

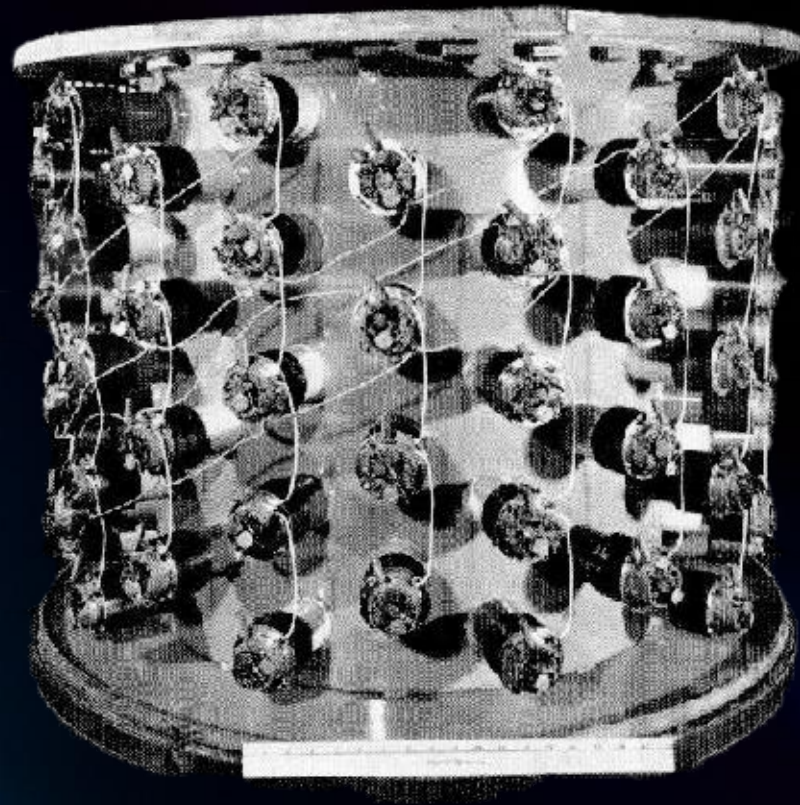
Transfer Symposium | 18th June 2026

Development & Characterisation of a Novel Fast Scintillator Formulation for Large Liquid Scintillator Neutrino Detectors

Heer K. Mann

History of LS Detectors

Origins



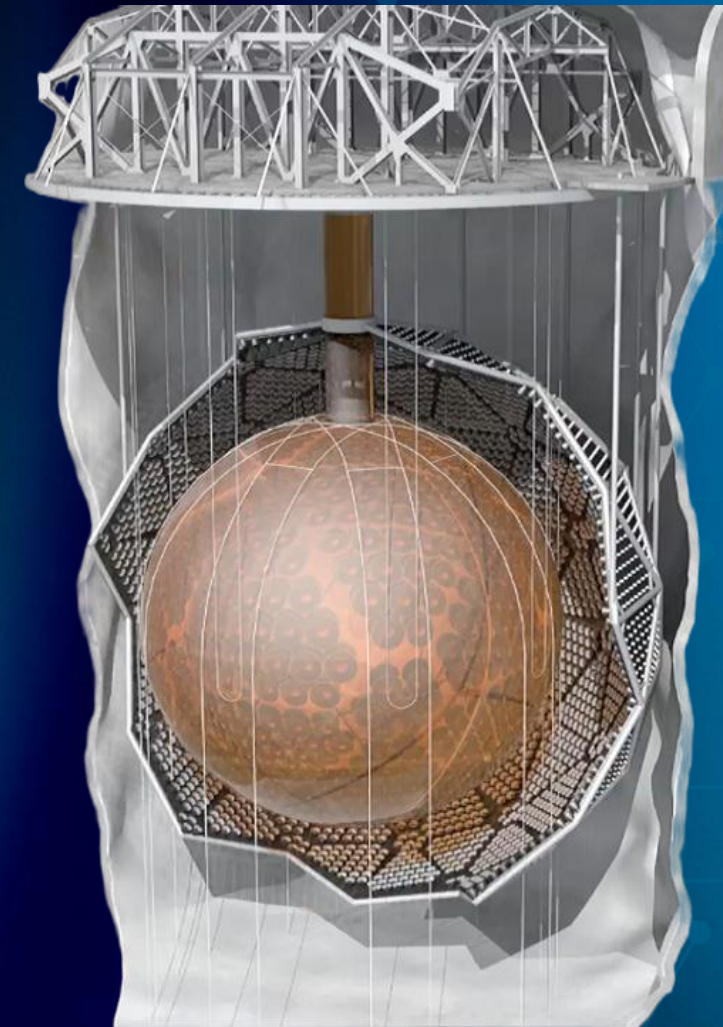
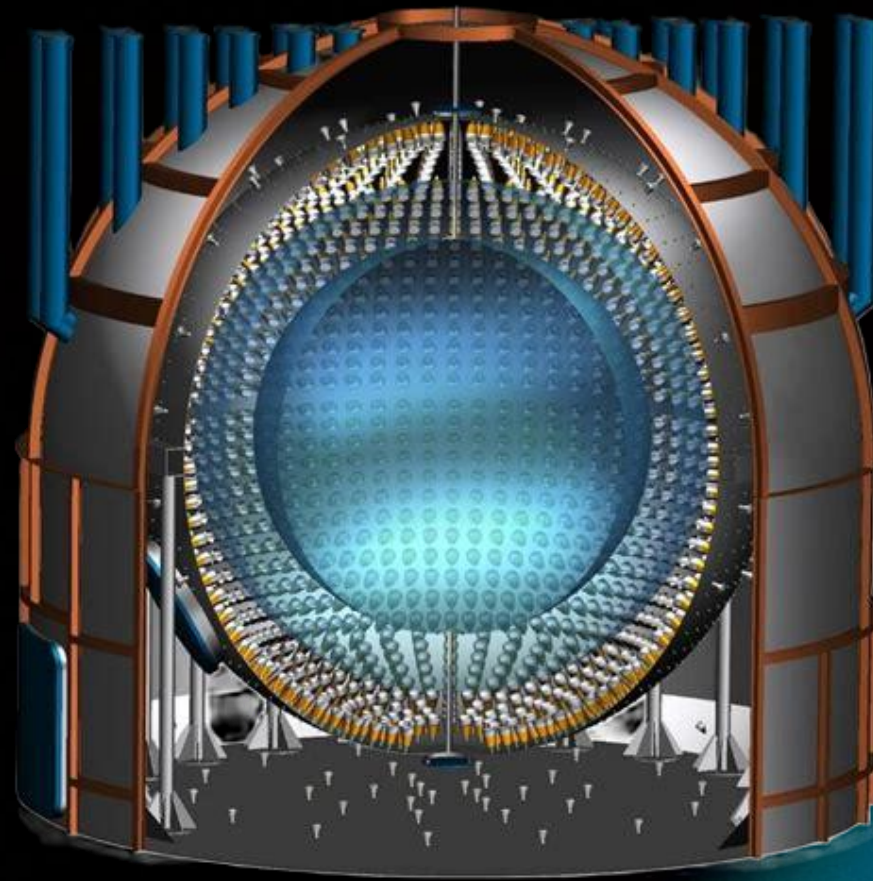
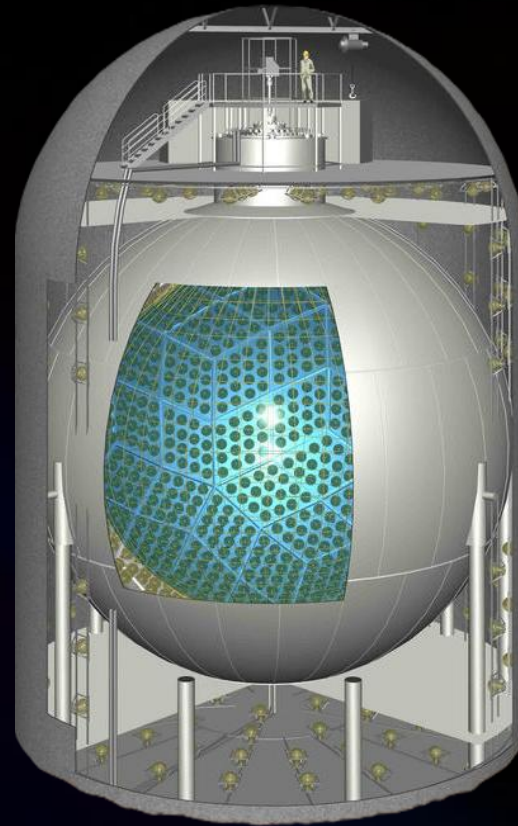
Project Poltergeist/ Savannah River Experiment

1953-56

- Water-liquid scintillator 'sandwich'
- ~ 200 L target; 1200 L scint
- 110 PMTs
- First neutrino observation!

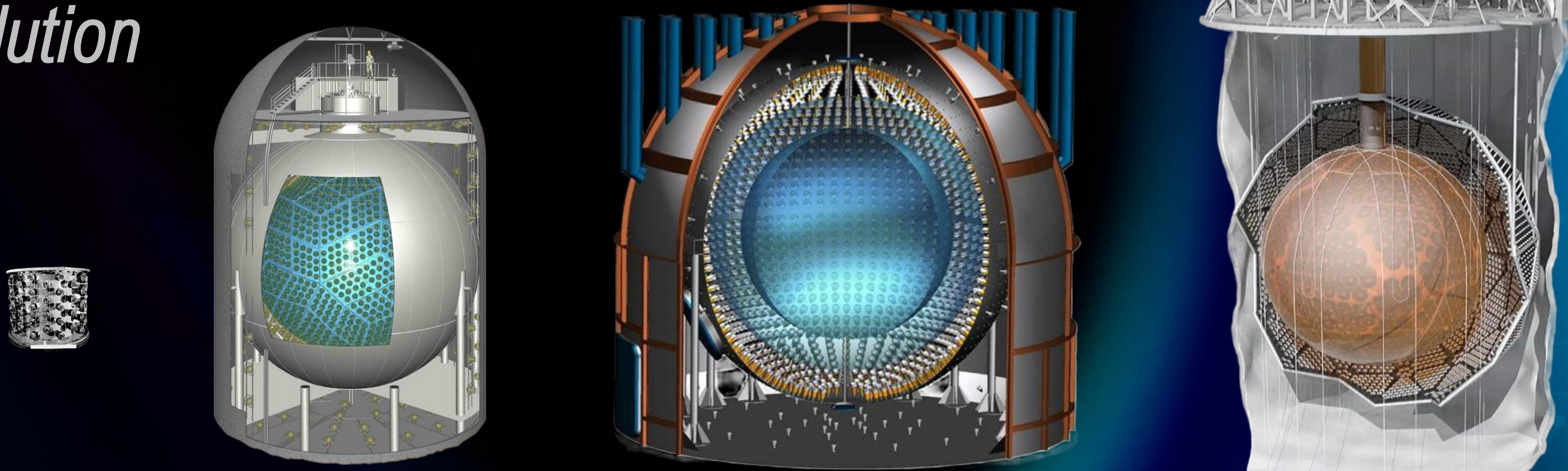
History of LS Detectors

Evolution



History of LS Detectors

Evolution



KamLAND

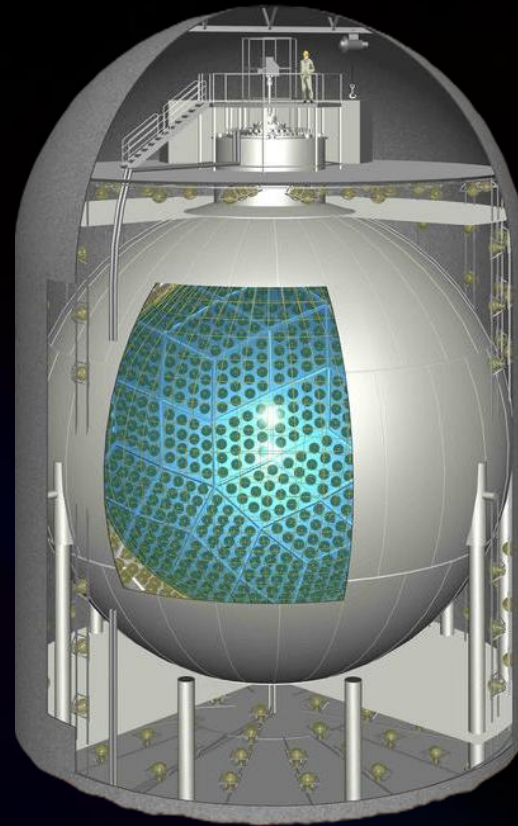
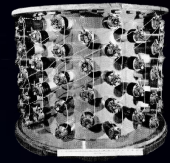
2002-2011

