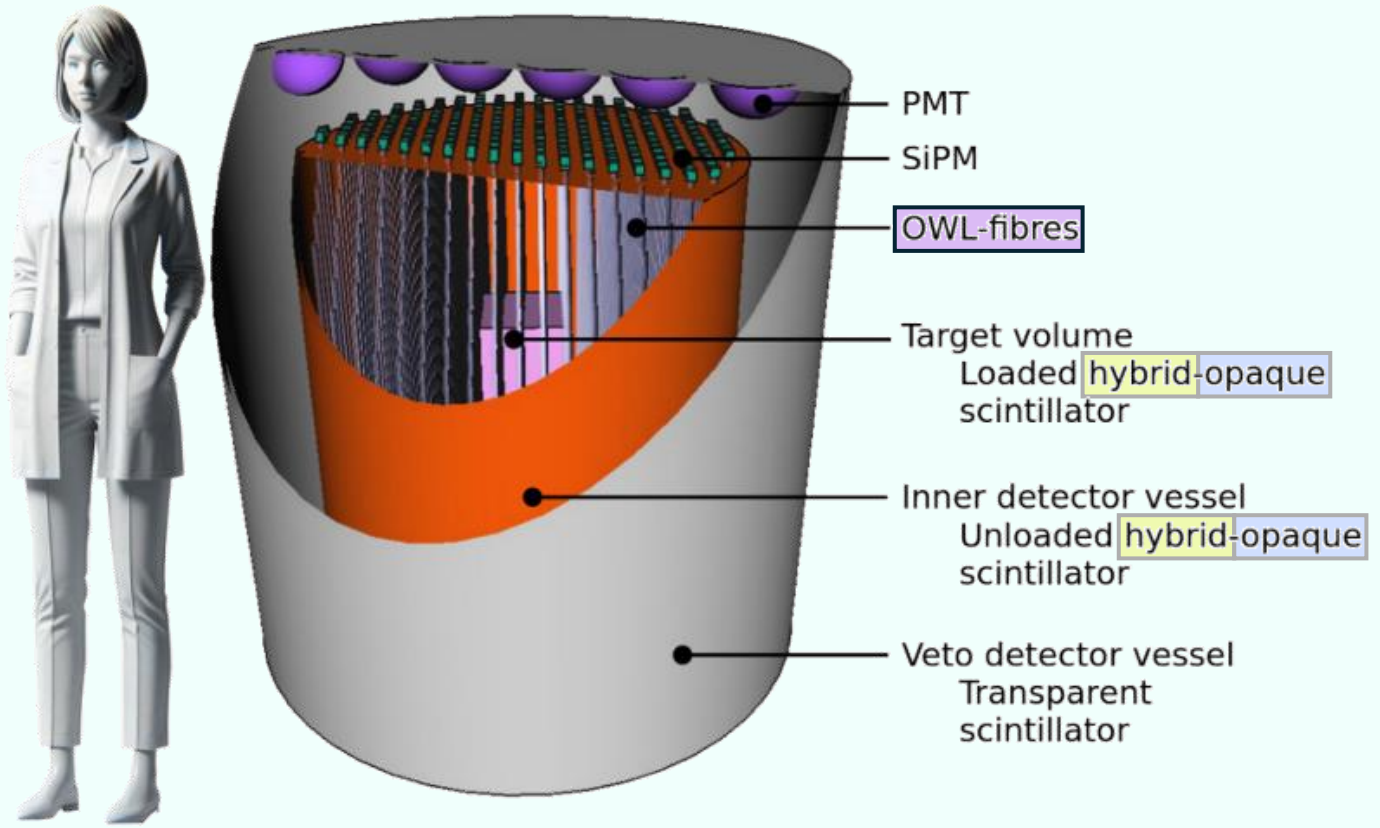
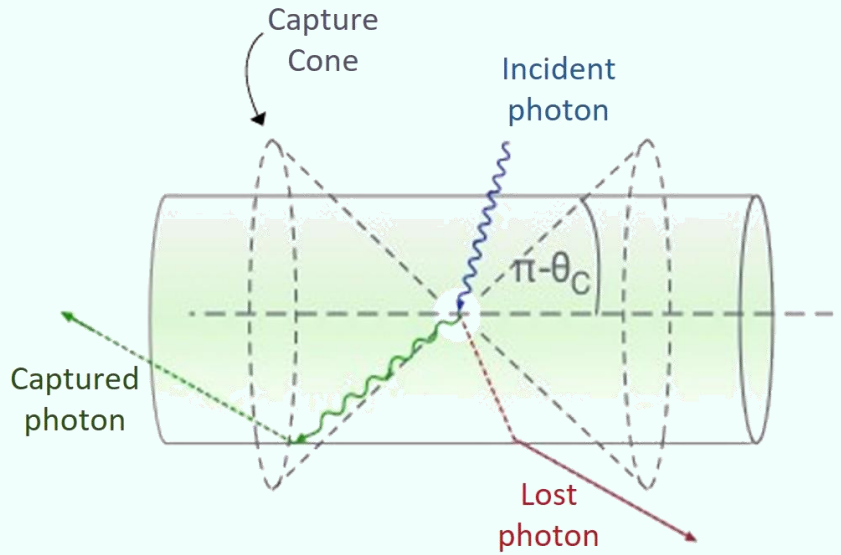


OWL-fibres

Based on IceCube's WOMs

Traditional wavelength-shifting fibres:

- Wavelength shifter dispersed throughout the fibre core



OWL-fibres

Based on IceCube's WOMs

Wavelength-shifting paint coated on PMMA fibres

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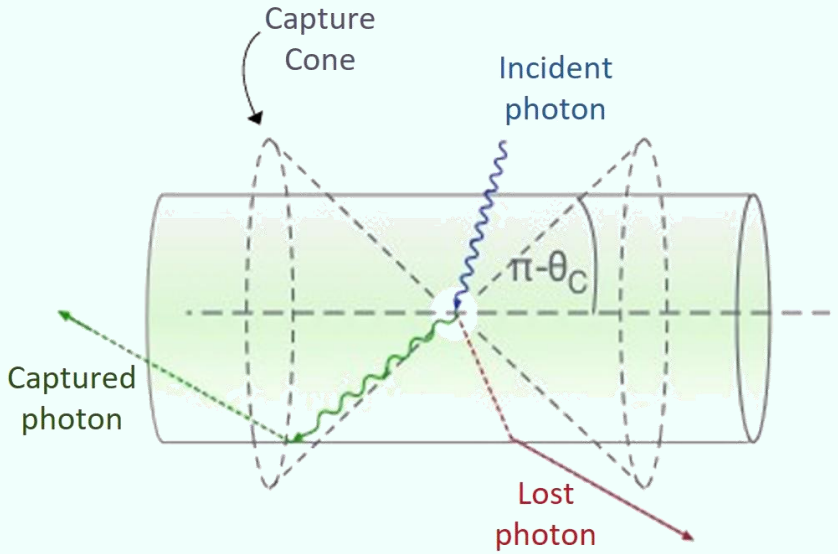
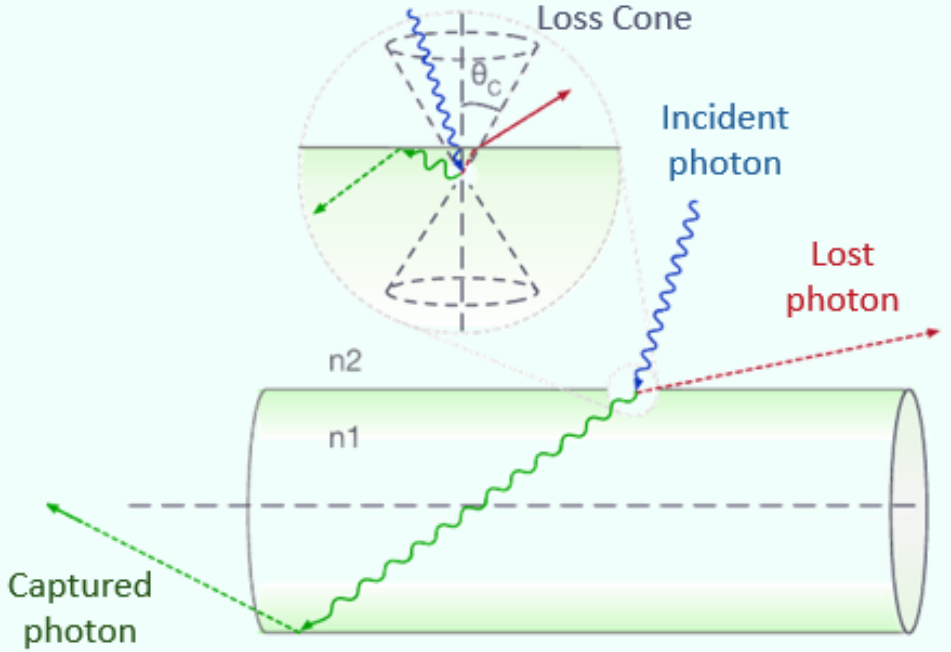


