Status of the DarkMESA Experiment.

Mirco Christmann

for the MAGIX Collaboration

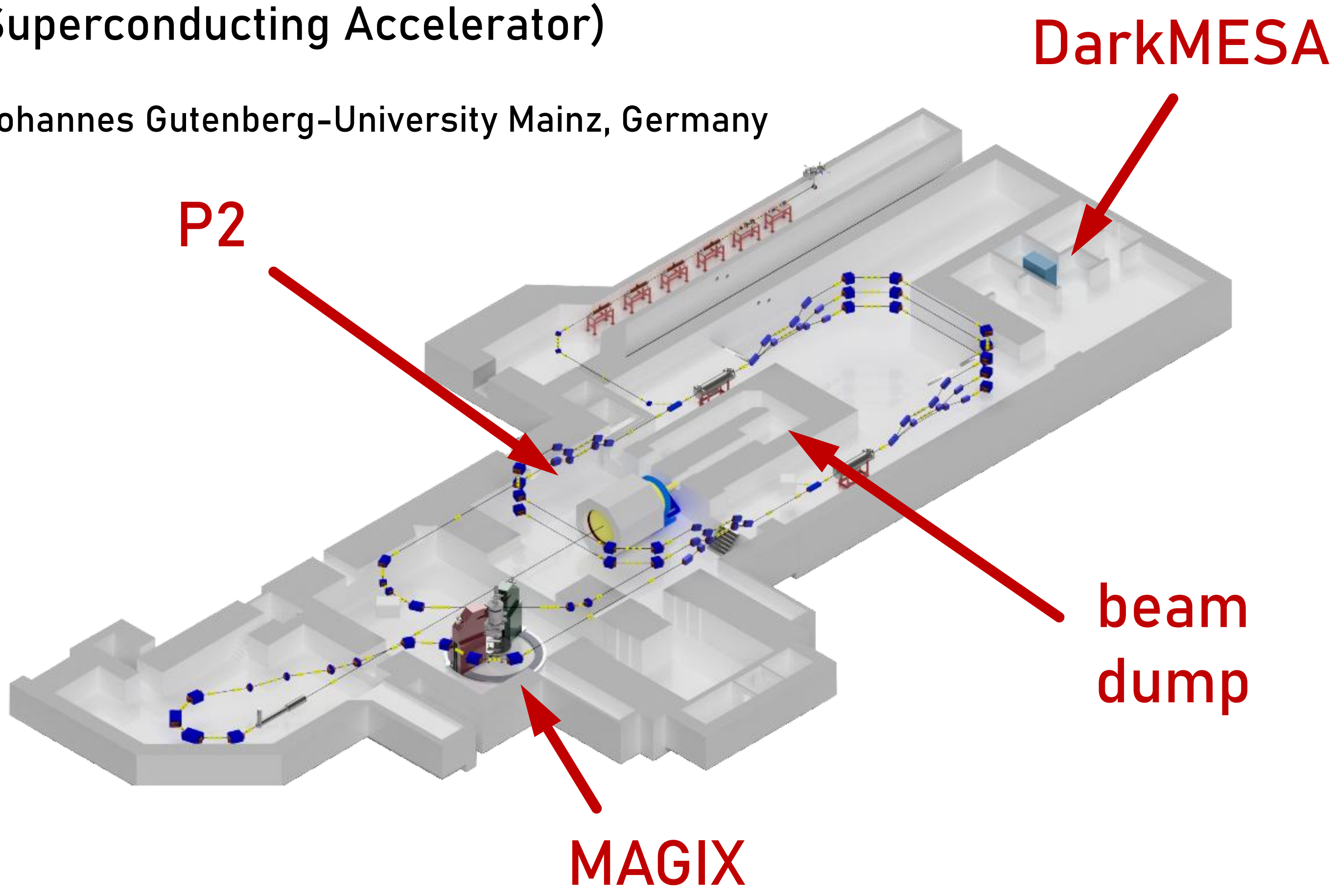
16th European Research Conference on Electromagnetic Interactions with Nucleons and Nuclei

28rd Oct – 1st Nov 2025

Experimental Location.

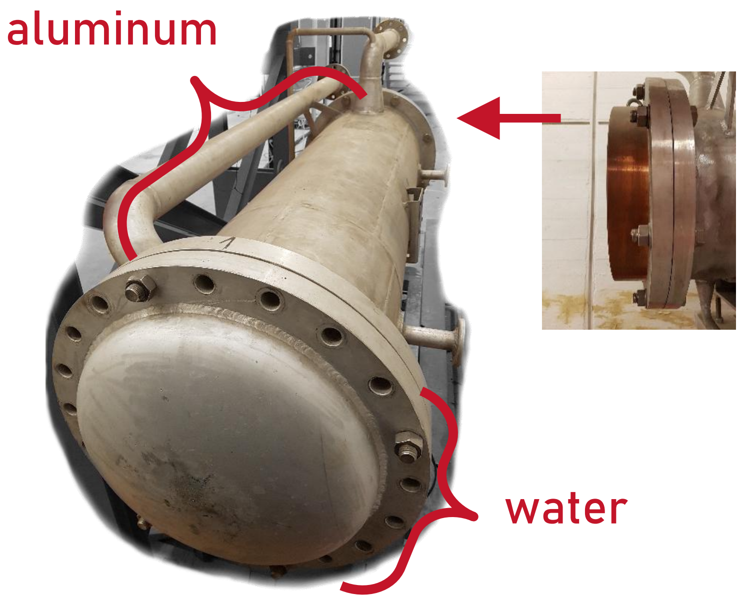
MESA (Mainz Energy-recovering Superconducting Accelerator)

Johannes Gutenberg-University Mainz, Germany



P2 & DarkMESA

- Extracted beam (EB) mode
- 155 MeV beam energy
- 0.15 mA beam current



Ideally suited for a parasitic dark sector experiment

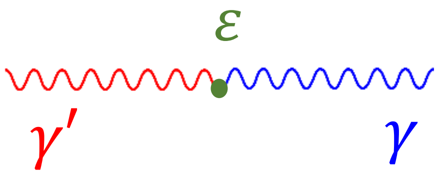
Outline.

- Dark Sector
- Experimental Concept and Proposed Phases
- DarkMESA Phase A - Status and Challenges
  - Calorimeter: Readout and Material Decision
  - Veto System & Full Calorimeter: First Case Study
- NuDoubt^{++}@DarkMESA
  - Enhanced Veto System with Gd Loaded Liquid Scintillator
  - Opaque Liquid Scintillator as Active Detection Material

Hidden (Dark) Sector.

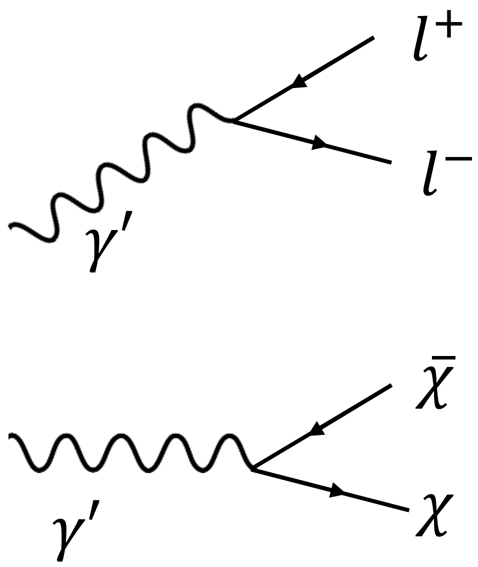
- Standard Model incomplete (astrophysical observations)
- No beyond SM particles found yet
- Hidden sector particles without SM interactions
- But interaction through portals is possible (vector, Higgs, neutrino)
  - ➡ e.g., coupling via kinetic mixing:

$$\mathcal{L}_{\mathrm{mix}} = -\frac{\varepsilon}{2} F_{\mu\nu}^{\mathrm{QED}} F_{\mathrm{dark}}^{\mu\nu}$$



The Dark Photon γ'.

- γ' is a massive vector particle coupling with ε and can mediate DM interactions
  - ➡ Visible decay to $e^+e^-,\ \mu^+\mu^-,\ \pi^+\pi^-$
  - ➡ Invisible decay into DM pairs (if $m_{\gamma'} > 2\, m_\chi$)



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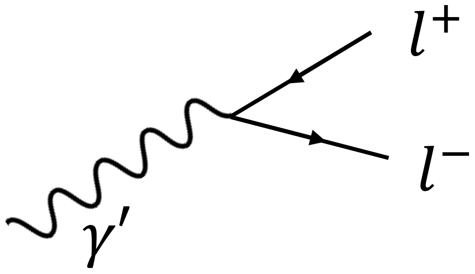
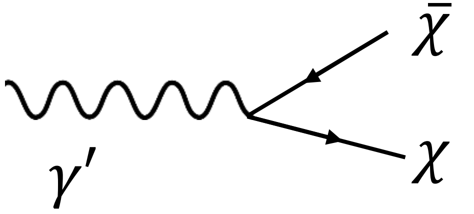
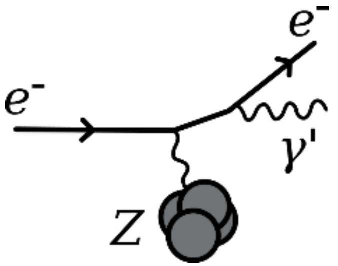




Dark Bremsstrahlung

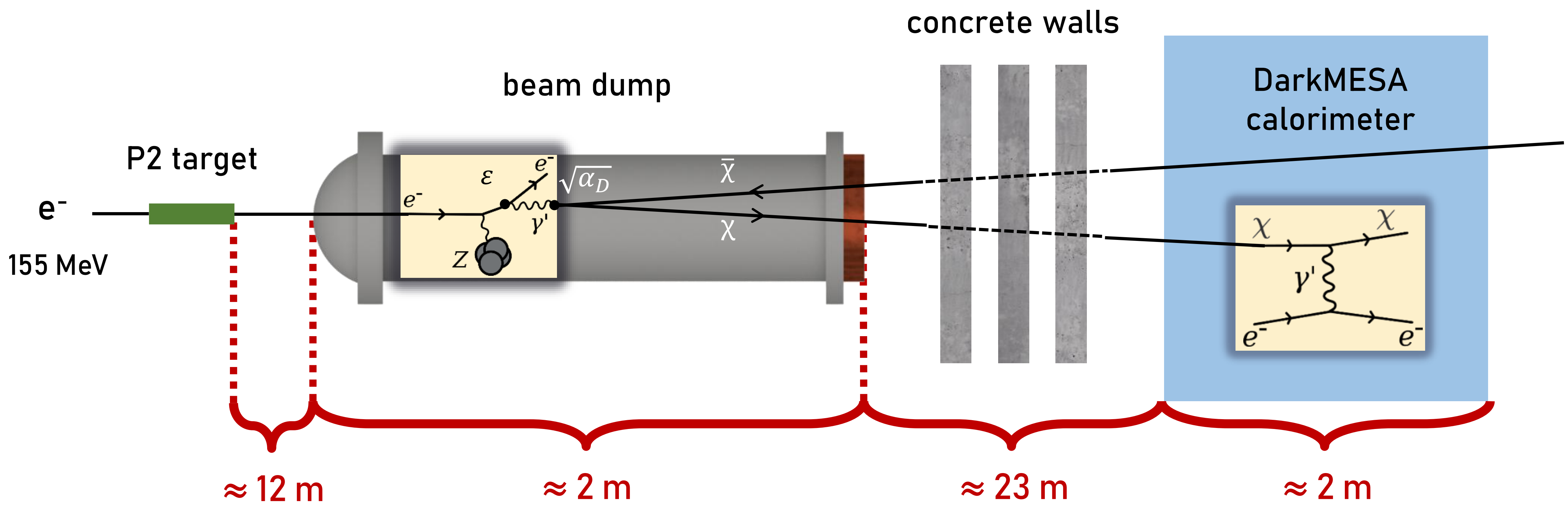
$$\mathrm{e}Z \rightarrow eZ\gamma'$$

- γ' carries away most of the beam energy in first reaction
- γ' emitted in a narrow forward cone
- Different kinematics compared to massless el.-magn. Bremsstrahlung



➡ Strategy: produce many hard photons

Experimental Concept.

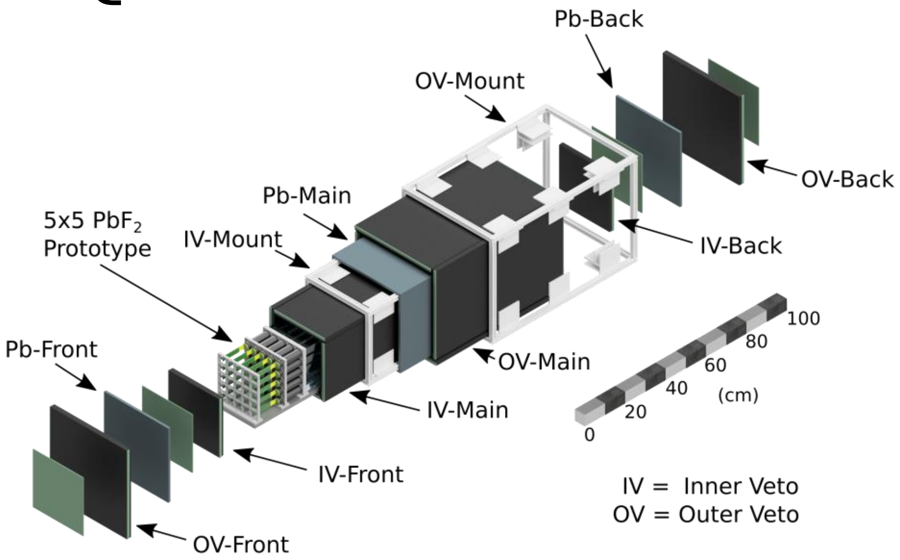


Testing ground for DM production at $\boxed{m_{\gamma'} < 140\ \text{MeV}}$

Proposed Phase A and B.

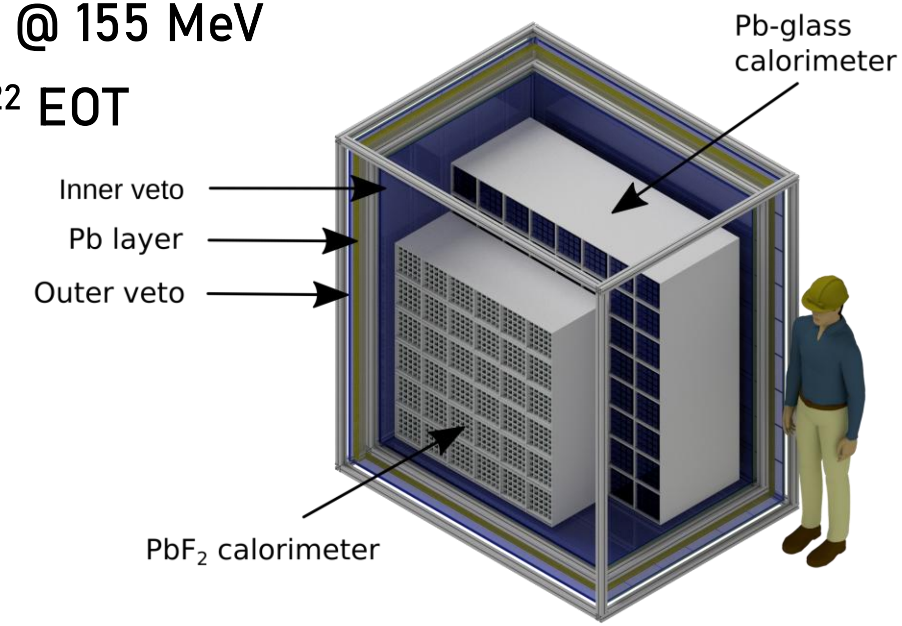
Phase A

- One PbF_2 module (5×5 crystals)
- 0.004 m^3 active volume
- 2,200 h @ 55 MeV



Phase B

- 36 PbF_2 + 64 SF5 modules
- 0.7 m^3 active volume
- 6,600 h @ 155 MeV
- $2.23 \cdot 10^{22}$ EOT



