Detector Technologies for beam-dump experiments at MESA and JLab

BDX & Beyond Workshop at JLab

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JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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

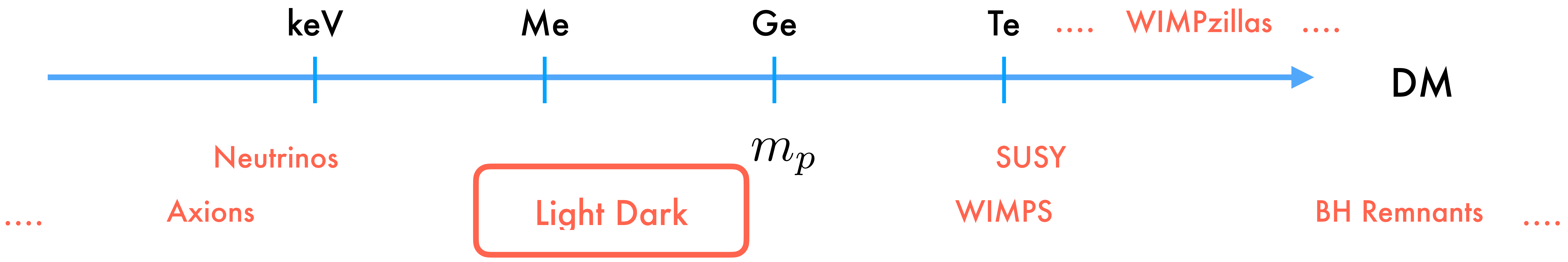
HIM Helmholtz-Institut Mainz

Overview

* Light Dark Matter
* The DarkMESA experiment
* Detector Technologies
* Applications at MESA and JLab
* Summary

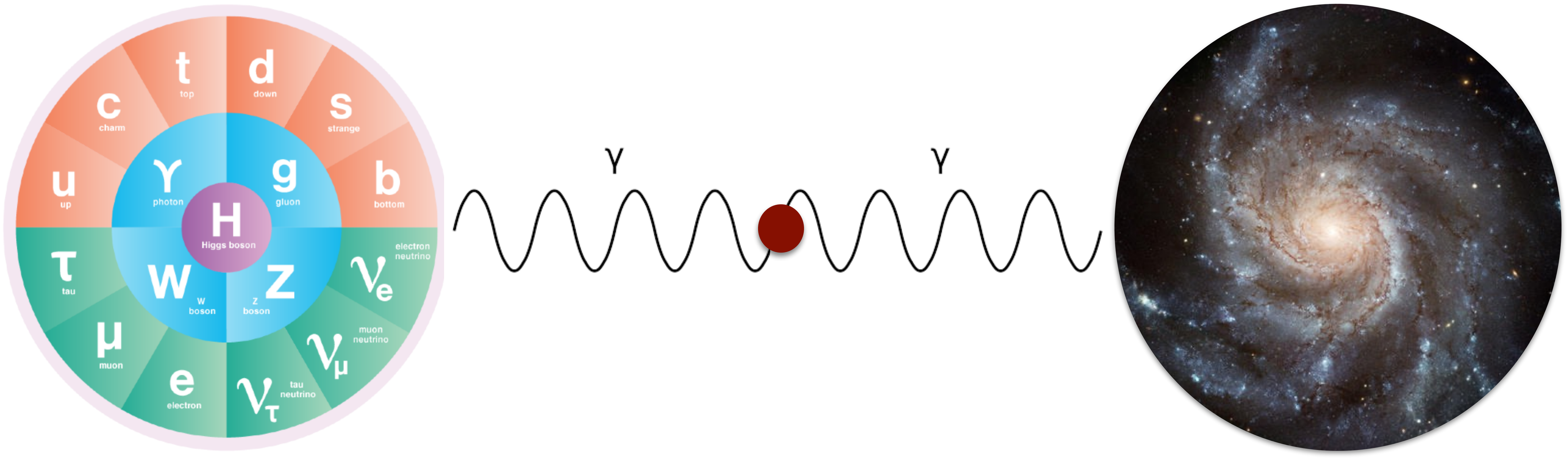
(Light) Dark Matter

Light Dark Matter



- Very wide mass range theoretically possible
- WIMP exclusion close to neutrino fog
- Alternative: new force and “light” DM

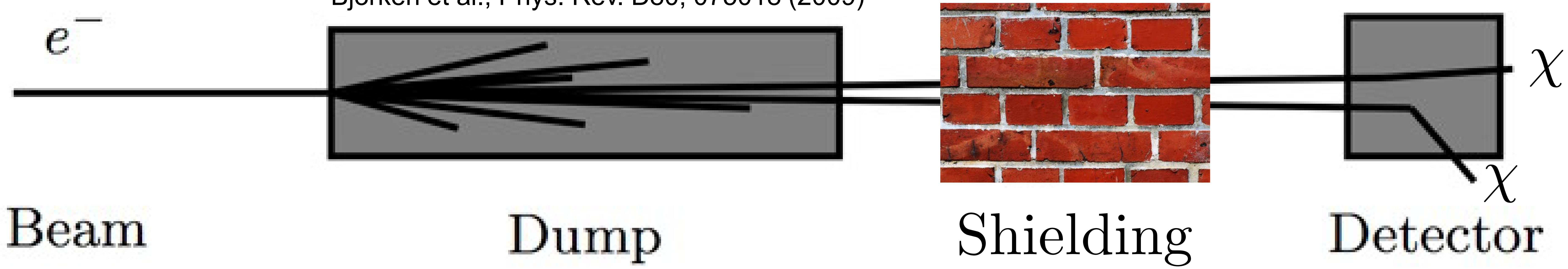
$$\sigma \sim \frac{g^4}{m_\chi^2}$$



- Benchmark: minimal dark photon model $m_{\gamma'}$; m_χ ; ϵ ; α_D

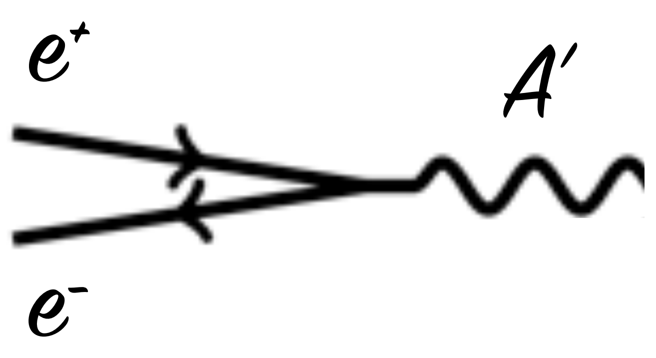
Beam-Dump Experiments

Bjorken et al., Phys. Rev. D80, 075018 (2009)

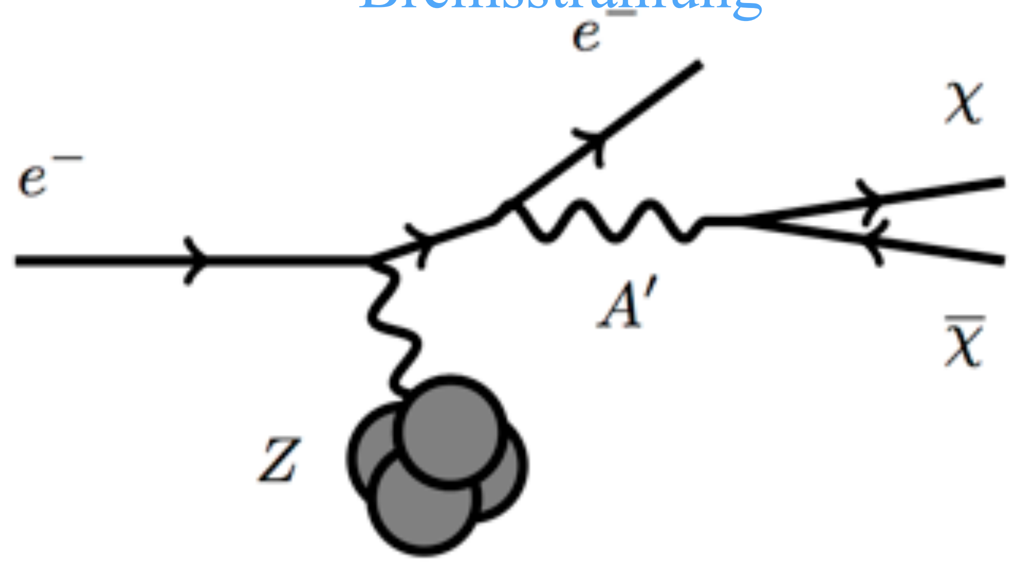


Production

Annihilation



Bremsstrahlung

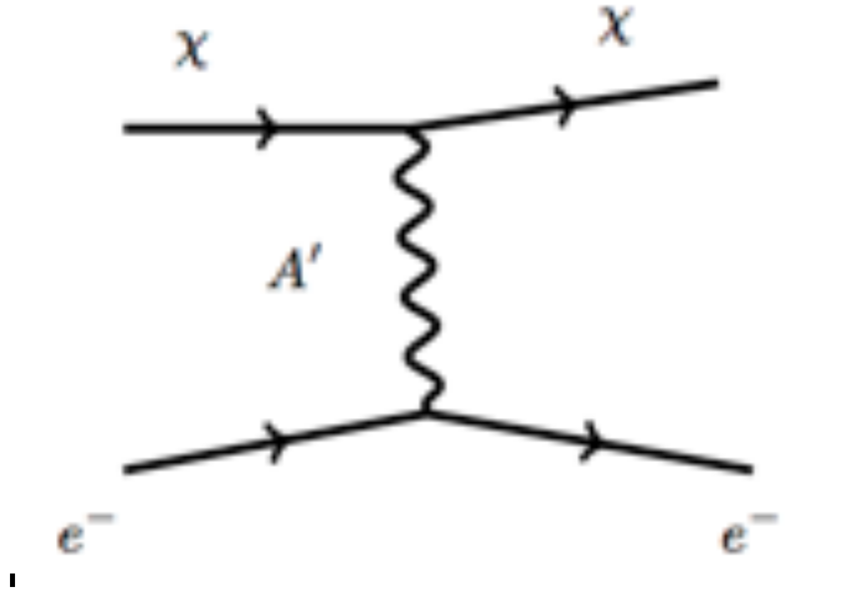


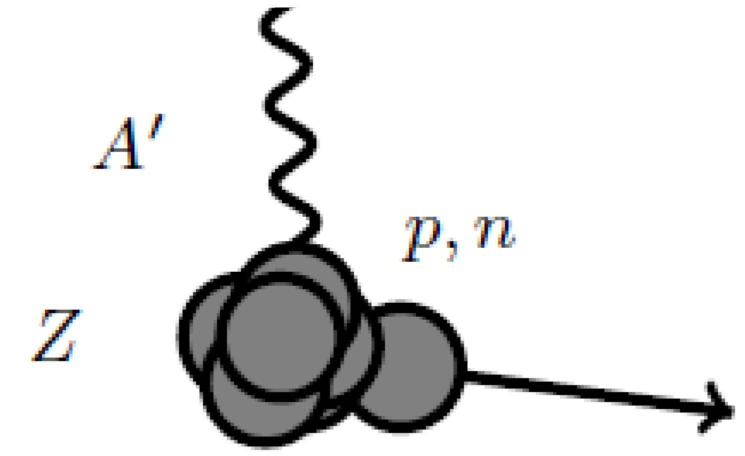
$$\theta_{A'\,\mathrm{max}} \sim \max\left(\frac{\sqrt{m_{A'} m_e}}{E_0}, \frac{m_{A'}^{3/2}}{E_0^{3/2}}\right)$$

$$\frac{d\sigma}{dx} \approx \frac{8Z^2\alpha^3\epsilon^2 x}{m_{A'}^2}\left(1 + \frac{x^2}{3(1-x)}\right)\mathcal{L}og$$

$$Y_{Prod} \sim \epsilon^2 / m_A^2$$

Detection

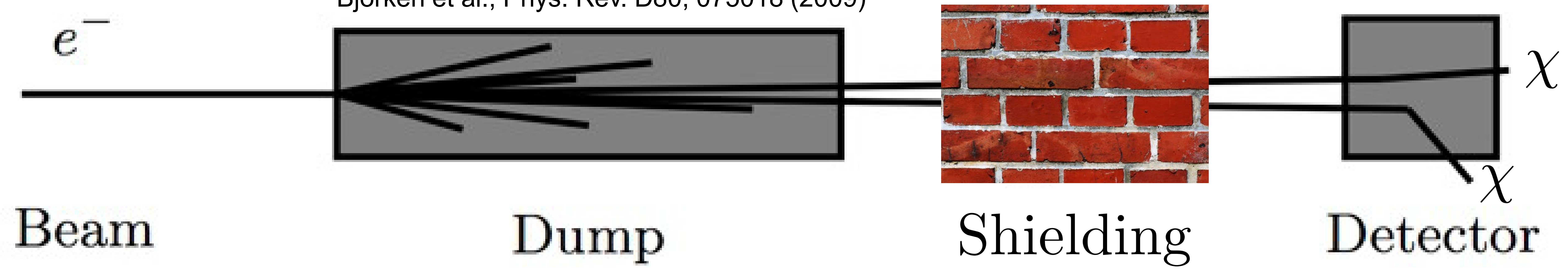




$$Y_{Det} \sim \epsilon^2 \alpha_D / m_A^2$$

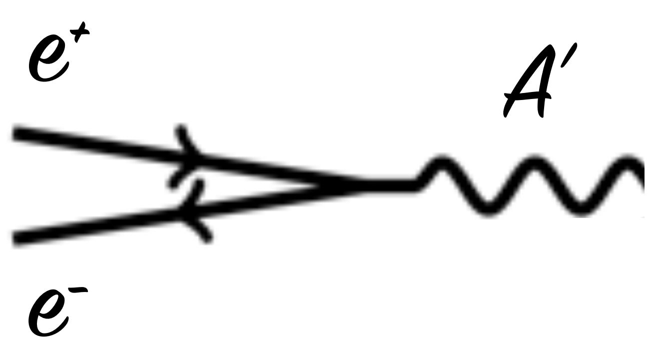
Beam-Dump Experiments

Bjorken et al., Phys. Rev. D80, 075018 (2009)



Production

Annihilation



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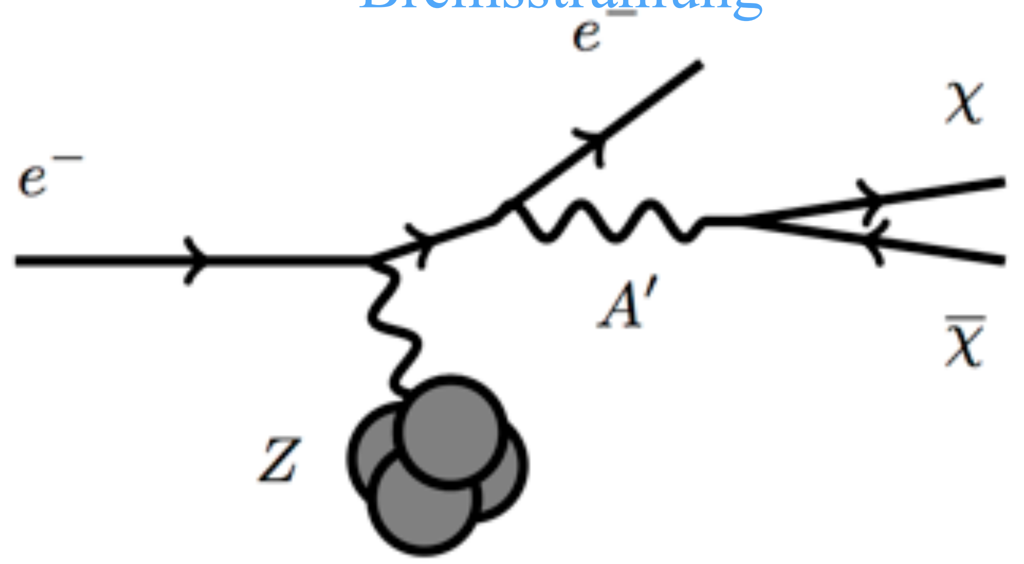

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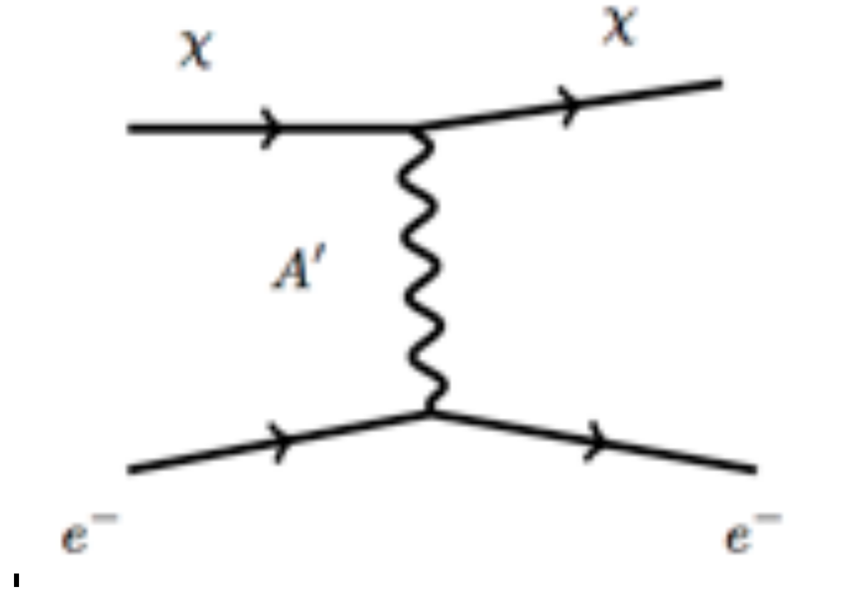
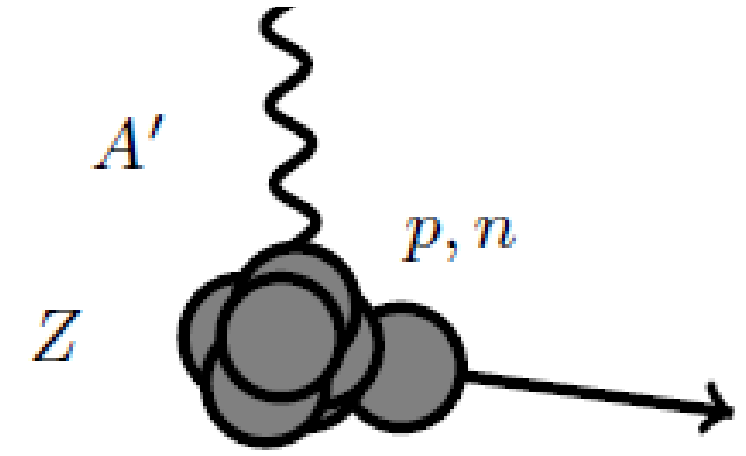
Detection





$$\frac{d\sigma}{dx} \approx \frac{8Z^2\alpha^3\epsilon^2 x}{m_{A'}^2}\left(1 + \frac{x^2}{3(1-x)}\right)\mathcal{L}og$$

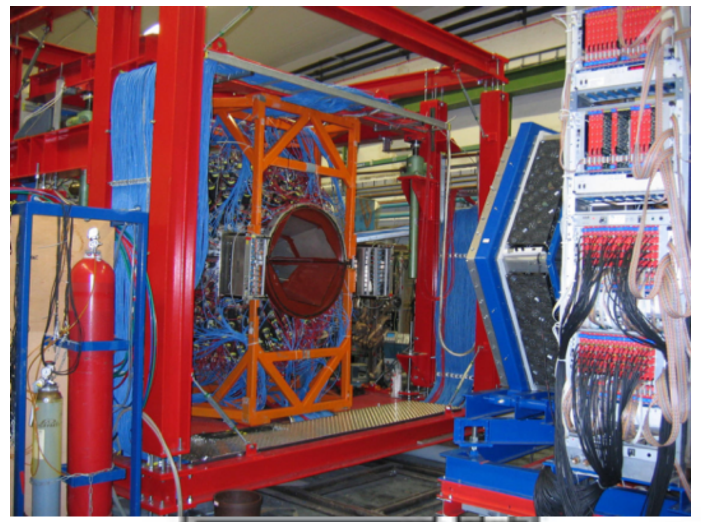
Total Yield

$Y_{Prod} \sim \epsilon^2/m_A^2$ → $Y_{TOT} \sim \epsilon^4\alpha_D/m_A^4$ ← $Y_{Det} \sim \epsilon^2\alpha_D/m_A^2$