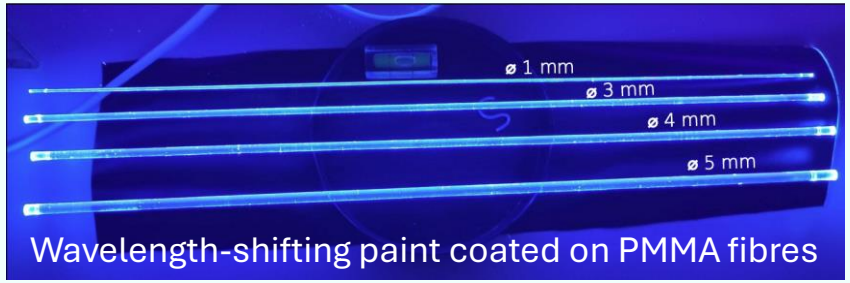
OWL fibres:

- Wavelength shifter on the fibre's surface only



OWL-fibres

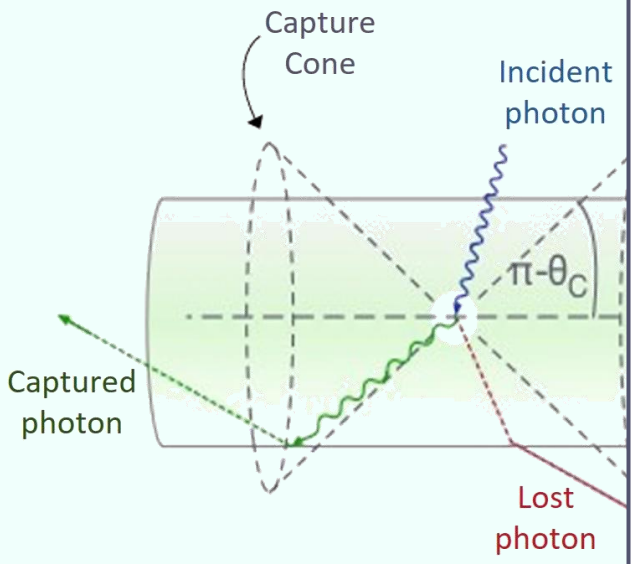
Based on IceCube's WOMs

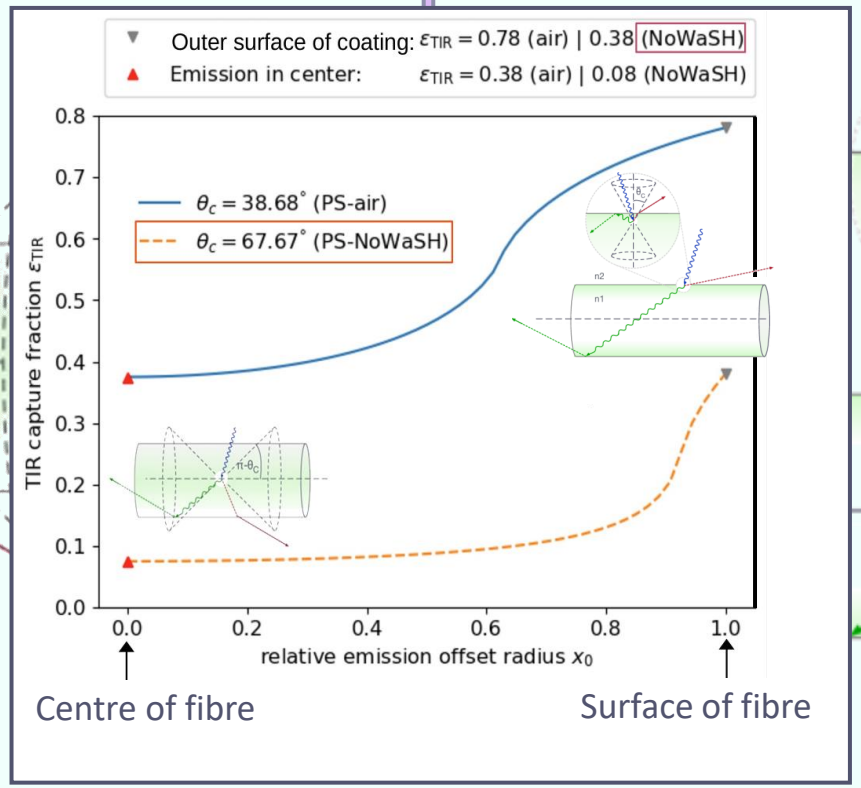


Wavelength-shifting paint coated on PMMA fibres

Traditional wavelength-shifting fibres:

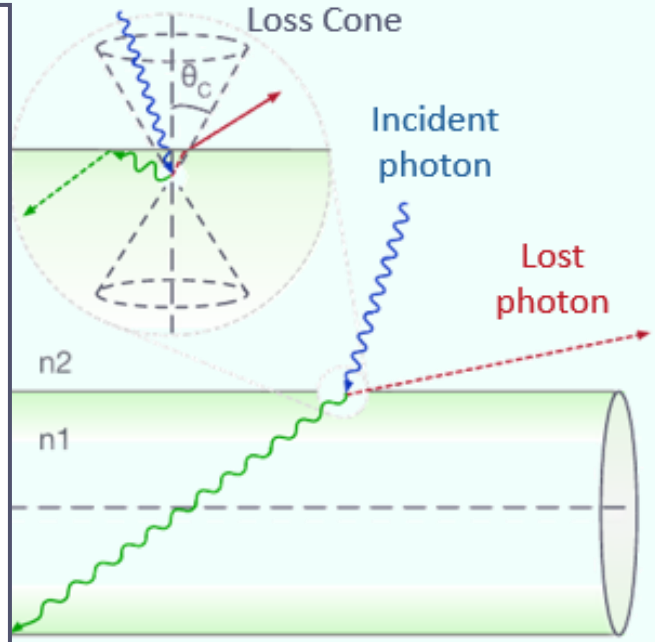
- Wavelength shifter dispersed throughout the fibre core





OWL fibres:

- Wavelength shifter on the fibre's surface only



OWL-fibres

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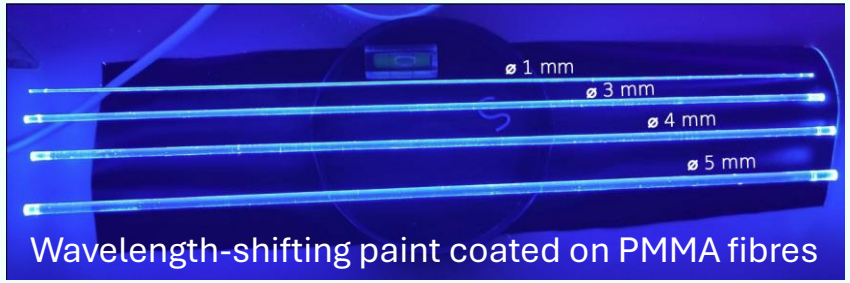

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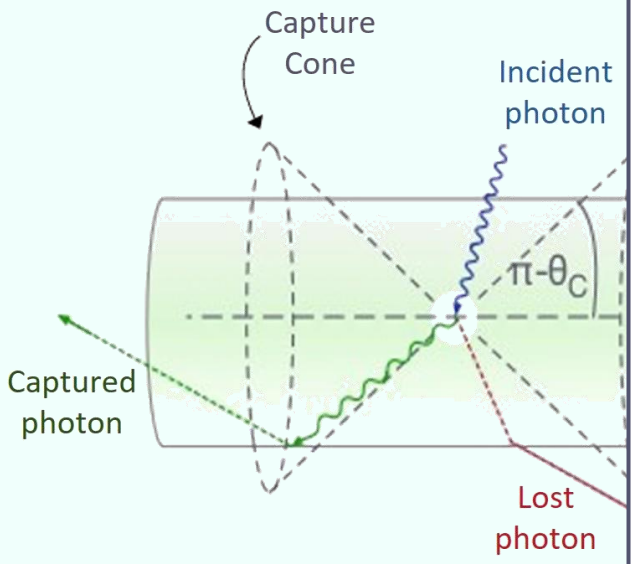

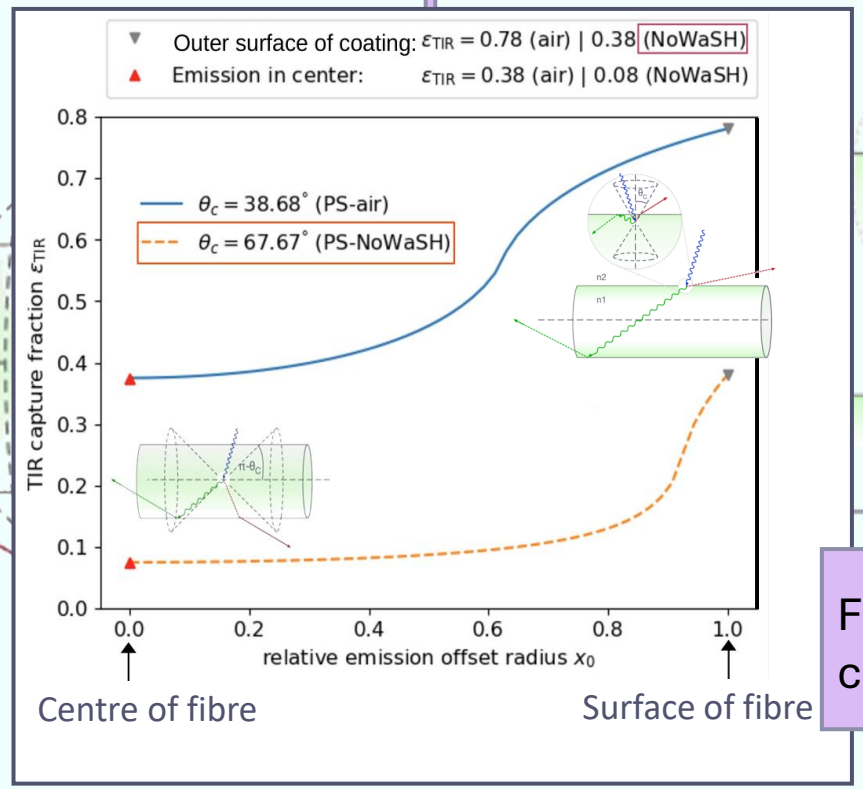

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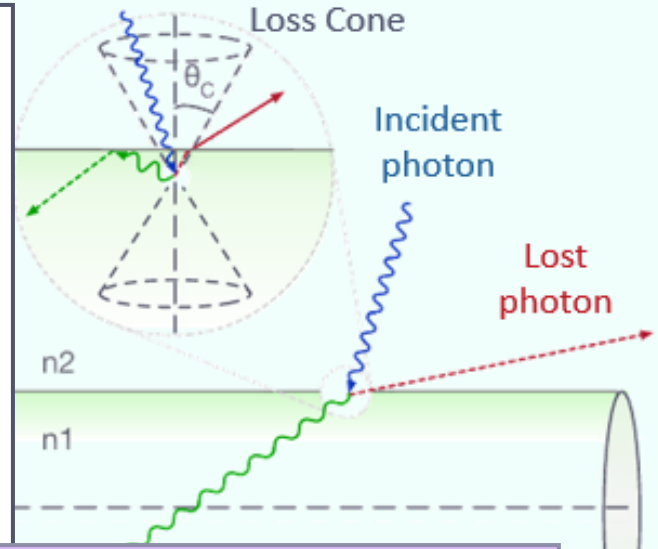