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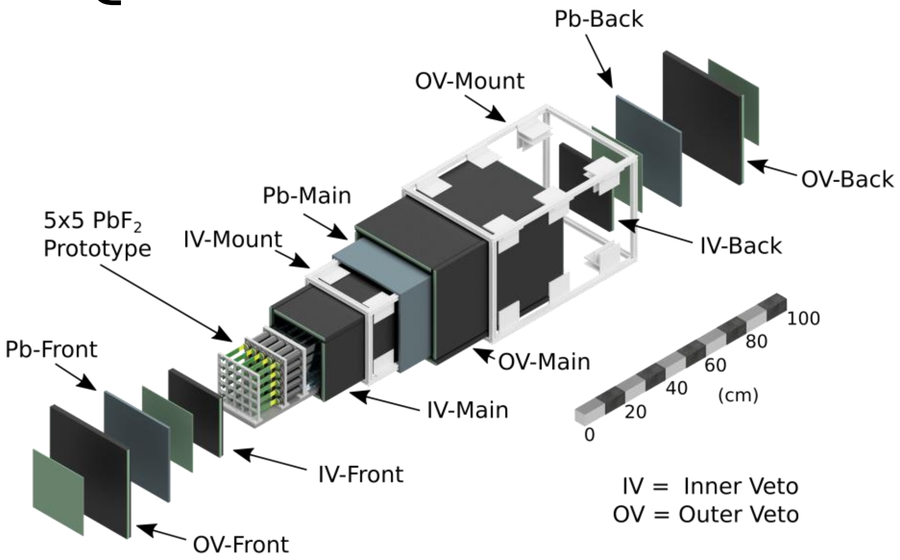
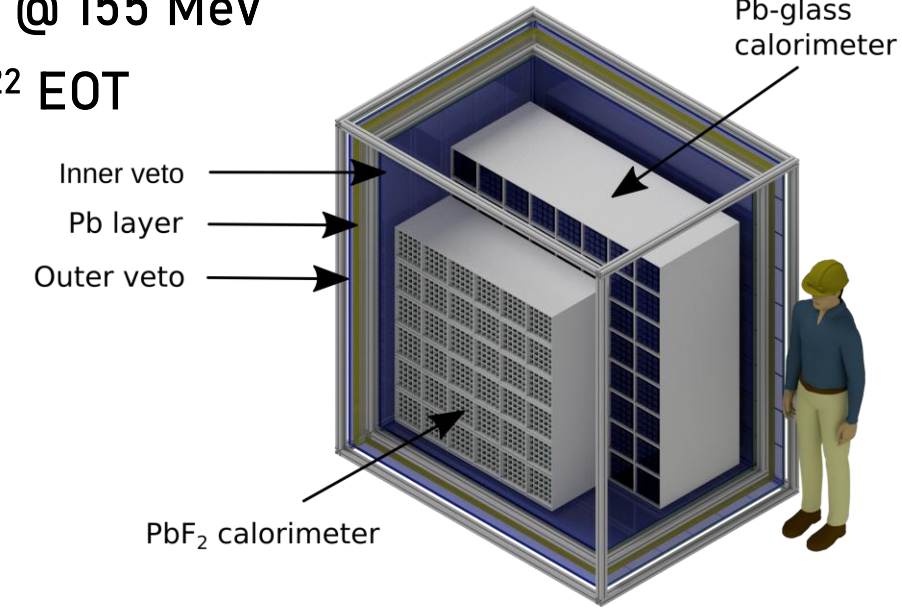


Phase B

- 36 PbF_2 + 64 SF5 modules
- 0.7 m^3 active volume
- 6,600 h @ 155 MeV
- $2.23 \cdot 10^{22}$ EOT

- ~1000 PbF_2 crystals and PMTs available (A4 exp., Mainz)
- Pb-glass SF5 (Münster)

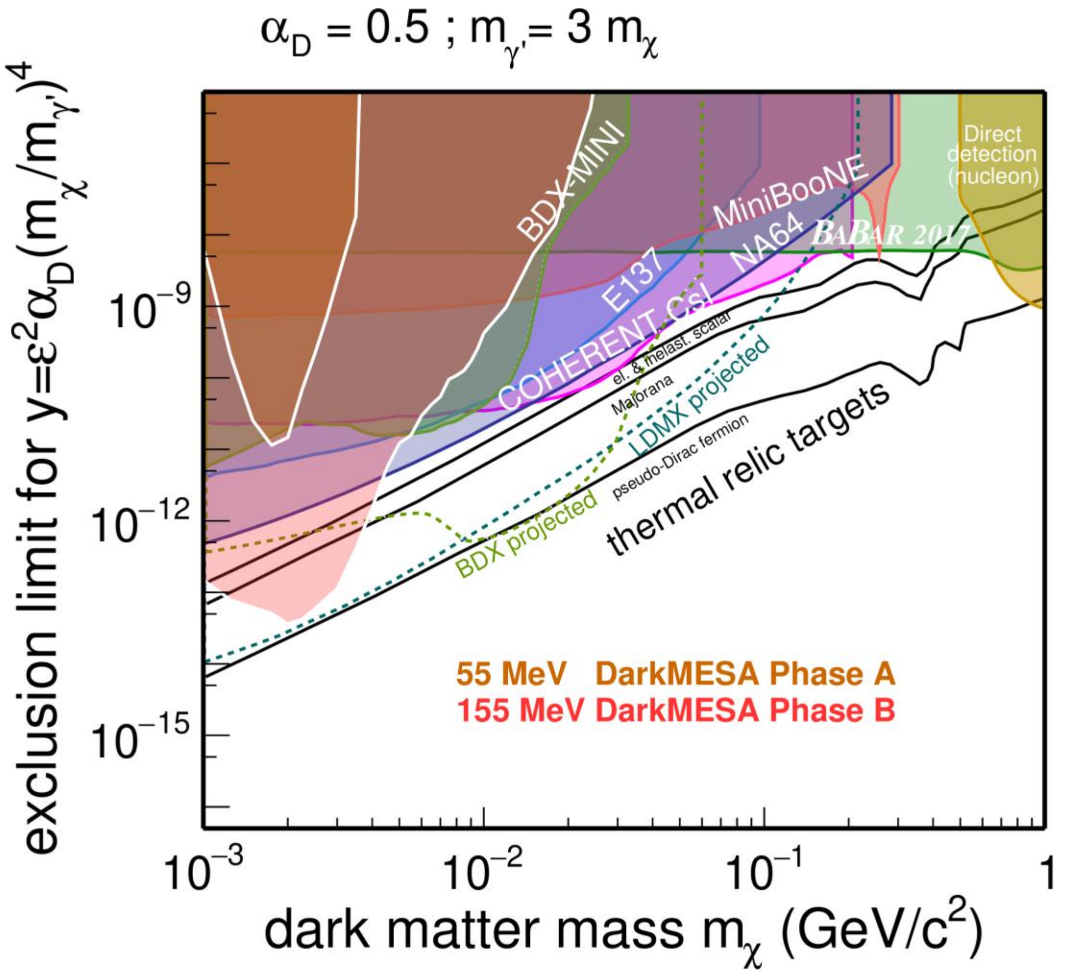


DarkMESA Exclusion Limits.

	Description	Time	EOT
Phase A	Prototype PbF_2	2,200 h	$7.42 \cdot 10^{21}$
Phase B	PbF_2 + SF5	6,600 h	$2.23 \cdot 10^{22}$

- Additional assumptions:
  - Detection threshold 10 MeV (electron recoil)
  - Detector efficiency 95%
  - Confidence level 90%
  - No backgrounds
- Positron annihilation on e^- of the beam-dump

$$e^+ + e^- \rightarrow \gamma'$$
$$e^+ + e^- \rightarrow \gamma + \gamma'$$



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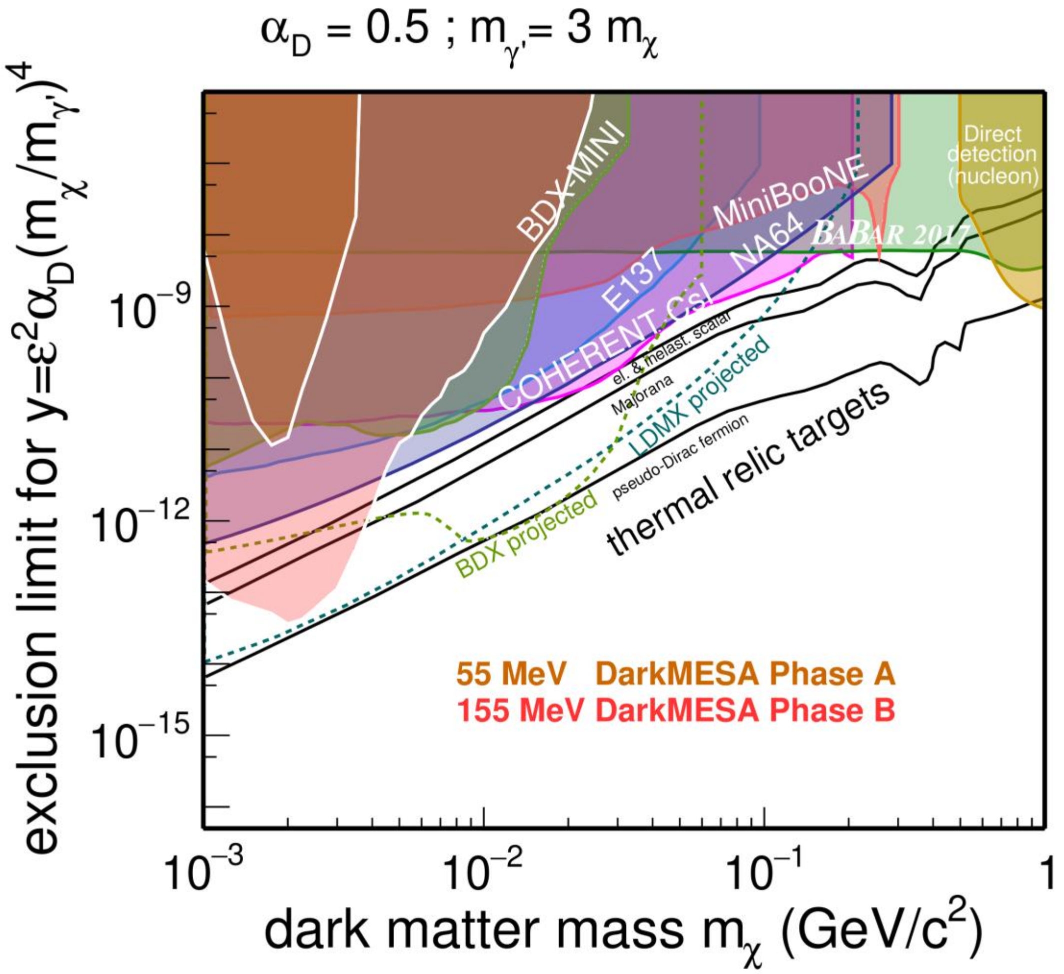
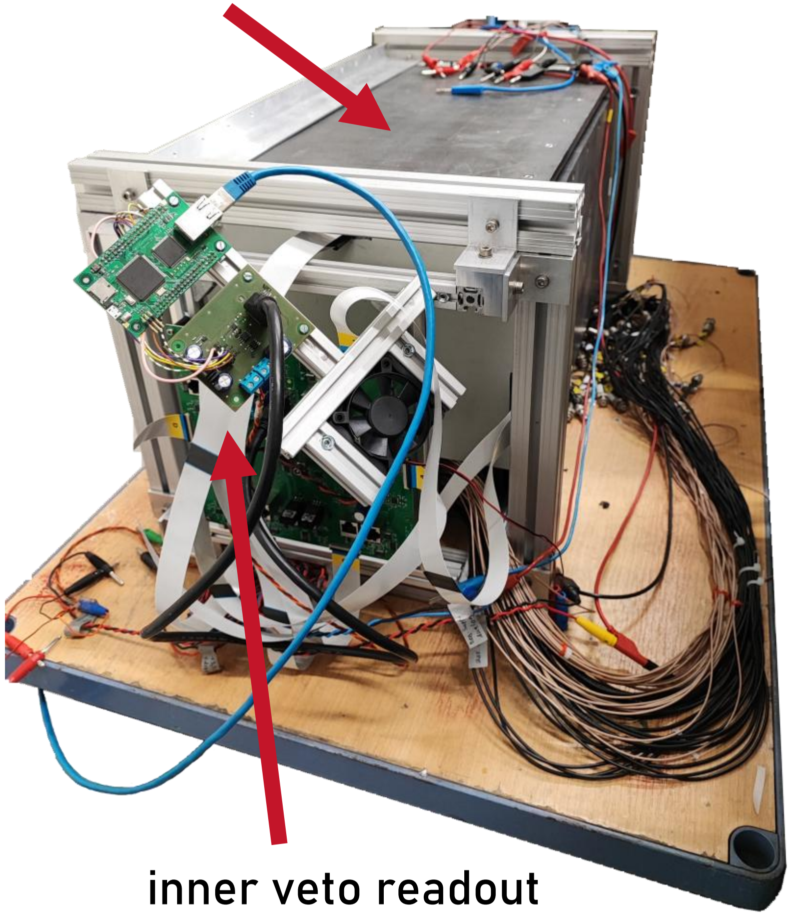


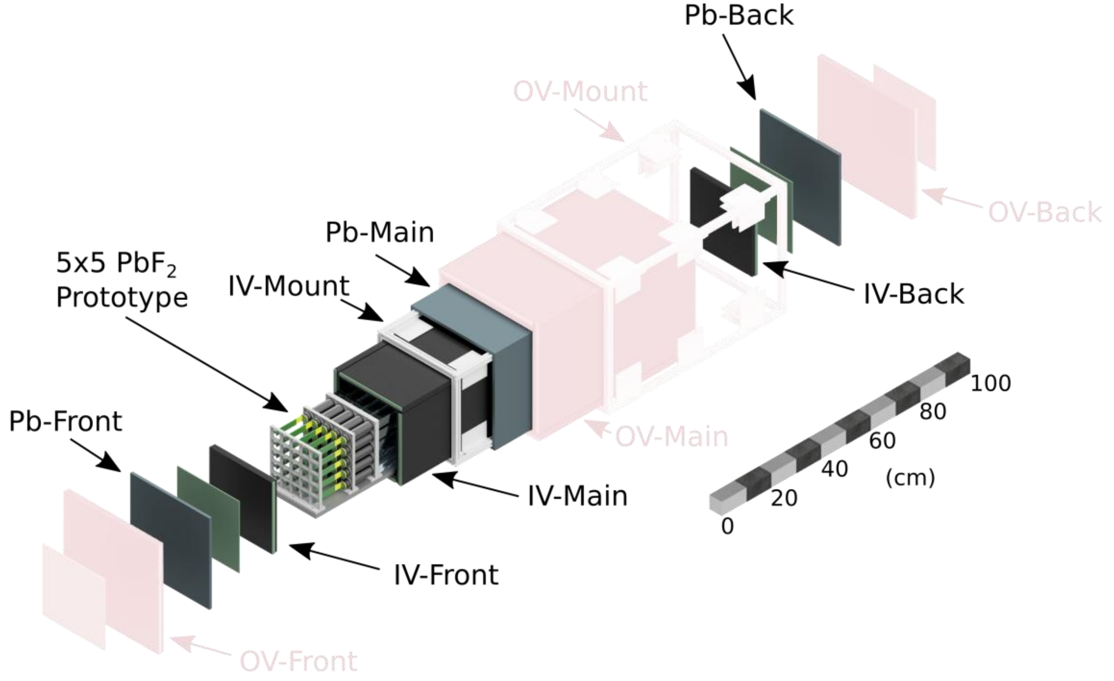
➡ Let us check the status of Phase A

Phase A - Status.