- 80% dodecane + 20% PC + 1.52 g/L PPO
- $R = 6.5$ m
- 1000 t target
- 1879 PMTs

*Approximately to scale

History of LS Detectors

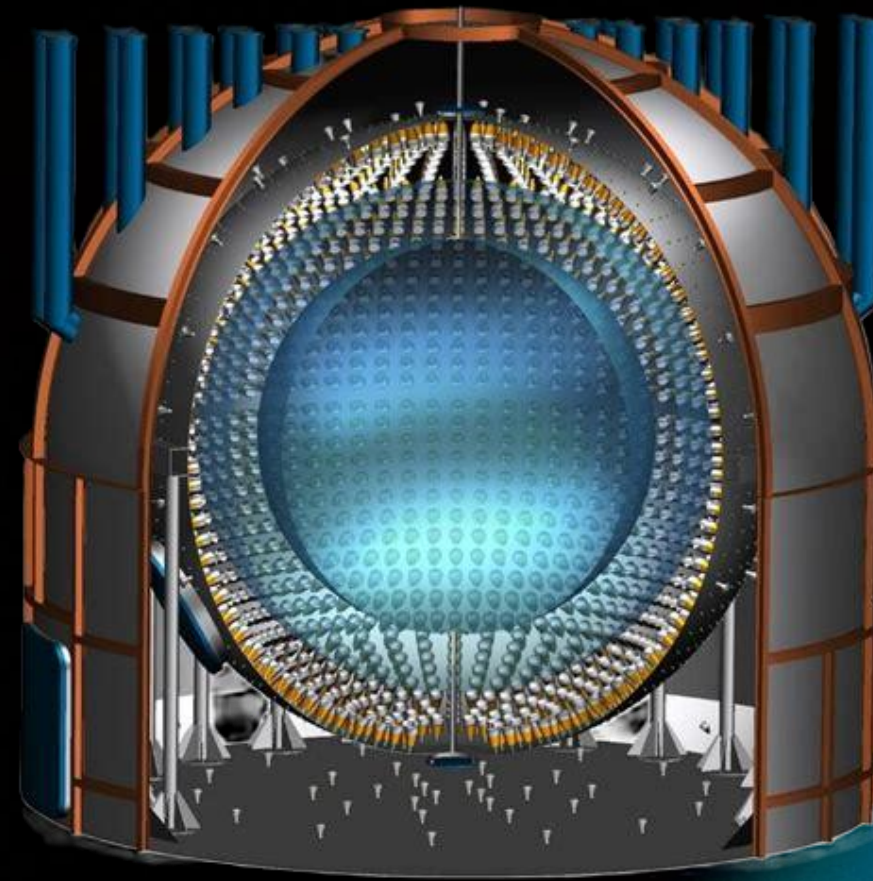
Evolution



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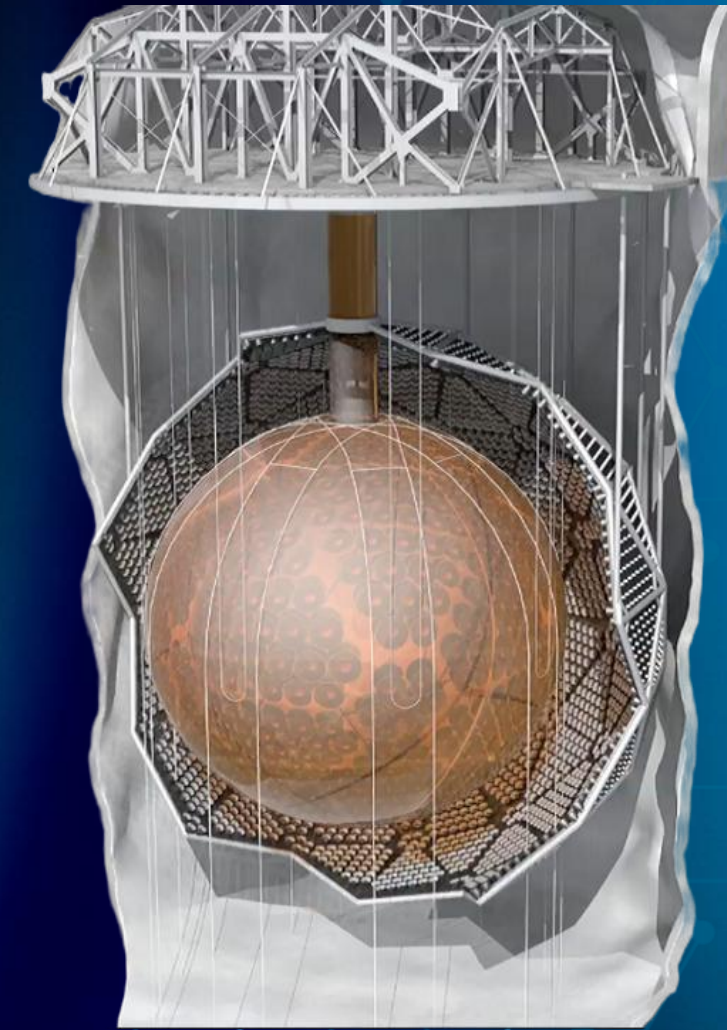
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BOREXINO

2007-2021

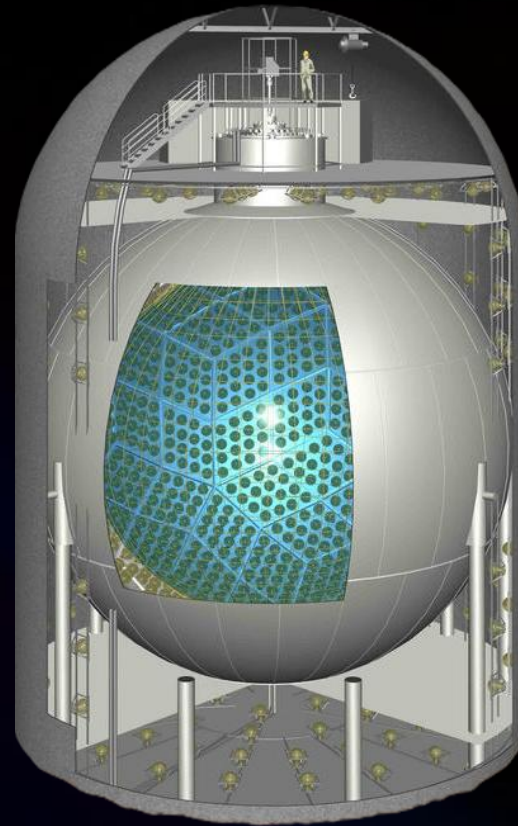
- PC + 1.5 g/L PPO
- $R = 6.85$ m
- 278 t target
- 2212 PMTs



*Approximately to scale

History of LS Detectors

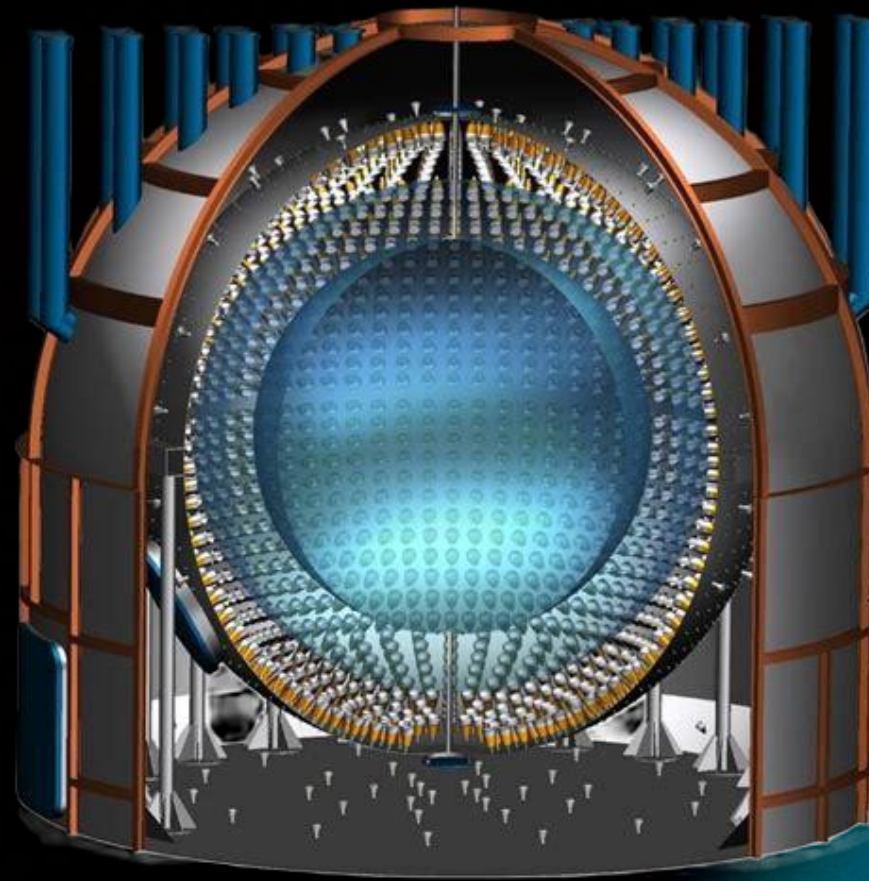
Evolution



KamLAND

2002-2011

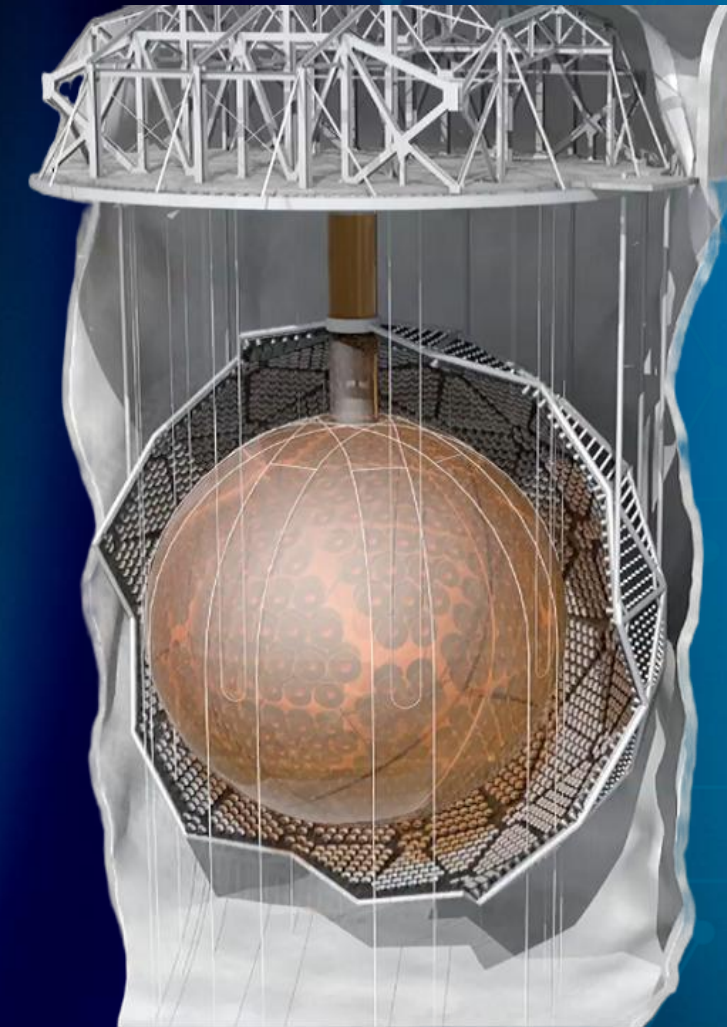
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SNO+