Factor ~2 improvement in capture efficiency

NuDoubt^{++} Prototype

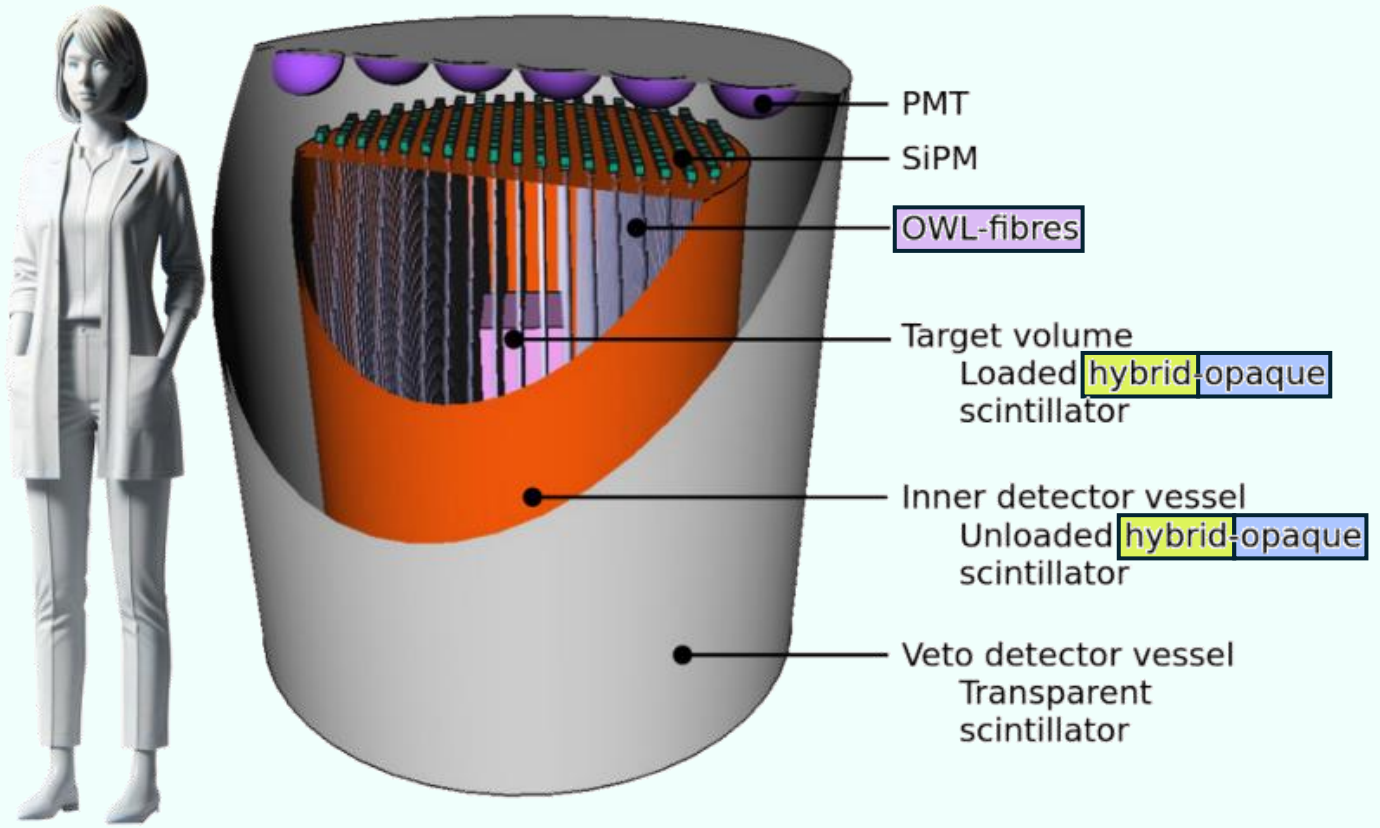
Combining 3 novel technologies

OWL-fibres

- Based on WOMs (IceCube)
- Wavelength shifter coated on fibre to maximise photon capture

Hybrid-Slow Opaque Scintillator

- Separate Cherenkov and scintillation light in time
- Stochastic confinement of light for improved PID

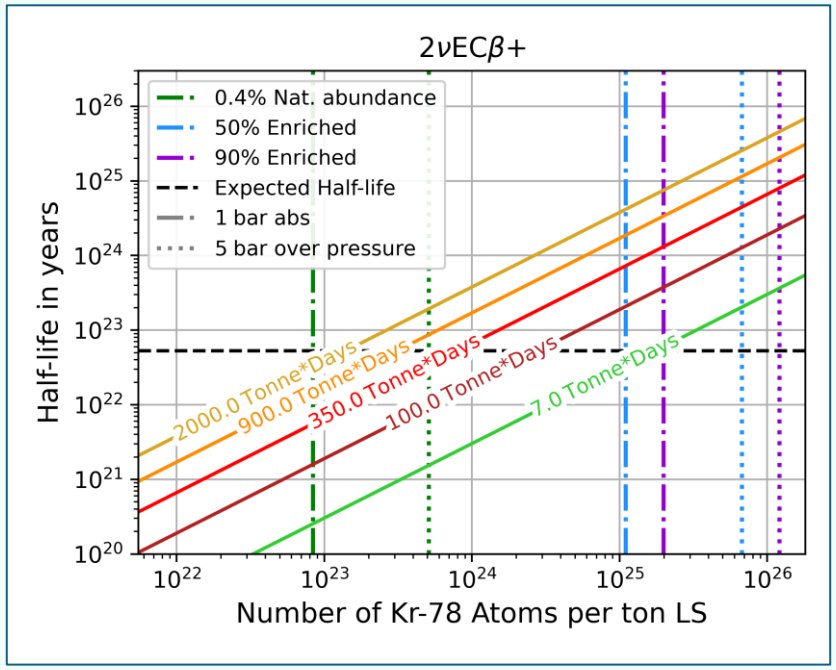


NuDoubt^{++}: Sensitivities

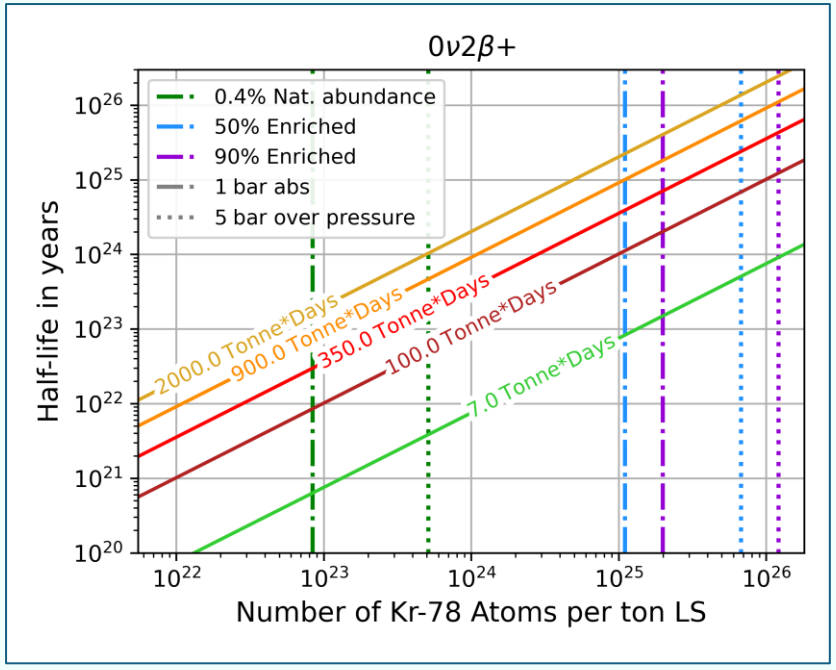
*Assuming Gran Sasso overburden

After 2 years of operation*:

2νββ++ (0νββ++)
2νECβ+ (0νECβ+)



Expected 5σ observation sensitivity



Expected 90% C.L. exclusion sensitivity

NuDoubt^{++}: Sensitivities

*Assuming Gran Sasso overburden

After 2 years of operation*:

First 4σ evidence ⟵ **2νββ++ (0νββ++)**

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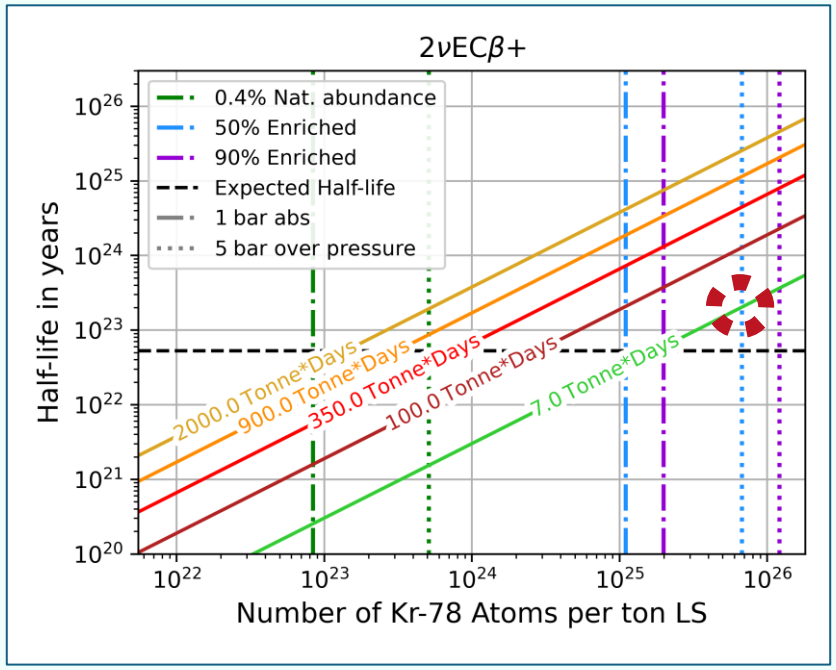
} Improvement of half-life limits by **3 orders of magnitude**