Pb absorber



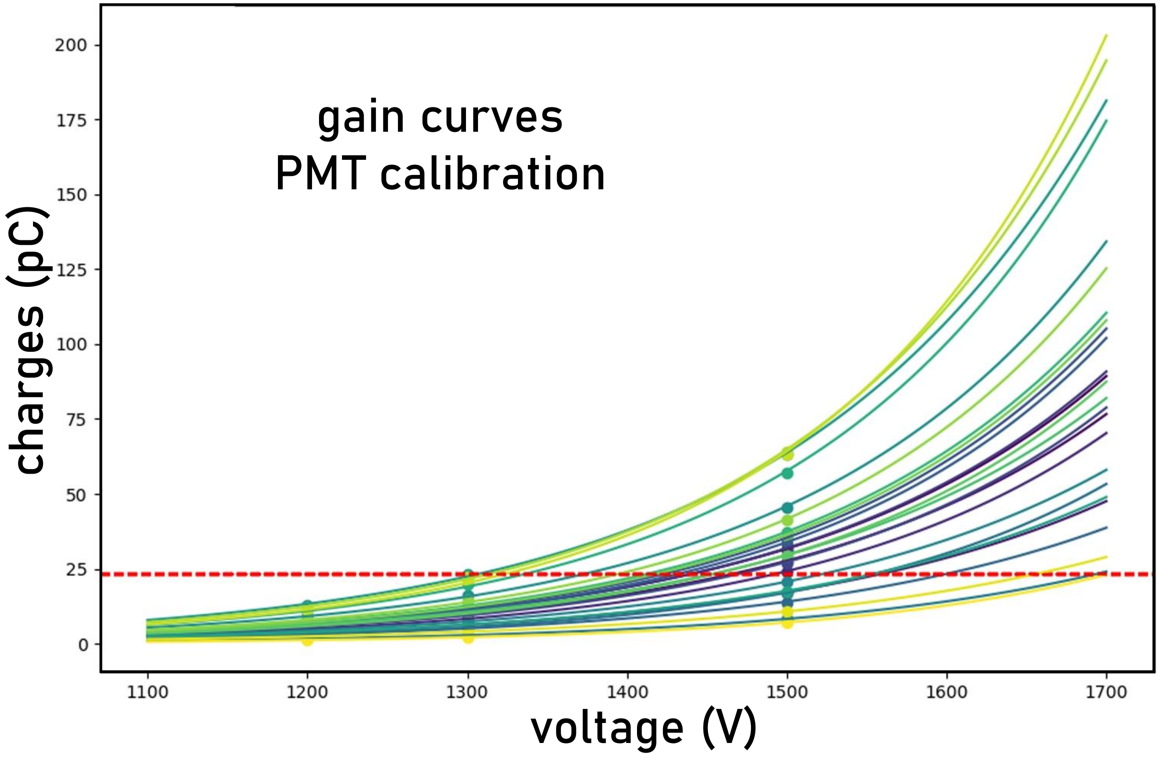
inner veto readout



- Outer veto electronics ready & assembly ongoing
- Not yet included in measurements

Phase A - Status.

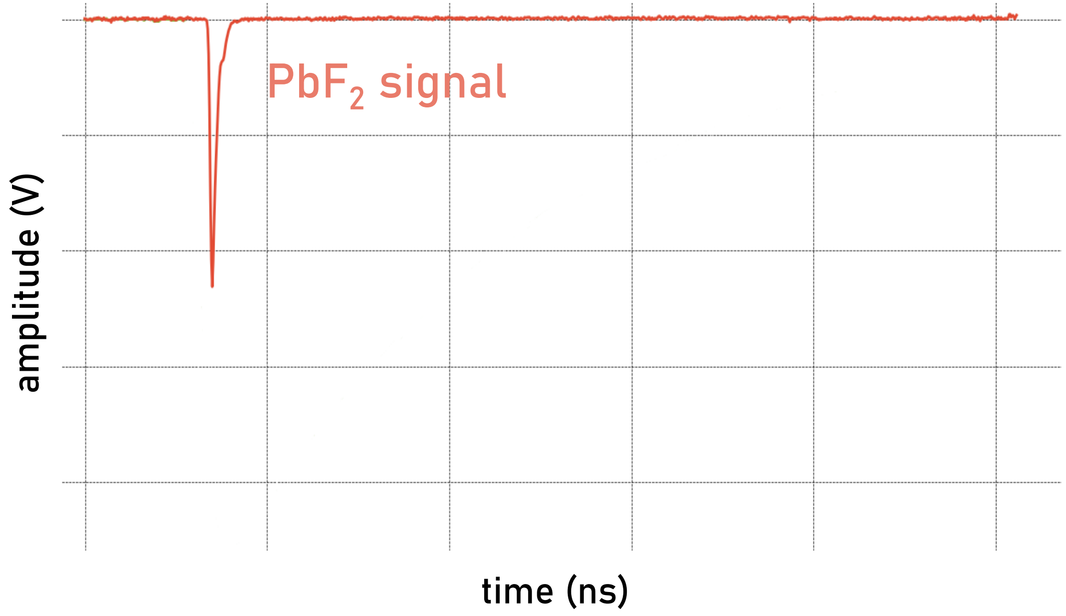
25 PbF_2 Cherenkov crystals



BSc thesis M. Kontogoulas

Challenge: Dark Counts.

- PMT noise signals are similar to PbF_2 Cherenkov signals, complicating distinction
  ➡ Single-sided PMT readout not sufficient



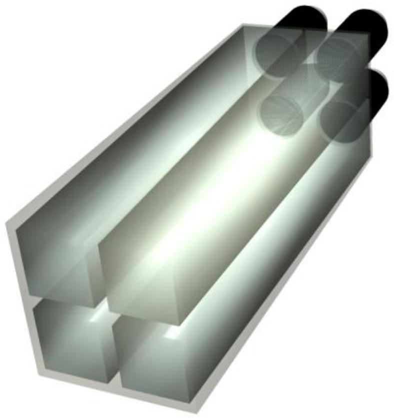
Challenge: Dark Counts.

- PMT noise signals are similar to PbF_2 Cherenkov signals, complicating distinction
  ➡ Single-sided PMT readout not sufficient
- How many coincidences are needed?
  - Accidental coincidence rate (3-fold) < 10^{-6} events/year
  - 2-fold coincidence rates acceptable for resolving times $\leq$ 10 ns

Calorimeter Readout Concepts.

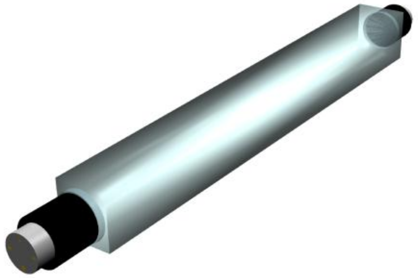
PbF_2 Calorimeter

Coupled crystal array



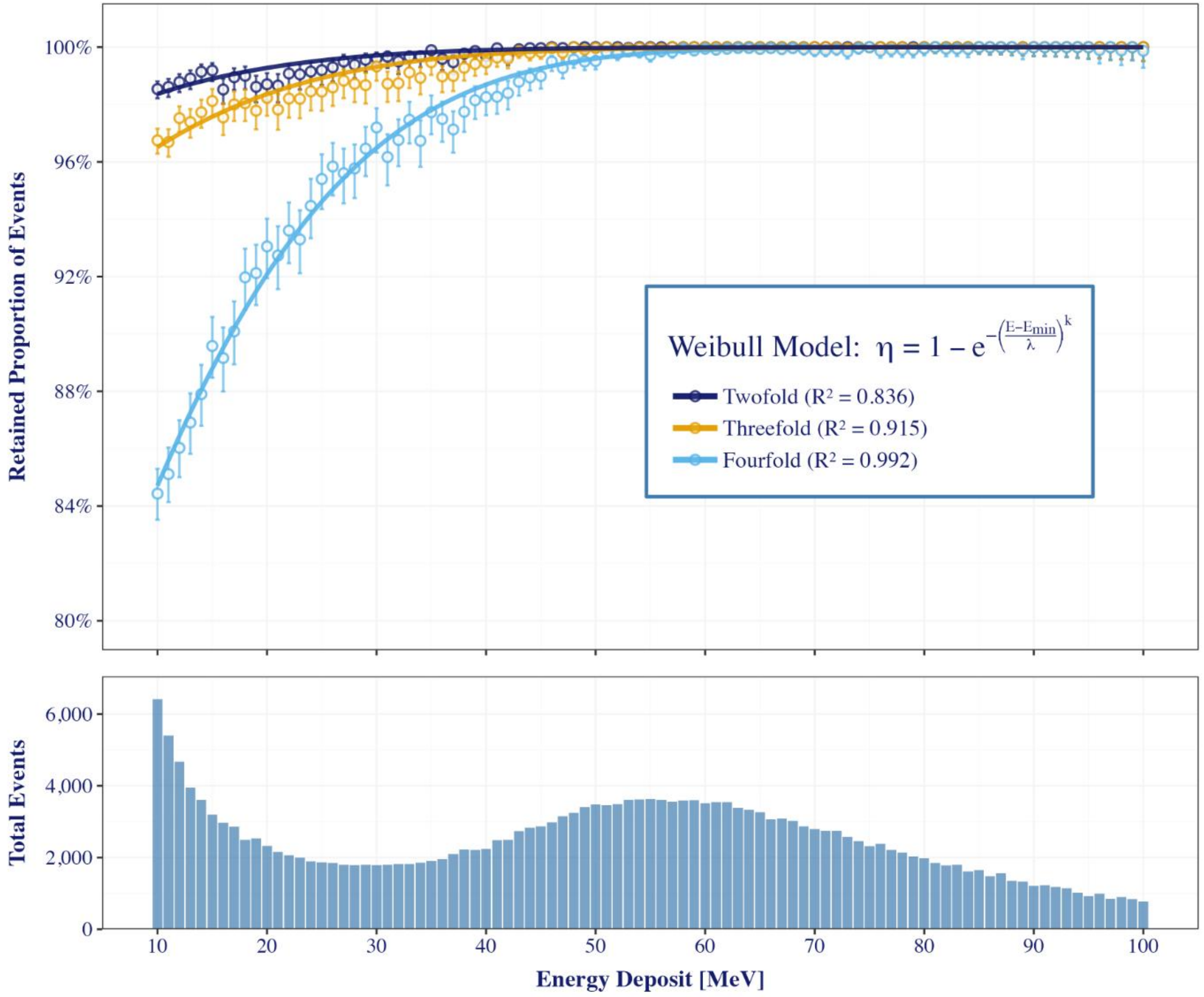
Hybrid (PMT & SiPMs)

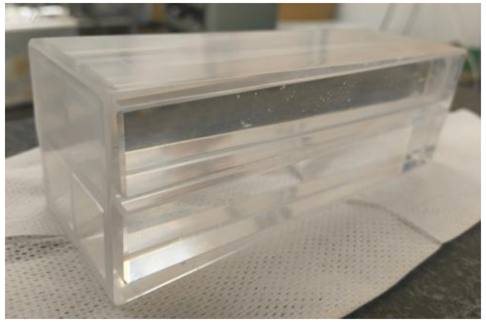
Double-sided PMT

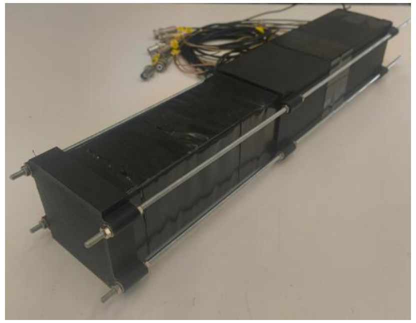


Coupled Crystal Array.

- + Number of available PMTs from A4 is sufficient
- + Retained proportion of events > 96% (10 MeV threshold)
- − Current gluing procedure is time- and cost-intensive

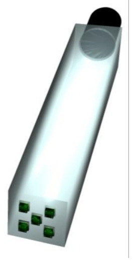




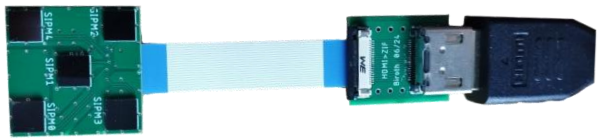


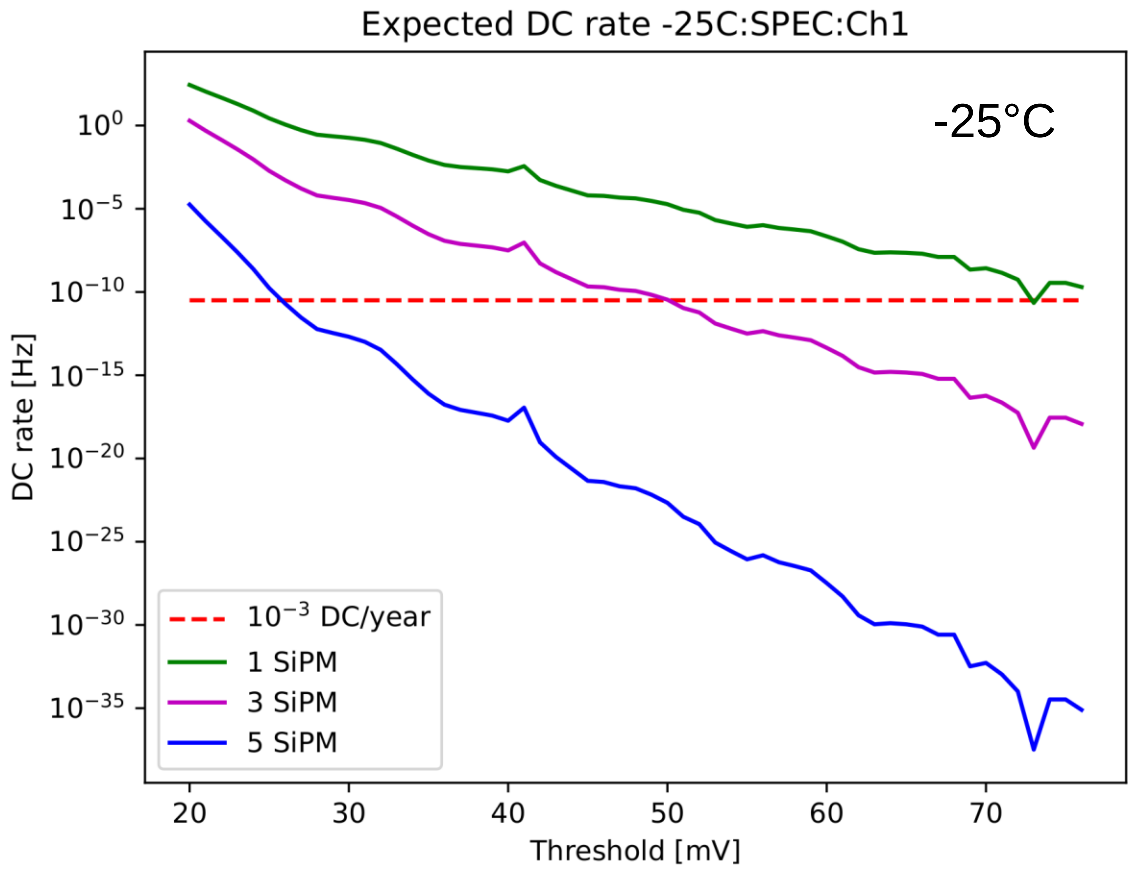
PhD thesis M. Lauß

Hybrid (PMT & SiPMs).