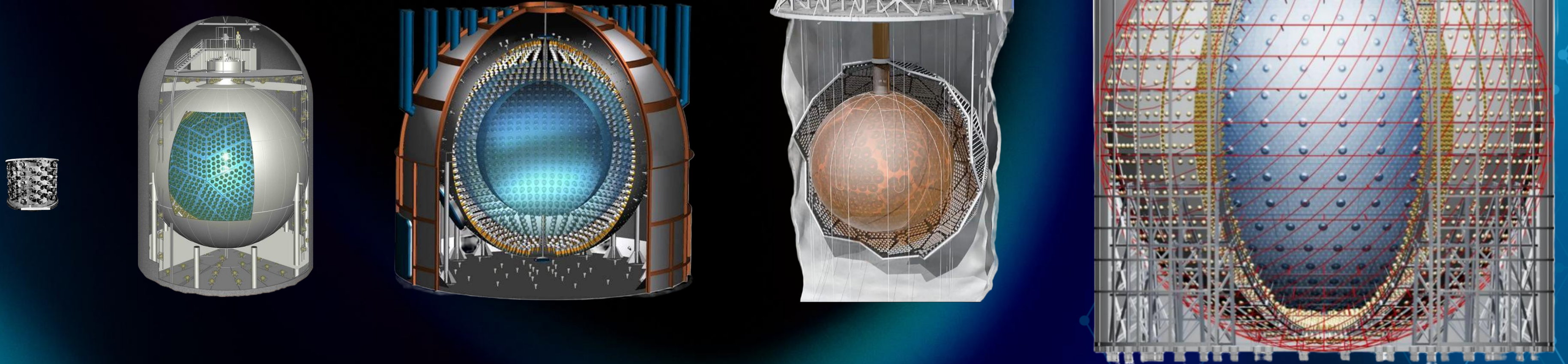
2022- (*scint phase*)

- LAB + 2.2 g/L PPO + 5 mg/L bis-MSB
- $R = 6$ m
- 780t target
- 9362 PMTs

*Approximately to scale

History of LS Detectors

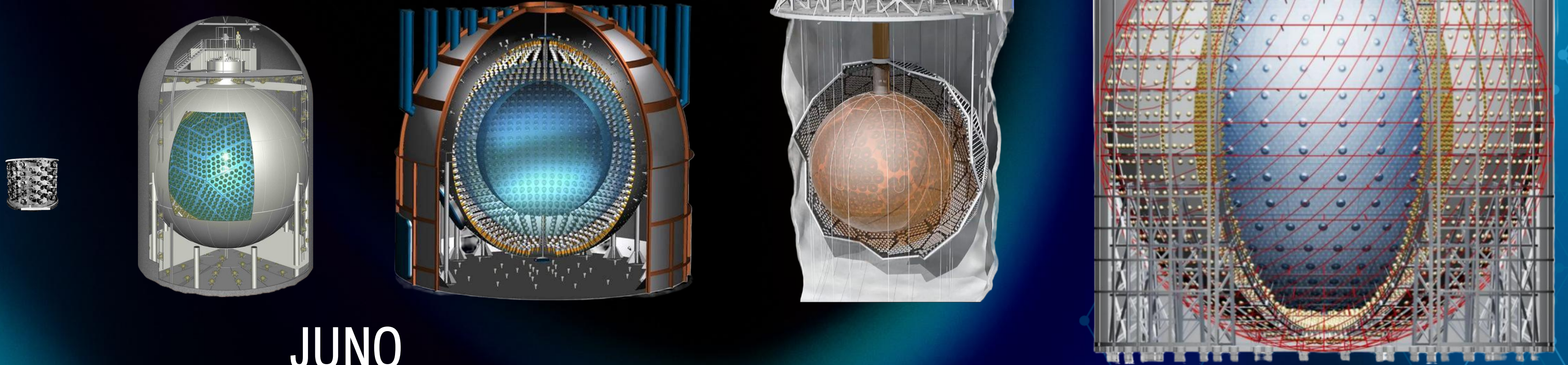
Reaching new heights...



*Approximately to scale

History of LS Detectors

Reaching new heights...



JUNO

Aug 2025 -

- LAB + 2.5 g/L PPO + 3 mg/L bis-MSB
- $R = 17.5$ m
- 20000 t target
- 43000 PMTs

*Approximately to scale

Principle of Scintillation

e.g. inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$



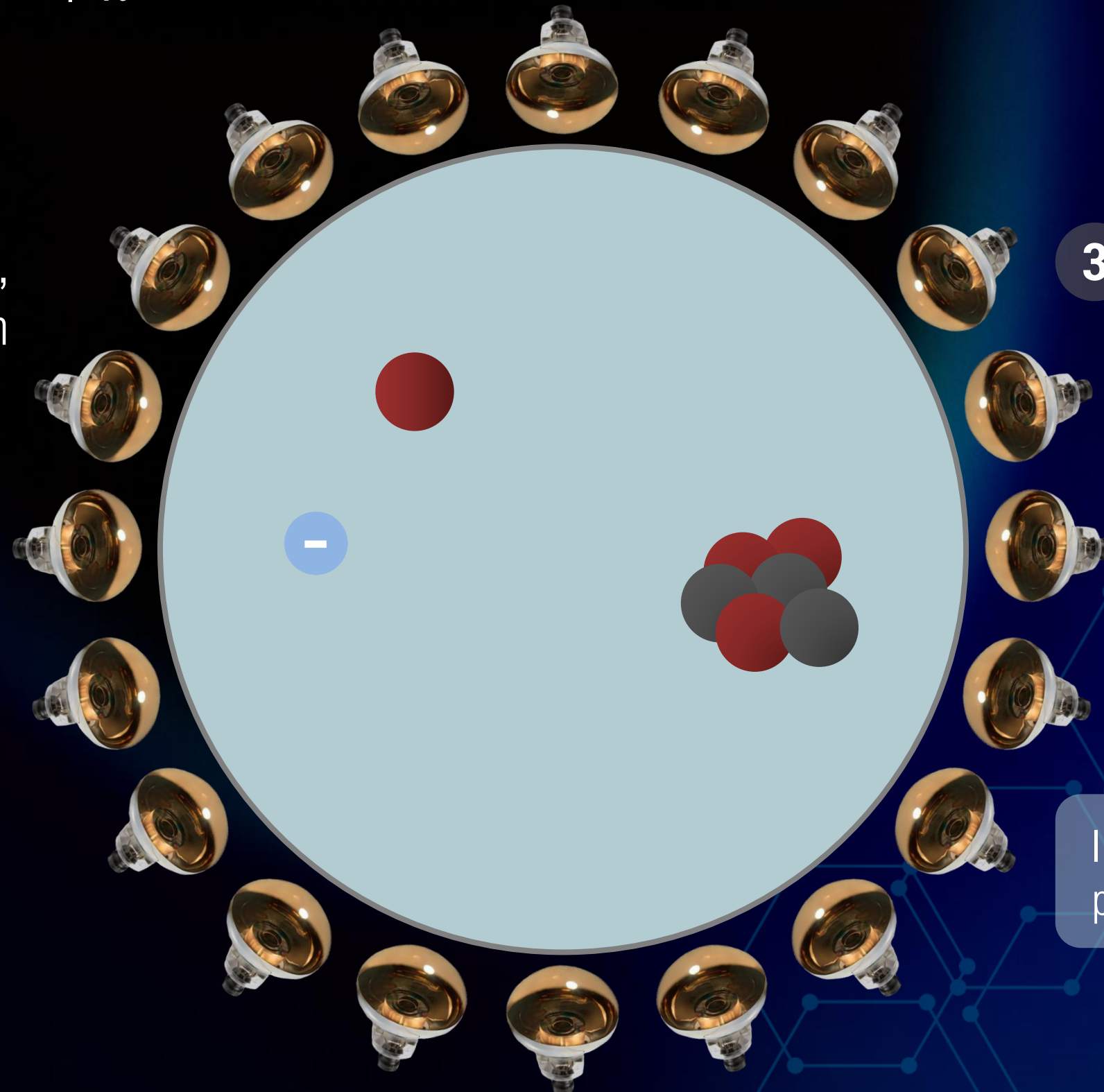
1 Collision with proton,
positron and neutron production

2 Positron annihilation
(prompt signal)

3 Neutron thermalisation

4 Neutron capture
(delayed signal)

Interaction with the scintillator medium
produces a cascade of detectable photons



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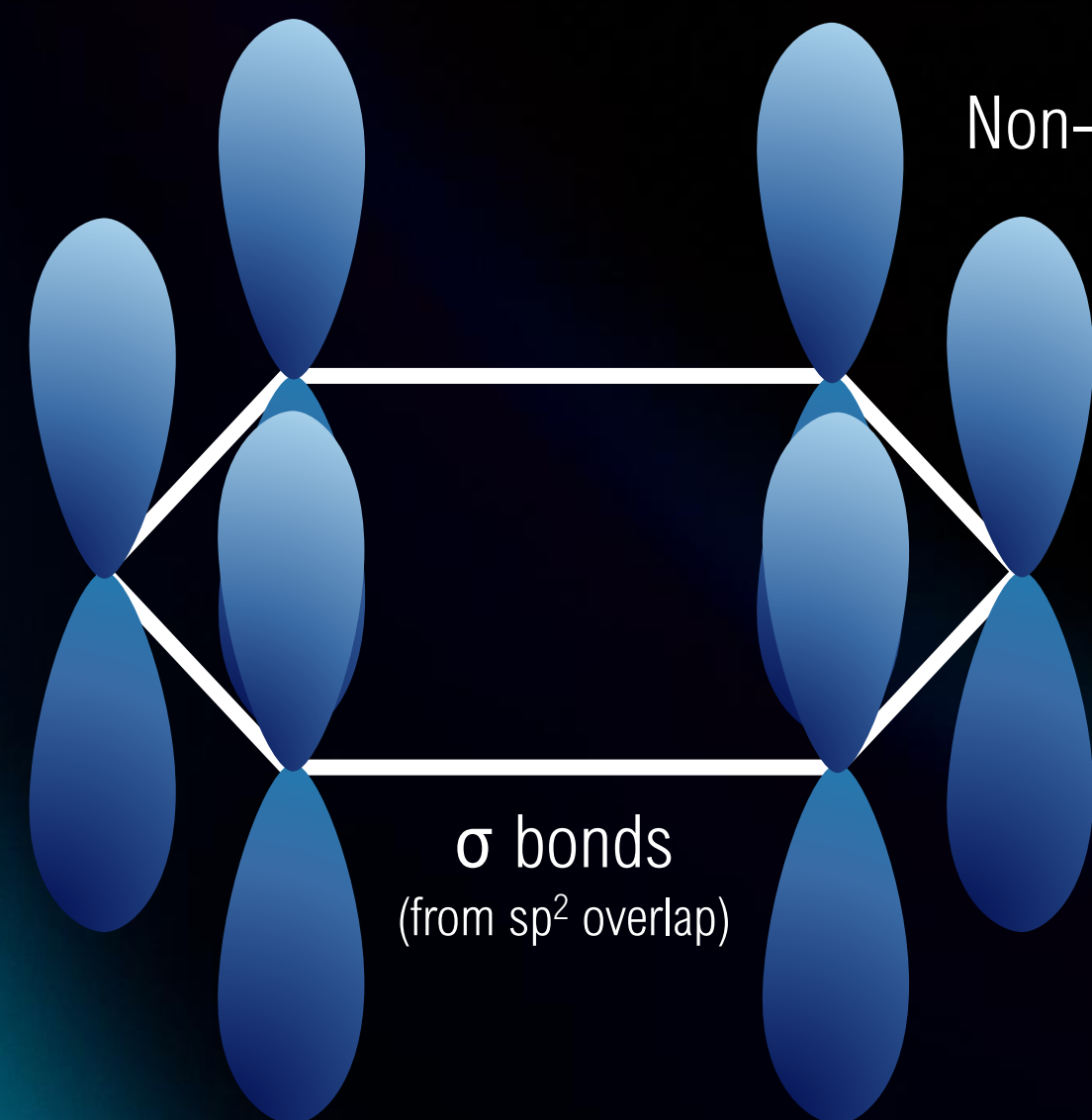
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(delayed signal)

Interaction with the scintillator medium
produces a cascade of detectable photons



Organic Scintillators

- Aromatic and/or double-bonded hydrocarbons
- Conjugated π -electron systems
- Highly delocalised e⁻s, with a small energy gap between electronic states (3-5 eV)
 - Easy to absorb, transfer and emit radiation