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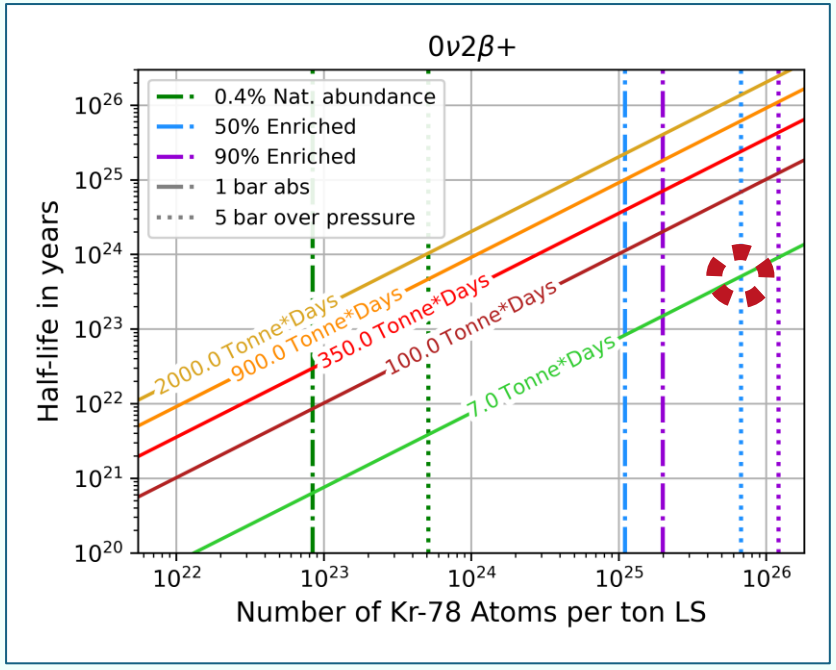


Expected 90% C.L. exclusion sensitivity

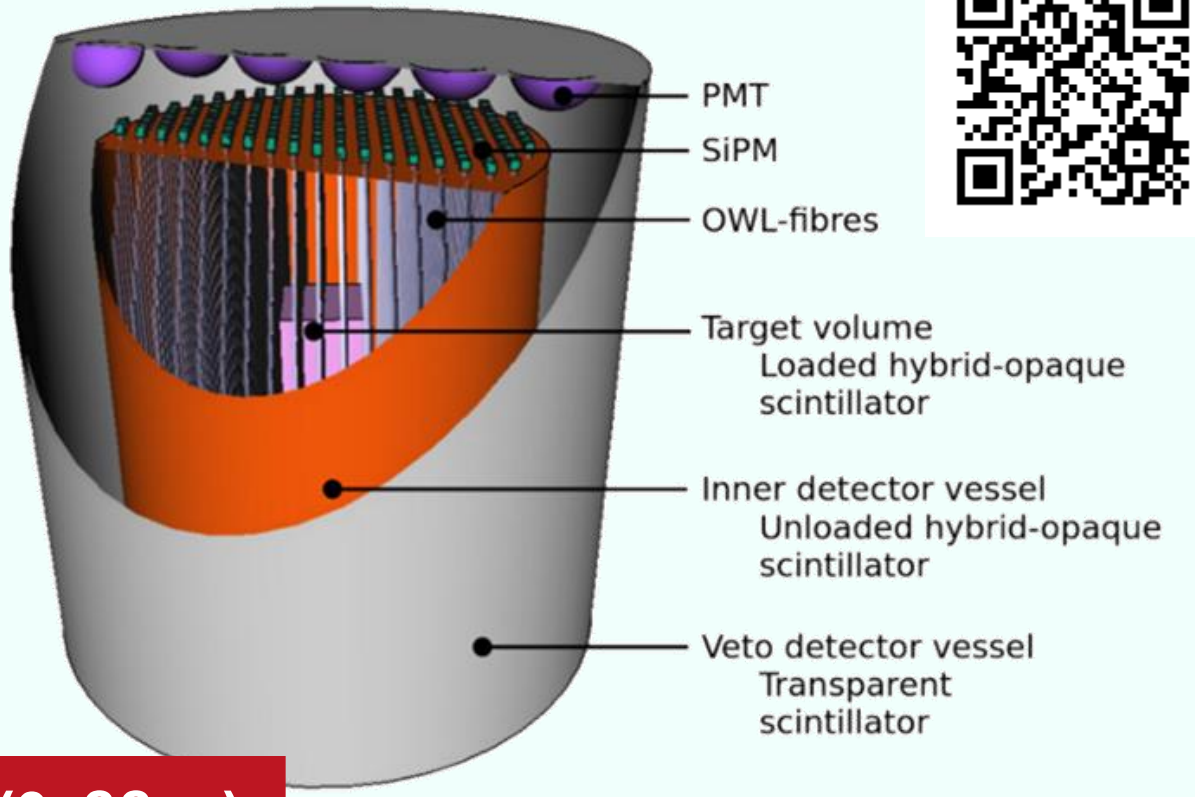
NuDoubt^{++} Experiment

Overview and Conclusion

NuDoubt^{++} paper:

Combining Hybrid and Opaque Scintillator Techniques in the Search for Double Beta Plus Decays

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



2νββ++ (0νββ++)
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NuDoubt^{++} Experiment

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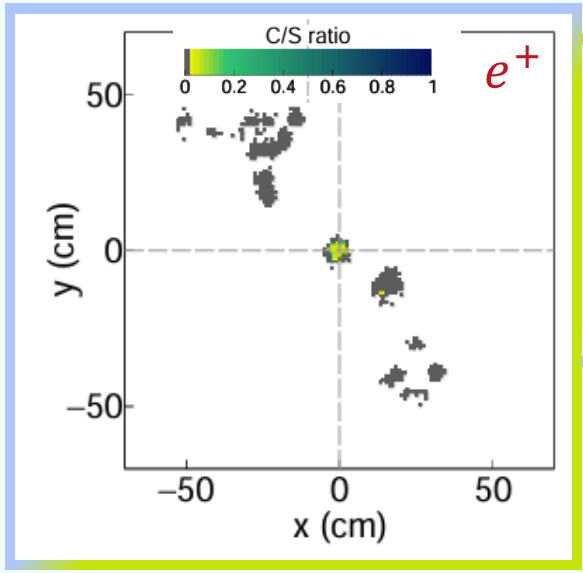

Using a Hybrid-Slow Opaque scintillator gives excellent **particle ID** and positron **energy** reconstruction