- \+ Low dark count rate of PMT
- \+ Multi coincidences via SiPMs
- – SiPM operation requires cooling
- – High and low voltage supply needed





PhD thesis C. Stoß

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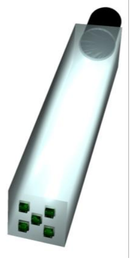

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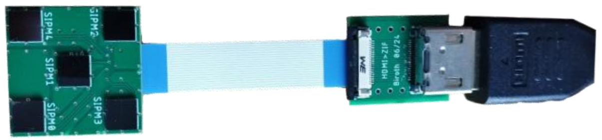

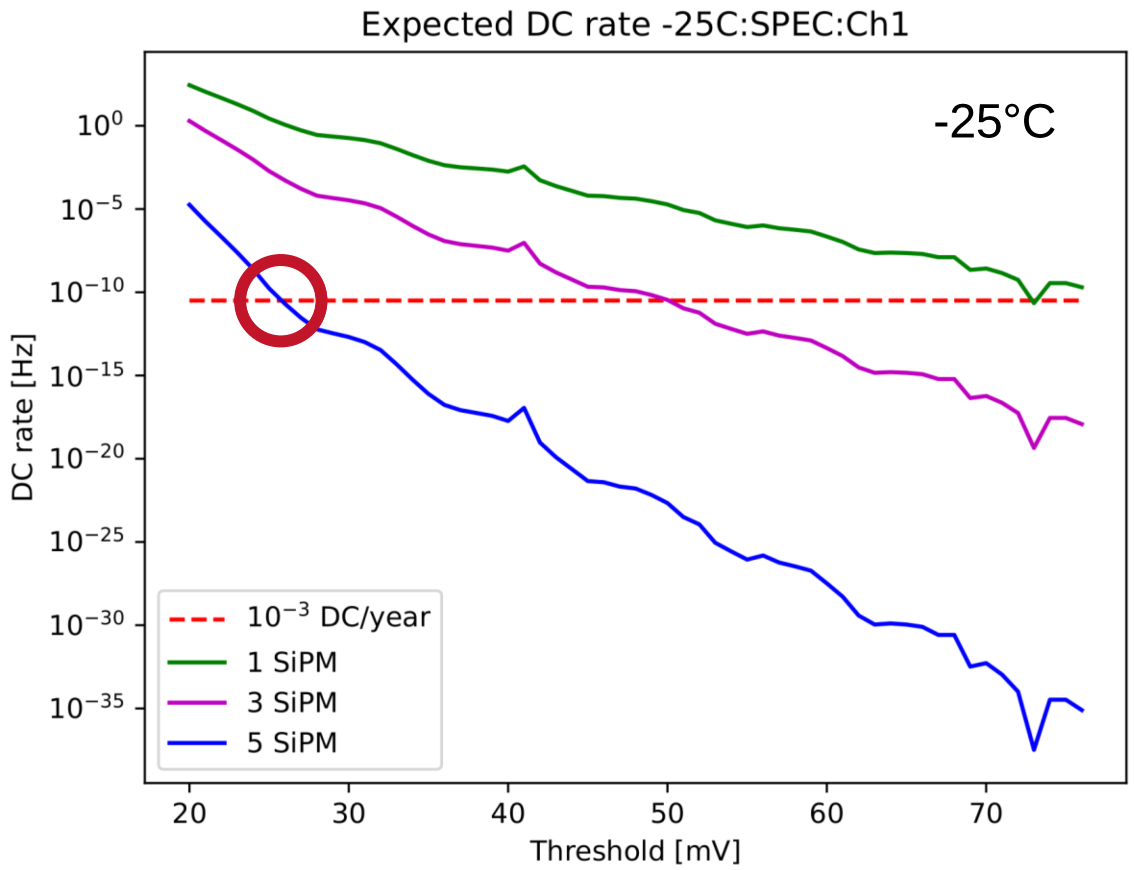

PhD thesis C. Stoß

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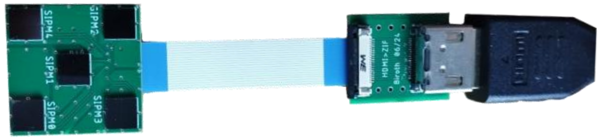
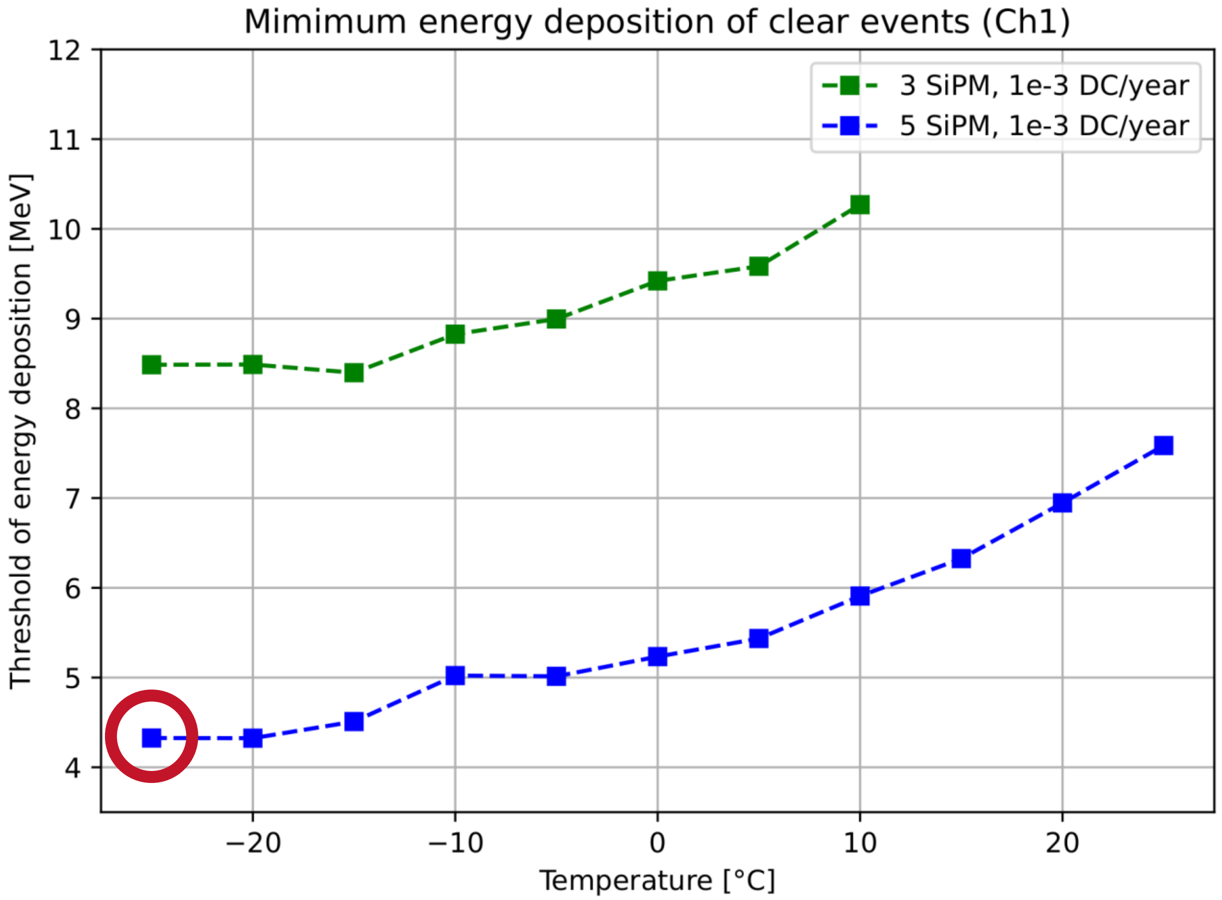
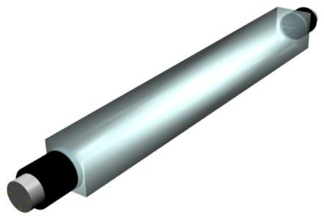




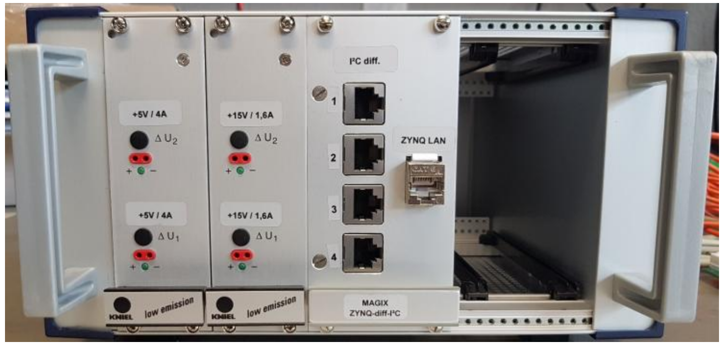
In this case: 25-30 mV ≈ 4-5 MeV

PhD thesis C. Stoß

Double-sided PMT.

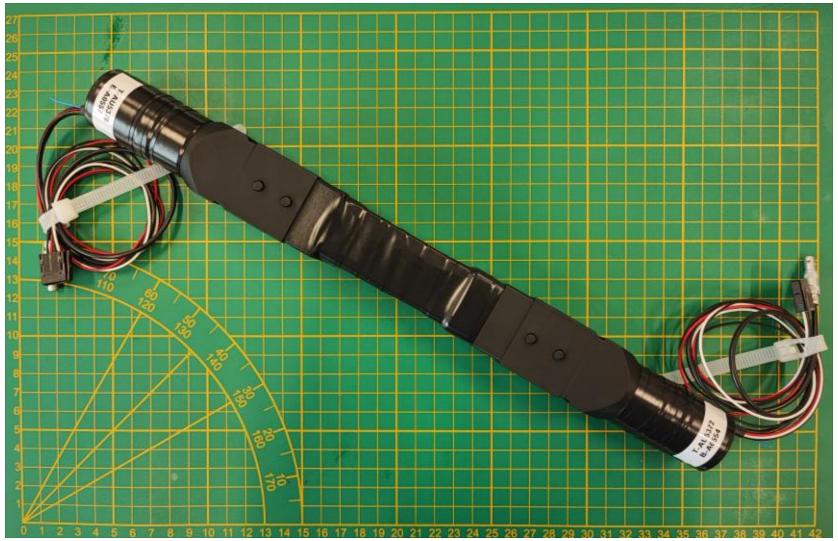


+ Low dark count rate of PMTs
+ No cooling required
+ Straightforward assembly
+ One voltage supply system
− Accidental coincidences on a low level still possible



voltage control rack

- Phase A prototype will use compact 1″ PMTs (Hamamatsu R1924A-03) & low voltage bases
- Voltage control rack and DAQ cards for 80 channels available



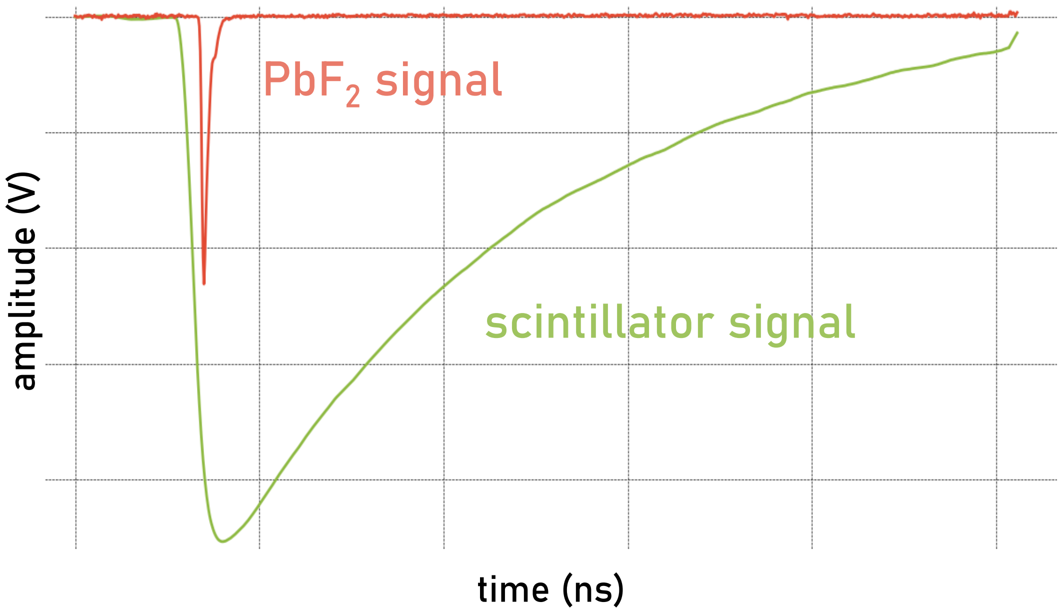
Challenge: Dark Counts.

- Multi Coincidence: Double-sided PMT readout for PbF_2 calorimeter in Phase A

Prototype No. 1 ✓

- Enhancement of active material? BGO, PWO?
  - \+ High density
  - \+ Higher light output
  - \+ Signal differs from noise
  - \- Availability & costs

Prototype No. 2 ?

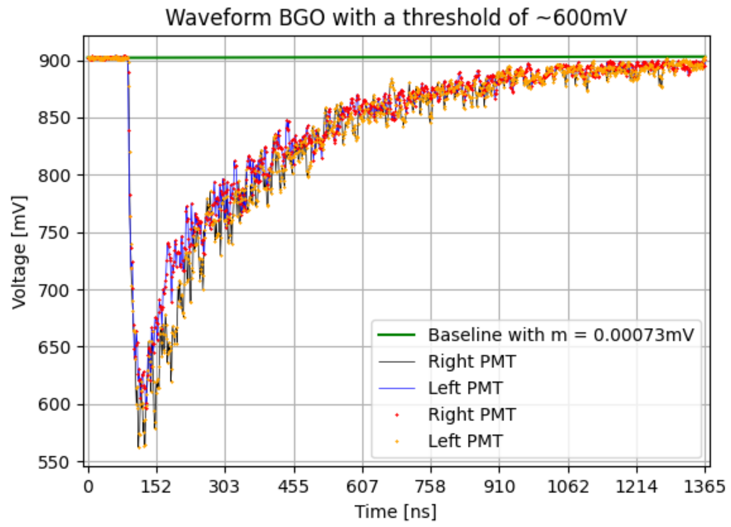


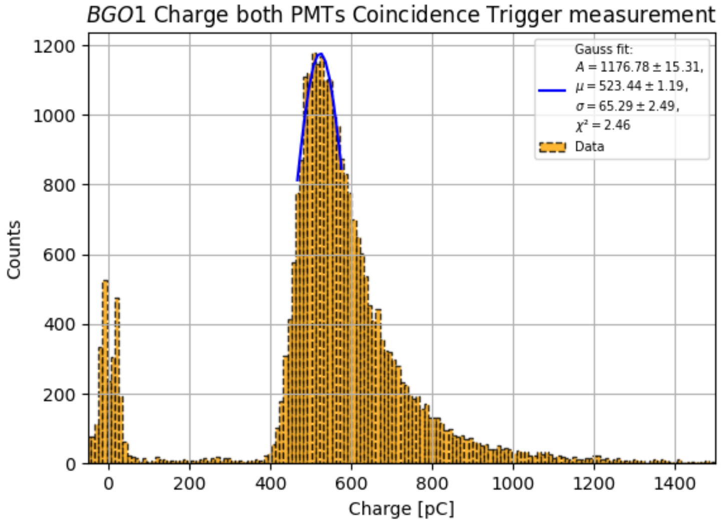
BGO (Bismuth Germanate).

- BGO detectors with double-sided PMT readout built and studied by L. Reitz

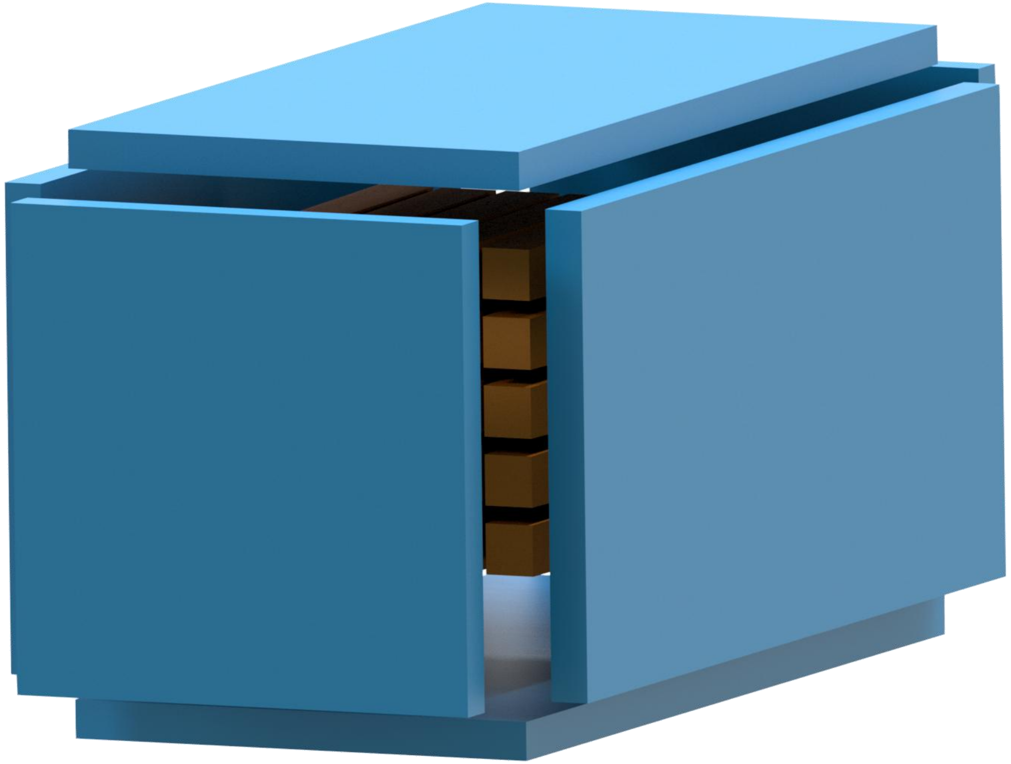
	BGO	PbF_2
type	inorganic scintillator	Cerenkov material
density (g/cm³)	7.13	7.77
light output (ph./MeV)	10,000	20-30
response	slow (300-600 ns)	fast (<20 ns)

- Background and efficiency study for BGO





BGO Case Study.