The MESA Facility

The MAMI Facility

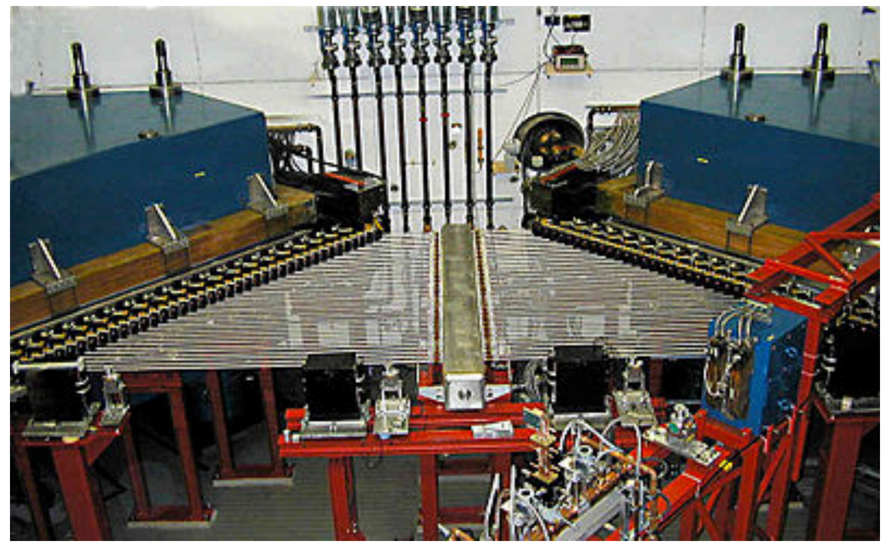
A2 Collaboration
Experiments with real photons

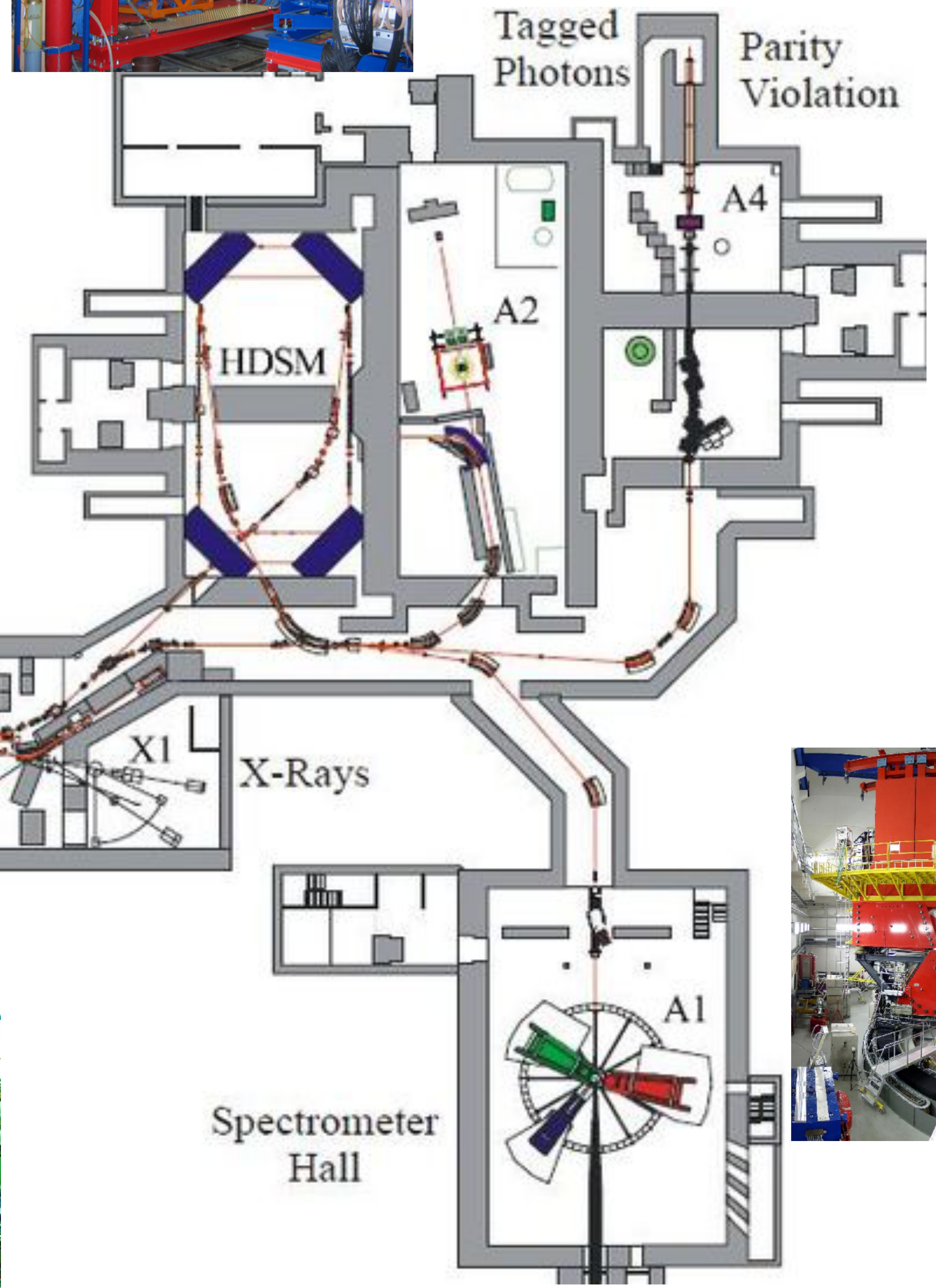
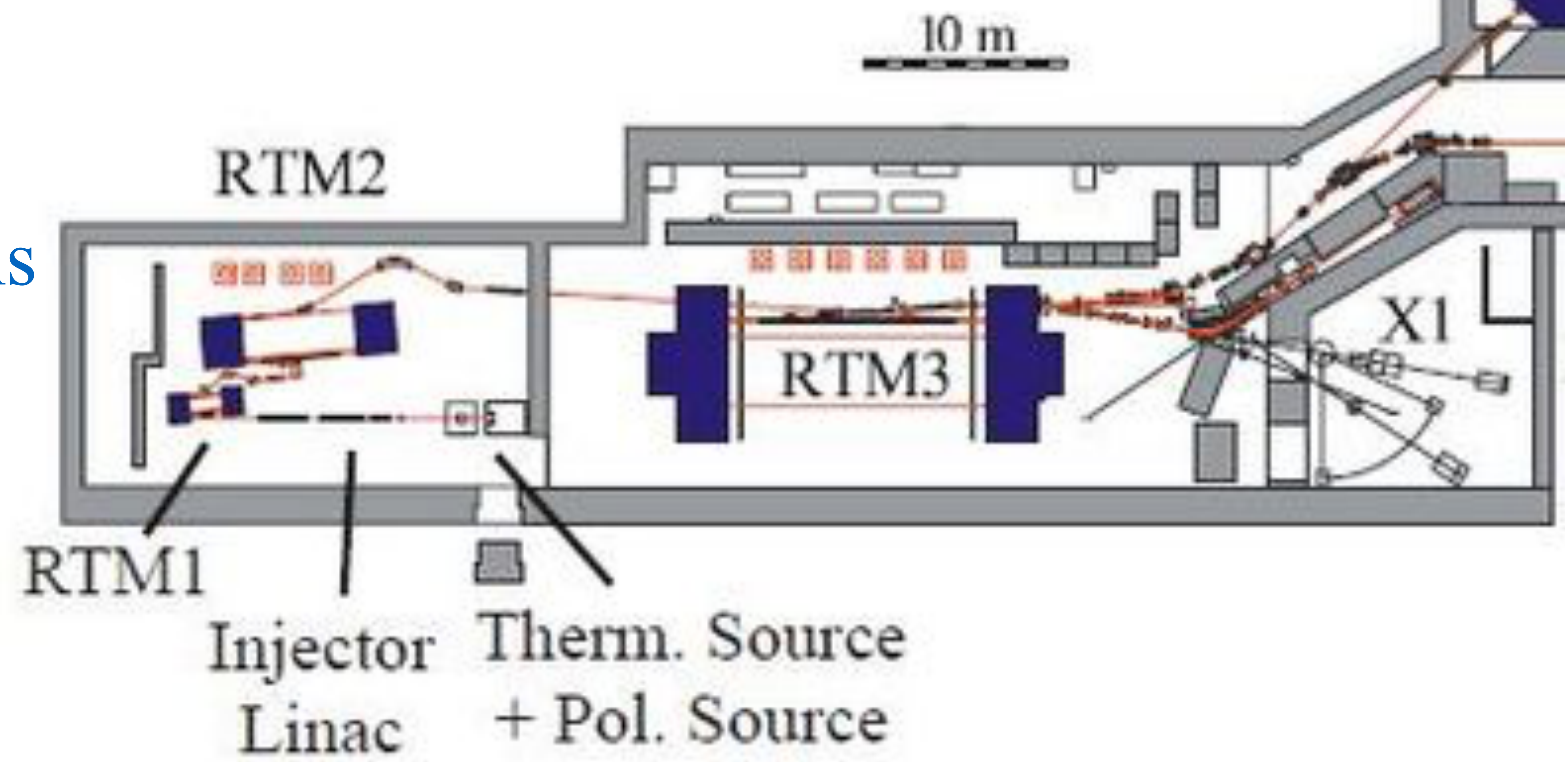


Existing High-power Beam Dump

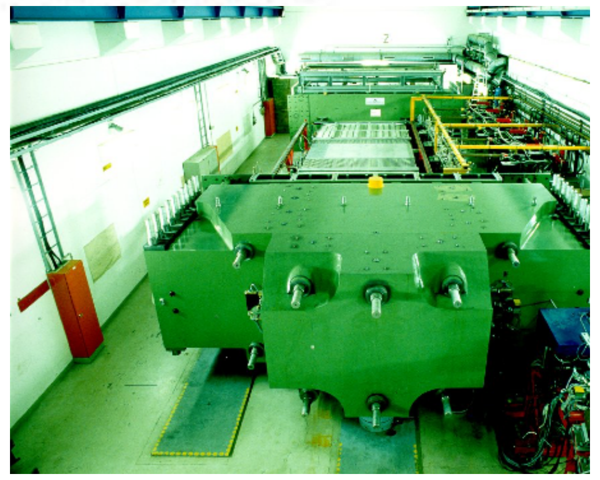
Existing Halls cleared for MESA

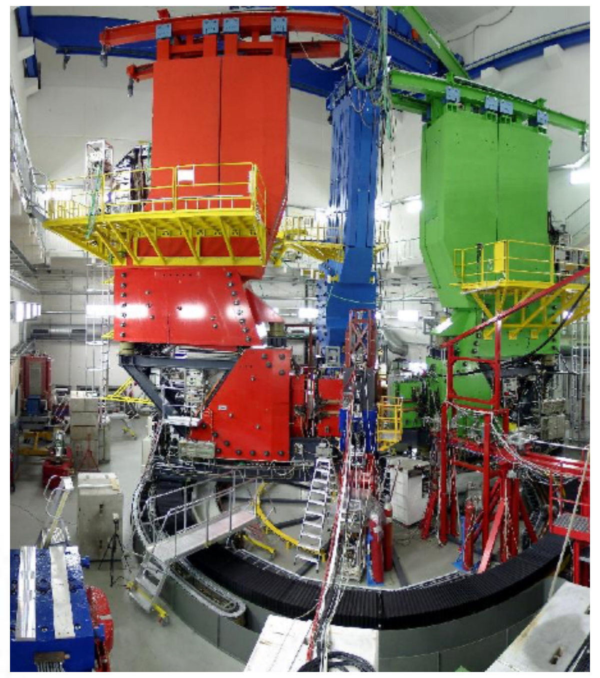
MAMI-C (since 2007)
Harmonic Double-sided Microtron
E= 1.6 GeV



MAMI-B
3 cascaded Racetrak Microtrons
E=180-883 MeV
Max beam current 100 uA c.w.

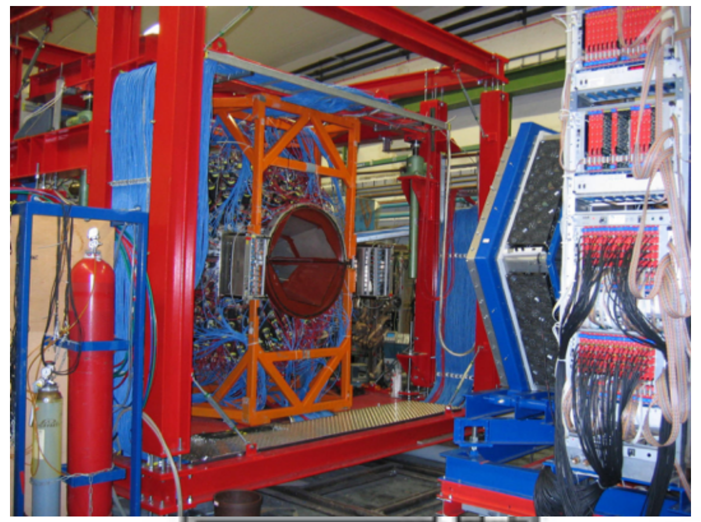




A1 Collaboration
3-spectrometer setup
Experiments with electrons

The MAMI Facility

A2 Collaboration
Experiments with real photons



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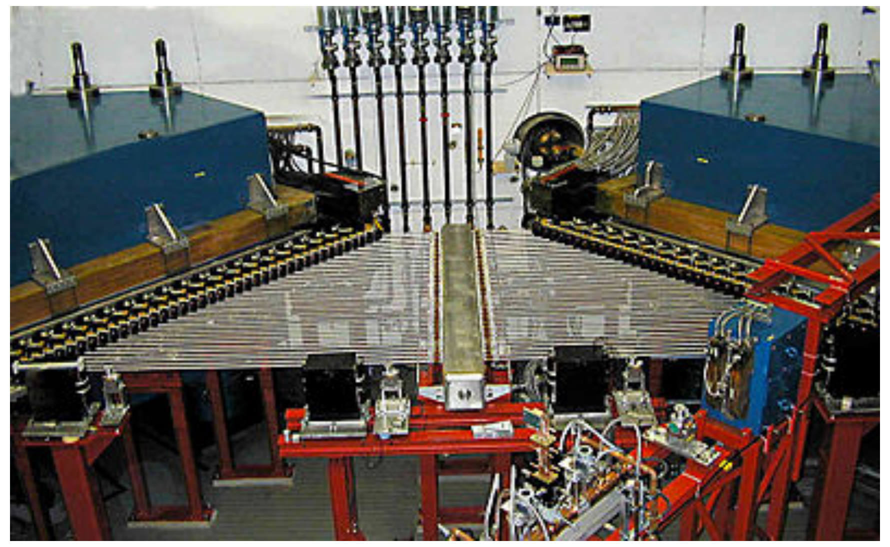

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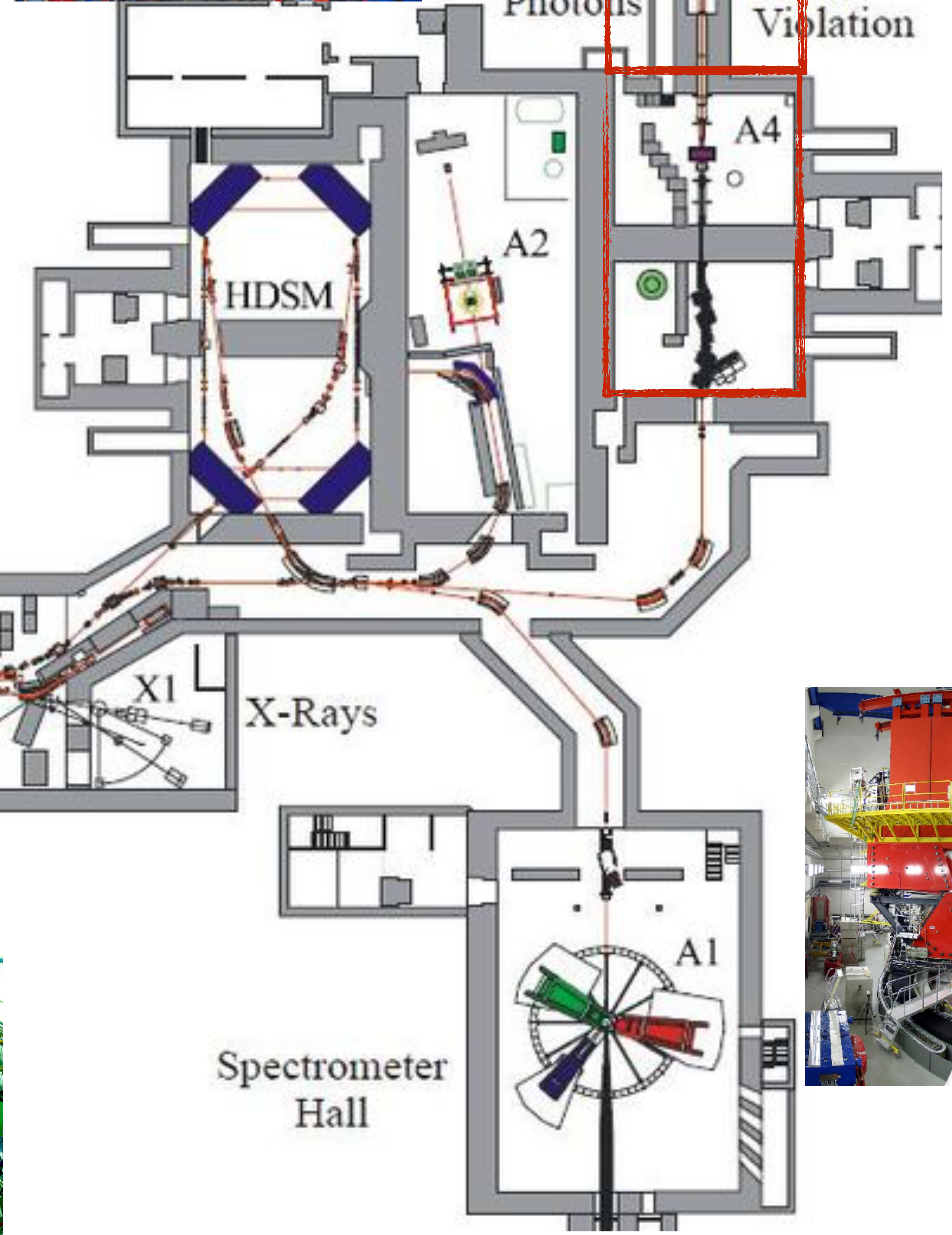
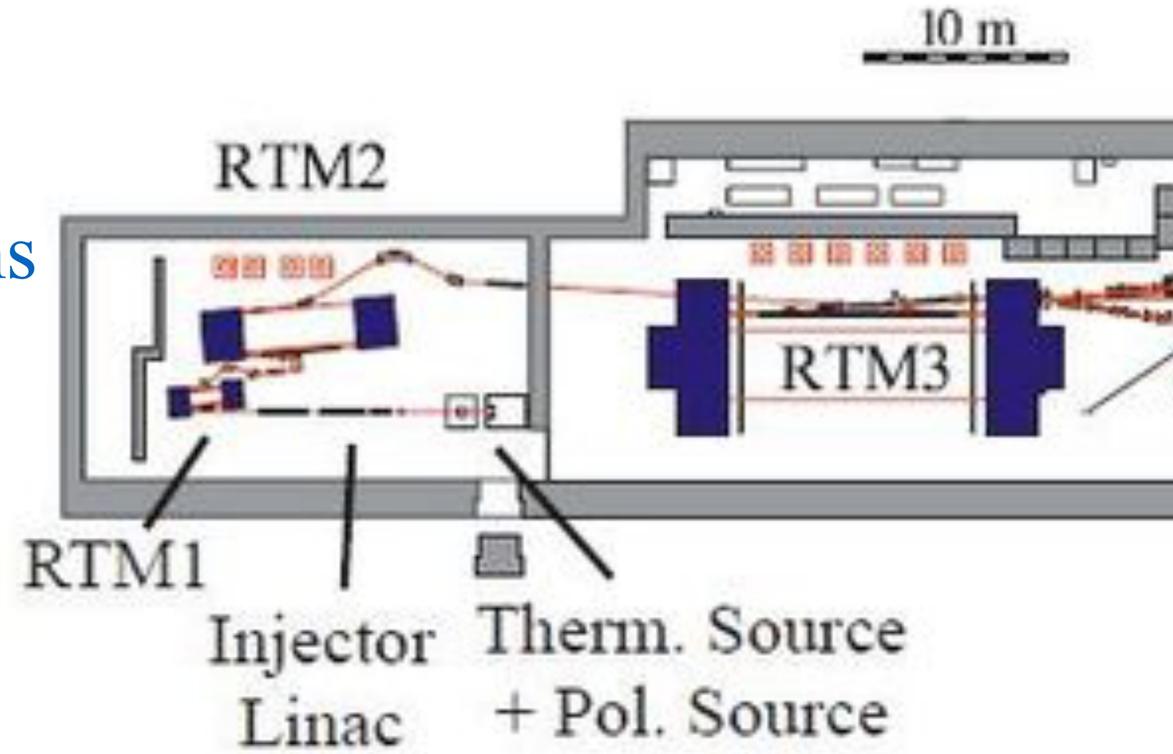
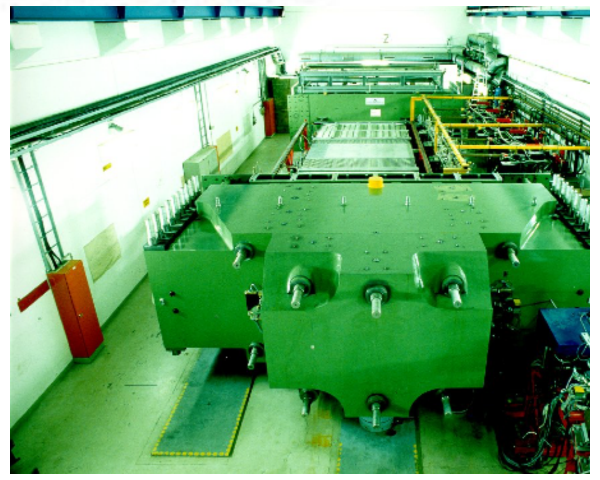