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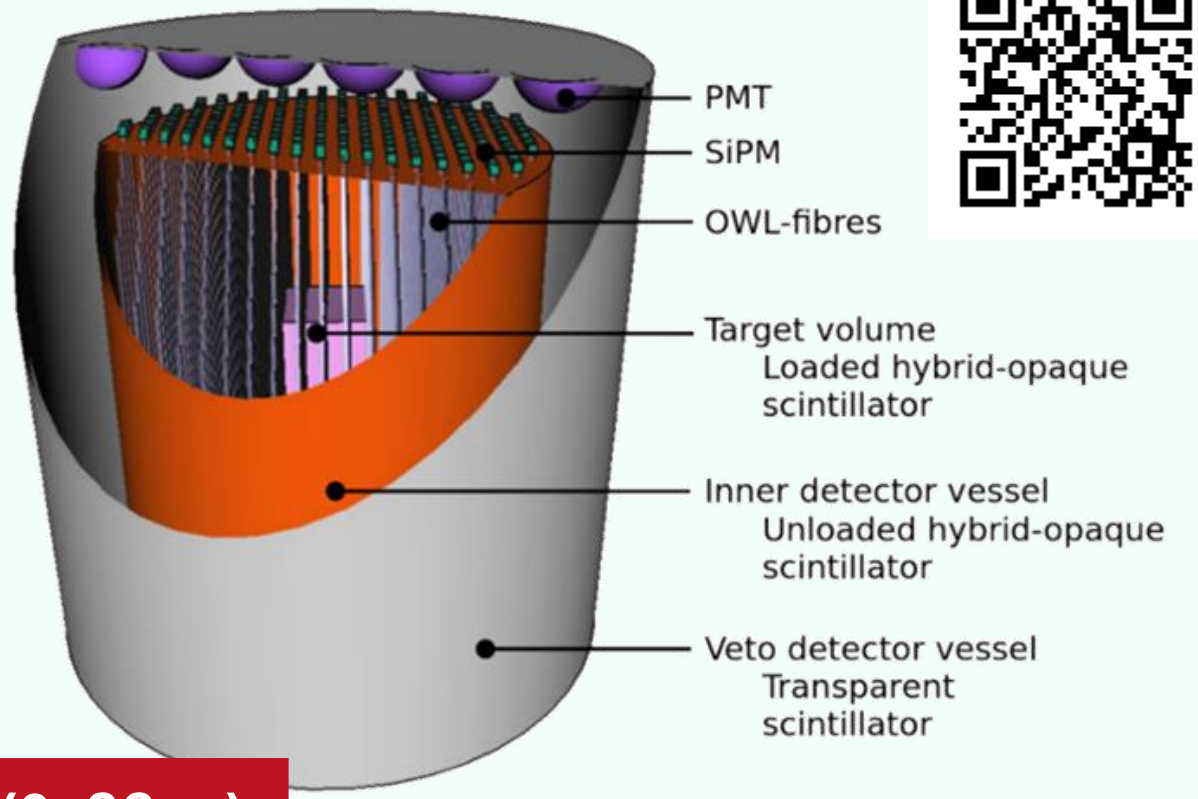

2vββ++ (0vββ++)
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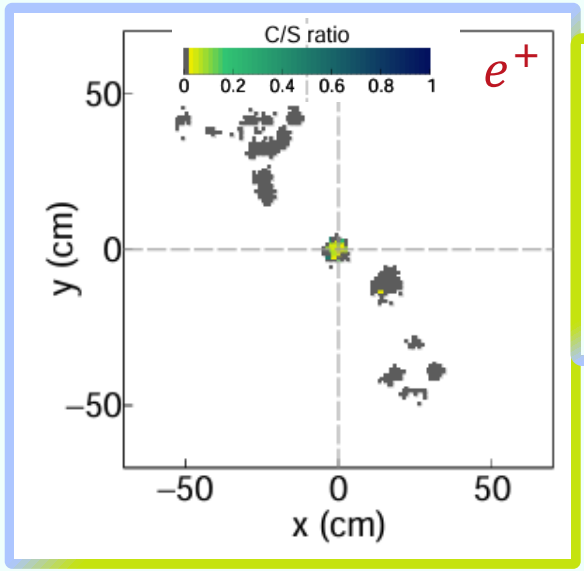

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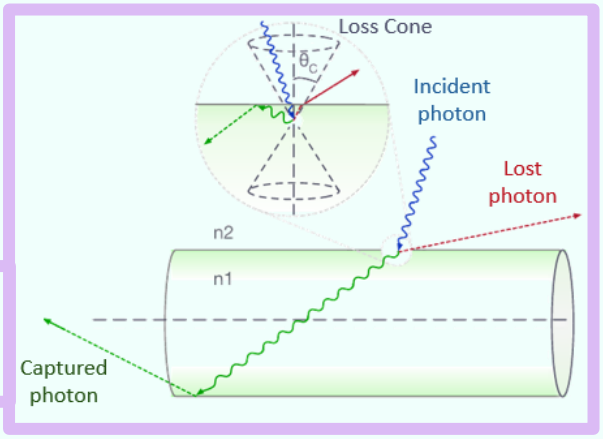
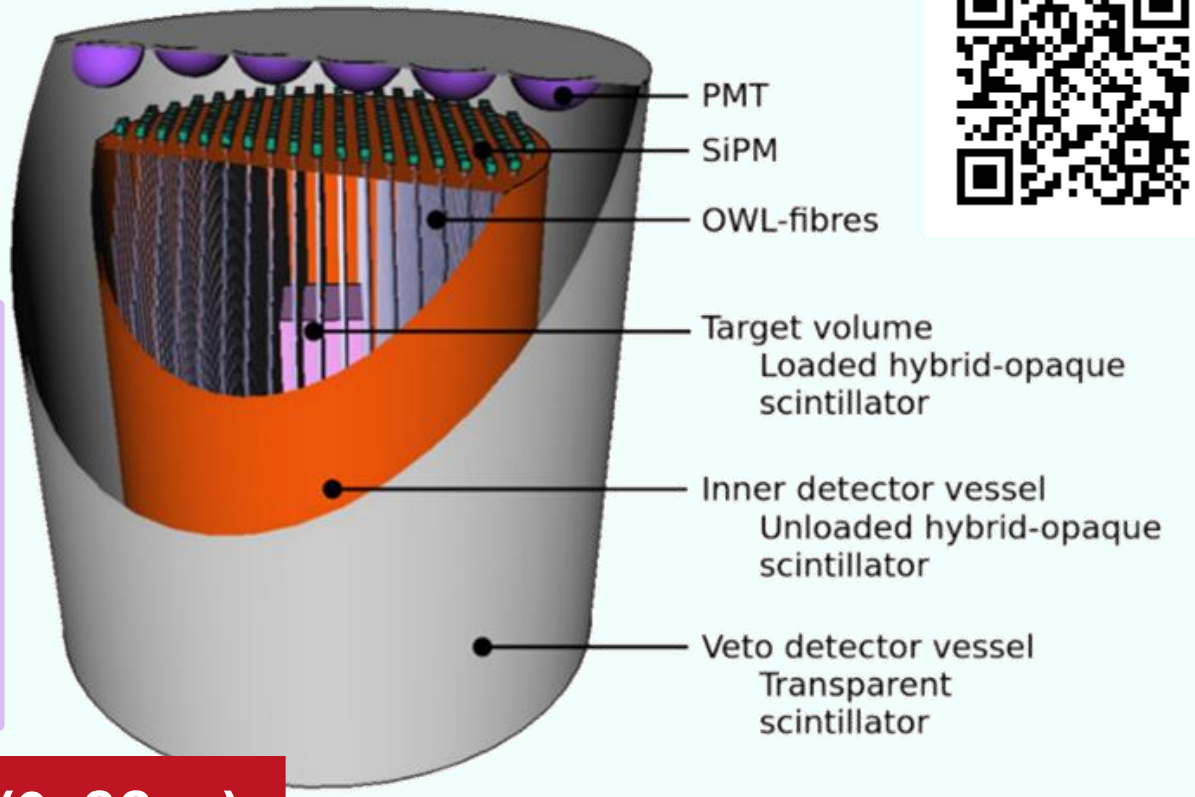


OWL fibres improve photon capture efficiency (factor ~2)



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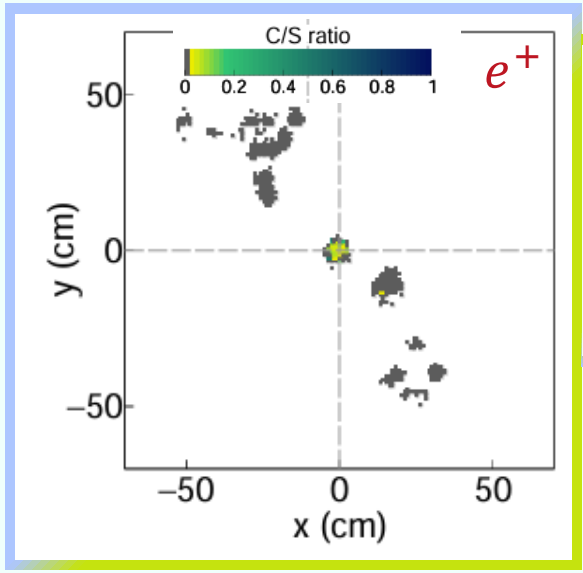