Plastic scintillator

PbF_2

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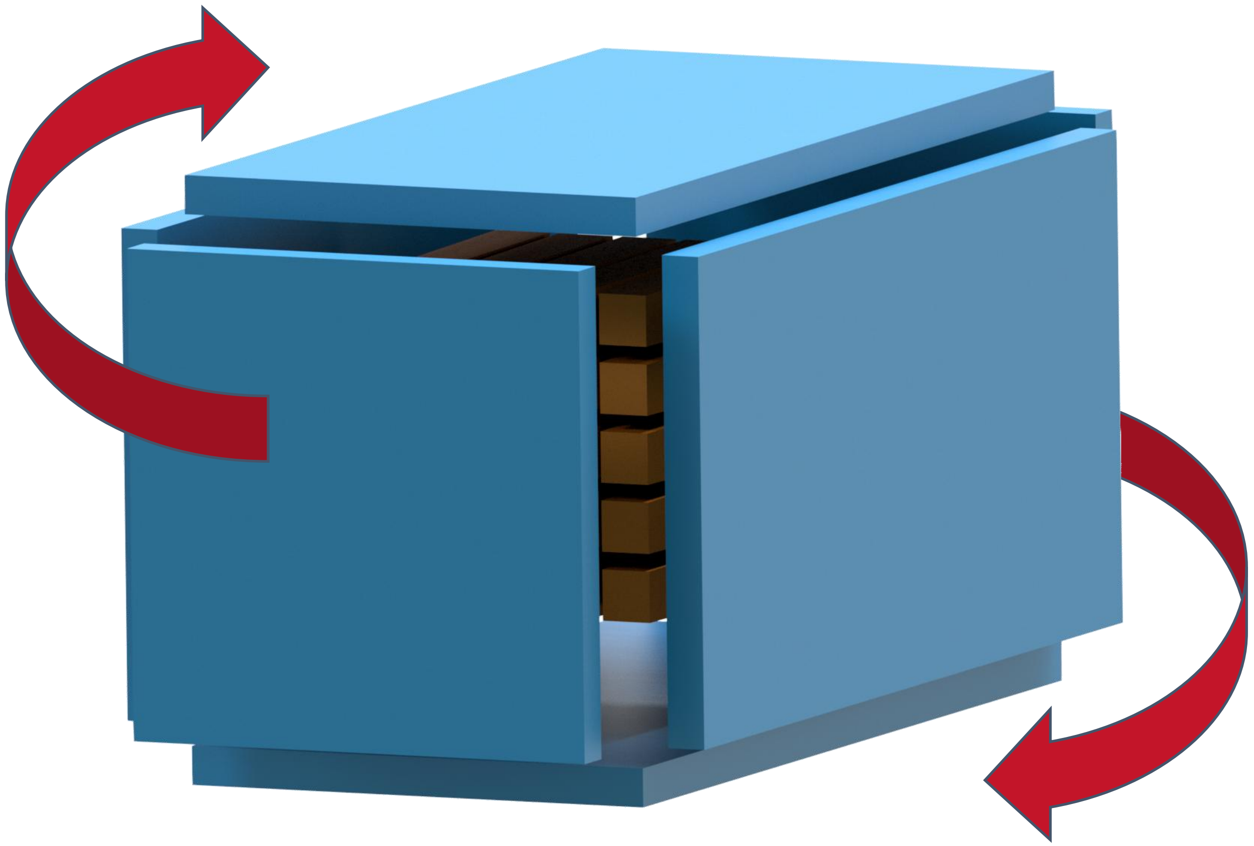

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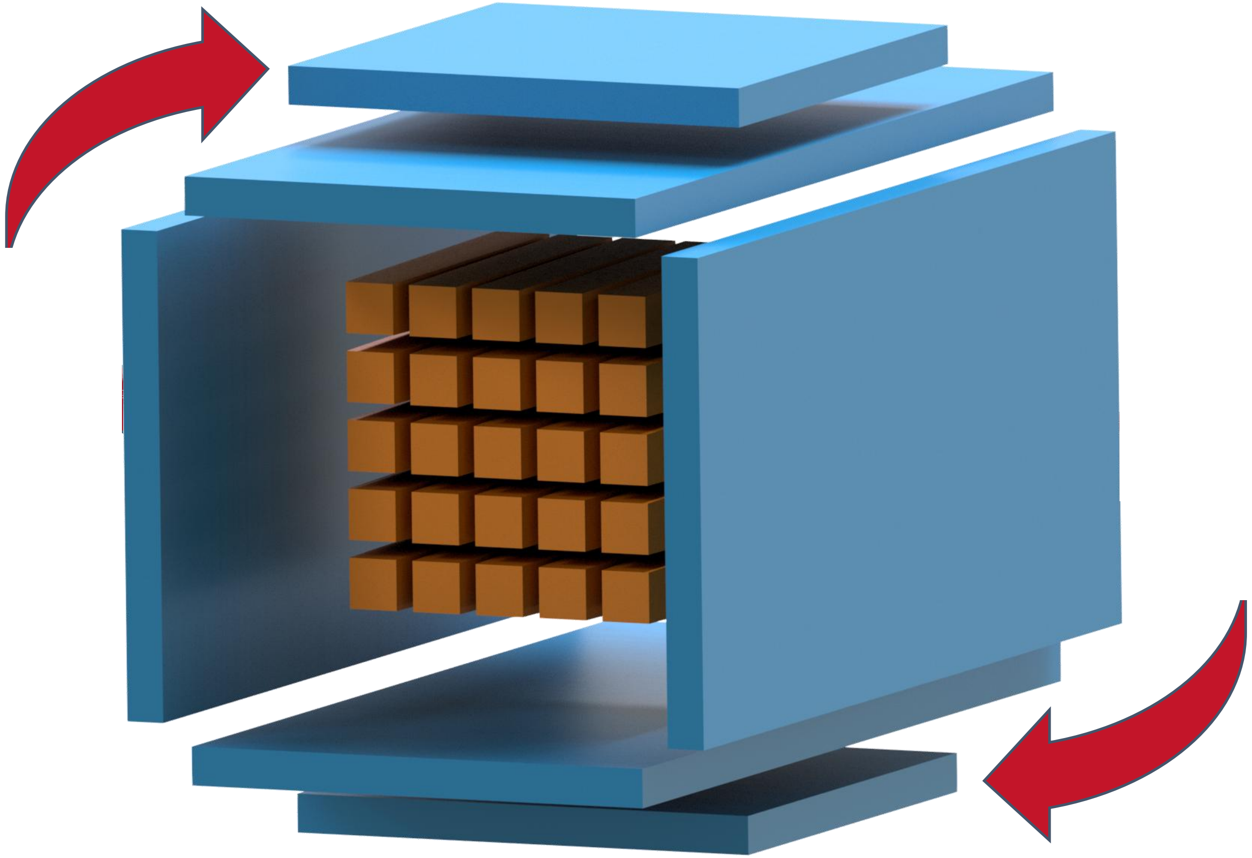

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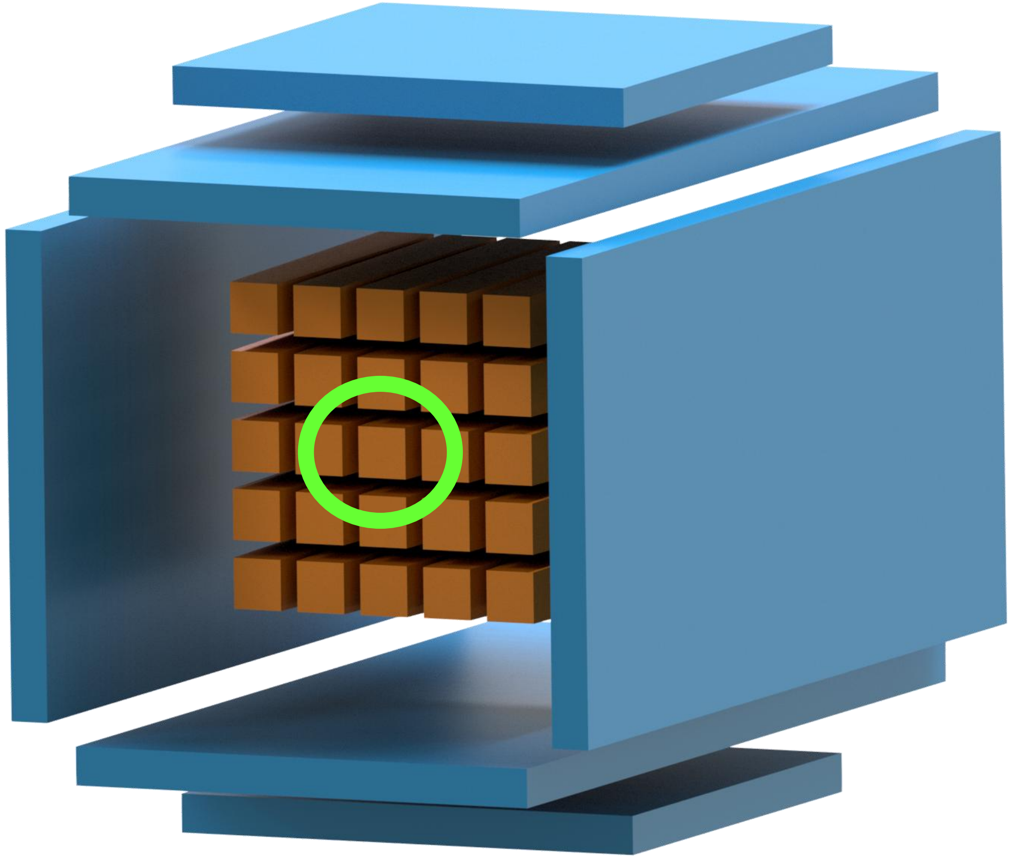

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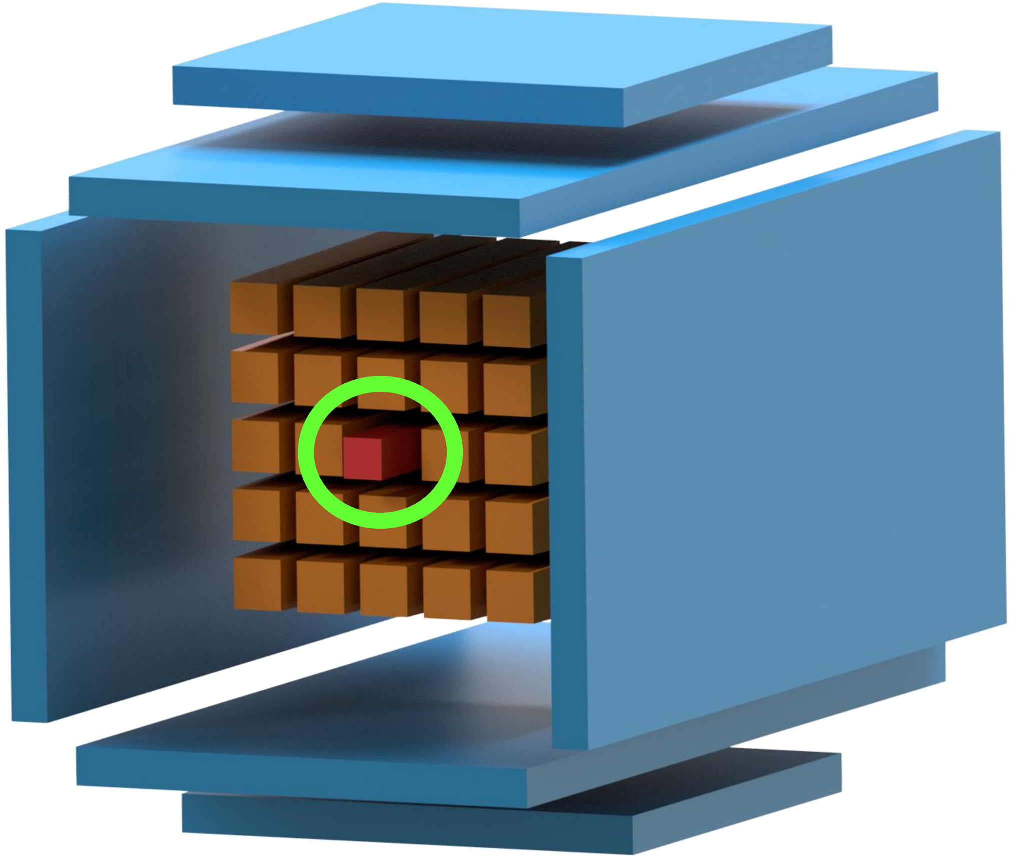

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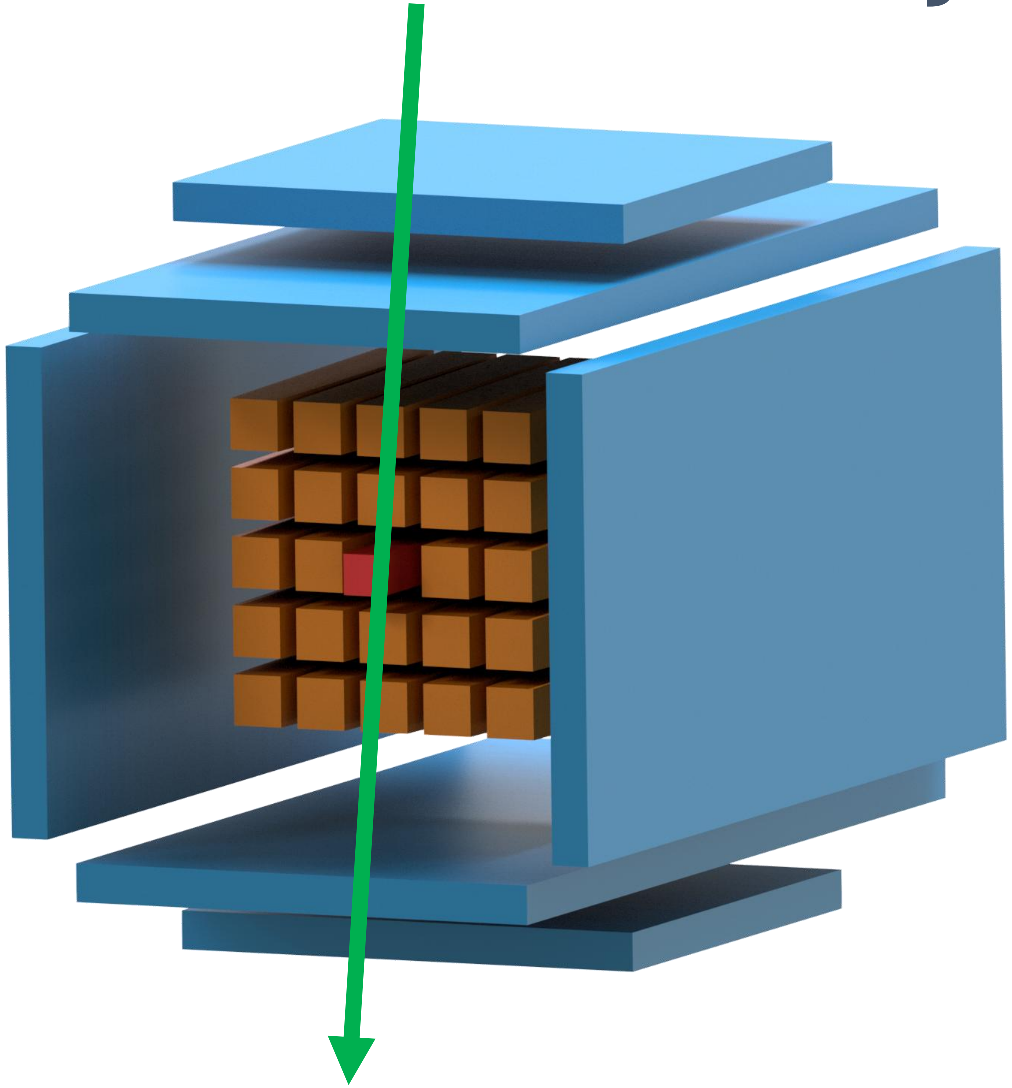
PbF_2

BGO

➡ BGO signal triggers full setup

BGO Case Study.