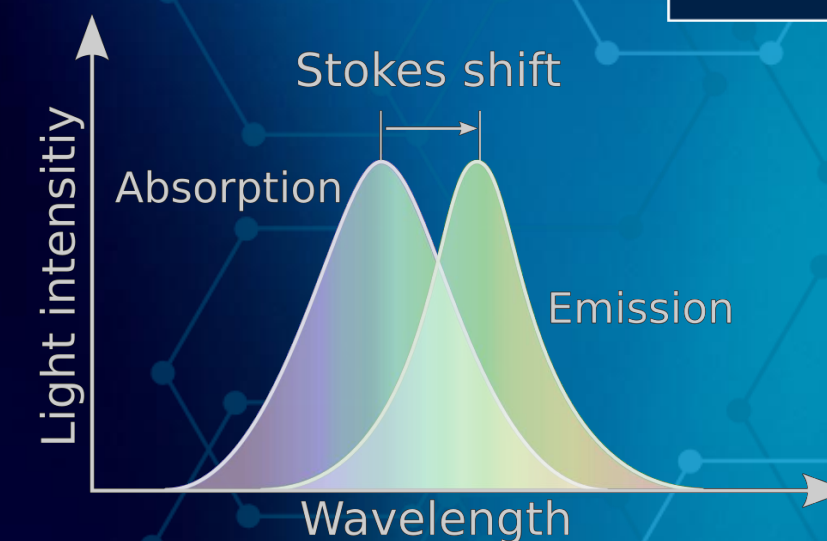
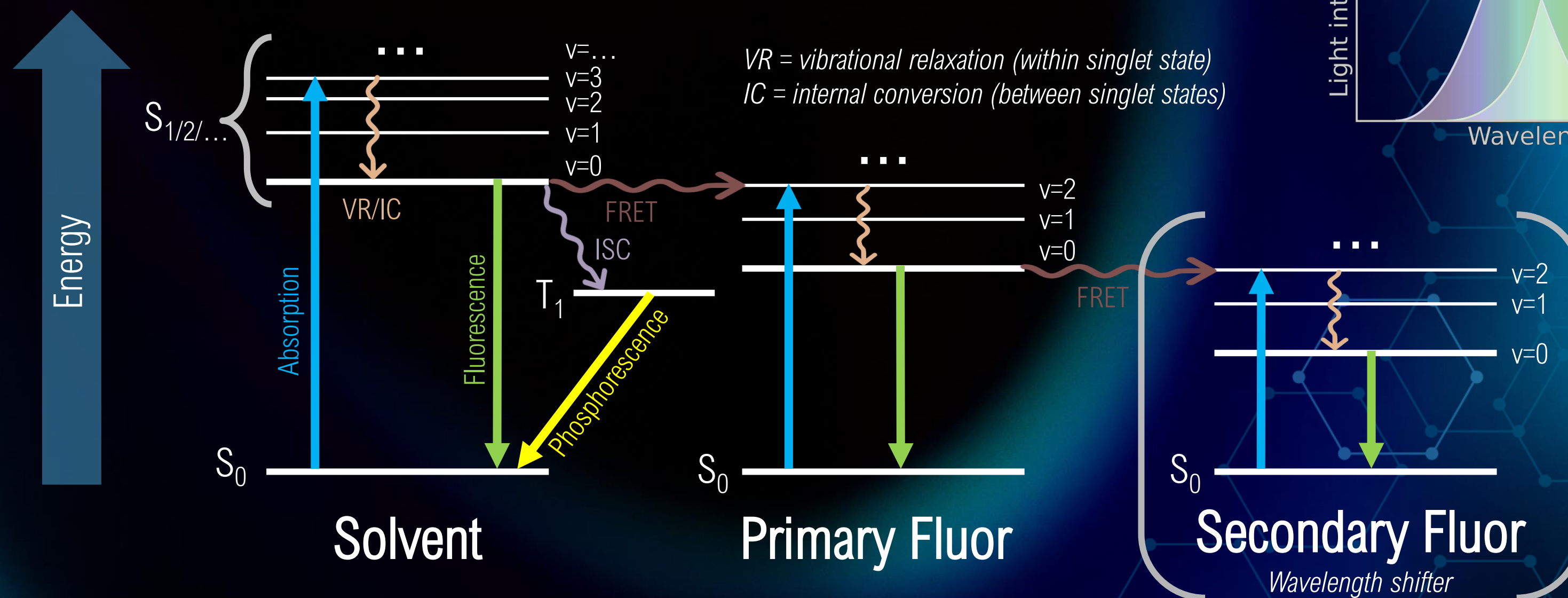
p orbital overlap



Organic Scintillators



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Light is incrementally shifted to longer wavelengths; better matches PMTs' peak quantum efficiency

What & Why Fast Scintillator?

	Traditional LS	Water Cherenkov
Energy Resolution	~ 3-5% at 1 MeV	~15-20% at 10 MeV
Energy Threshold	~0.3 MeV (SNO+)	~3.5 MeV
Position Resolution	~10 cm at 1 MeV	~ 20 – 30 cm at 10 MeV
Topology	All events appear as isotropic, point-like spheres	Track imaging and ring crispness for PID, excellent at high energy (GeV-scale)
Directionality	Washed out by isotropic scintillation	Highly directional $\cos\theta_c = \frac{1}{\beta n}$ $\theta_{\text{res}} \sim 20^\circ$

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$$t_{\text{res}}^i = t_{\text{hit}}^i - t_0 - t_{\text{flight}}^i$$

i^{th} PMT hit time
 $\sigma_{\text{hit}} \approx \text{PMT's TTS} \sim 1 - 2\text{ns}$

Global event time

TOF
 σ_{flight} dominated by scintillator emission time

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Better position resolution
(~10 cm → few cms)

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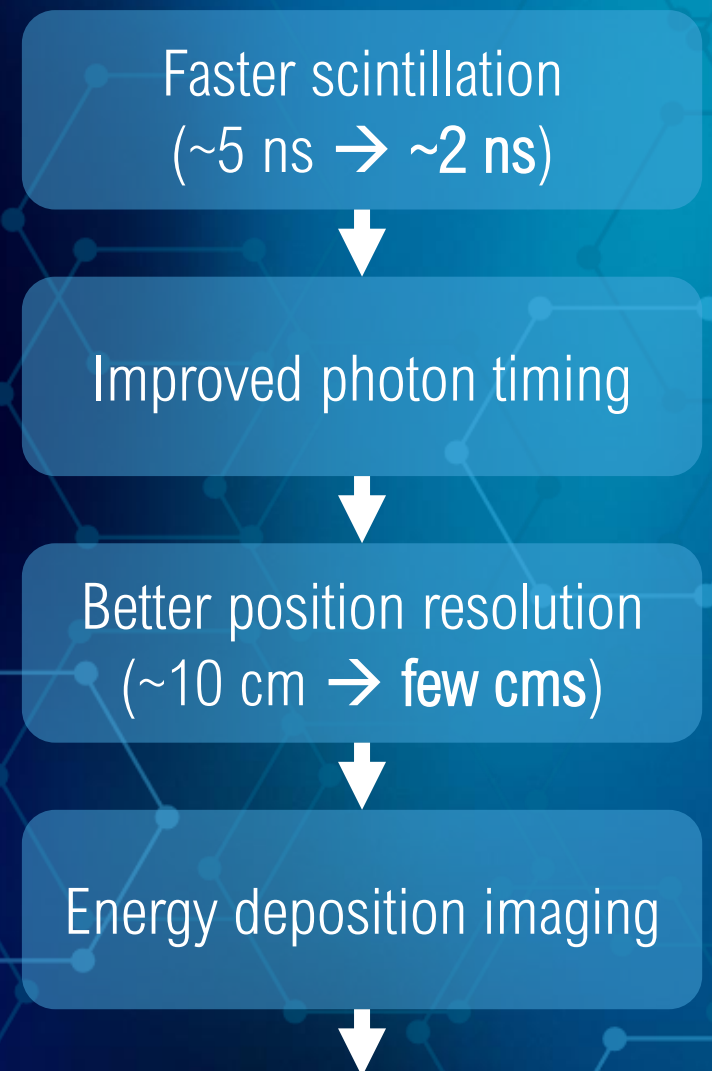
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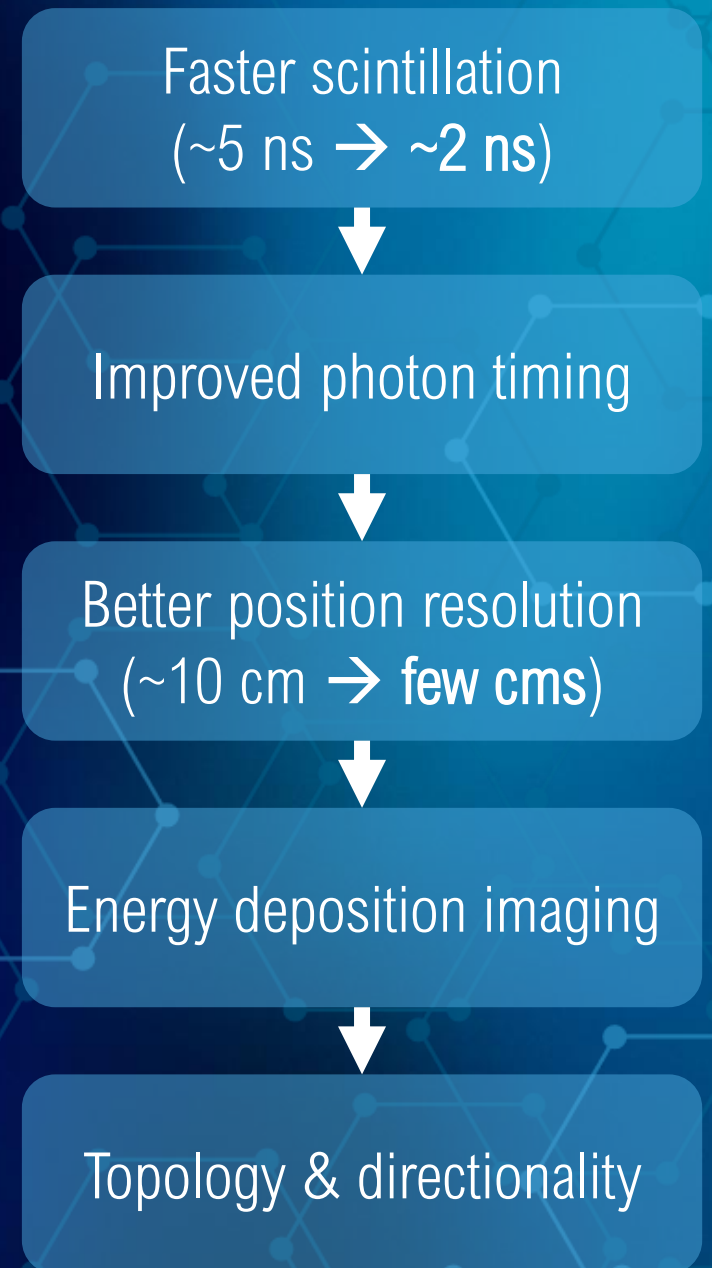
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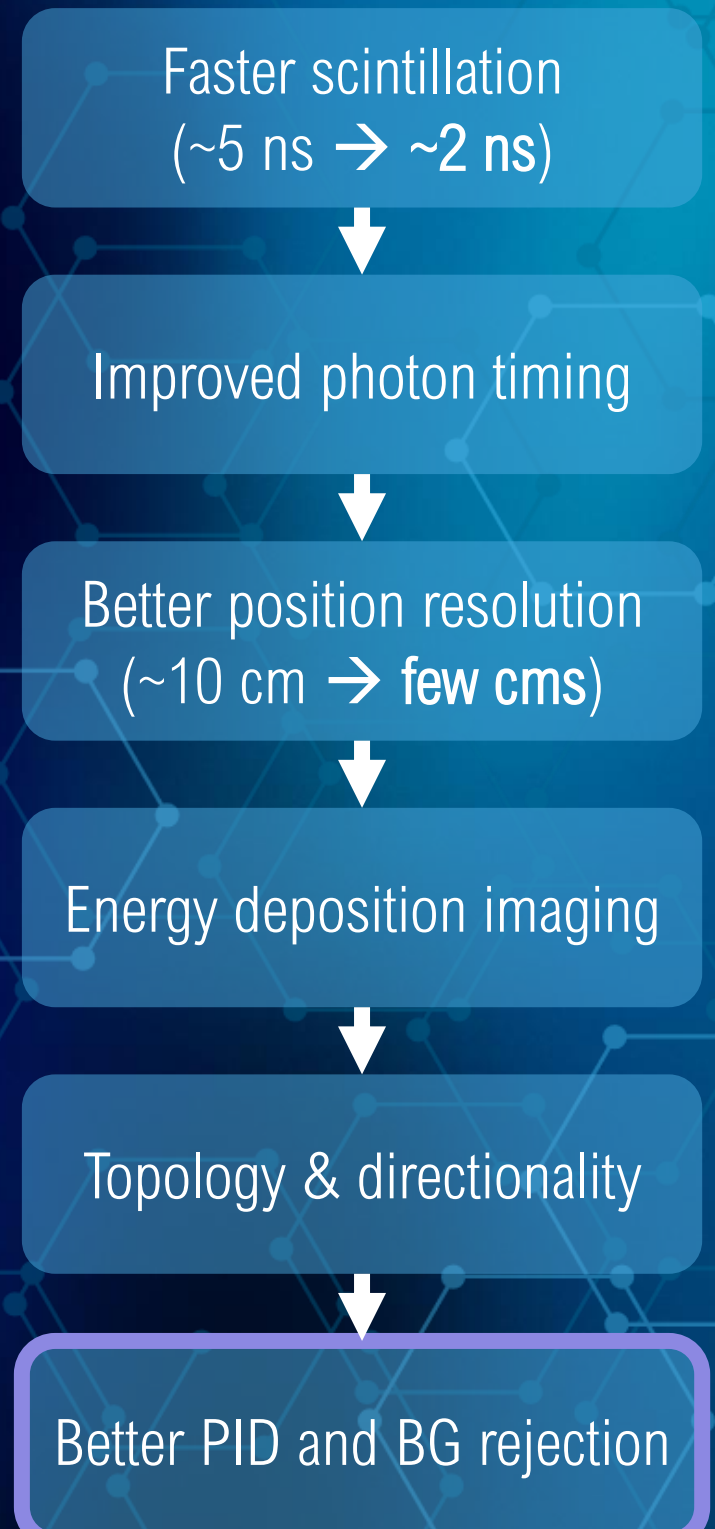
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 σ_{flight} dominated by scintillator emission time