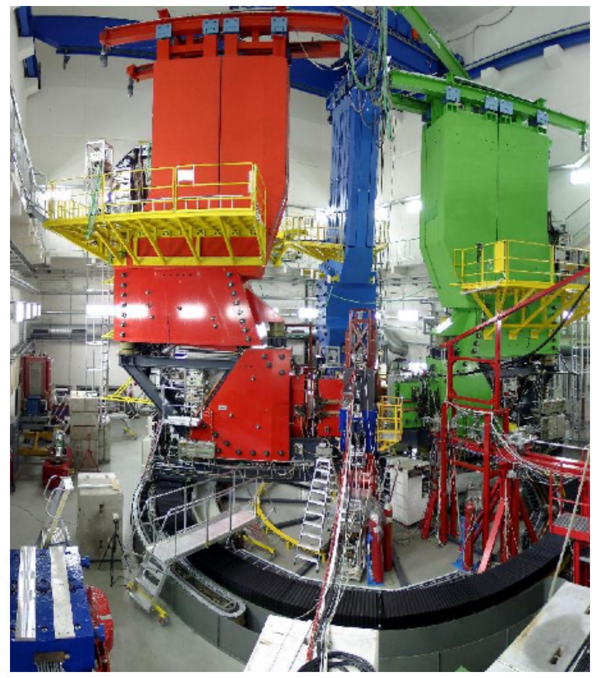


New MESA Hall and Building

Existing High-power Beam Dump

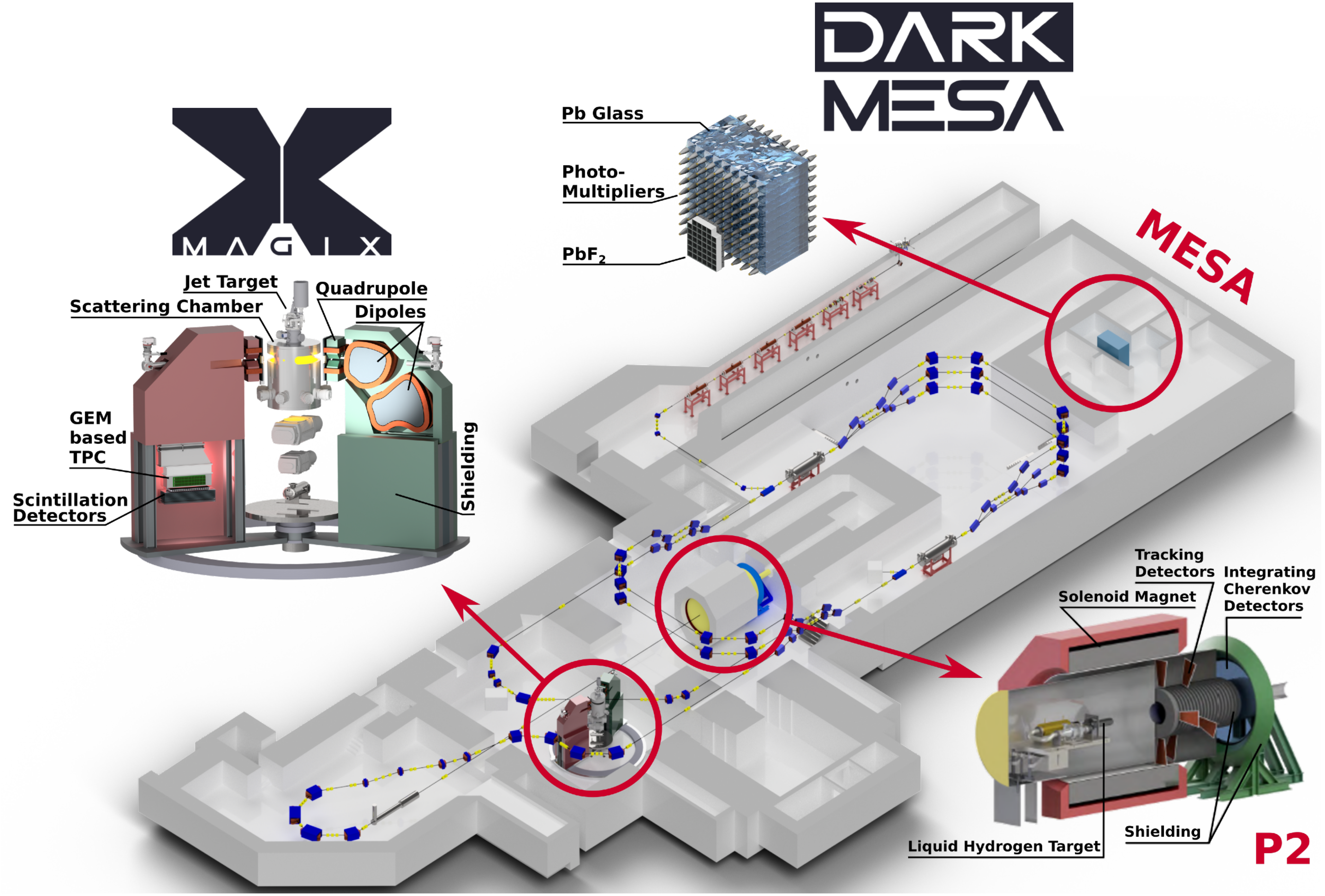
Existing Halls cleared for MESA





A1 Collaboration
3-spectrometer setup
Experiments with electrons

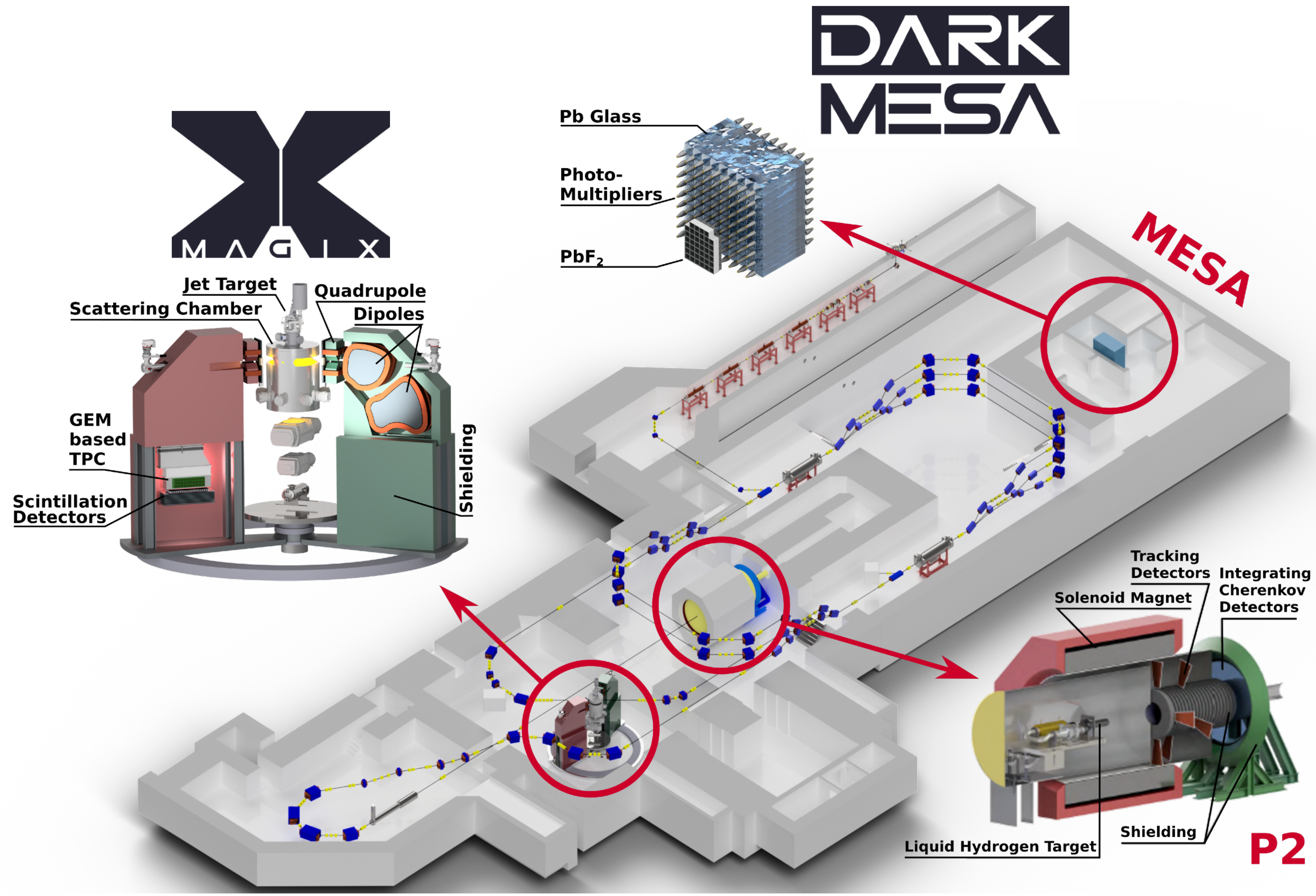
The MESA Facility



The MESA Accelerator

- 155 MeV max. beam energy
- 2 SC TESLA-like cavities
- >1mA beam current
- Operation:
- Extracted beam mode
- Energy recovery/3x recirculation
- Experimental Hall ready!

The MESA Facility



The MESA Accelerator

- 155 MeV max. beam energy
- 2 SC TESLA-like cavities
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- Operation:
- Extracted beam mode
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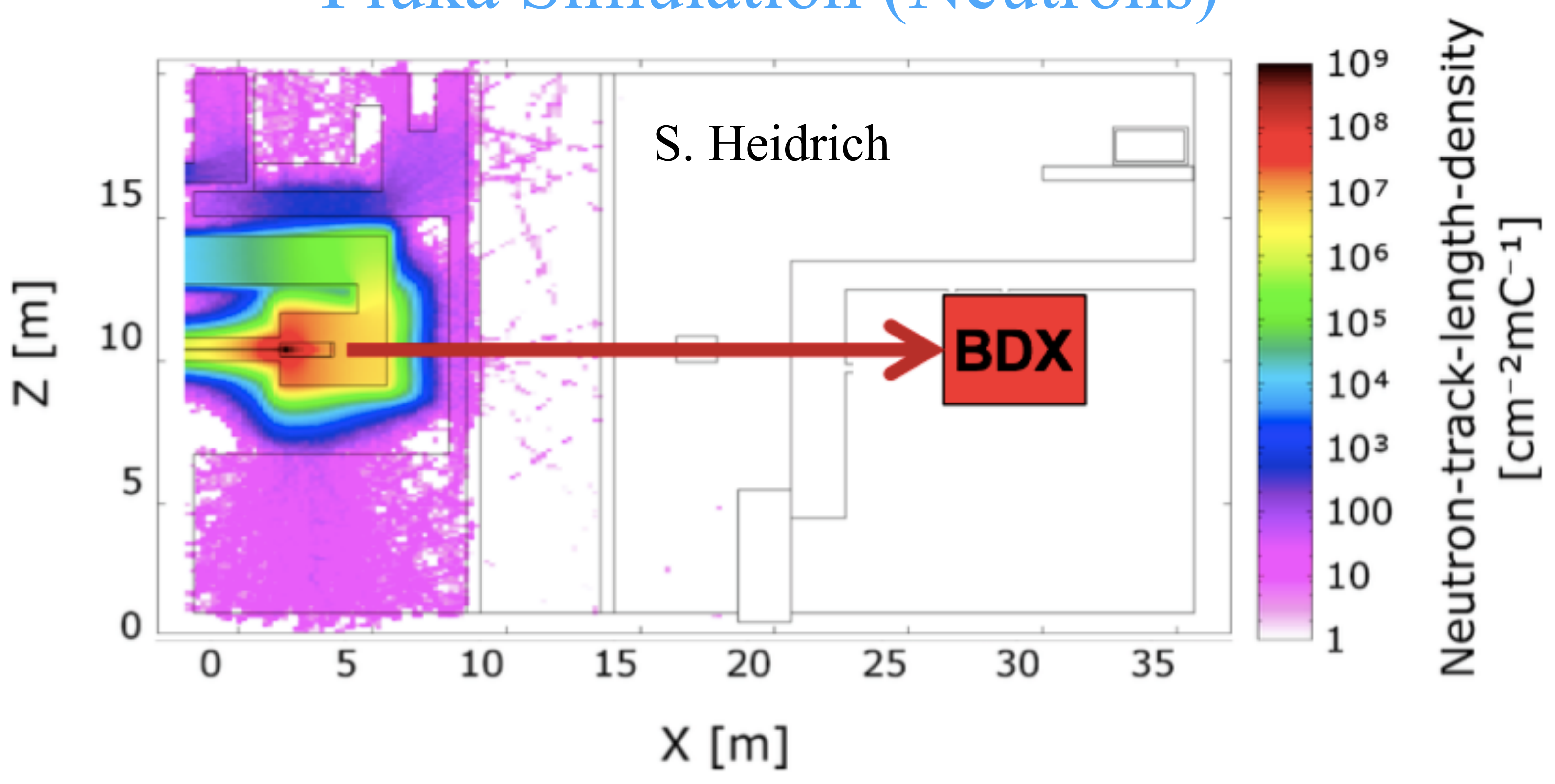
- Experimental Hall ready!

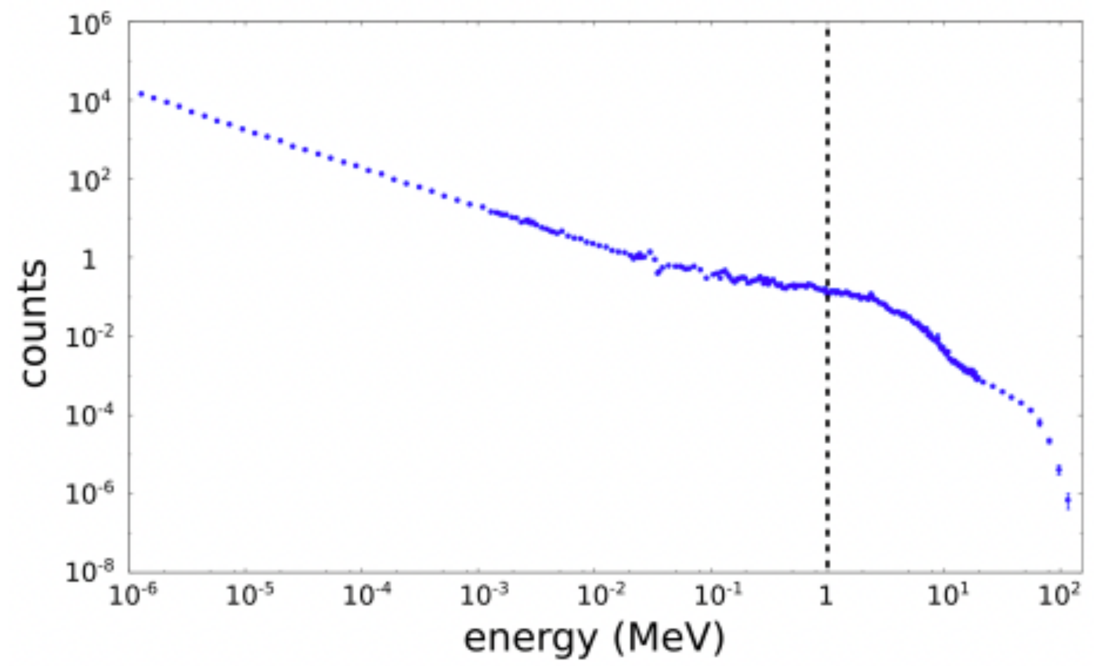
The DarkMESA experimental principle

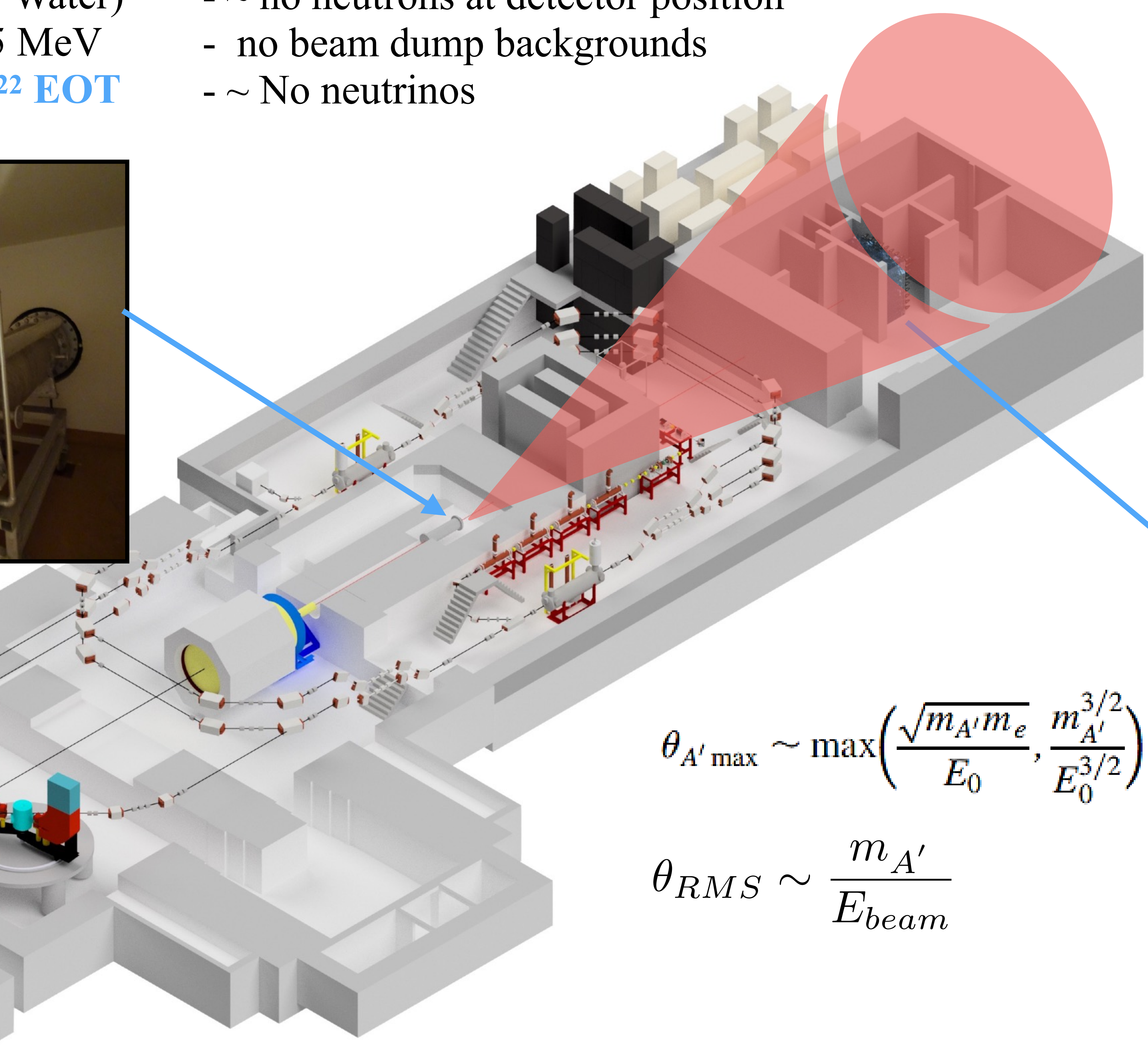
Beam Dump
- 20 X_0 Beam Dump
- Material: Aluminum (+ Water)
- Energy on Dump: ~135 MeV
- **10^4 h of operation; 10^{22} EOT**