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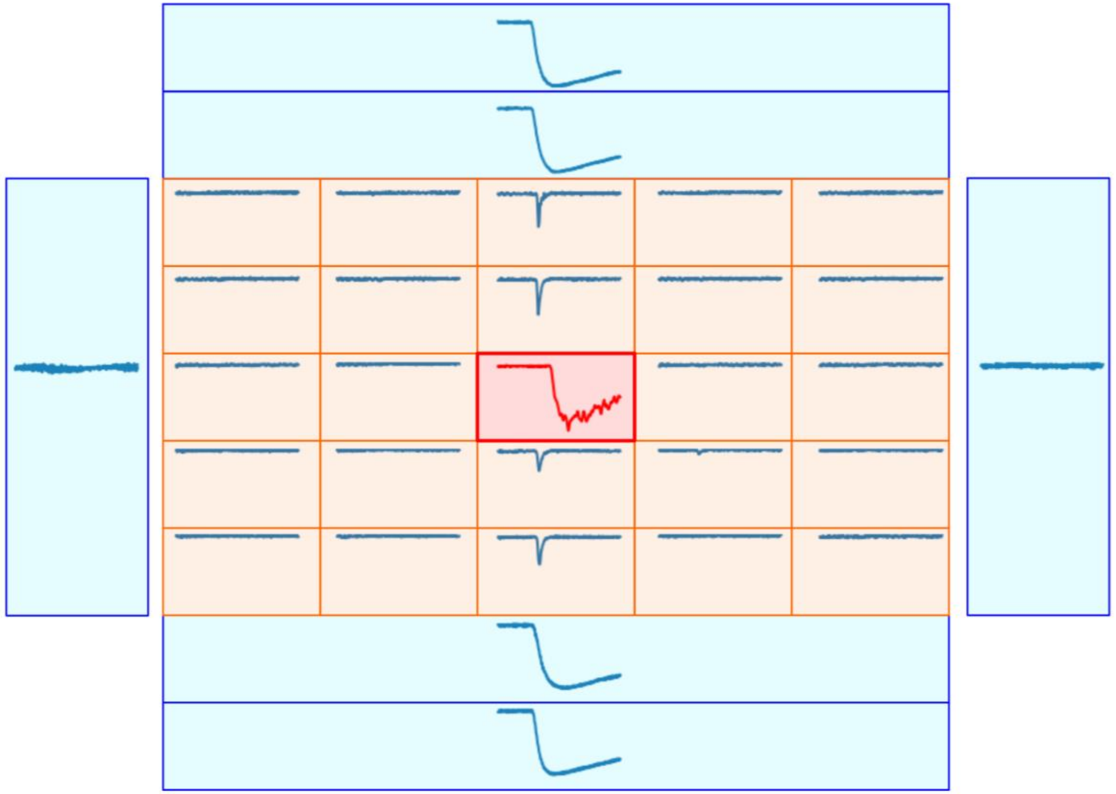
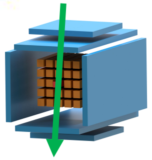
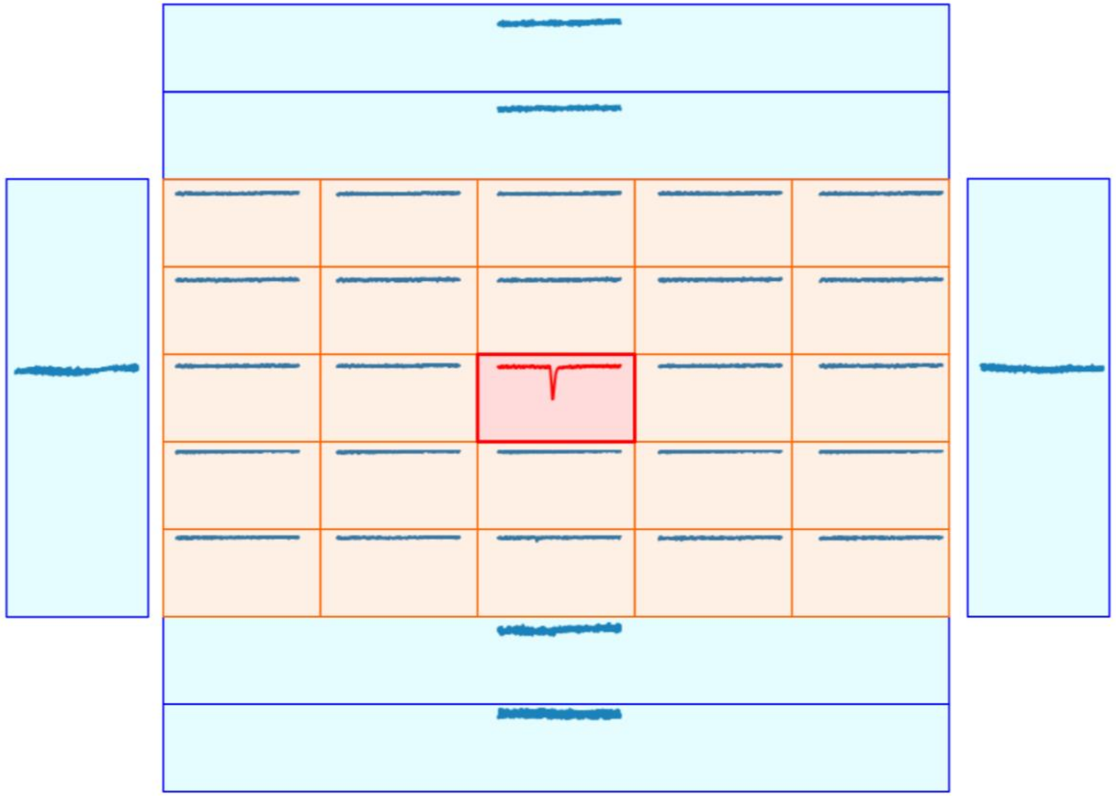


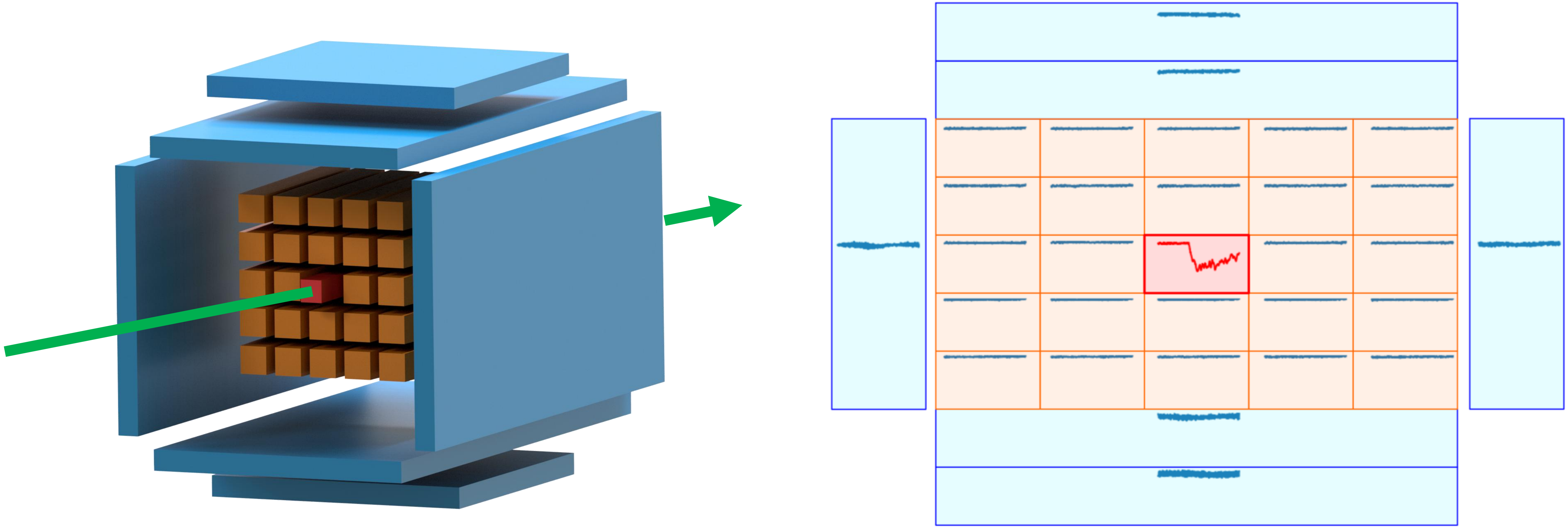
vertical cosmic particle





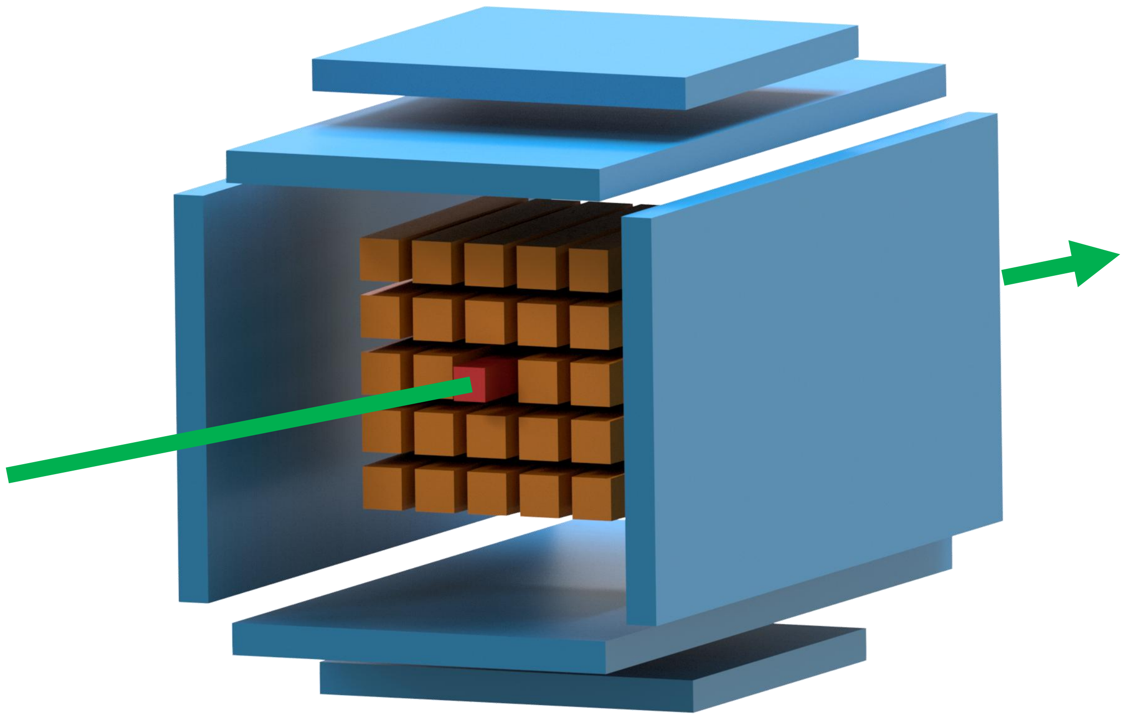
PMT noise signal

BGO Case Study.



horizontal cosmic particle or not? ➡ hermetical sealing needed

BGO Case Study.



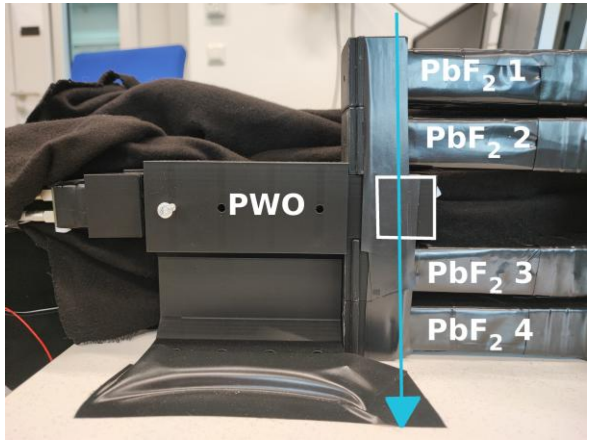
- Analysis with virtual endcaps shows an inner veto efficiency > 99%
- Results consistent with simulation study

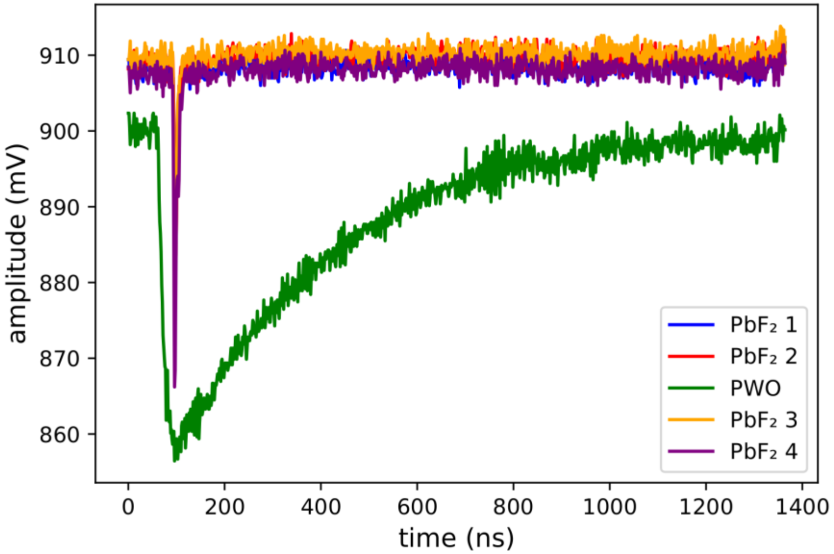
➡ Redo measurement with full veto and shorter PMTs (but with only one BGO)

BSc thesis L. Reitz

First PWO ($PbWO_4$) studies.

- Hybrid: inorganic scintillator with Cerenkov component
- Good scintillation properties
- Light yield of ~ 200 ph/MeV
- T stabilization improves yield
- High density 8.28 g/cm³





MSc thesis S. Mitra

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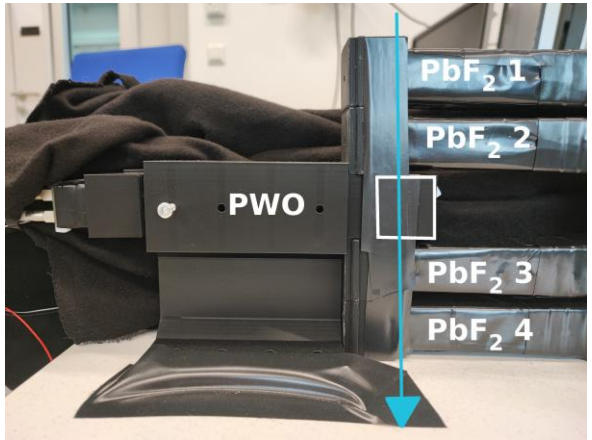
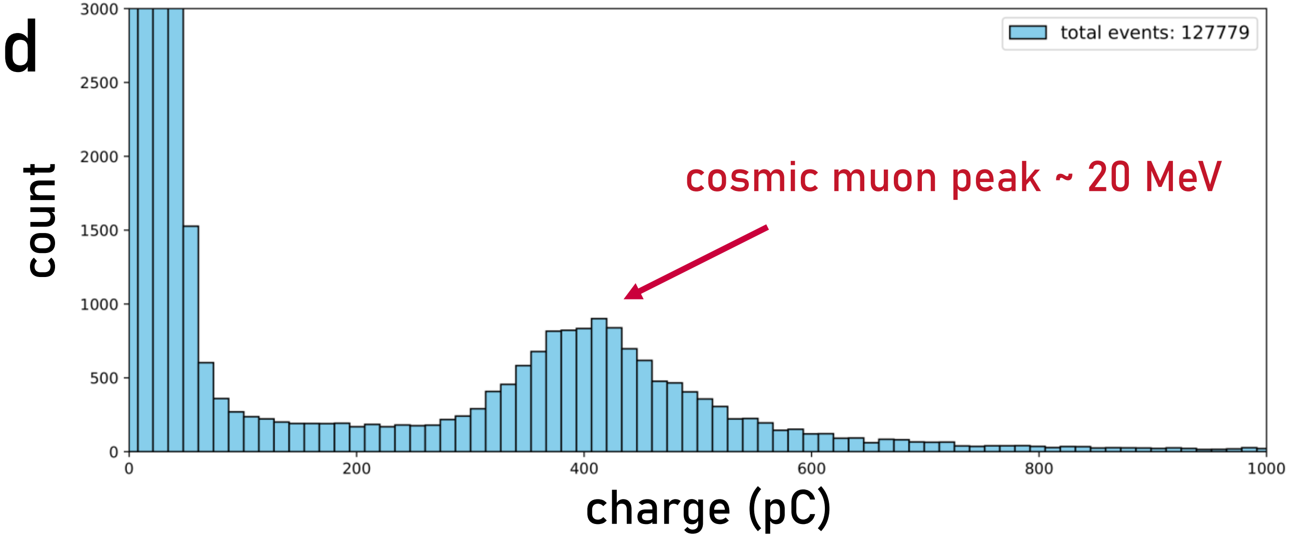


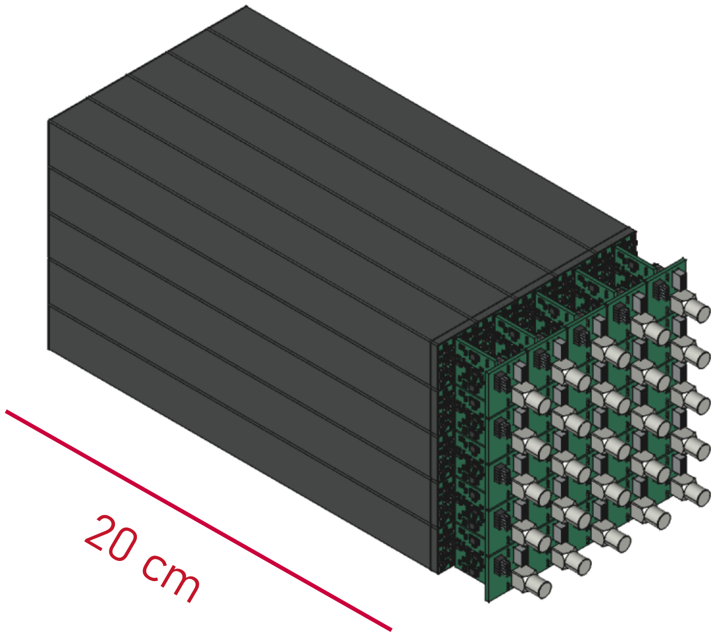


MSc thesis S. Mitra

PWO Calorimeter.