Combining LS E resolution and threshold with imaging = high sensitivity to rare low-energy events,
e.g. $0\nu\beta\beta$

Faster scintillation
(~5 ns → ~2 ns)

Improved photon timing

Better position resolution
(~10 cm → few cms)

Energy deposition imaging

Topology & directionality

Better PID and BG rejection

Fast Scintillator Criteria



1. Timing

- $\mathcal{O}(0.1\text{ns})$ rise time & $\mathcal{O}(1\text{ns})$ decay time
- Faster timing = better position reconstruction

2. Light yield

- $\mathcal{O}(10000 \text{ photons/MeV})$
- Higher light yield = better energy resolution

3. Thermal stability

- Melting point $< \sim 10^\circ\text{C}$ (typical detector operating temperature)

4. Attenuation

- $L_{\text{att}} \sim \mathcal{O}(10 \text{ m})$
- Signals should reach PMTs with minimal degradation

5. Efficient energy transfer between solvent and fluor

6. Large Stokes shift

- To minimise self-absorption by the solvent

7. Chemical compatibility

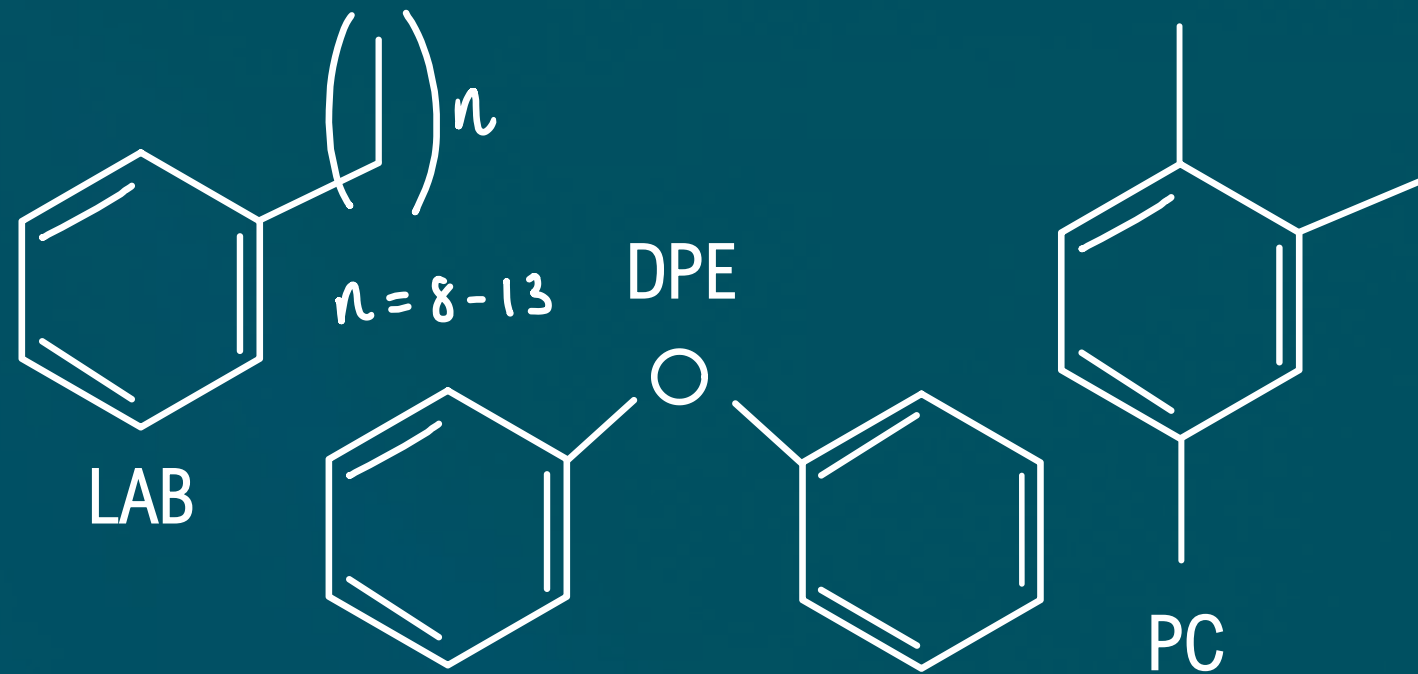
- Must not damage the vessel housing the scintillator, over typical decades-long experiment lifespan

8. Hazard level

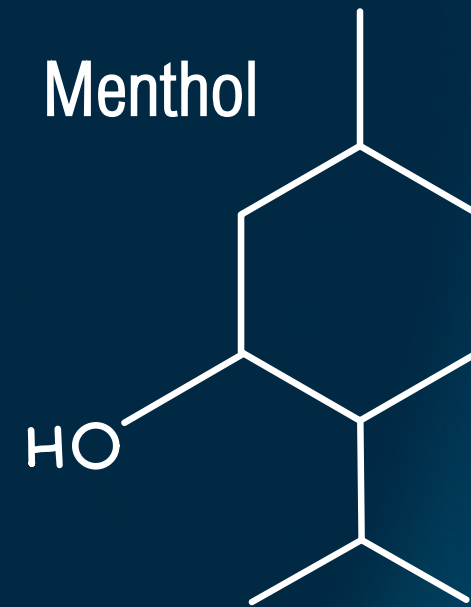
- Minimal handling, storage and environmental risks

Component Candidates

Solvent



Menthol



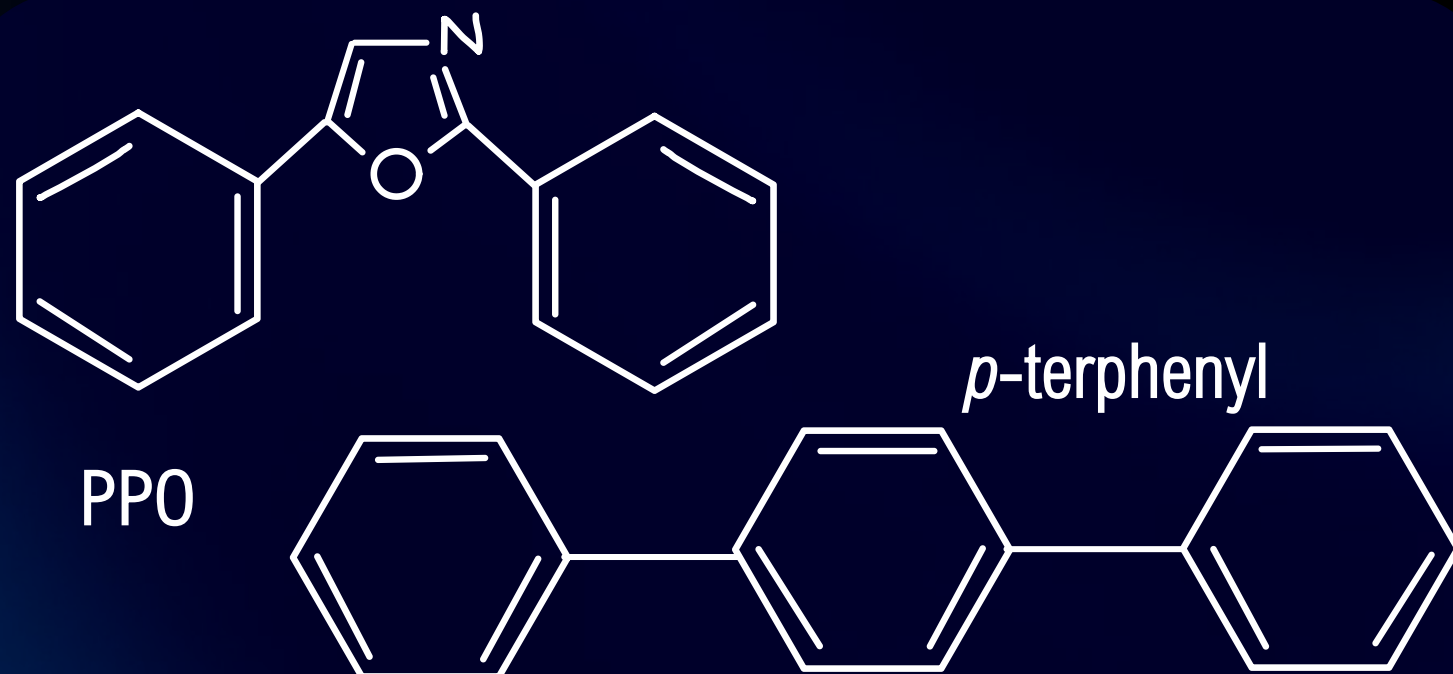
DPE crystallisation
(m.p. = 25-27°C)