Experimental Area
- 70 X_0 (~8m) barite concrete
- ~ no neutrons at detector position
- no beam dump backgrounds
- ~ No neutrinos

Fluka Simulation (Neutrons)

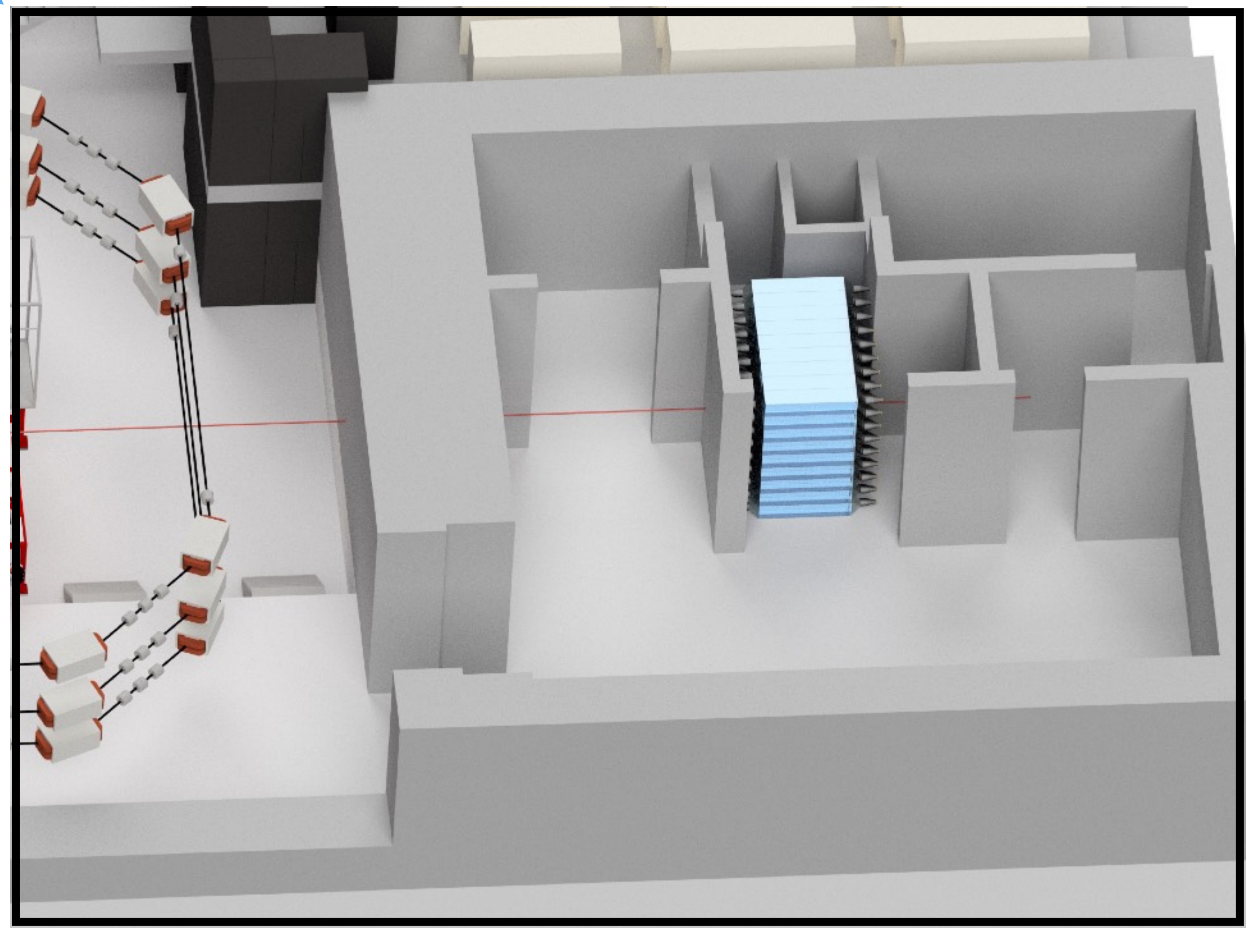




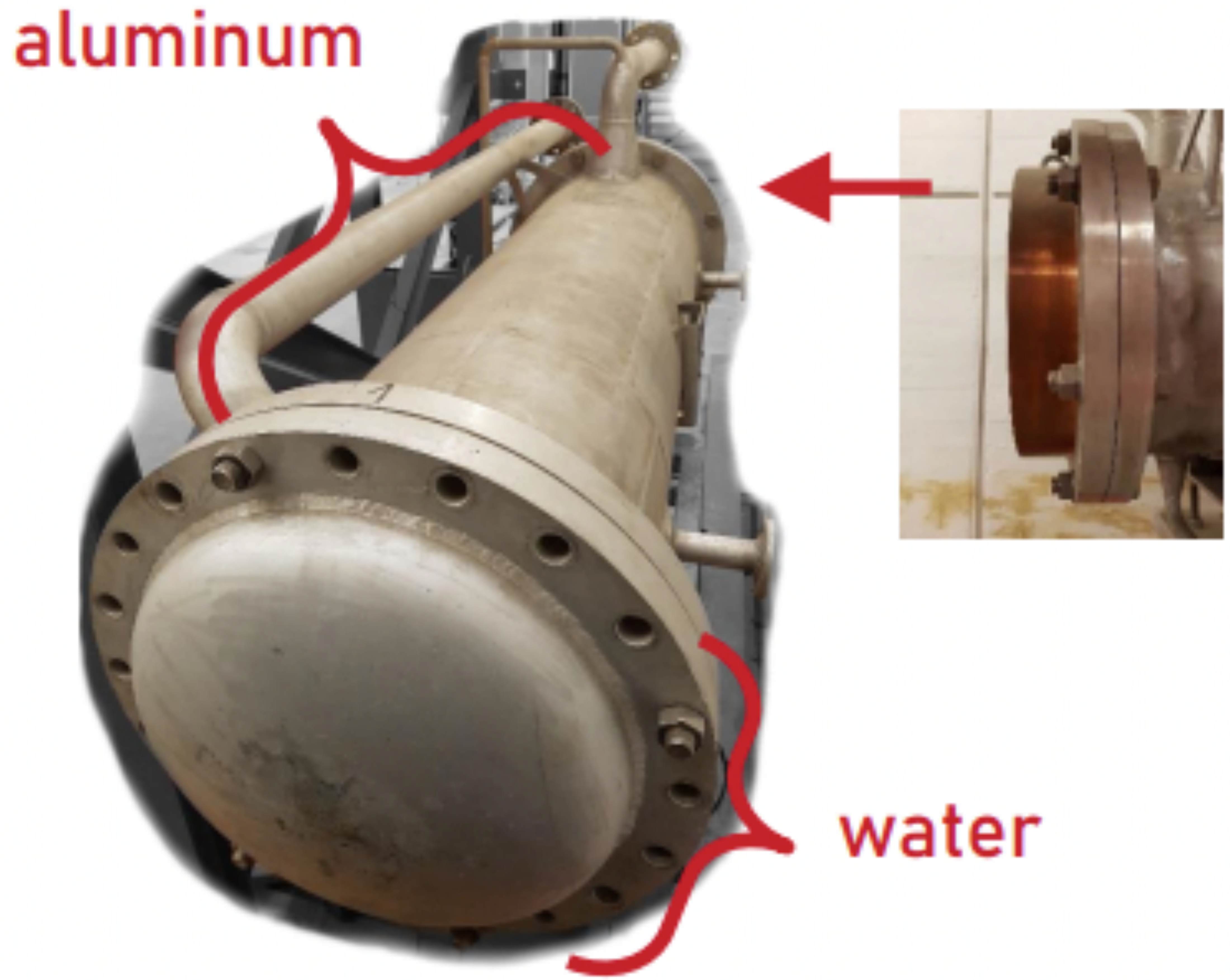


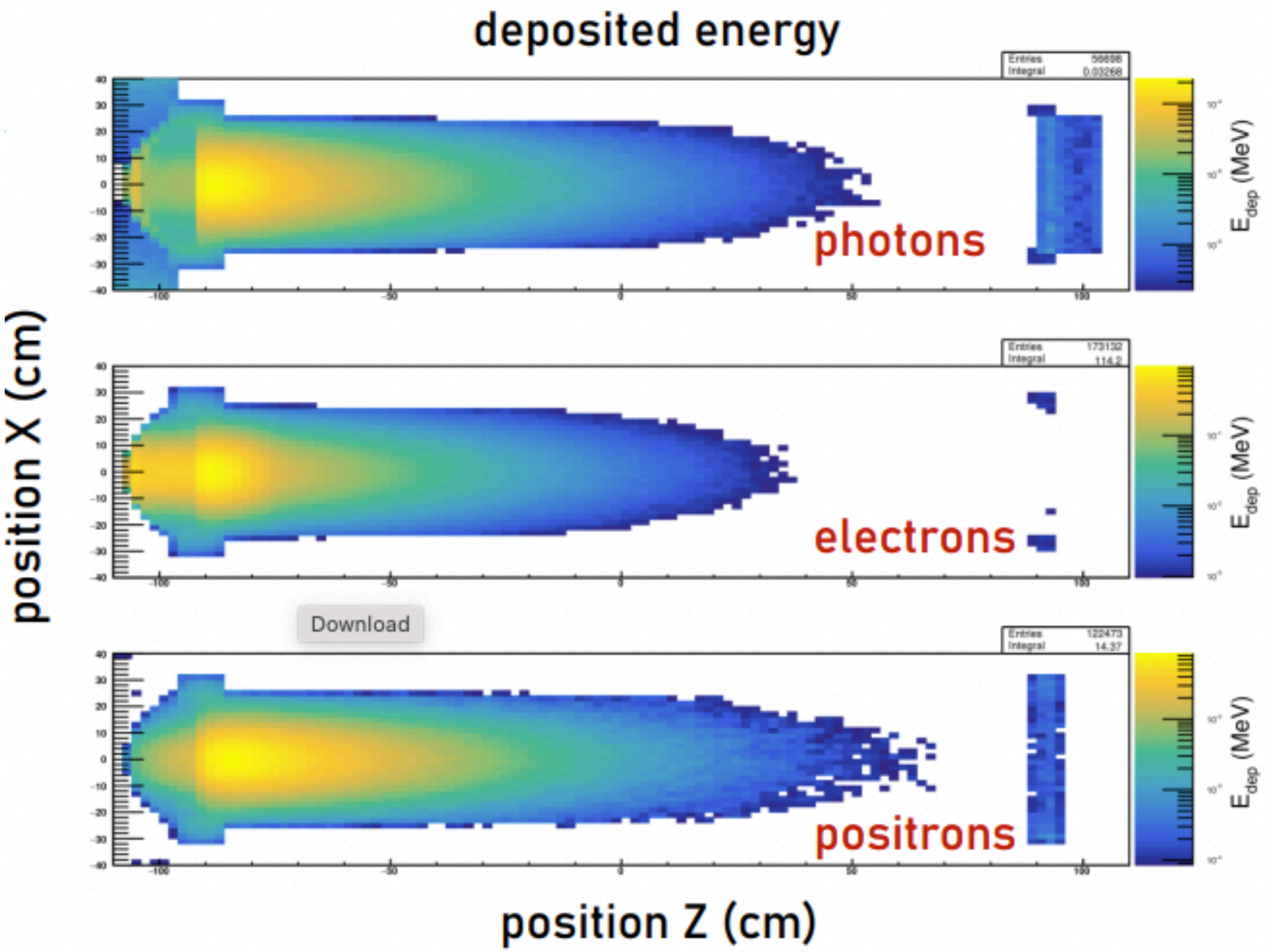
$$\theta_{A'\,\max} \sim \max\left(\frac{\sqrt{m_{A'} m_e}}{E_0}, \frac{m_{A'}^{3/2}}{E_0^{3/2}}\right)$$

$$\theta_{RMS} \sim \frac{m_{A'}}{E_{beam}}$$



The "Target"


aluminum
water


deposited energy
photons
electrons
positrons
position X (cm)
position Z (cm)
Download

Detector Technologies

M. Lauß *et al.*, Nucl. Instr. Meth. A, 1012, 165617 (2021)
M. Christmann *et al.*, Nucl. Instr. Meth. A, 960, 163665 (2020)
M. Christmann *et al.*, Nucl. Instr. Meth. A, 958, 162398 (2020)

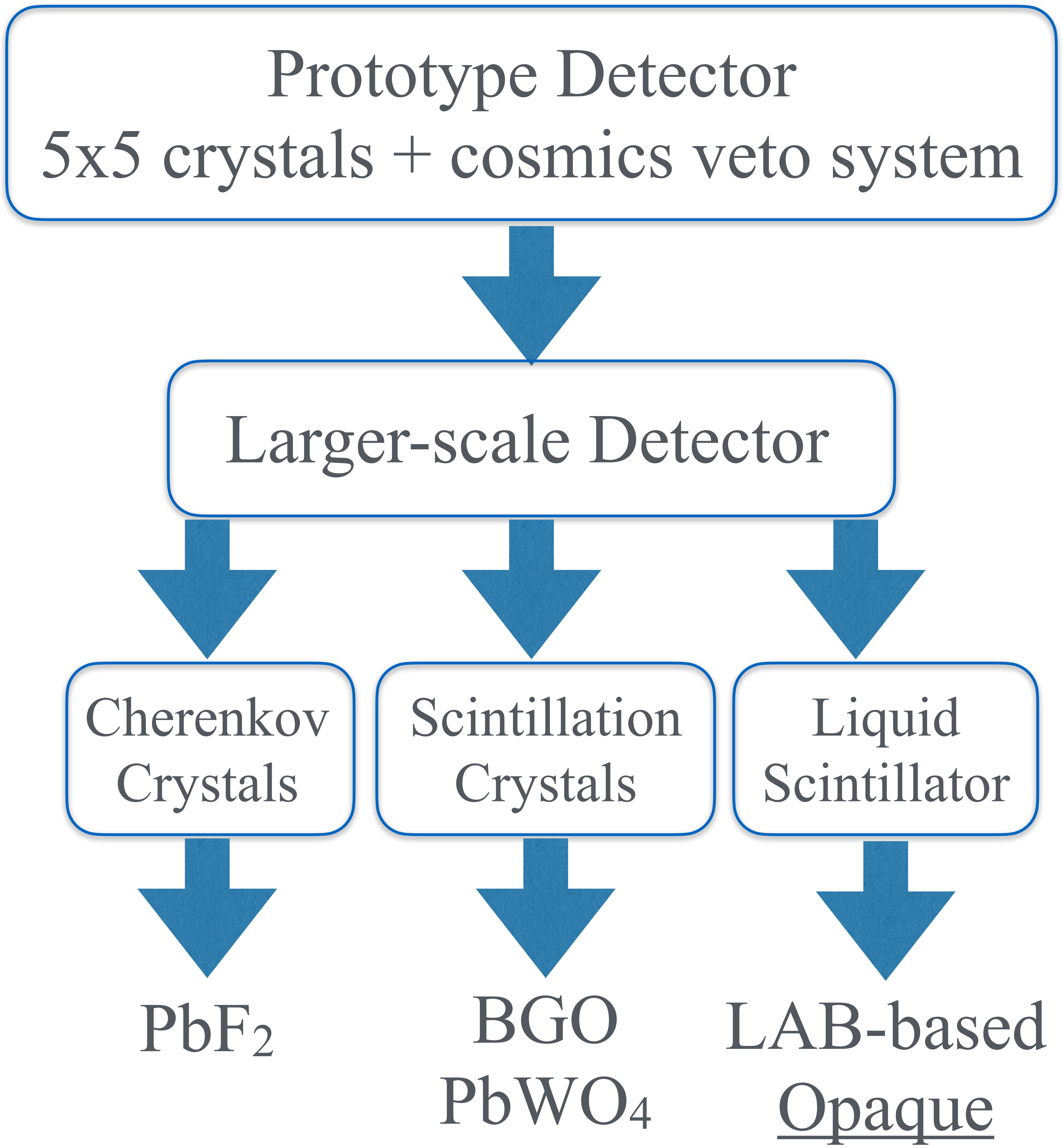
Staged Approach to the final detector

Prototype Detector
5x5 crystals + cosmics veto system

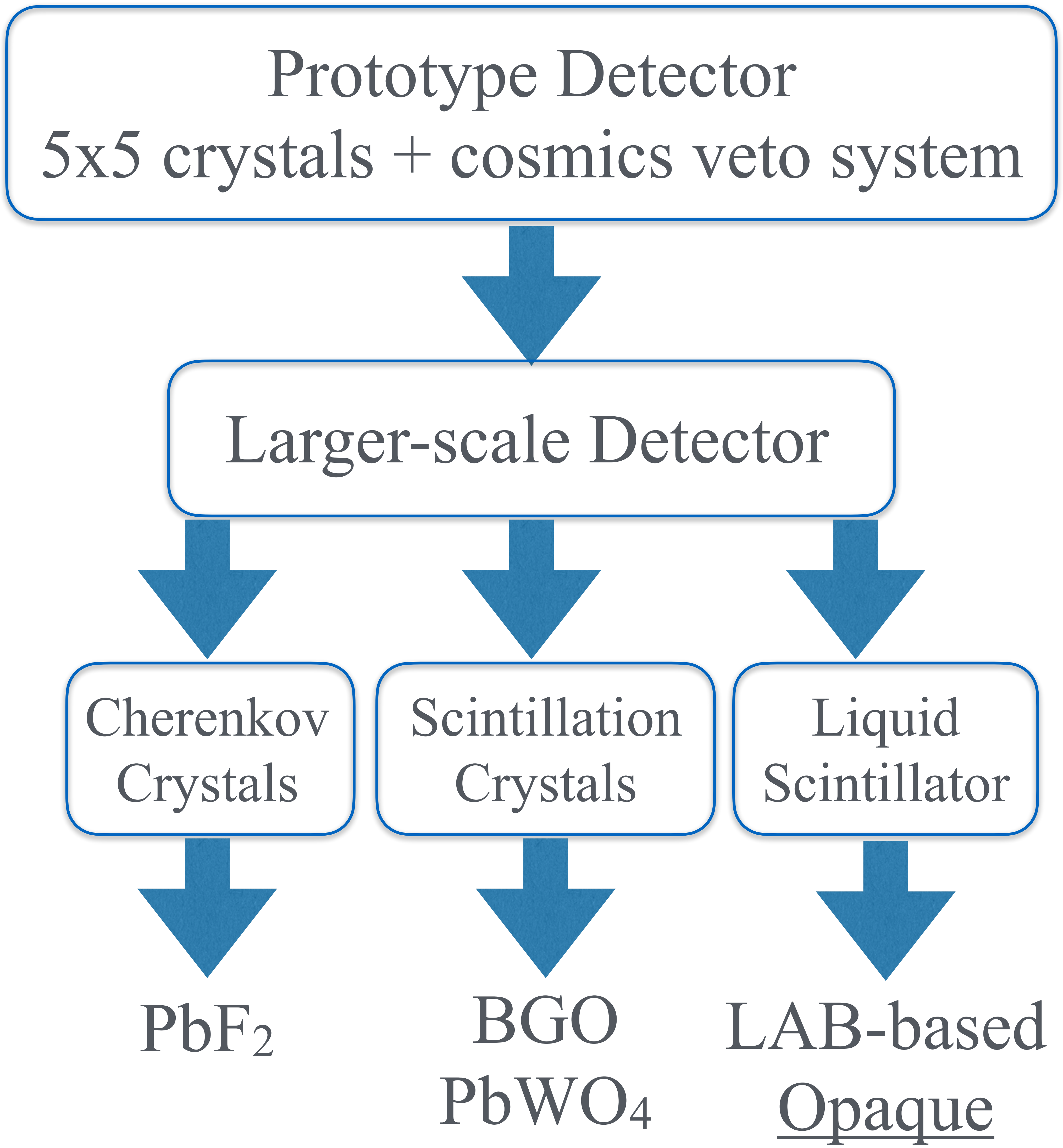
↓

Larger-scale Detector

Staged Approach to the final detector



Staged Approach to the final detector



$PbWO_4$

Density ~8.3 g/cm³
Output 50-200 ph./MeV
Fast (~10 ns)