Co-operation with Uni Gießen and CRYTUR

- Fully functioning PWO Prototype from CRYTUR
- 5x5 PWO array with SiPMs
- Frame with cooling system
- Will arrive in Mainz soon
- Data taking to be finished in February 2026



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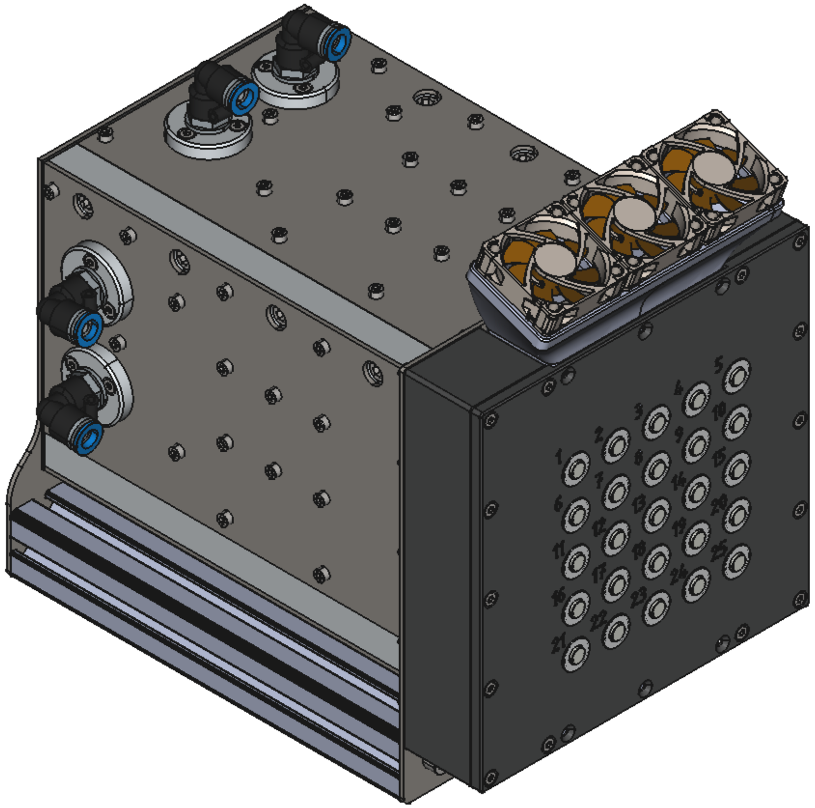
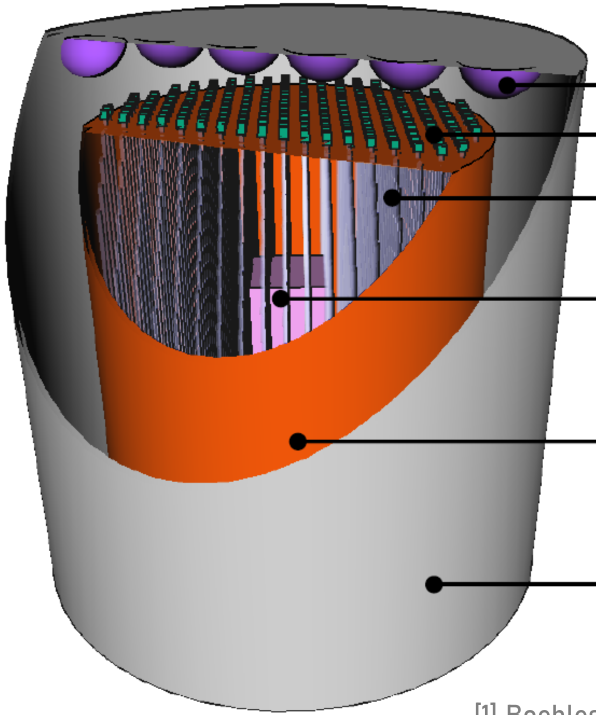


Prototype No. 2 ✓

Liquid Scintillator – NuDoubt^{++}.

- Search for double beta plus decays
- 1 m³ demonstrator
- Hybrid-opaque liquid scintillator
  - ➡ Cherenkov and scintillation light
  - ➡ Particle dependent ratio
- Particle track information
- Lower threshold possible (~MeV)



[1] Boehles et al., arXiv:2407.05999v2 [hep-ex]

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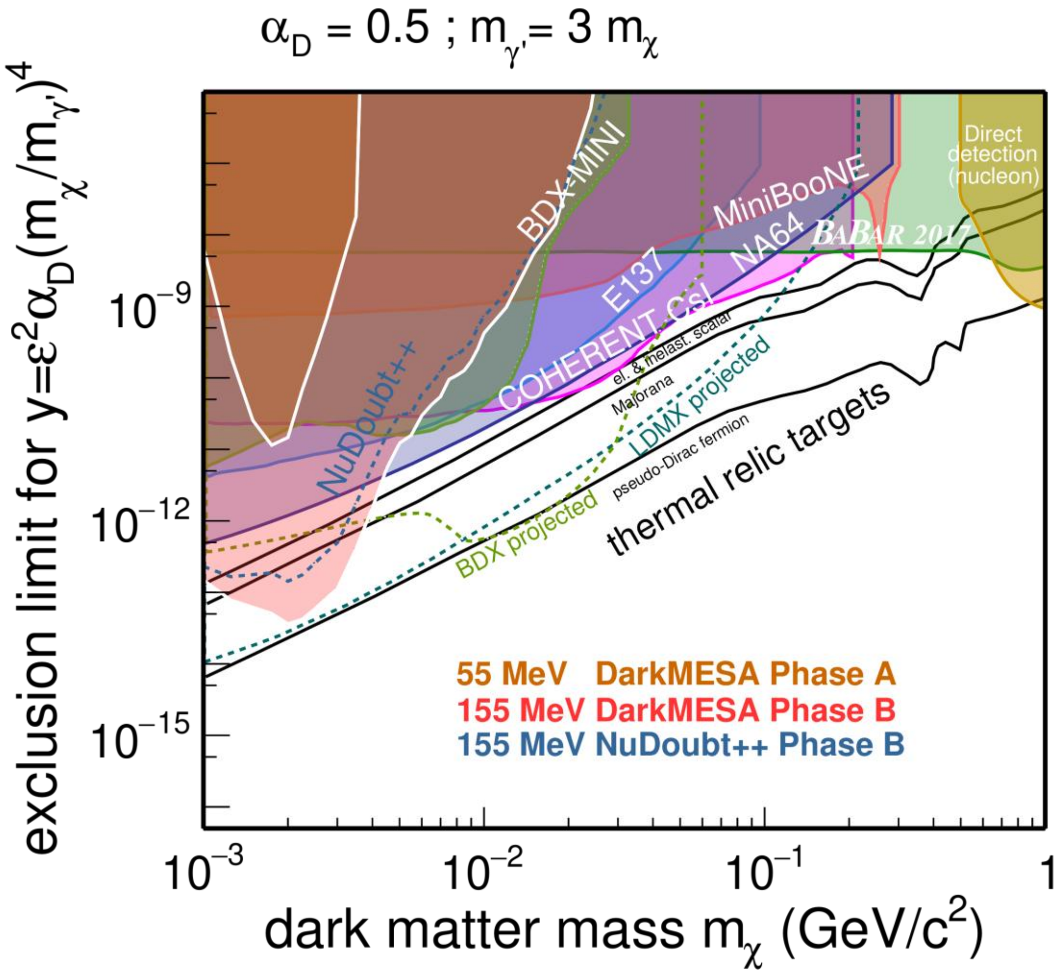
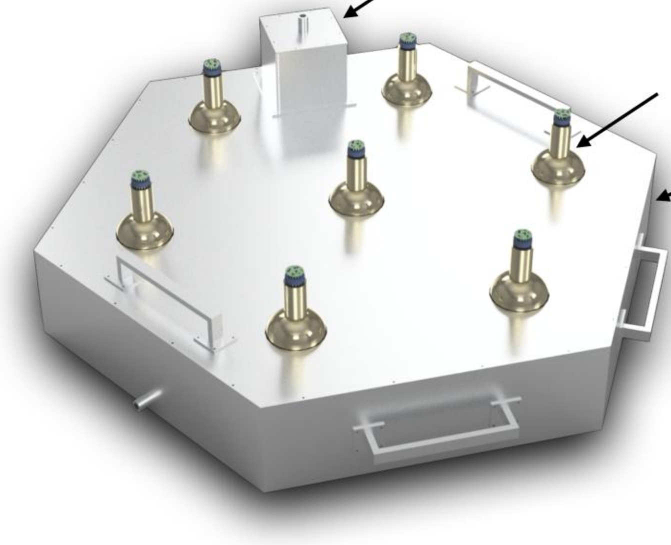
- First projection of NuDoubt^{++}@DarkMESA



Liquid Scintillator – NuDoubt⁺⁺.

- Enhanced **veto system** with **Gd loaded liquid scintillator**
- 350 liter volume
- System with improved neutron veto capabilities
- Currently under construction



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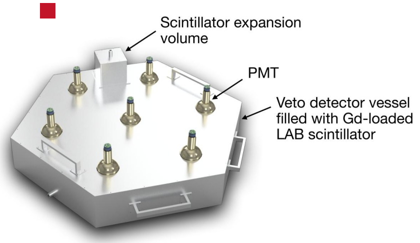
Liquid Scintillator – NuDoubt++.



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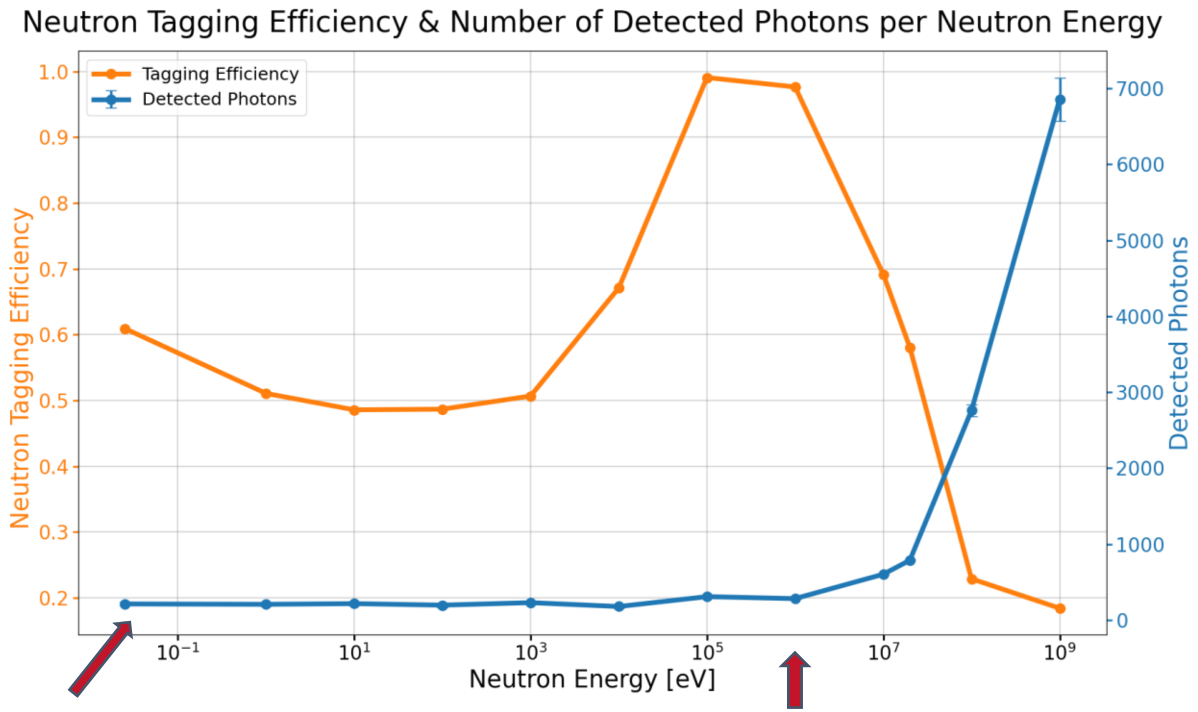
- 350 liter volume
- System with improved neutron veto capabilities
- Currently under construction
- Simulation study with Geant4
  ➡ Veto tagging efficiency



always >200 det. ph.

1 MeV

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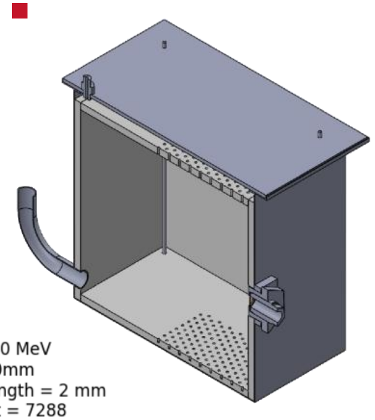
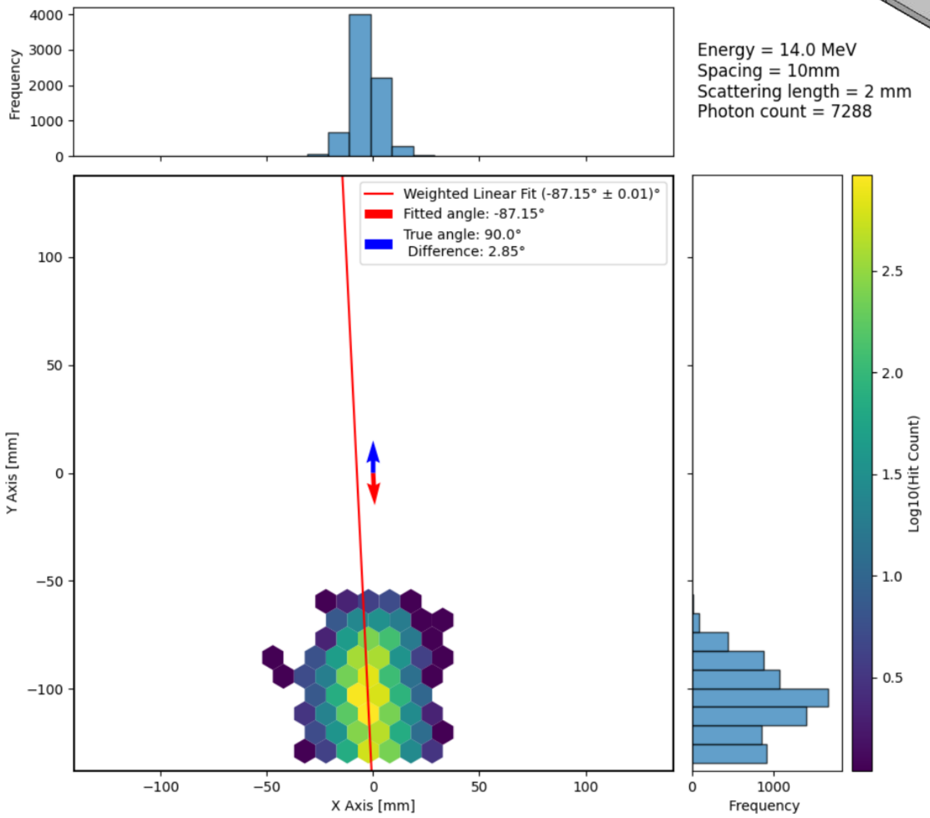
Liquid Scintillator – NuDoubt^{++}.