BCH



Melting Point Depressant

Primary Fluor



bis-MSB



Secondary Fluor

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Melting Point Depressant



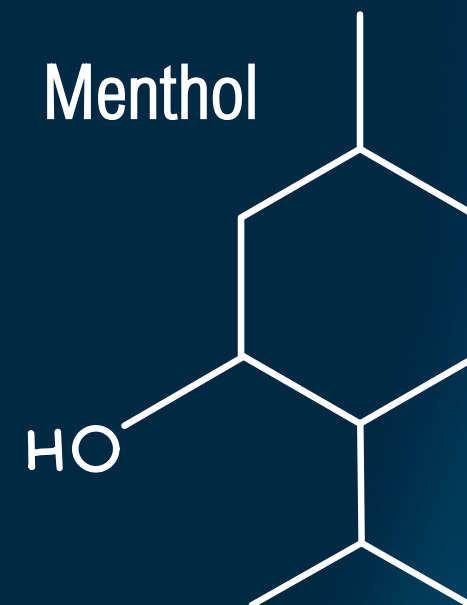
BCH

More expensive

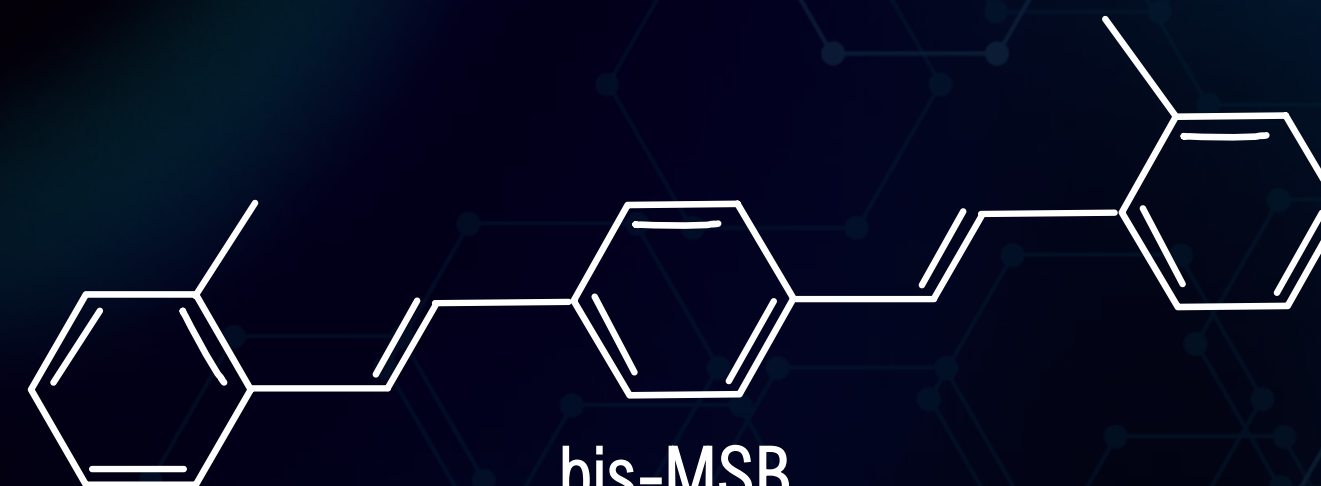
Toxic & flammable

Secondary Fluor

Menthol

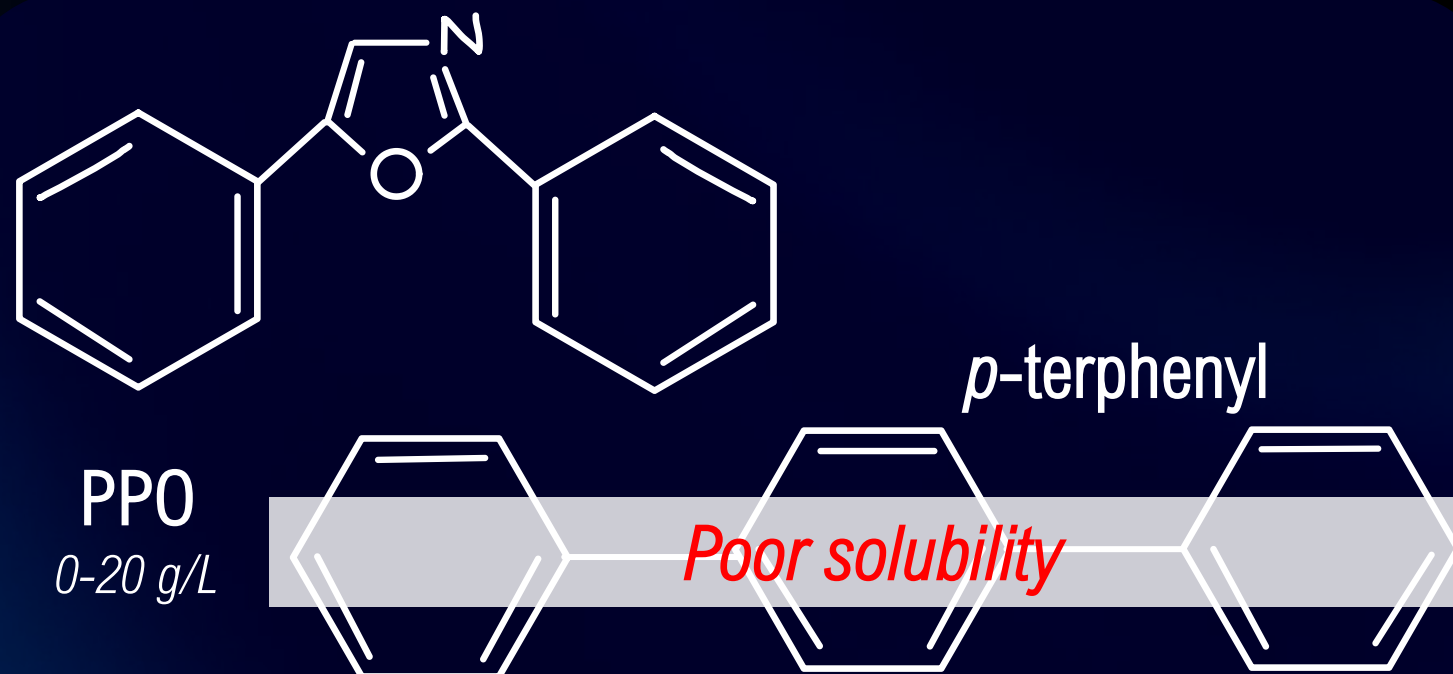


bis-MSB
0 - 2 g/L



Poor solubility

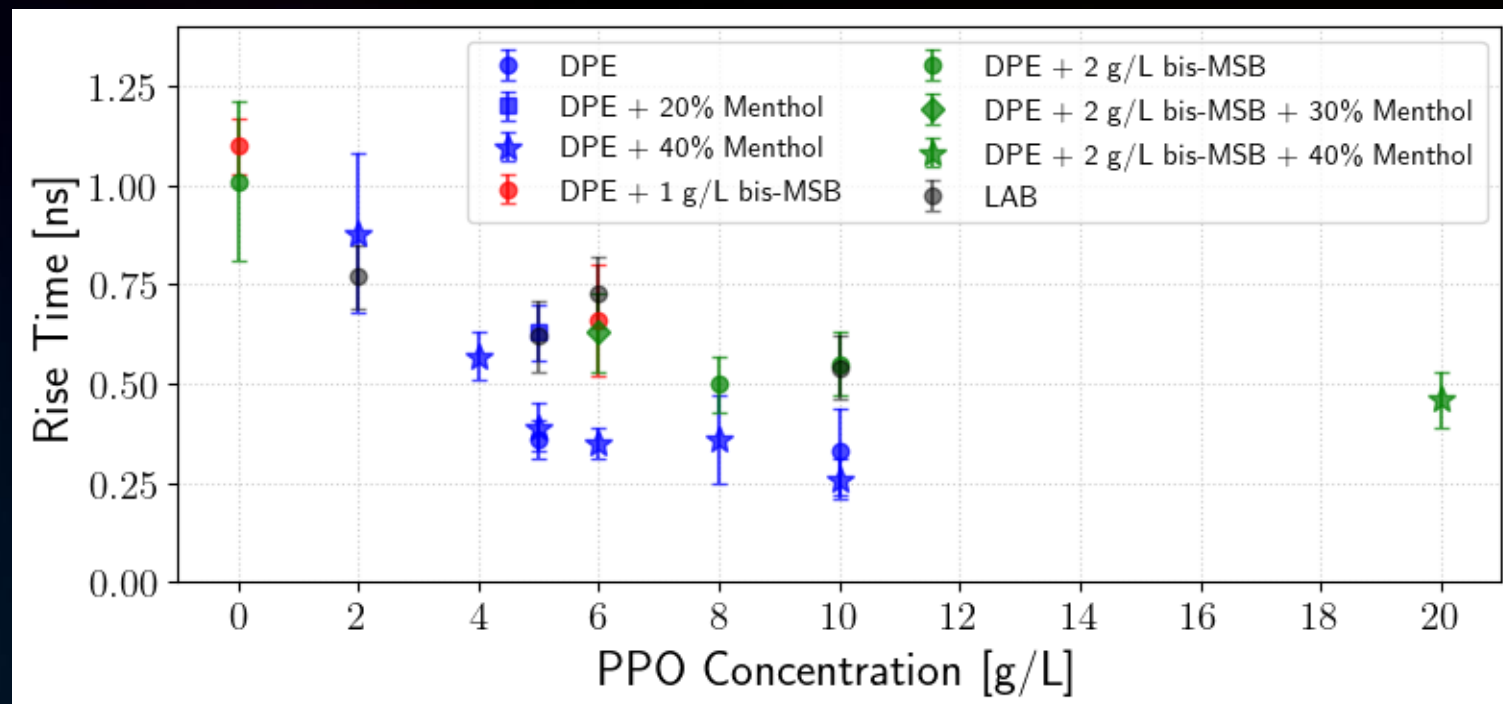
PPO
0-20 g/L



p-terphenyl

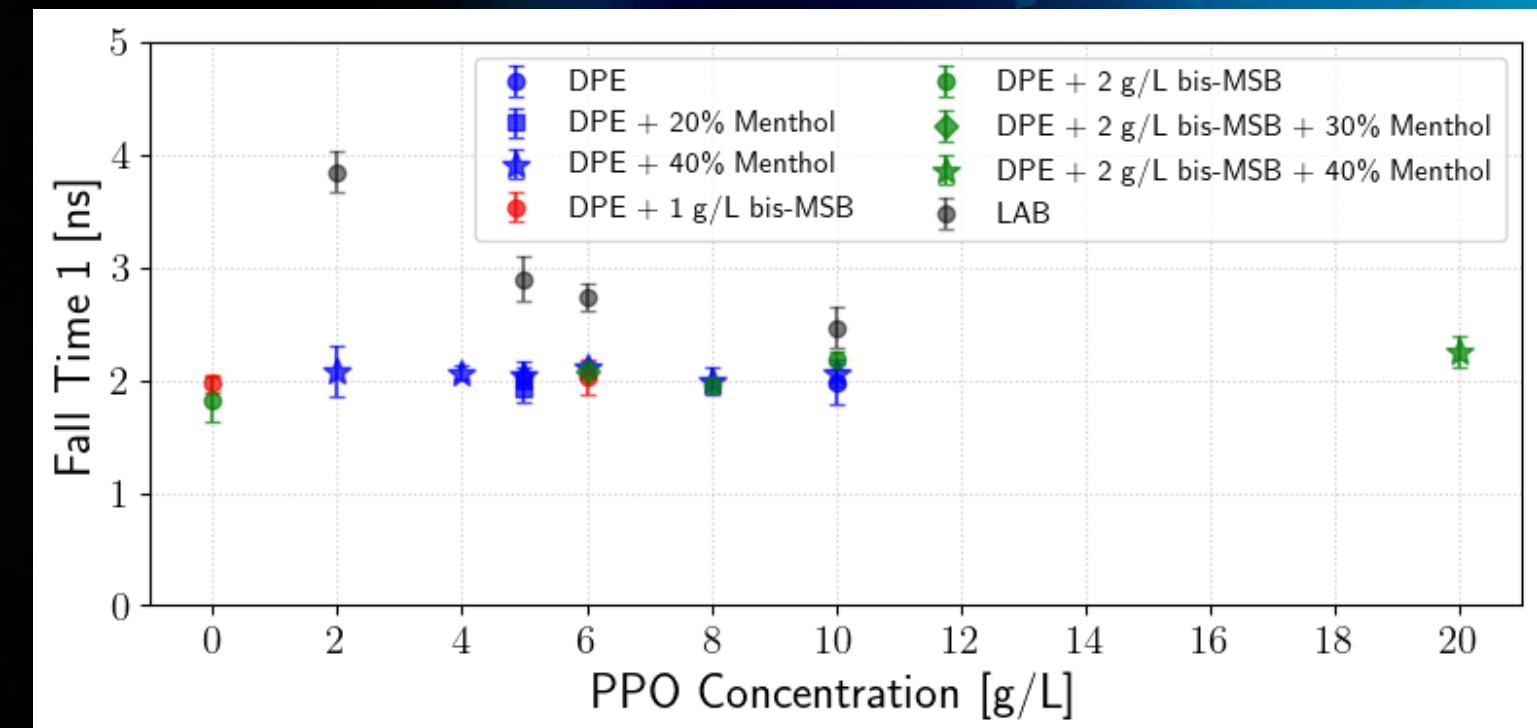
Results

Rise Time



- DPE + 40% menthol cocktails rise times ~twice as fast as LAB-based cocktails at identical PPO concentrations
- Increasing PPO concentration improves rise time up to ~6 g/L; minimal improvements thereafter
- Adding bis-MSB slows rise time by 0.2 ns
 - Due to extra energy transfer step