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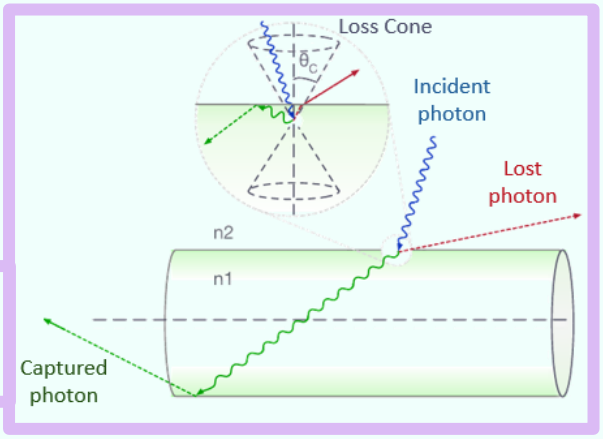

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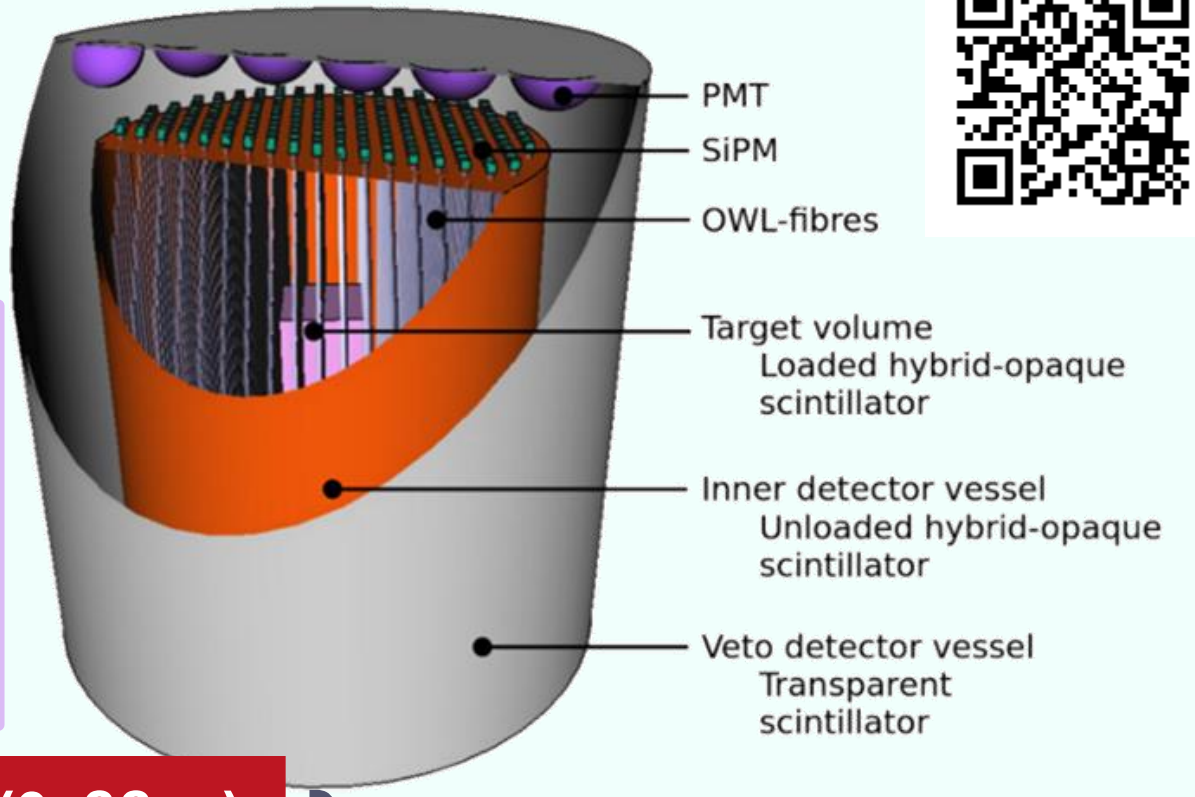

First 4σ evidence ← **2νββ++ (0νββ++)**

First 5σ discovery ← **2νECβ+ (0νECβ+)**

} Improvement of half-life limits by **3 orders of magnitude**

Back-up Slides

Combining Hybrid and Opaque Scintillator Techniques in the Search for Double Beta Plus Decays

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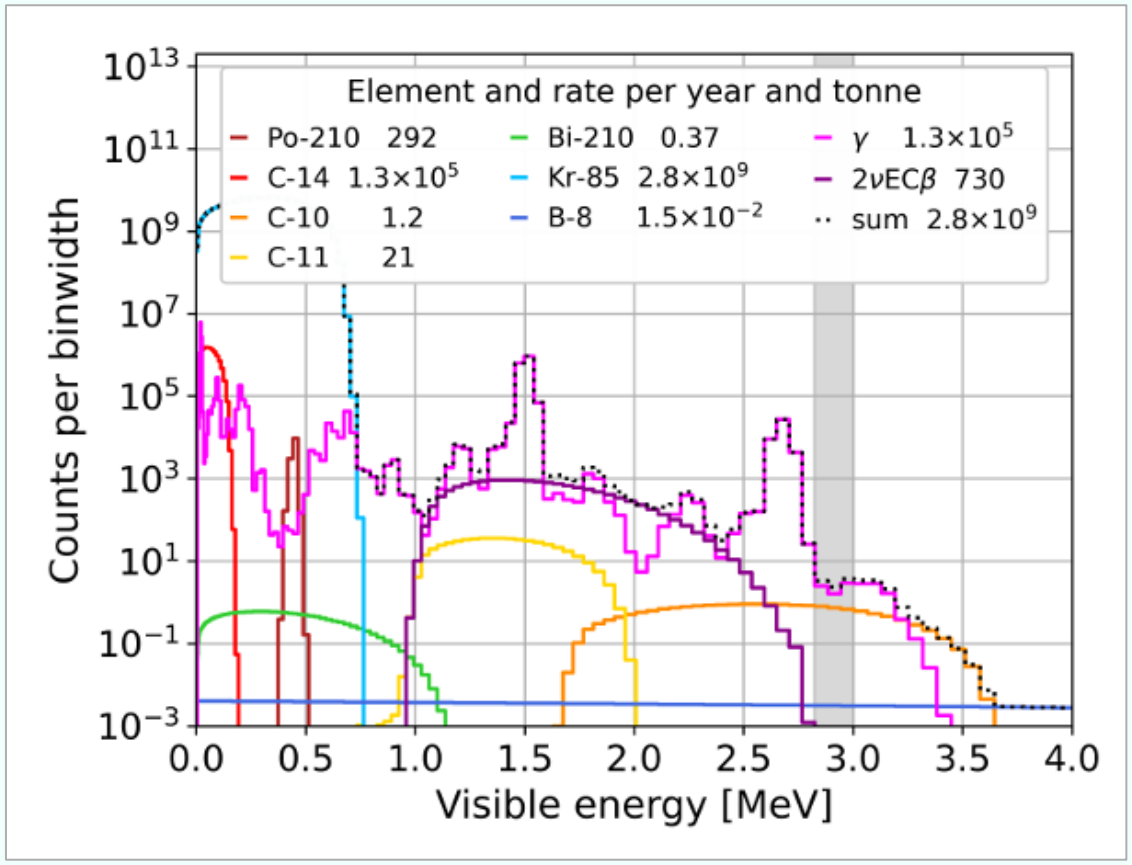
NuDoubt++ paper