BGO

Density ~ 7.1 g/cm³
Output ~10,000 ph./MeV
Slow (~300-600 ns)

PbF_2

Density ~8.4 g/cm3
Output ~16 ph./MeV
Fast (~10ns)

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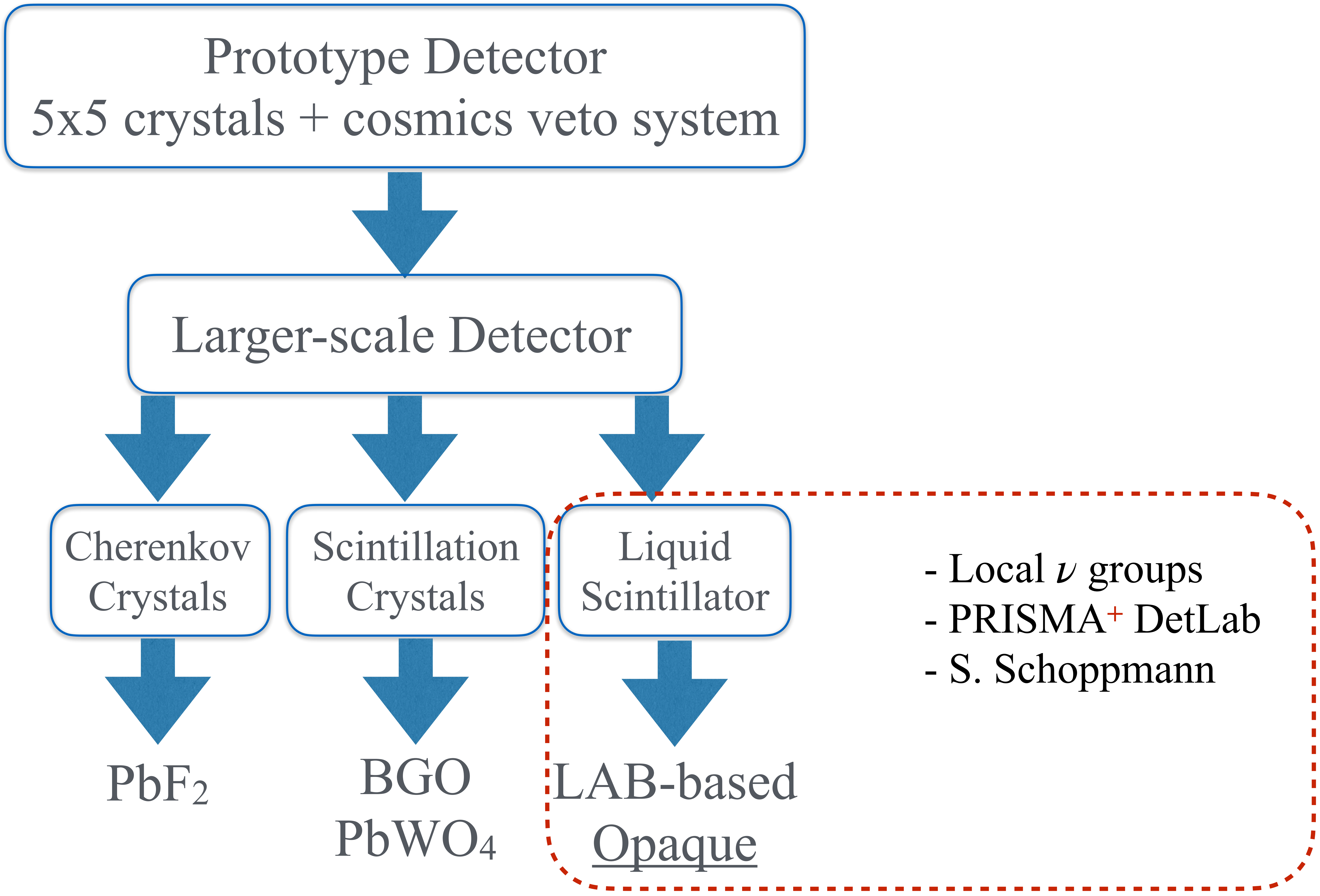
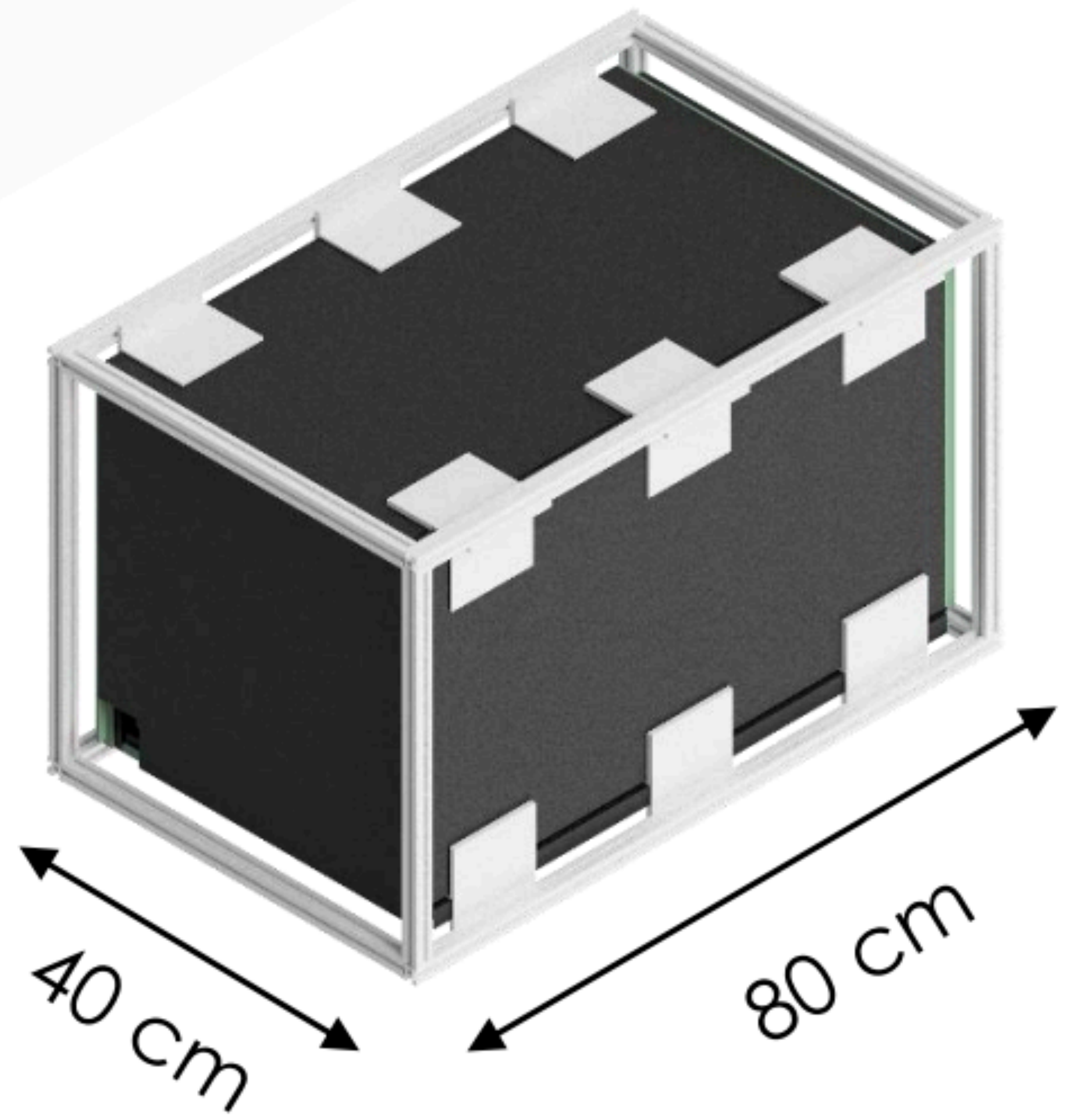


Prototype Detector





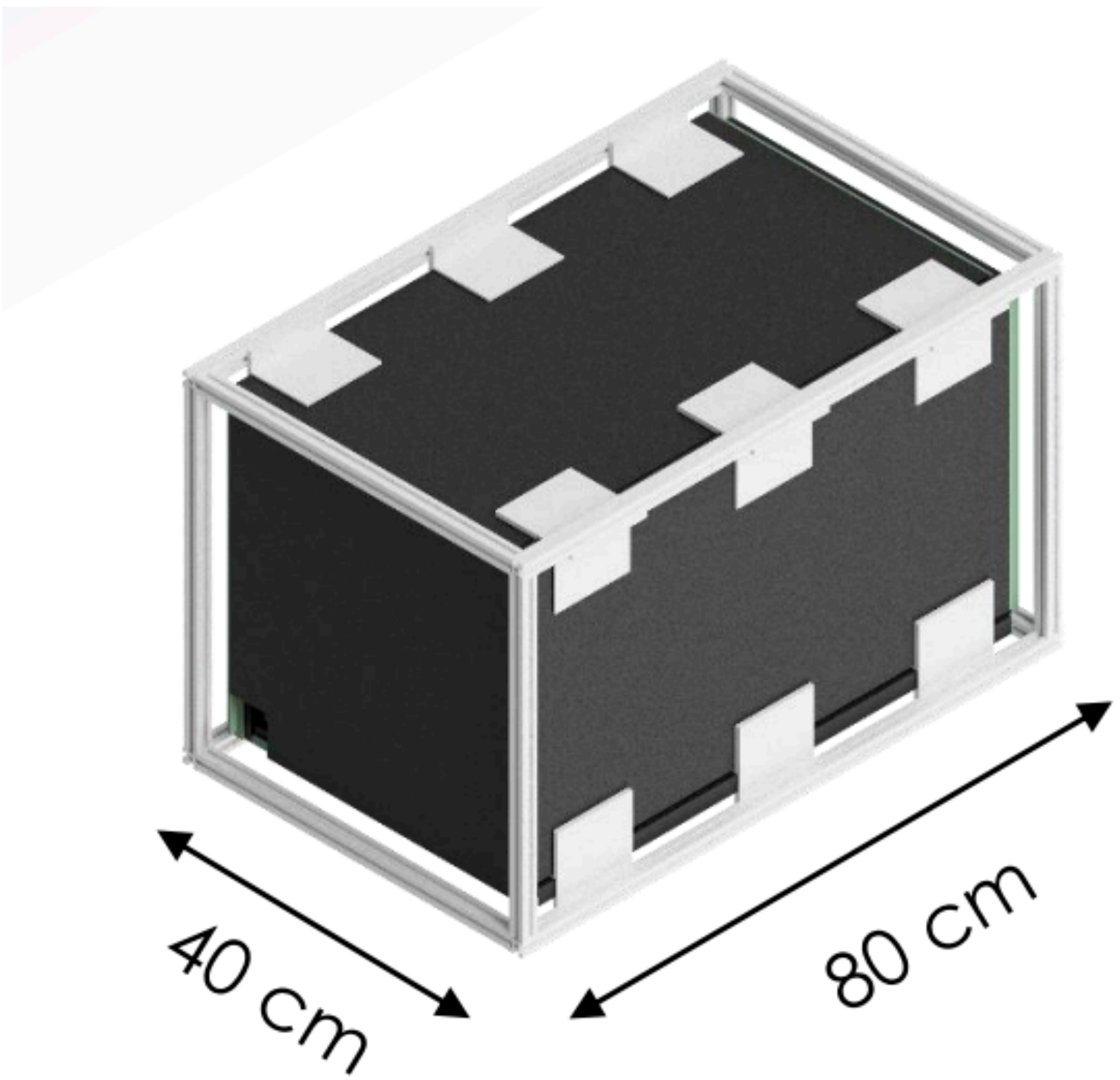
Mirco Christmann

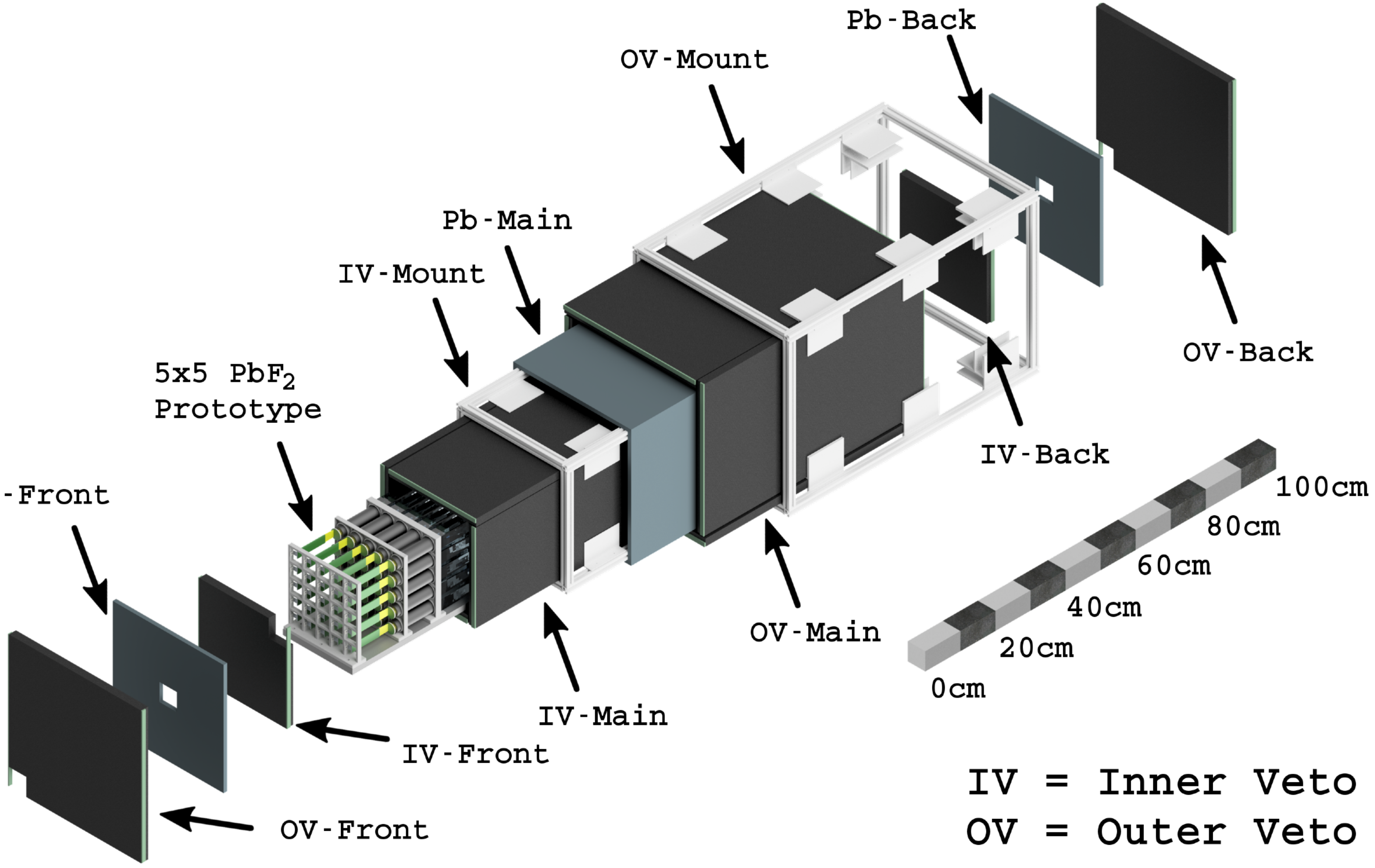
Matteo Lauss

Christian Stoss

Michail Kontogoulas

Prototype Detector





Mirco Christmann

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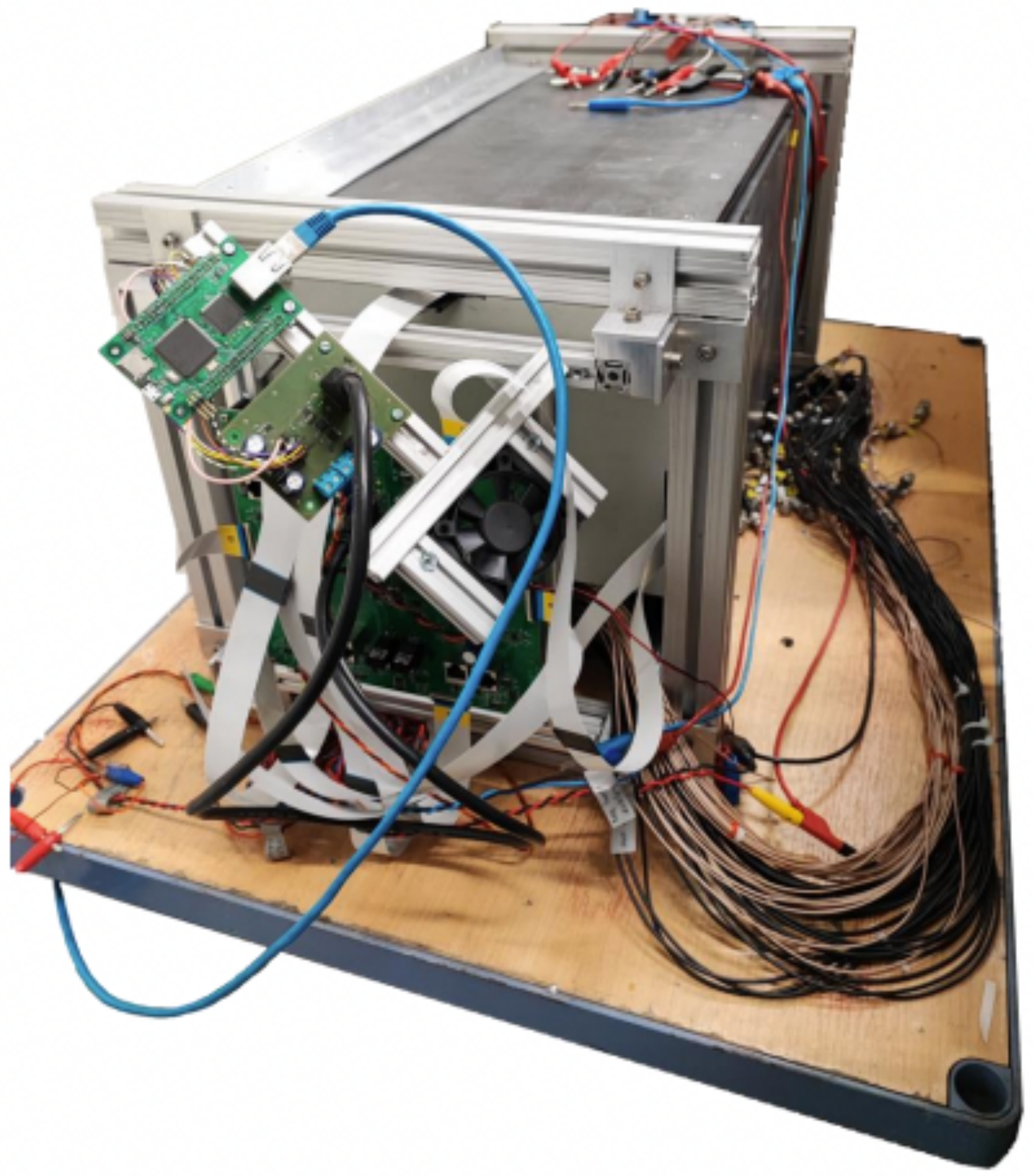
First Tests