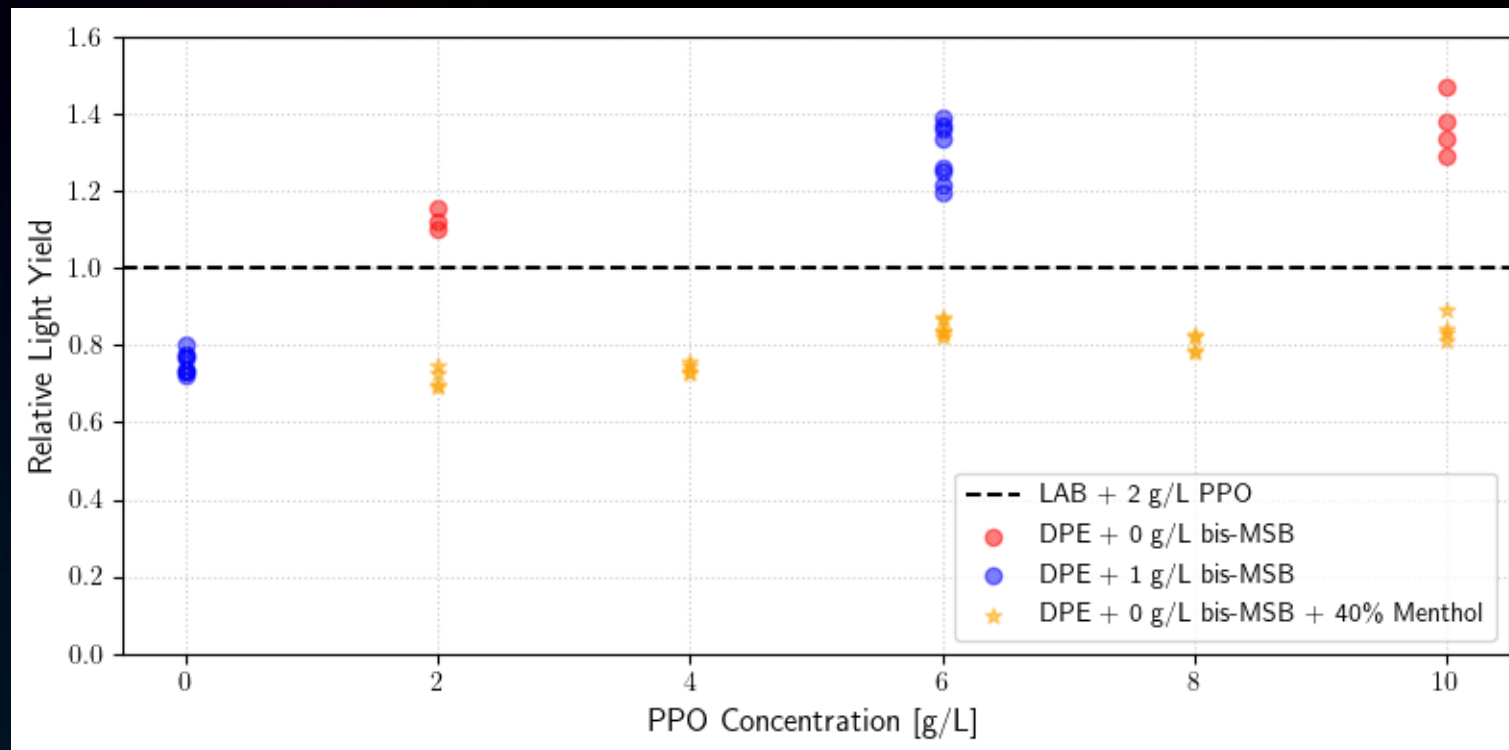
Fall Time 1



- DPE-based mixtures have consistent fall time of ~2 ns
 - Close to the intrinsic 1.6 ns decay of PPO
- Menthol has no impact on either the rise or fall times

Results

Light Yield



- DPE + PPO samples w/o menthol: 10-40% higher LY than the LAB + 2 g/L PPO reference
- Addition of menthol reduced LY by $(21.05 \pm 0.05)\%$ on average relative to the reference
 - Still an appreciable LY

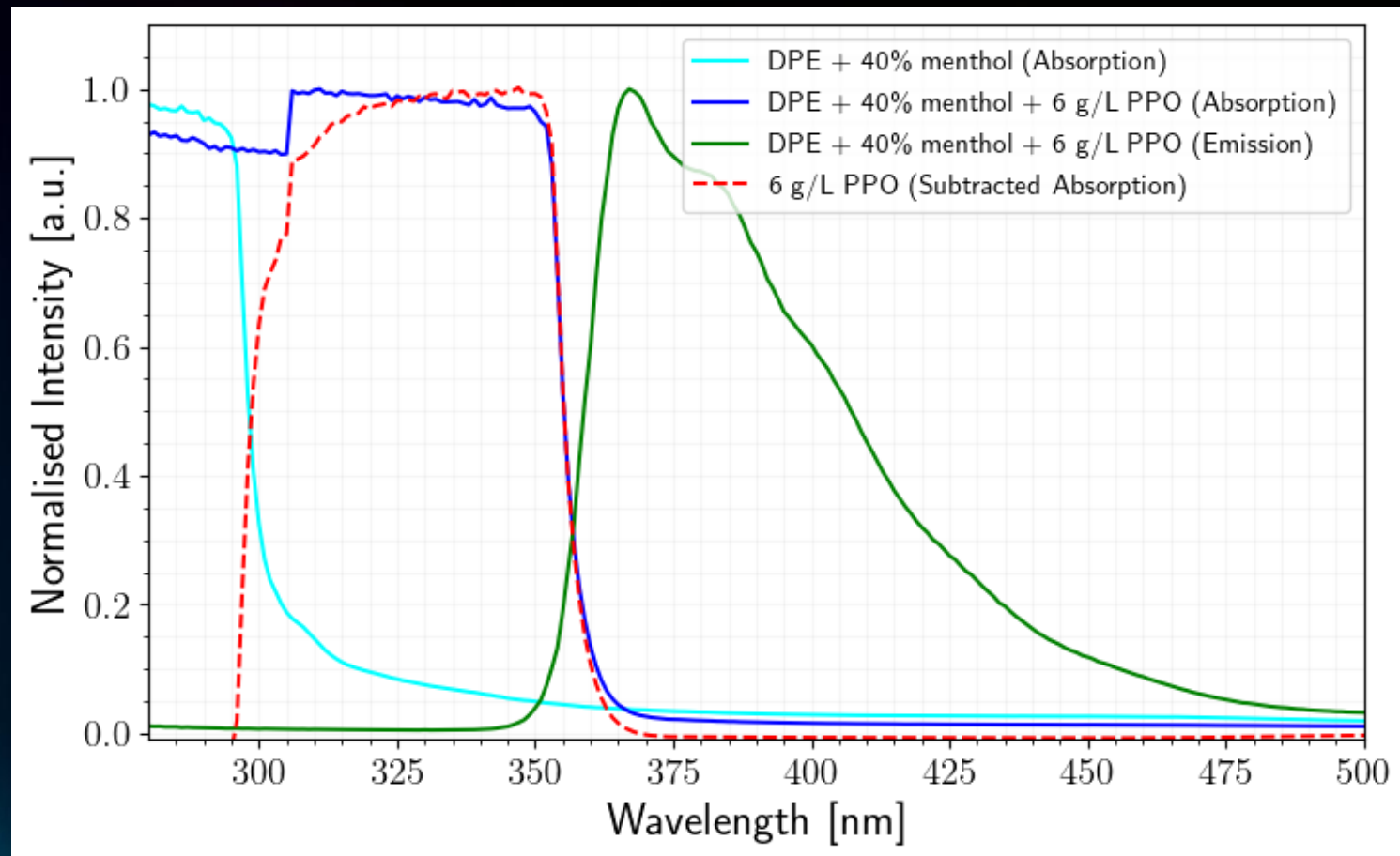
Optimal Formulation:
DPE + 40% menthol + 6 g/L PPO

τ_{rise} [ns]	0.35 ± 0.04
τ_{f1} [ns]	2.11 ± 0.05
τ_{f2} [ns]	15.94 ± 1.82
Light Yield [photons/MeV]	10065 ± 630

- Balances quick timing with significant LY
- Option to add 1 g/L bis-MSB in future studies
 - Boosts LY, at cost of slower timing

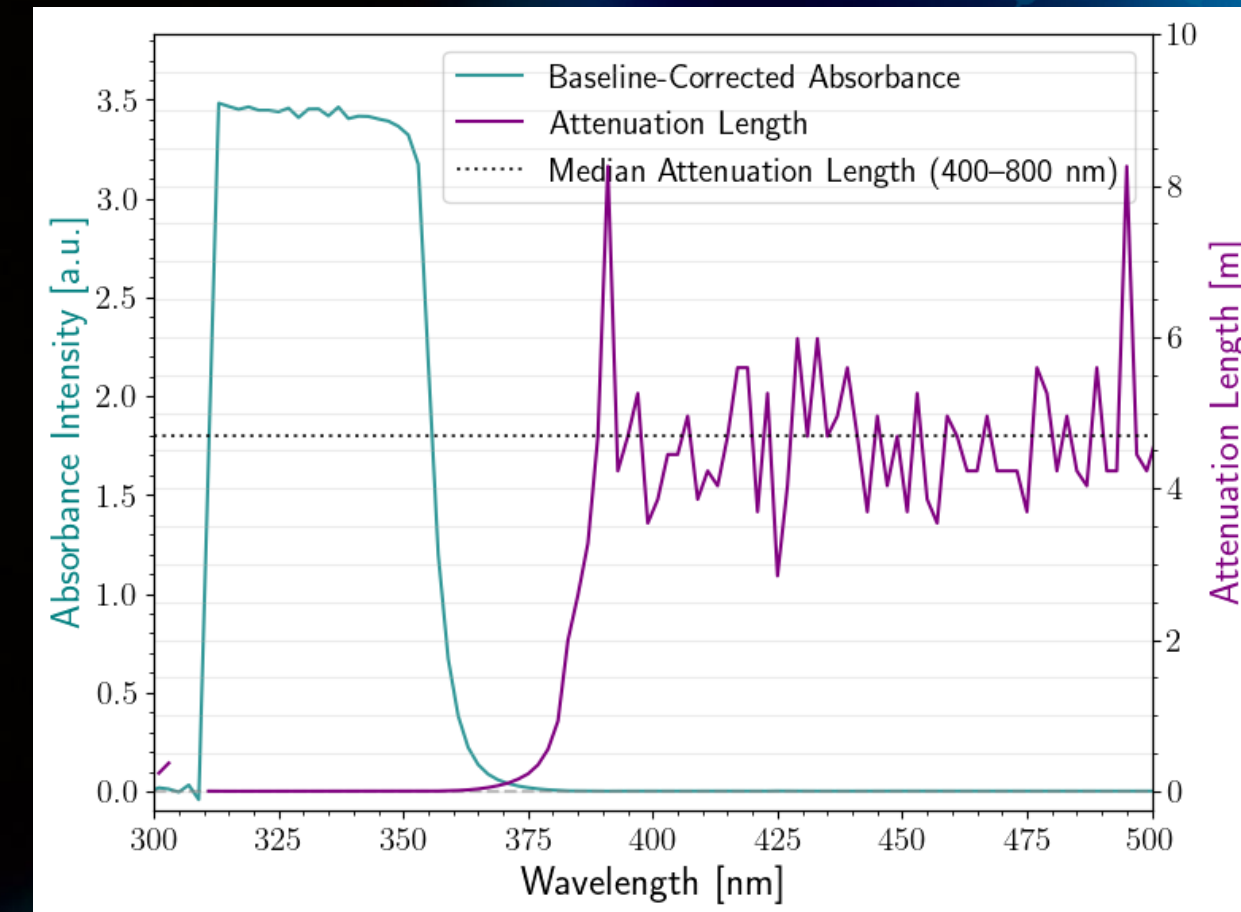
Results

Absorption & Emission Spectra



- Small abs/em overlap → non-negligible reabsorption
- $\lambda_{\text{emitted}} = 362\text{nm}$