- **Opaque liquid scintillator** as **calorimeter** material @DarkMESA
- Prototype Test with up to 255 fibres at MAMI: 10th-14th Nov 2025
  - $\leq$ 14 MeV electrons
  - Test of angular reconstruction and calorimetry
- Lower detection threshold
- Enhanced tracking information





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Summary and Outlook.

- Final Adjustments to Phase A: Efficiency studies in the lab this year; background studies (e.g. beam induced neutrons) at MAMI and in the DarkMESA hall to follow soon
- Study of Complementary Detector Concepts: BGO, NuDoubt^{++} and also $PbWO_4$ from PANDA ongoing
- Geant4 Simulation Undergoing Major Changes: More LDM models to be studied (e.g. ALPs)

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Thank you for your attention!

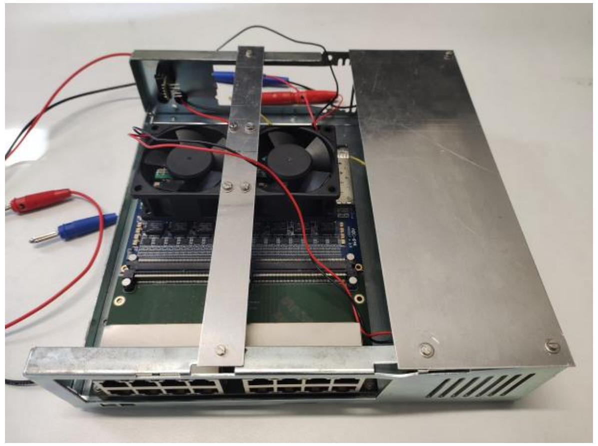
Backup.

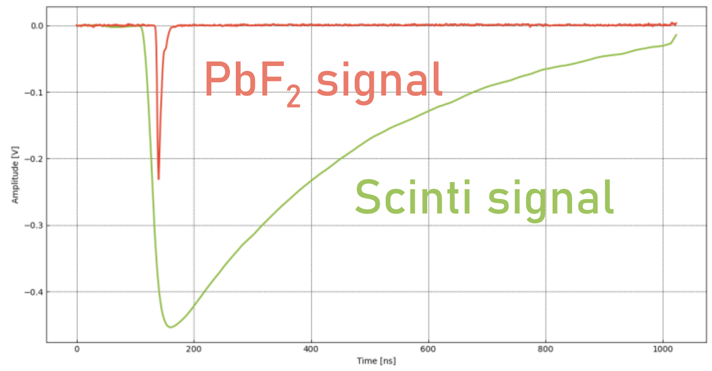
Data Acquisition Status.

- CAEN Digitizer V1742 (5 GHz, 32 channels, single-ended)
  - ➡ Fast, expensive, more sensitive to interference
- PANDA SADC (80 MHz, 64 channels, differential)
  - ➡ Slow, cheaper
  - ➡ Shaping and amplifying required

Digitizer

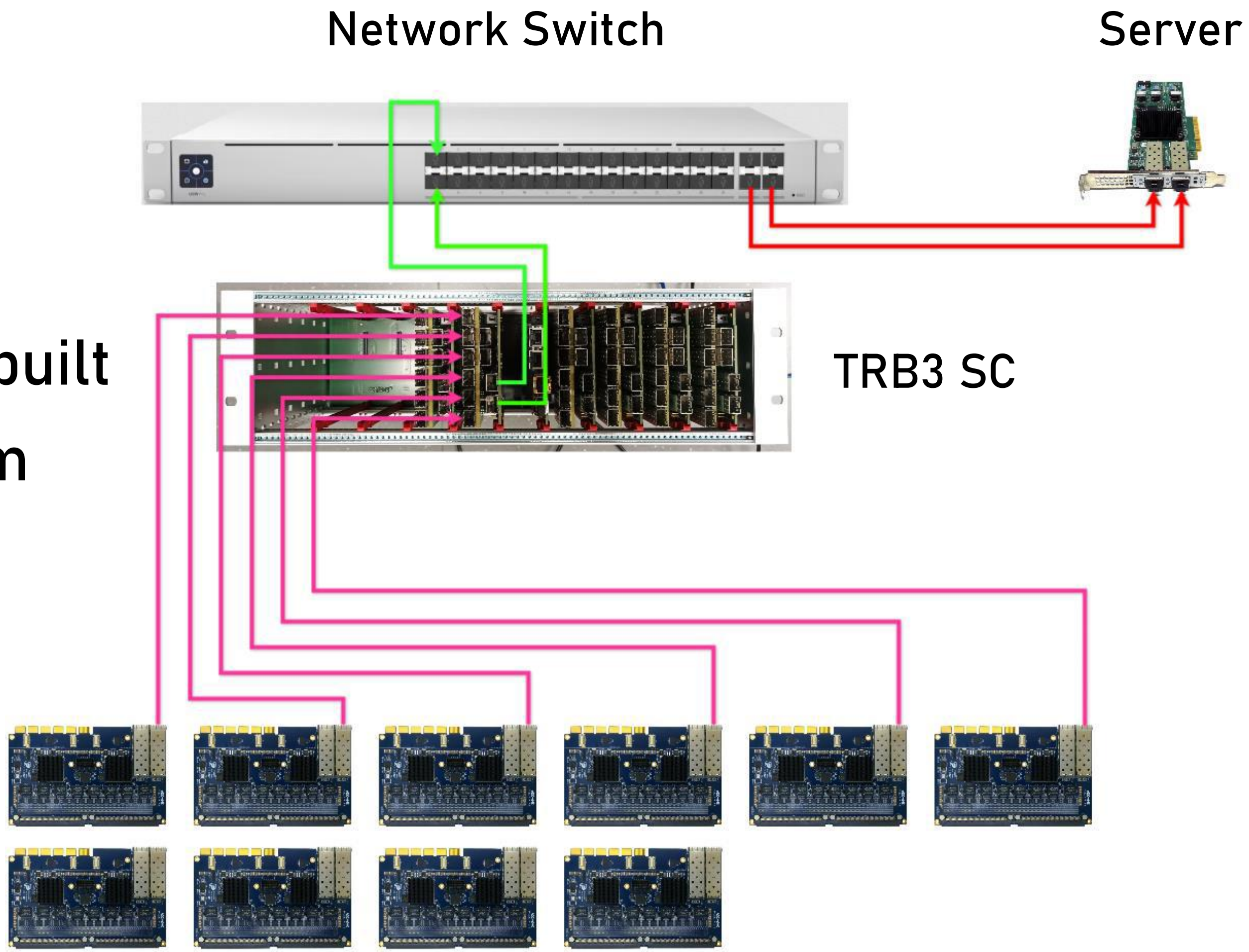
SADC





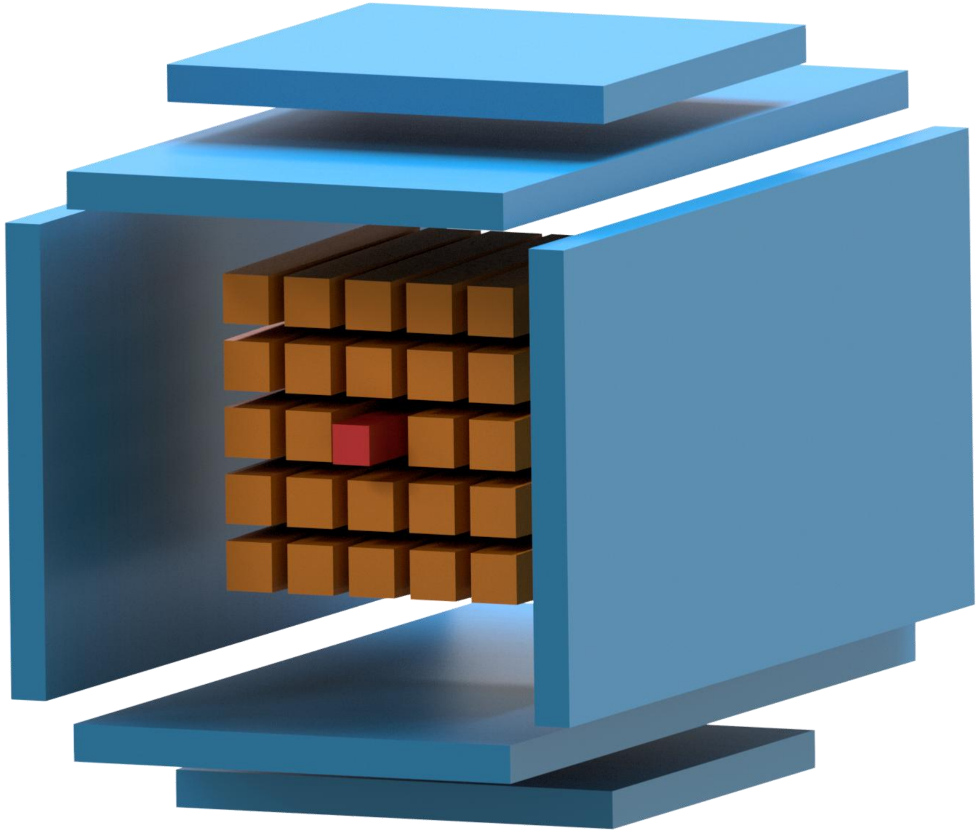
Data Acquisition Status.

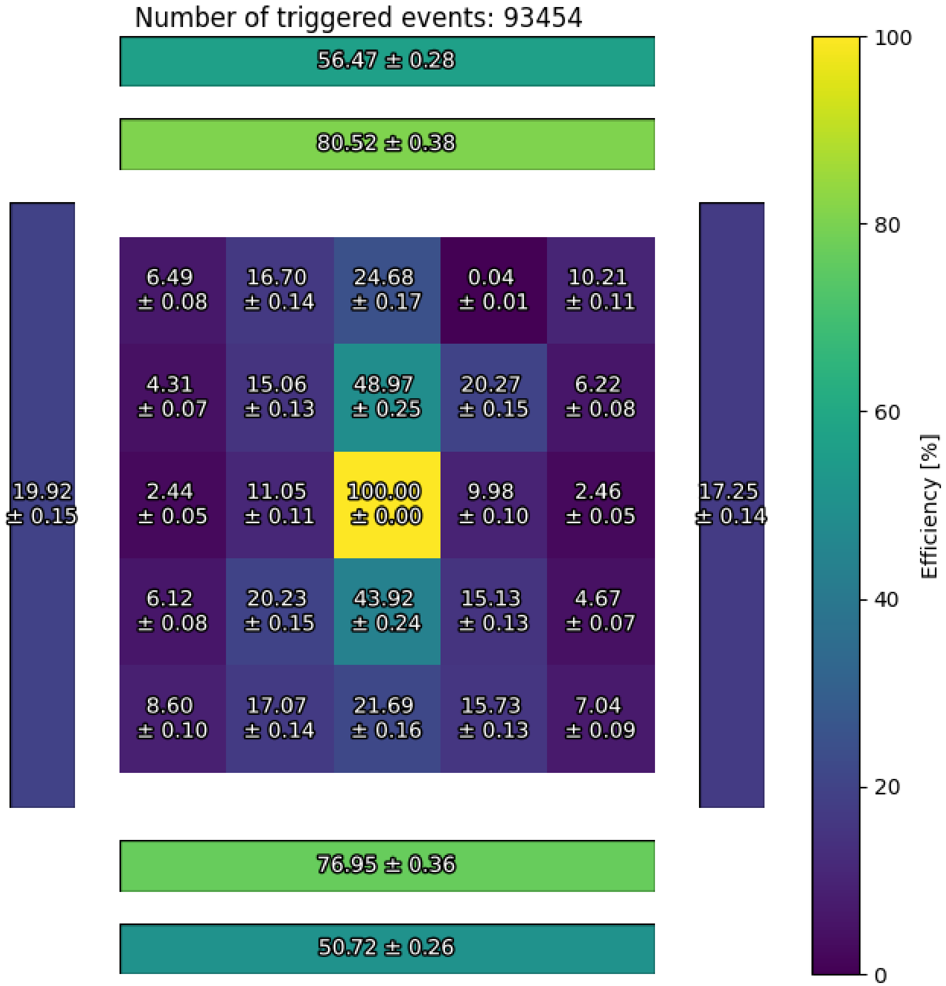
- 2 PANDA SADCs available
  - ➡ Newest firmware
  - ➡ Enough for full prototype
- Shaper & amplifier for PMT signals built
- Clock and trigger distribution system (TRB 3 SC)
  - ➡ 1 primary and 2 secondary boards available
  - ➡ No firmware yet, small bugs
  - ➡ Firmware development: Michael Böhmer and Luigi Capozza
- Adjustment of DAQ software ongoing



[1] Oliver Noll, PANDA FEE/DAQ Workshop, PANDA Collaboration Meeting 24/2

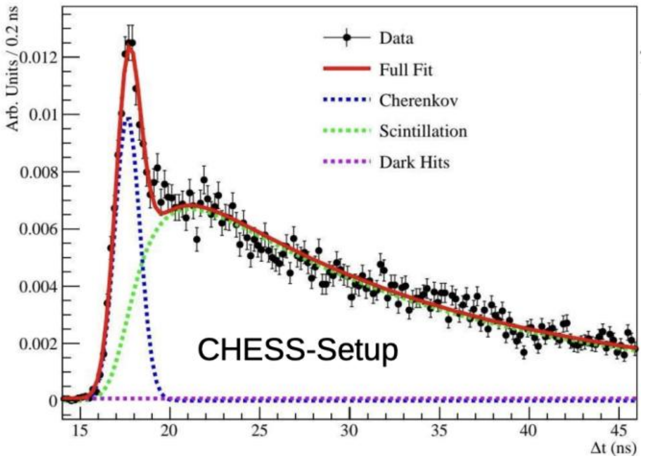
Initial Phase A full calorimeter studies.





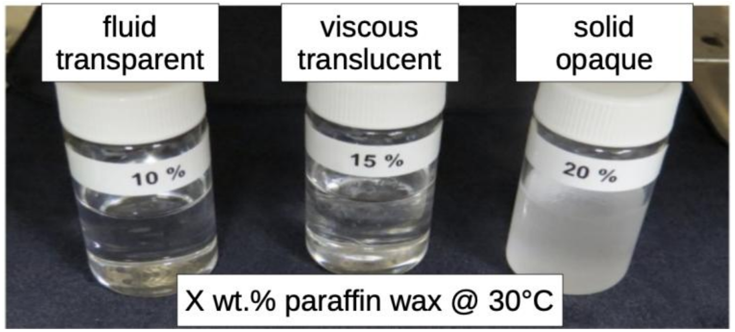
Hybrid and Opaque Scintillator.

- Hybrid scintillator:
  - Water-based with 1-10% scintillator
  - Slow scintillation pulse: $\tau \geq 10\ \mathrm{ns}$
  - Particle ID: ratio of Cherenkov to Scintillation light (C/S)

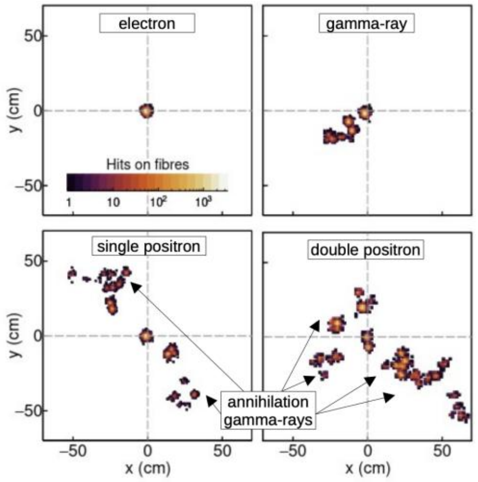


[1] H. Steiger et al., arXiv:2405.01100

- Opaque scintillator:
  - Wax-based (e.g. 80% LAB + 20% wax)
  - Opaqueness through scattering without absorption (Mie scattering)
  - Particle ID: topology of vertices readout by optical fibers



[2] Stefan Schoppmann, "NuDoubt++: Search for Double Beta Decays in a Novel Hybrid Opaque Scintillation Detector"



[3] M. Böhles et al., arXiv:2407.05999

Potential for Dark Matter detector

Slow hybrid scintillator: Full DarkMESA detector.