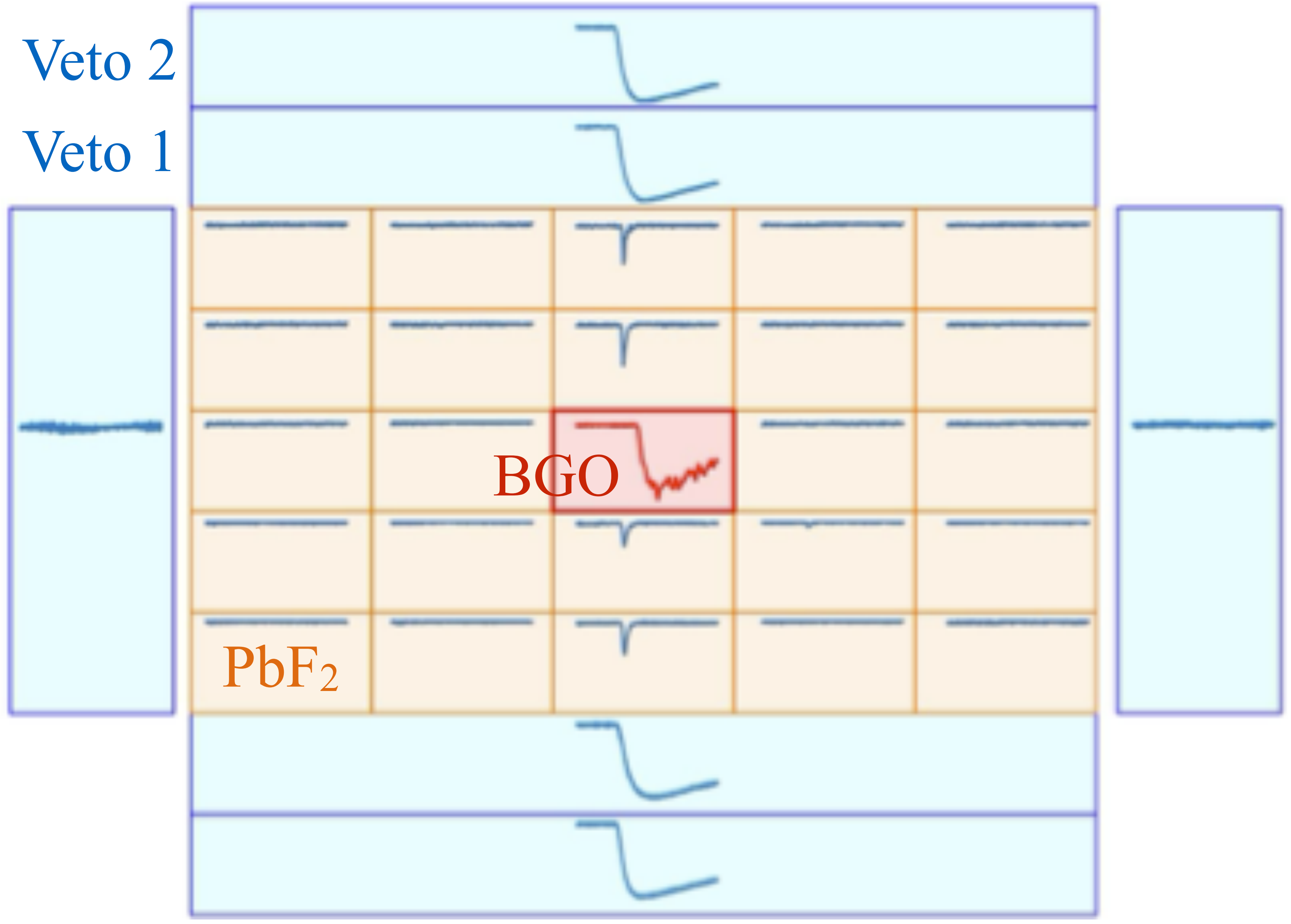


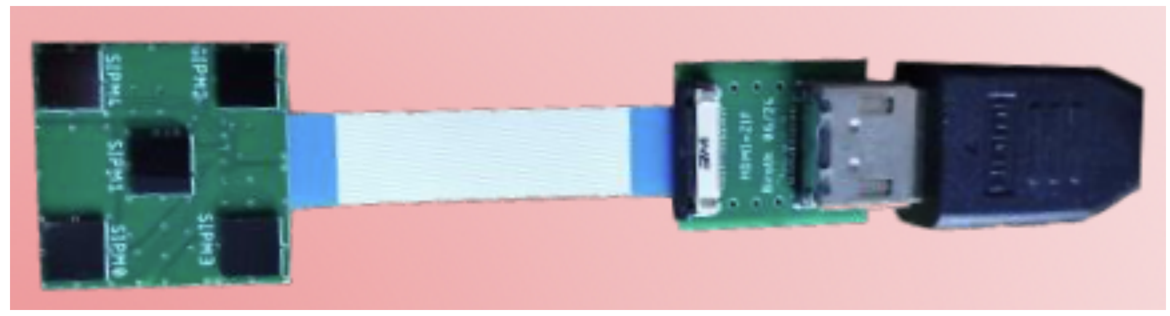
Electronics/DAQ

CAEN V1742 (5GHz, 32ch, sigle ended)
- Fast, more expensive

PANDA sADC (80 MHz, 64ch, diff.)
- Slower, cheaper, shaping required.

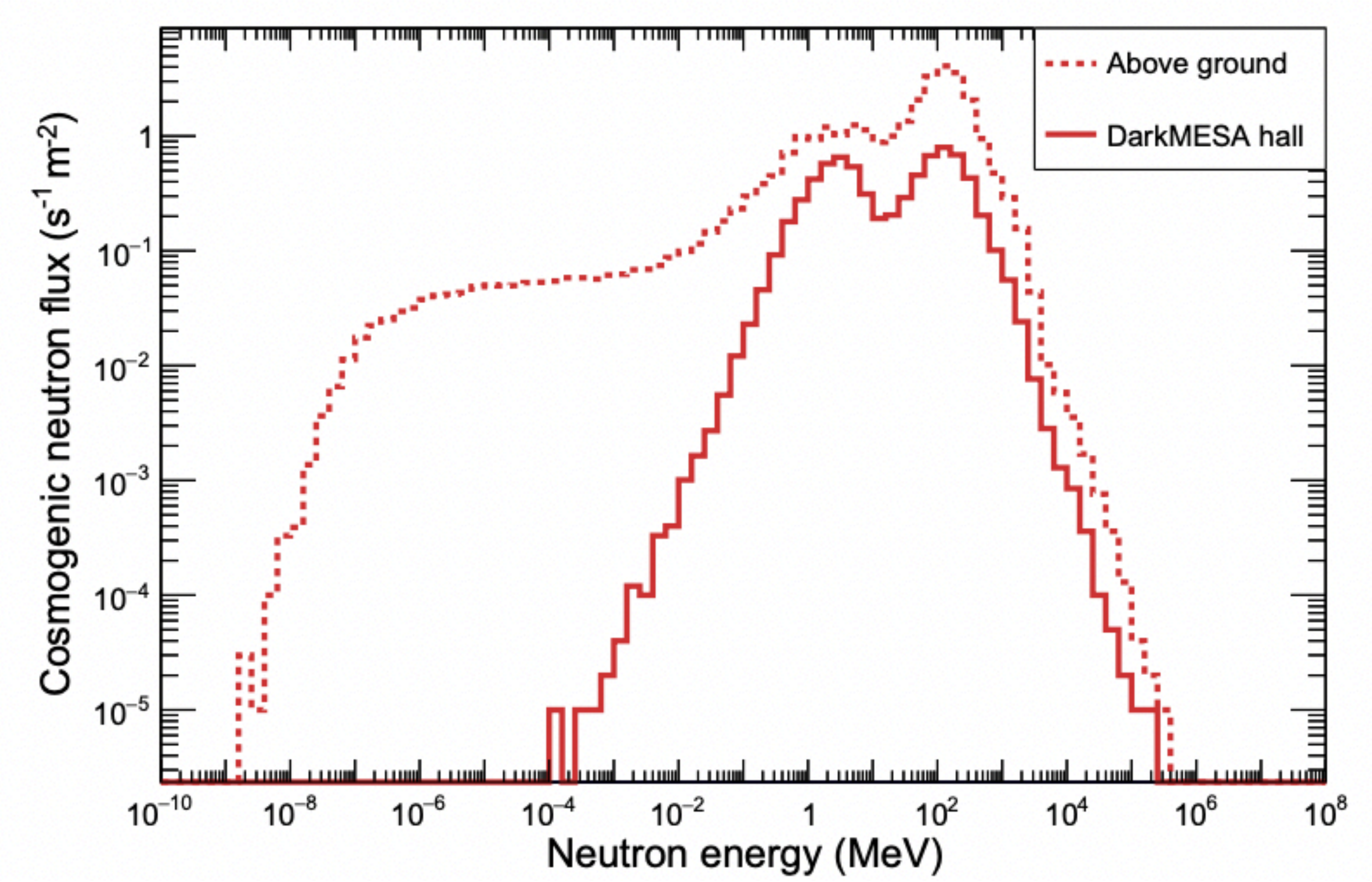
Operation with cosmics started:
Central BGO crystal for test.
Surrounding crystals: PbF_2.