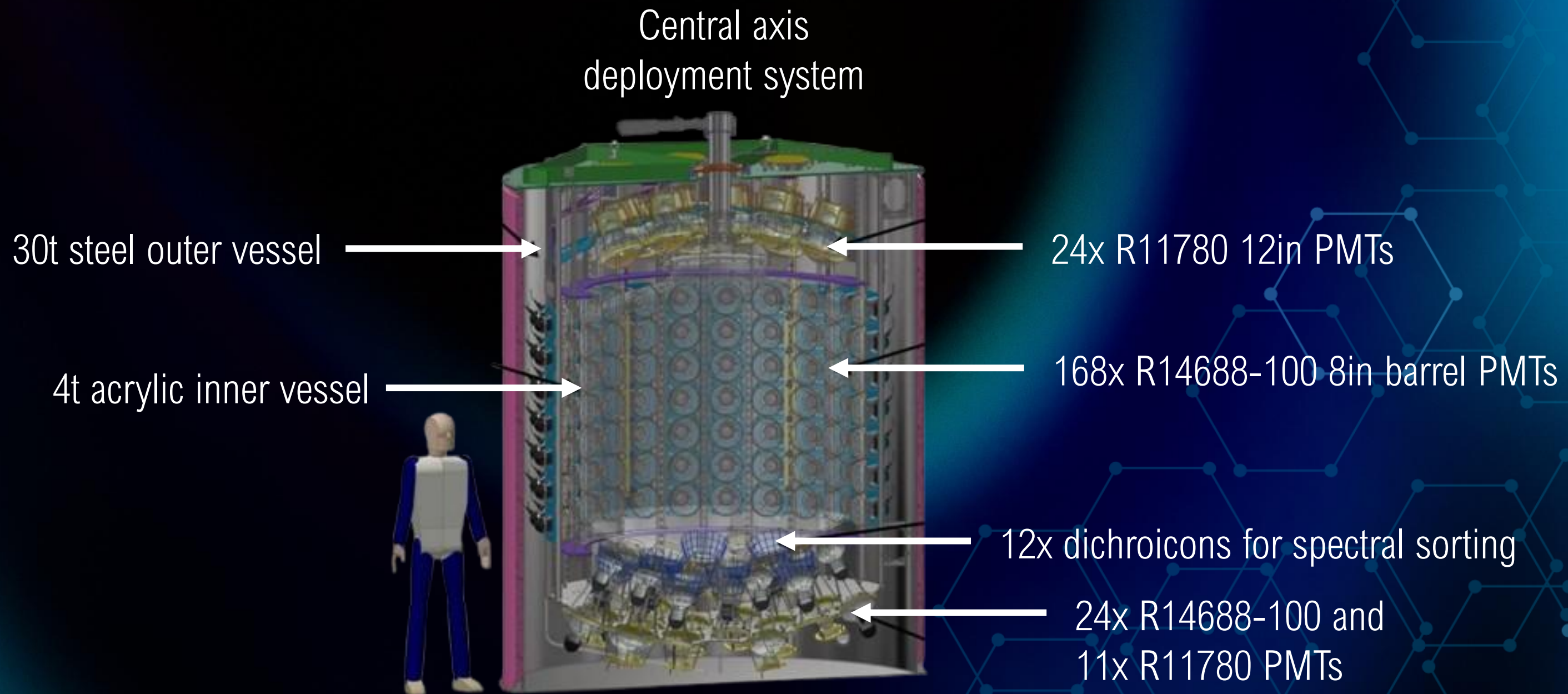
Attenuation Length



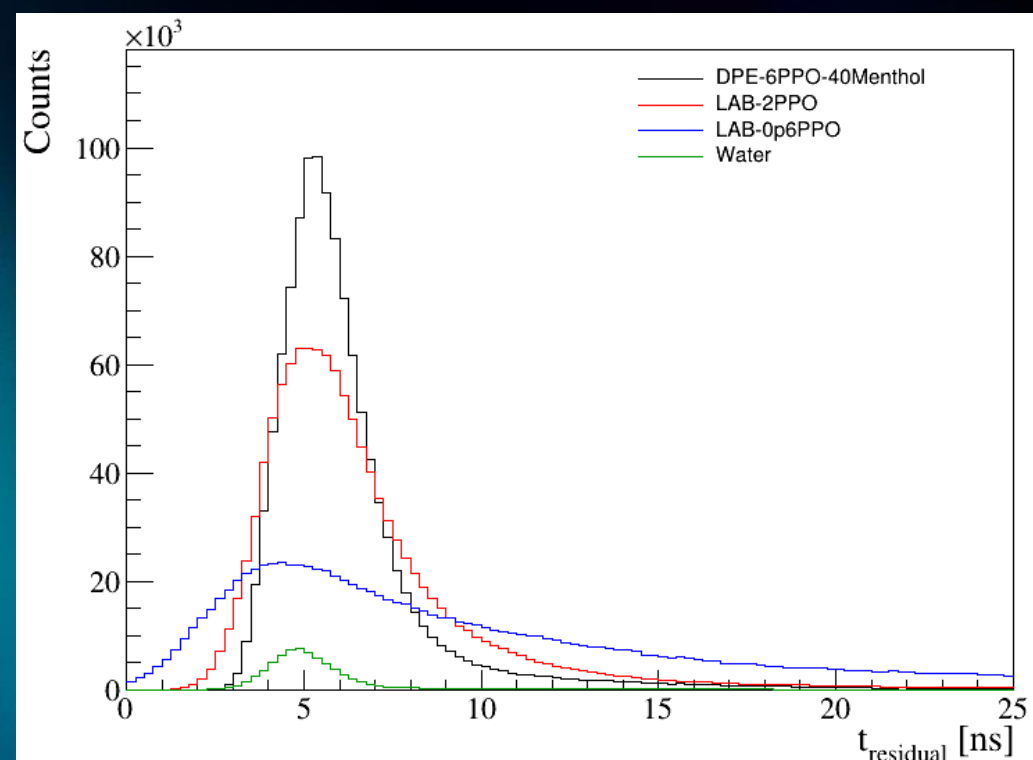
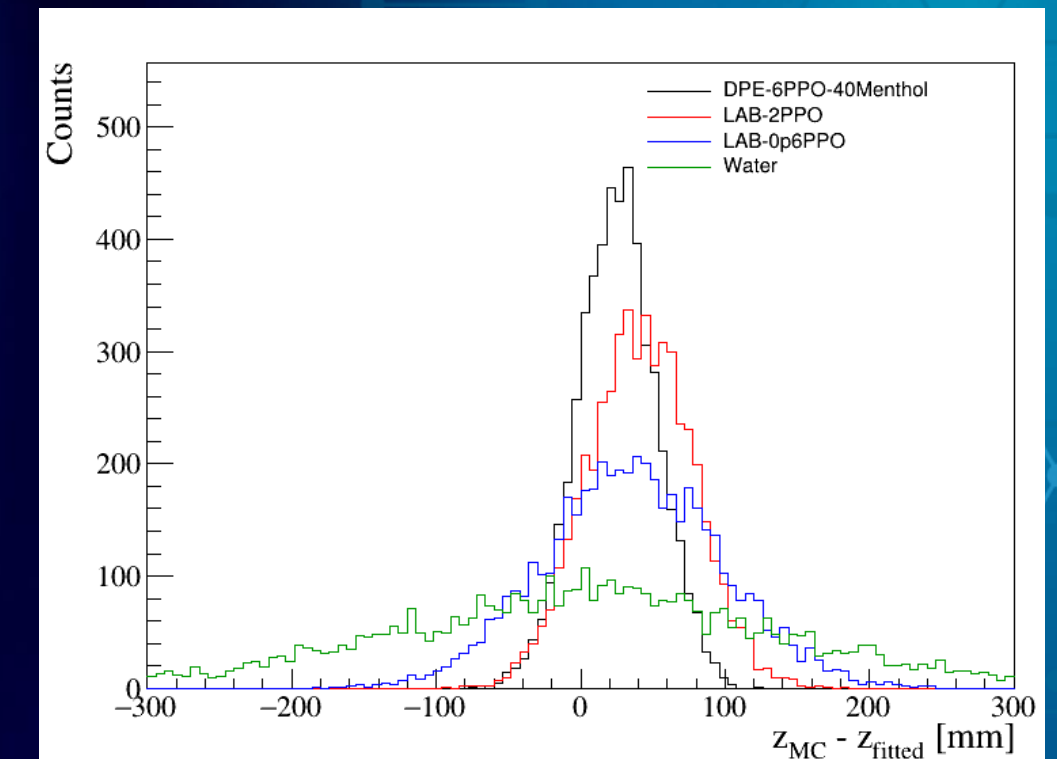
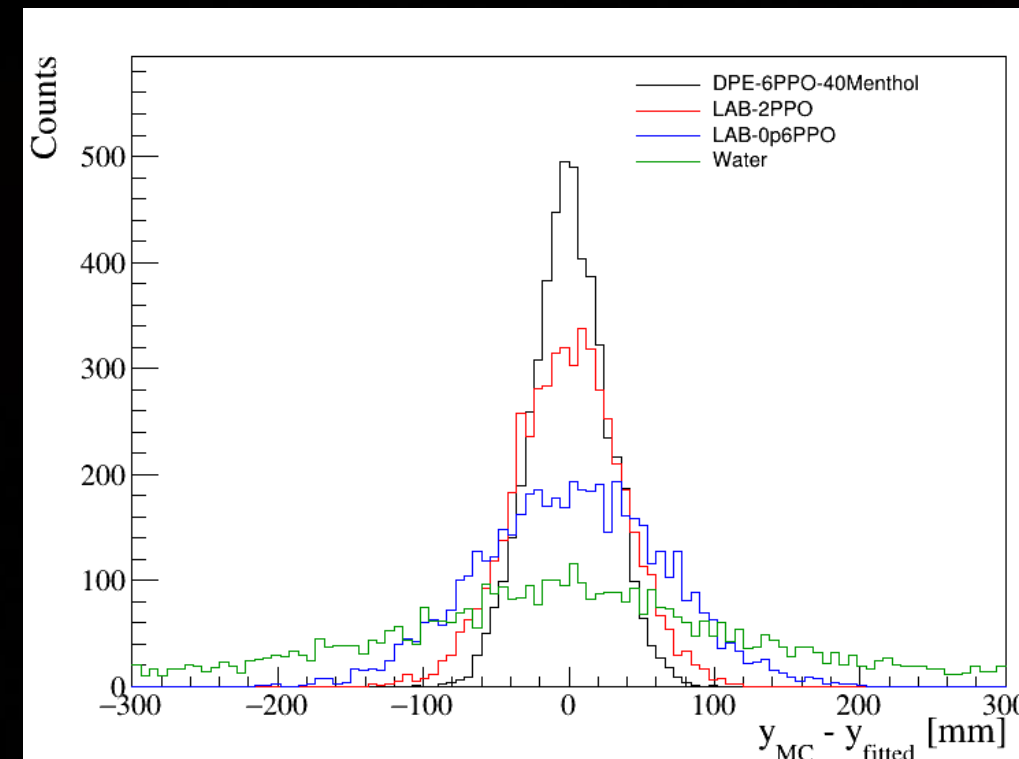
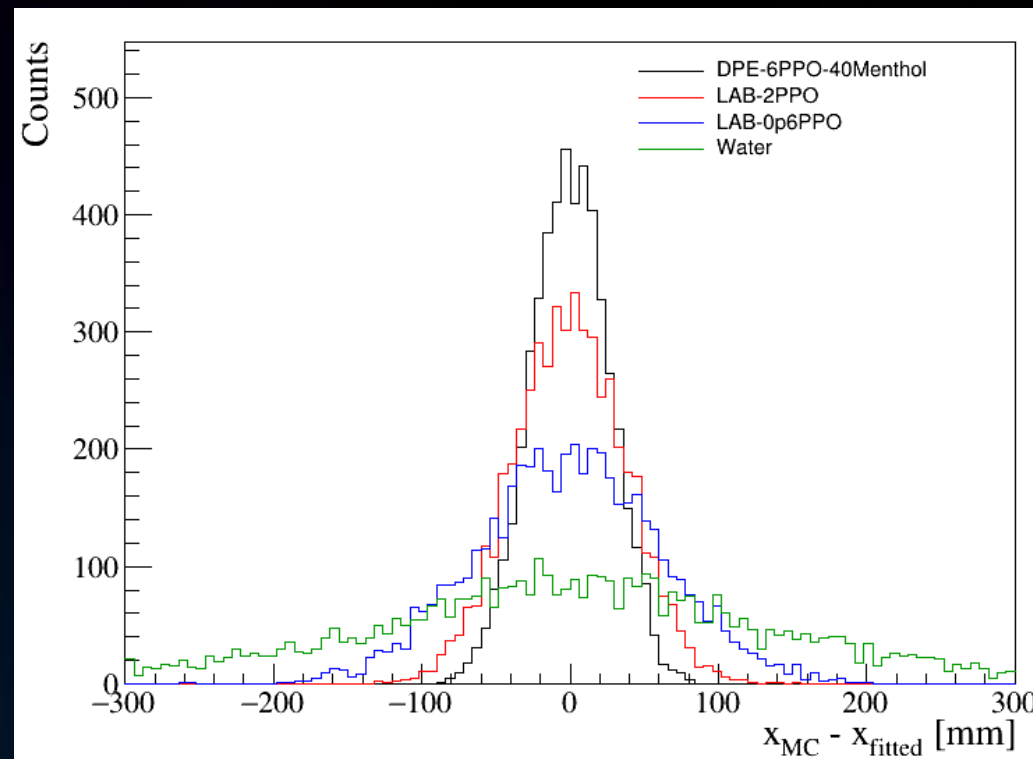
- Instrumental sensitivity-limited attenuation length measurements
- $L_{\text{att}} = 4.69\text{m}$ (median above 390 nm)
- To be improved with longer-length cuvette measurements

The EOS Detector

- Testbed for novel technologies for next-generation LS neutrino detectors
 - Sub-ns photodetectors, dichroicons, slow scint, fast scint, etc.
- 12 cm diameter, 6m long glass 'lightsaber' containing proposed FS to be deployed in EOS



Preliminary Simulation Results



- 5000 2 MeV electrons simulated at the centre of the detector (within the lightsaber)
- Reconstructed with `quadfitter`
- Proposed FS (DPE + 6 g/L PPO + 40% menthol) outperformed LAB-based cocktails and water in position and timing reconstruction
- Also reduced skew in the reconstructed z-coordinate
- **Very promising!**

Future Work

- 1 Extend simulation studies with **mimir**, a likelihood-based fitter
 - Enhanced position and timing reconstruction compared to `quadfitter`
- 2 Develop & apply a **multi-site event classifier**
 - Separation of single-site (i.e. β -like) events from multi-site (i.e. γ -like)
- 3 Characterise FS samples from Berkeley
- 4 **Deploy FS cocktail** in the Eos lightsaber & commission the system
- 5 Calibrate with range of radioactive sources
- 6 Compare calibration data with MC simulation predictions

Backup