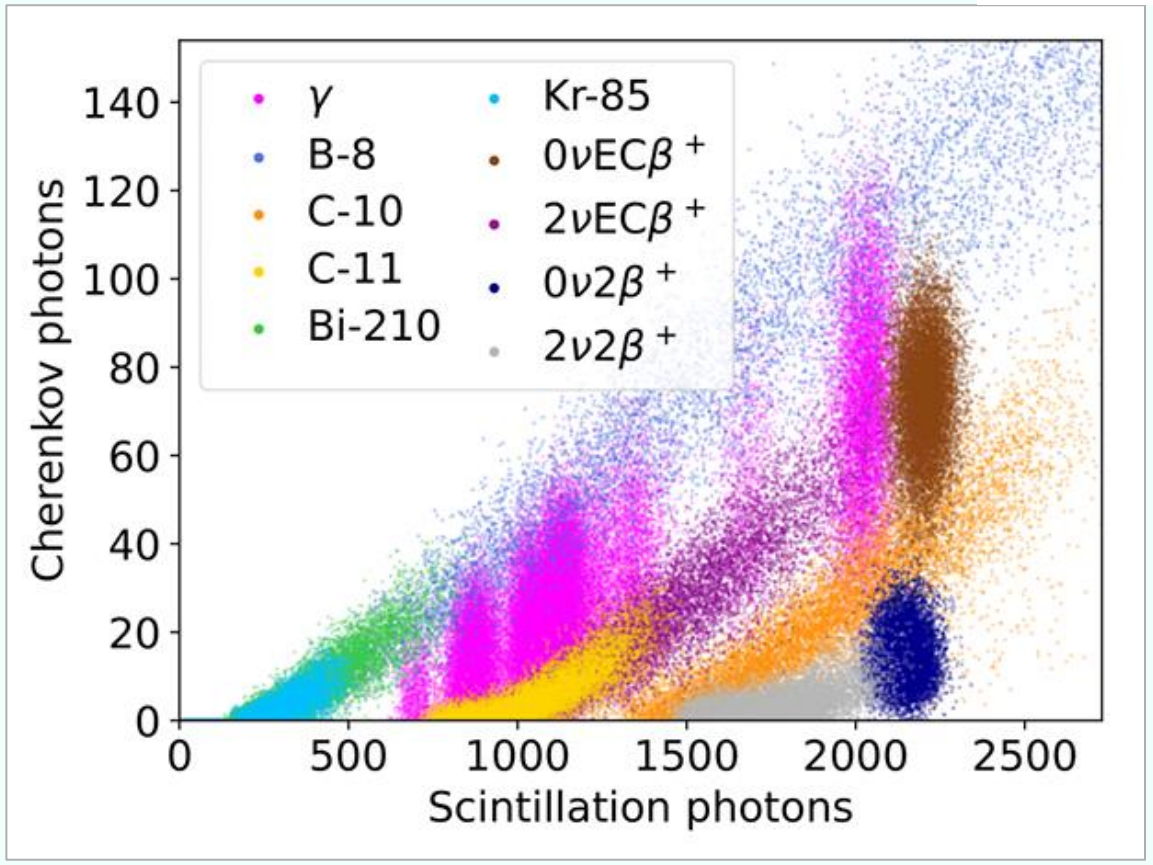
Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

Backgrounds

NuDoubt++ paper:

- C/S ratio for background discrimination

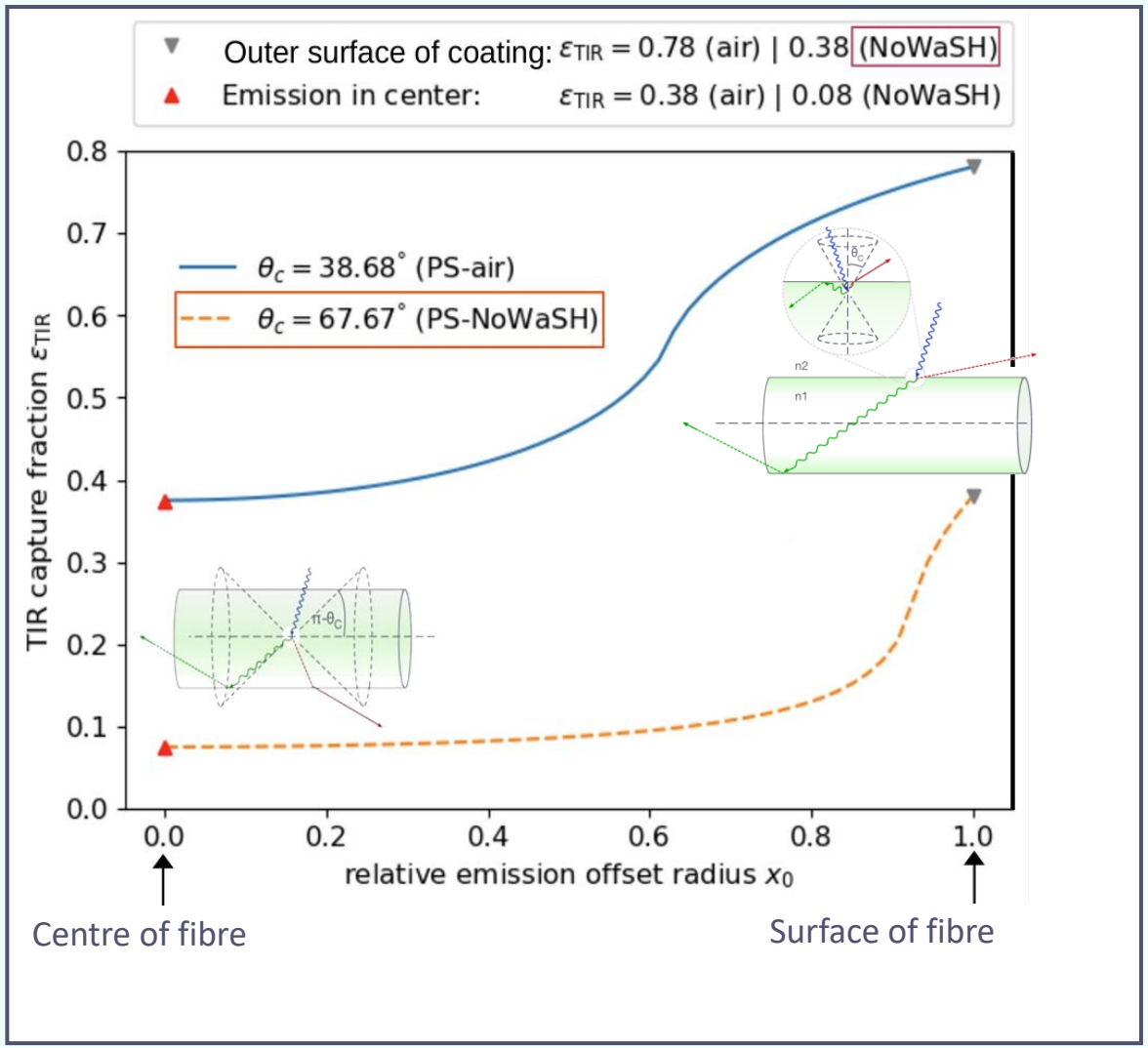




OWL-fibres

Based on IceCube's WOMs

- Factor ~2 improvement in capture efficiency
- Capture ≠ Detection
- OWL photon abs length ~2m



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