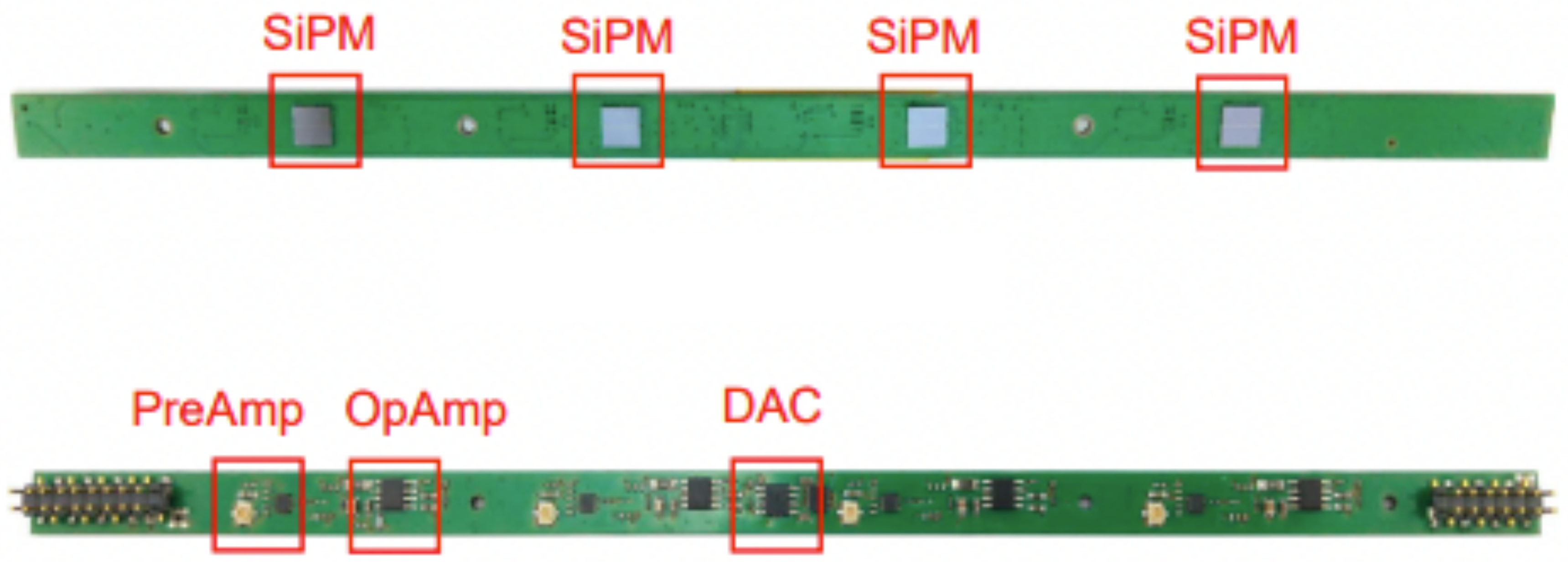


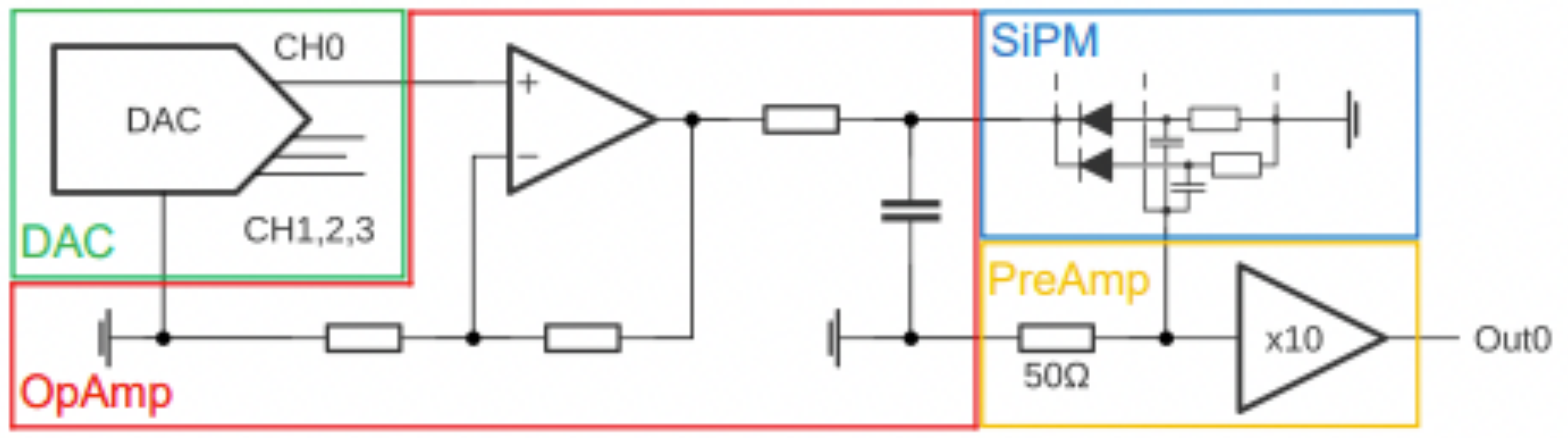


SiPM readout

Background Studies







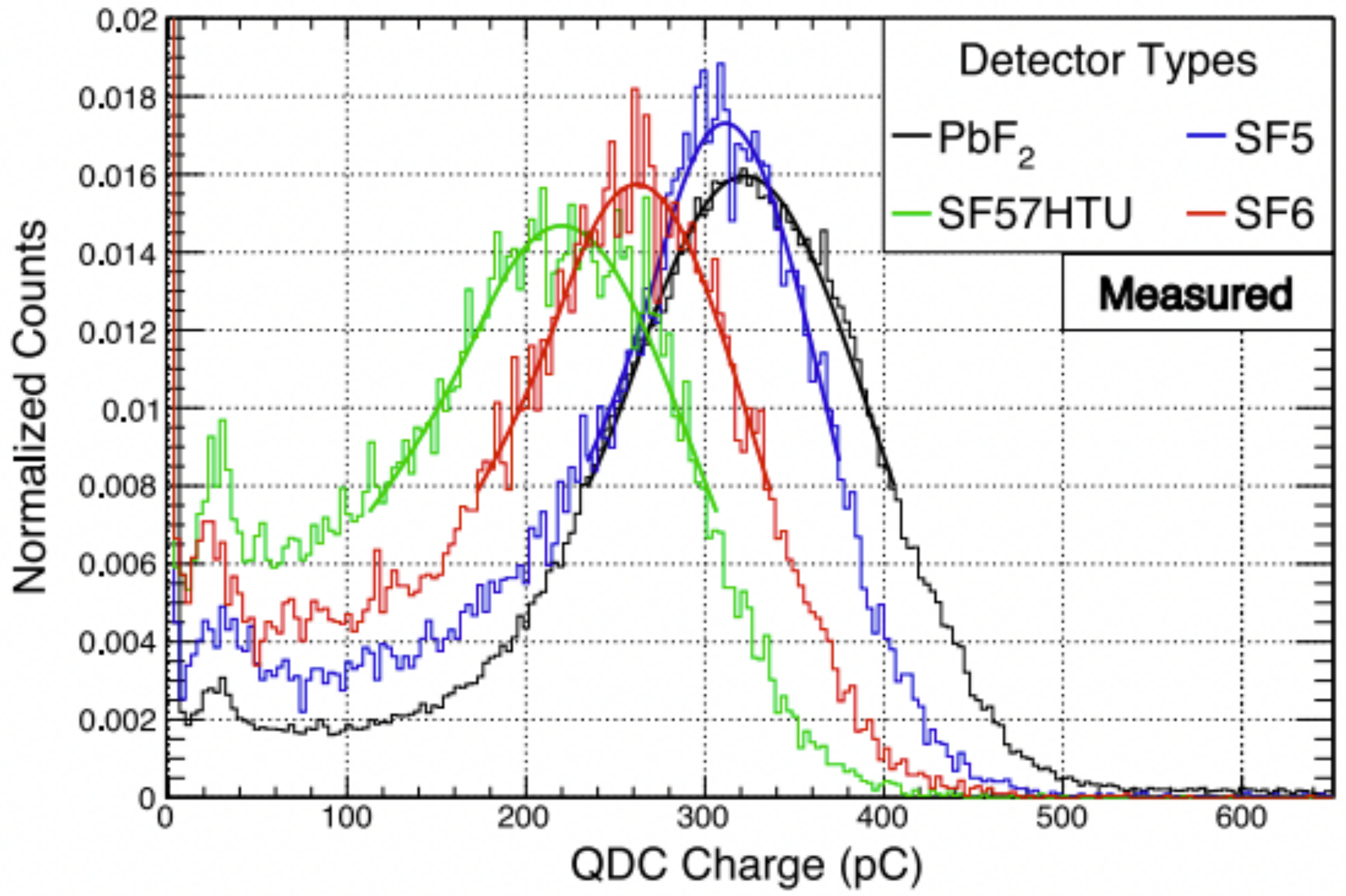
Cosmic Rays Simulation

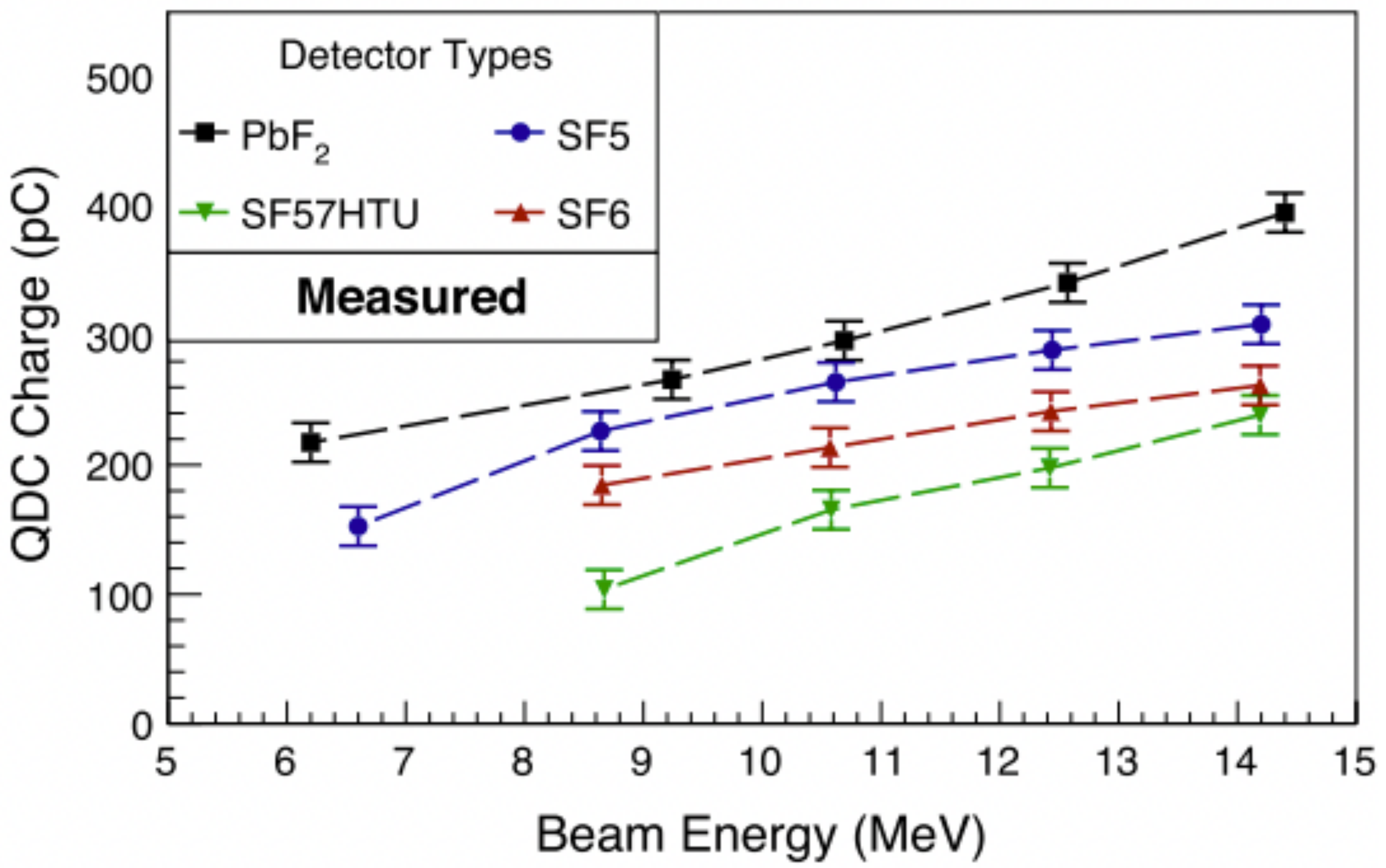
- CRY Library (LANL)
- Overburden
- Neutrons

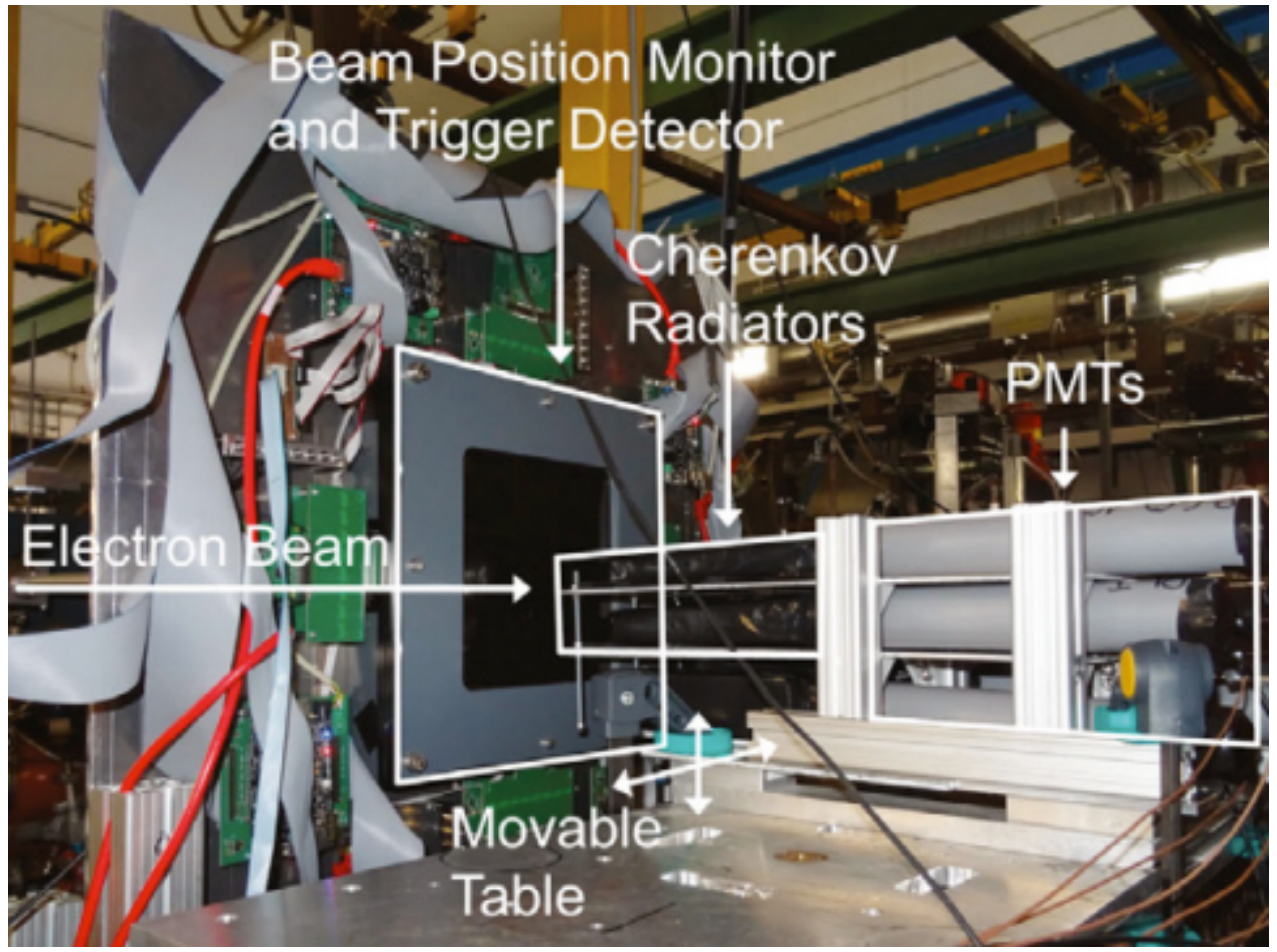
Cosmic Rays Veto Detector

- Plastic Scintillators
- SiPM readout
- Custom electronics

Beam Tests (Cherenkov Radiators)

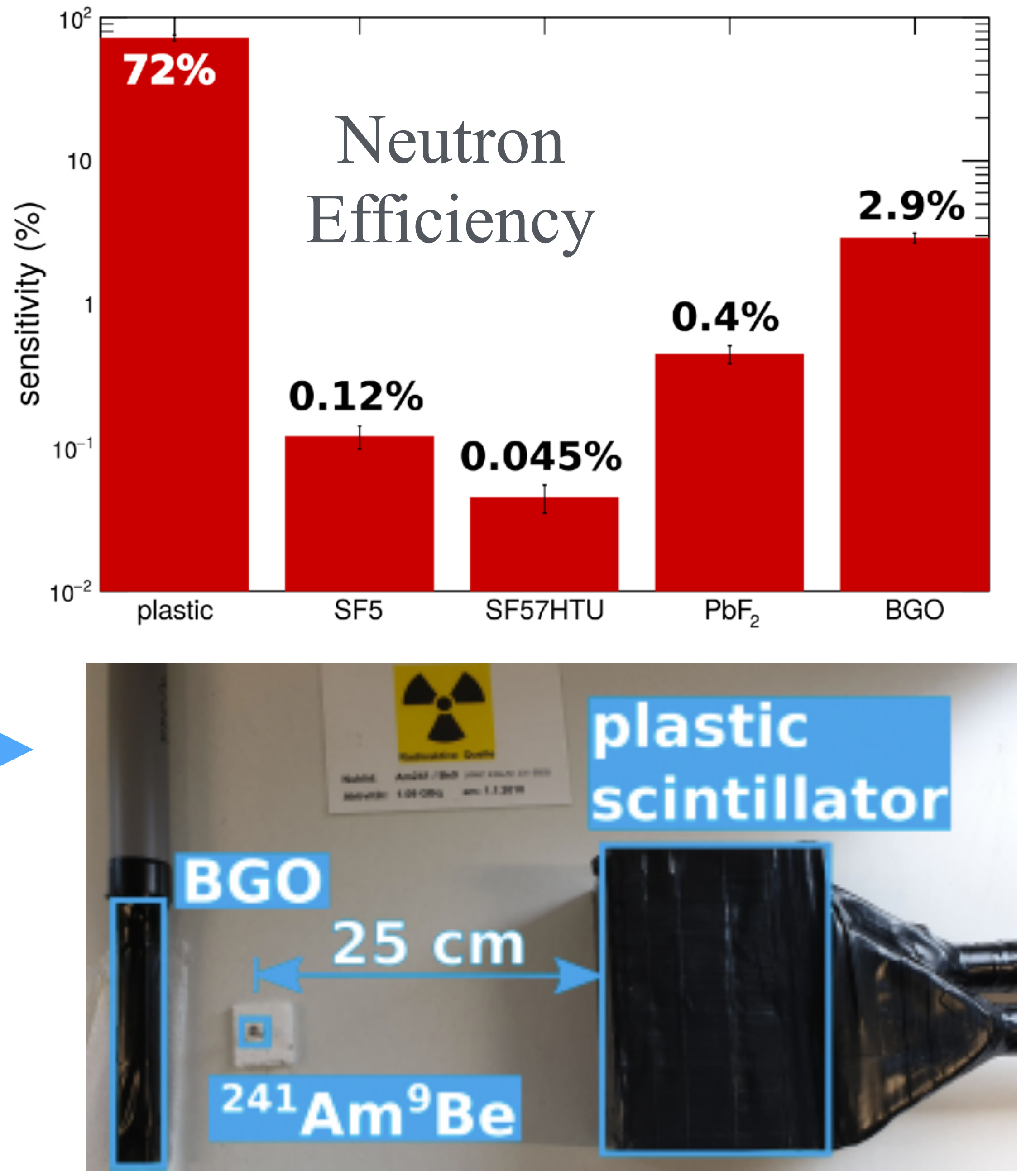






MAMI Beam (6-14 MeV)

- Produced PEs
- Lower Threshold
- Neutron efficiency (source)

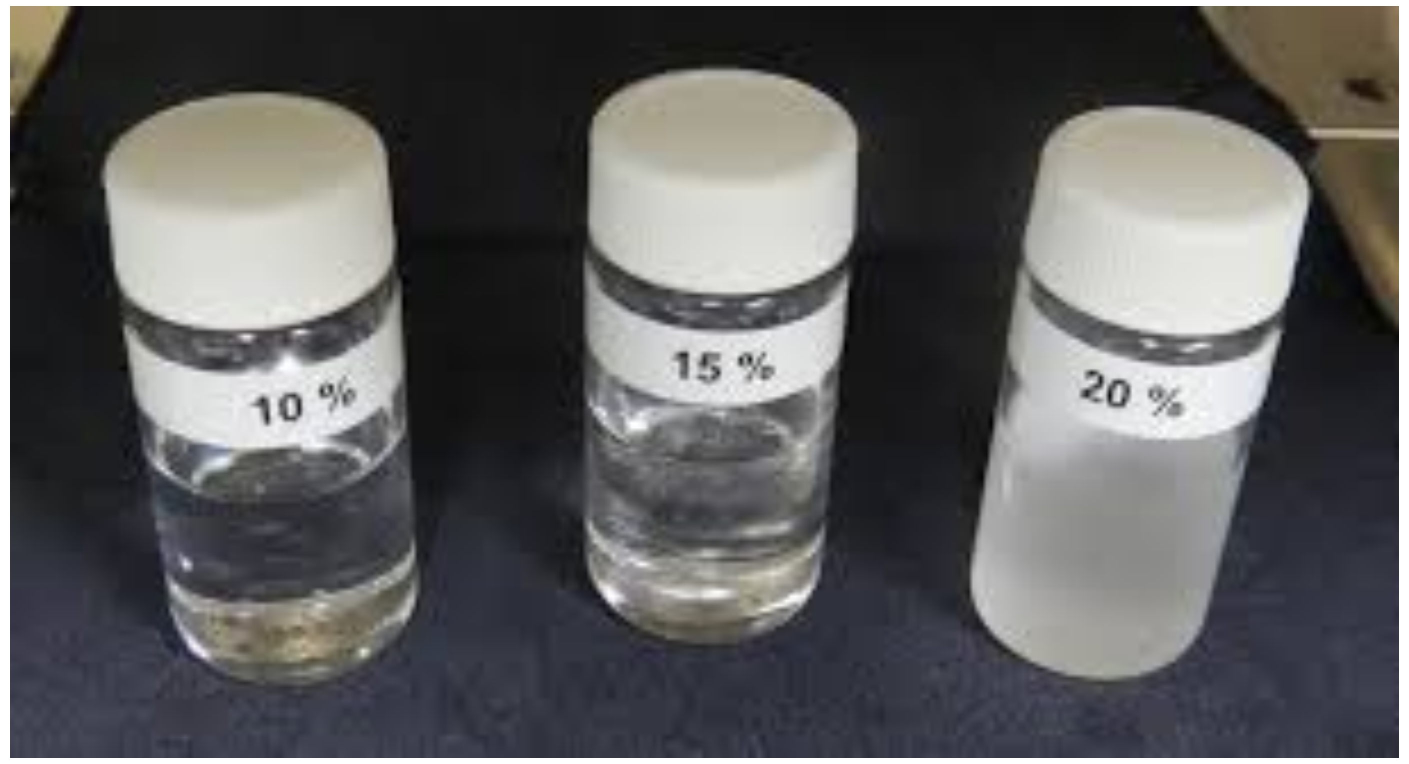


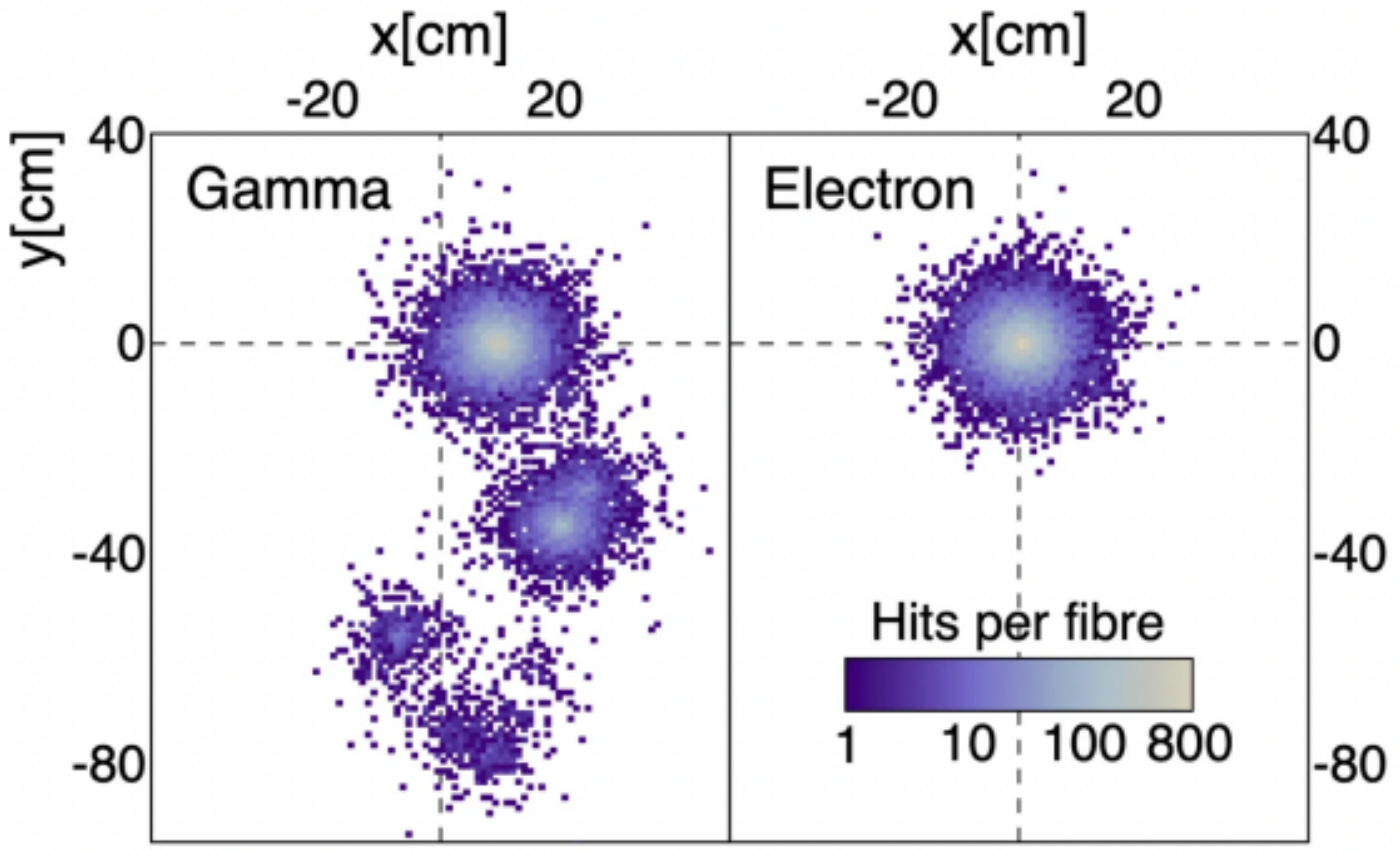
In preparation:

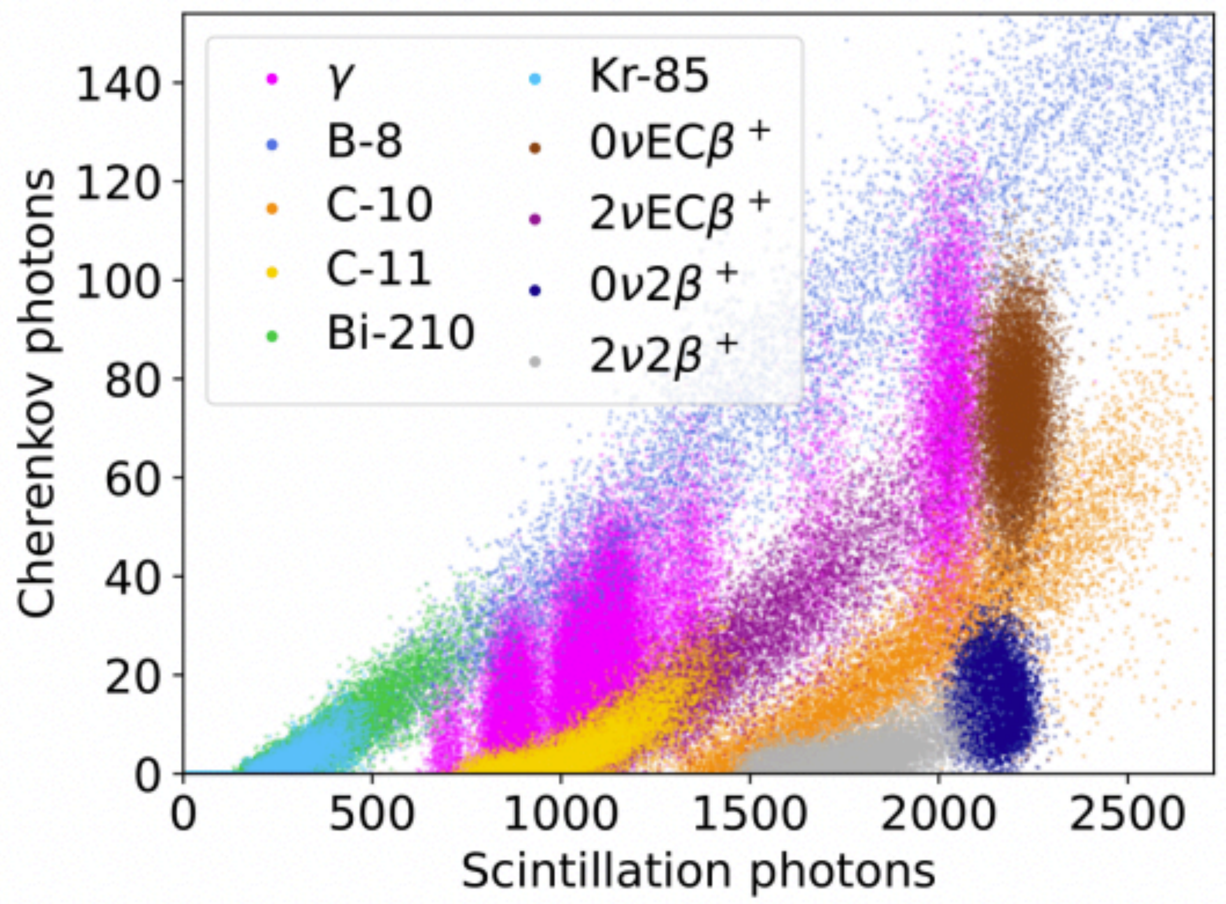
- Test at LNGS
- Radioactive Assay

Opaque Liquid Scintillators

(Opaque) Liquid Scintillators



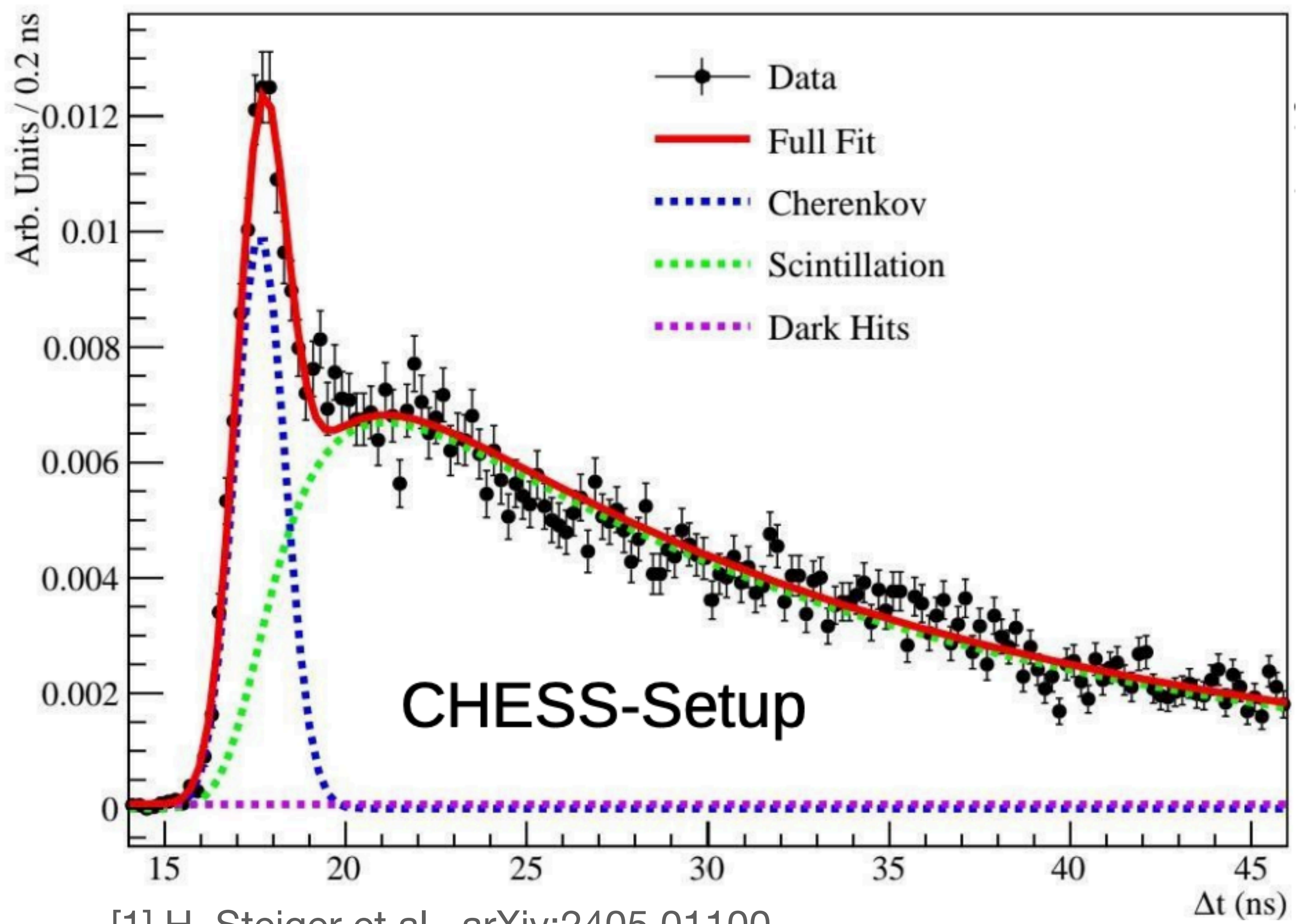




<u>Opaque Scintillators</u>
Load LS with wax (e.g. 80%-20%)
Opaqueness: scattering w/o absorption
PID: topology of vertices
Readout: optical fibres.

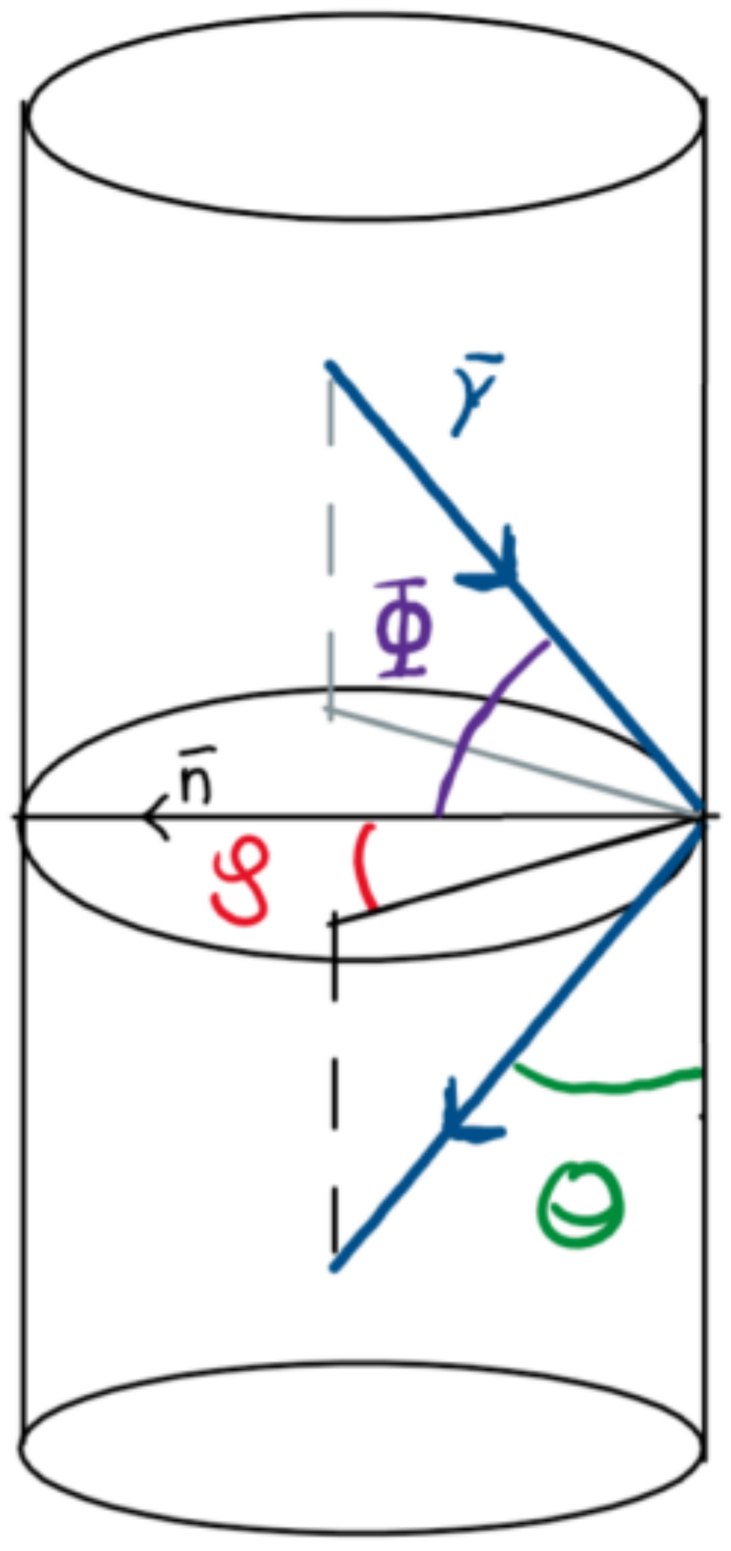
Stefan Schoppann et al. (JGU)
arXiv:2407.05999

<u>Water-Based Scintillators</u>
1%-10% scintillator
Long time component > 10ns
PID: Cherenkov/Scint ratio



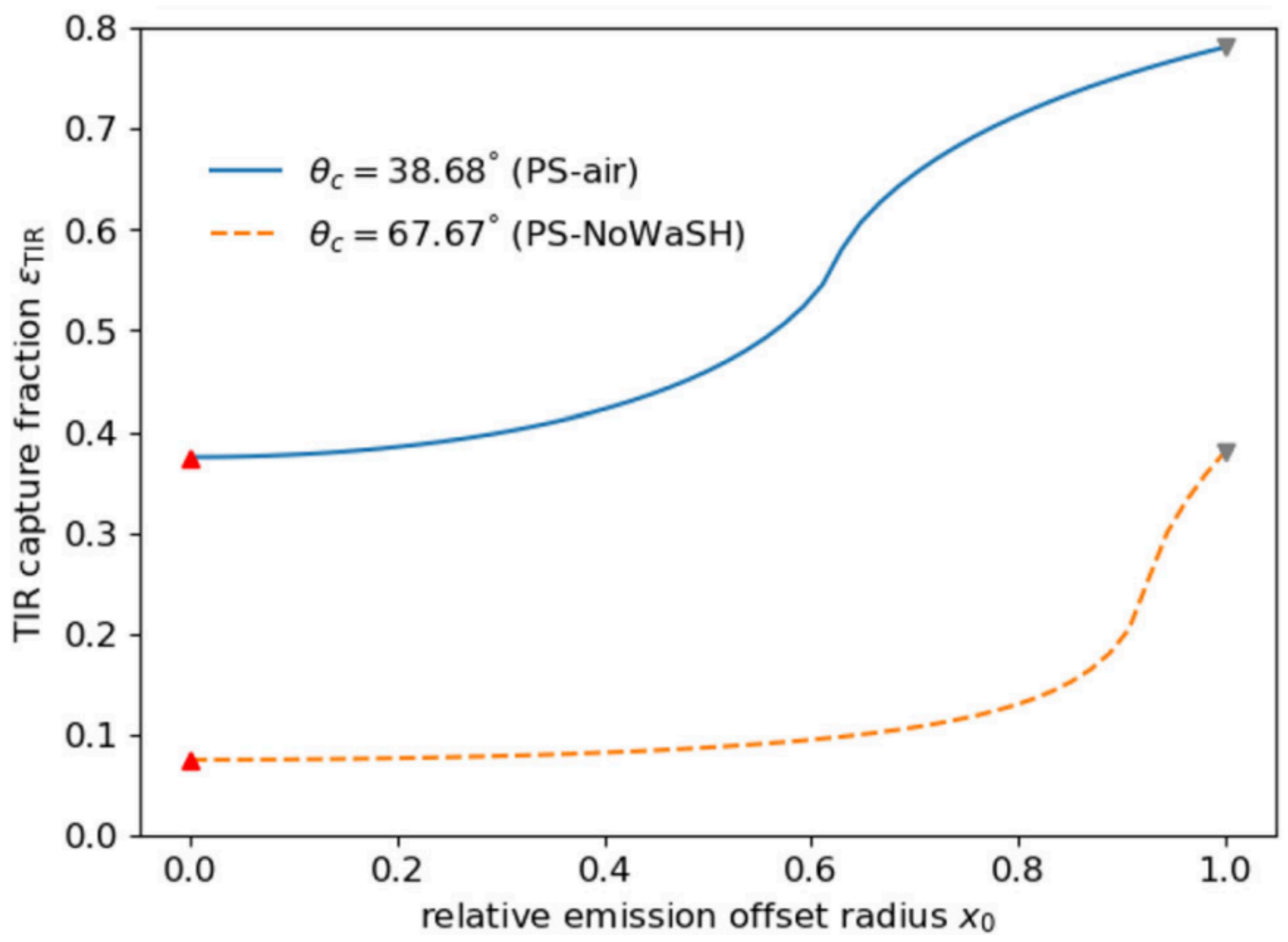
[1] H. Steiger et al., arXiv:2405.01100

Optimised Wavelength-Shifting Fibres (OWLs)



B. Kessler M.Sci Thesis

- In commercial fibers, the wavelength shifter is distributed isotropically in the fibres core.
- By a purely geometrical argument, total internal reflection $\sin\alpha\sqrt{1-\rho\sin^2\phi} < \sin\beta$
- is enhanced concentrating the wavelength shifter at high radii ρ K.F.Johnson, NIM-A, 334 (2), 432 (1994)
- With this arrangement, light capture can be **increased by a factor 3-4**.

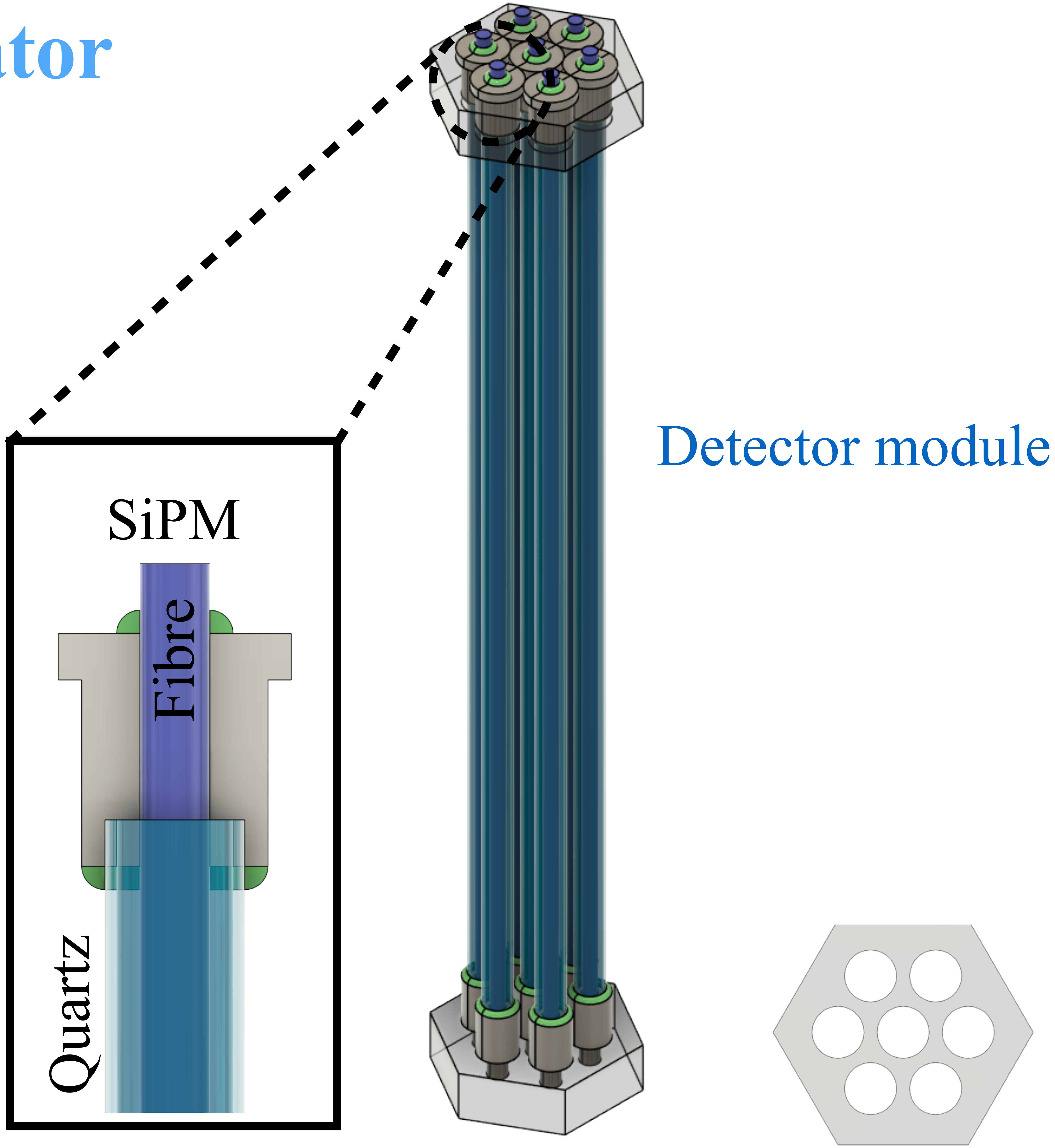


M. Böhles et al, Eur.Phys.J C 83 (2) (2025)

- Relevant for large experiments (long fibers)
- Largest loss at the fiber/scintillator interface
- OWLs can compensate for this.

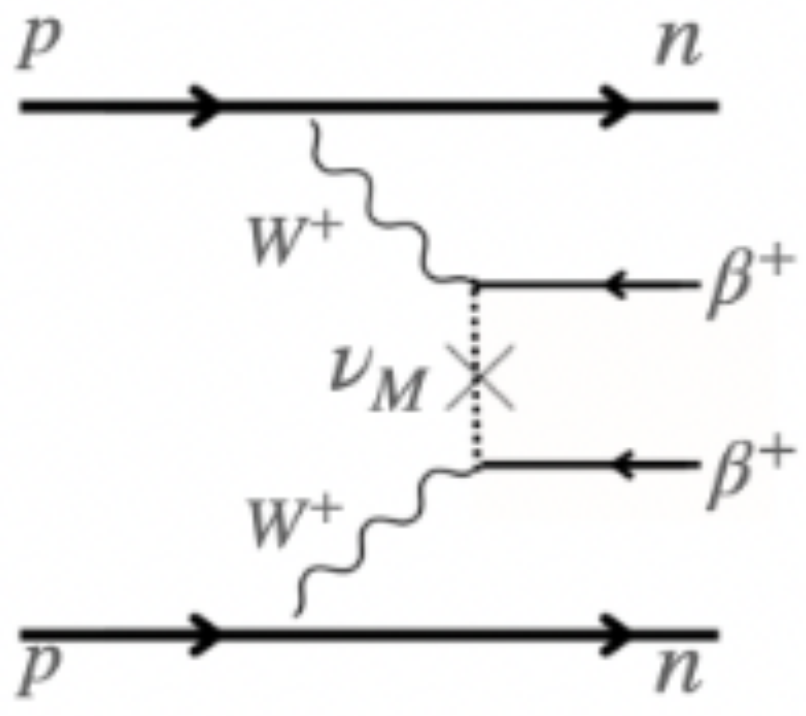
OWLs and the Liquid Scintillator

- The WLS paint can dissolve in the LS
- Fibres protected by a hollow quartz rod
- Mechanical stability
- Enhanced average light transport



Detector Concept

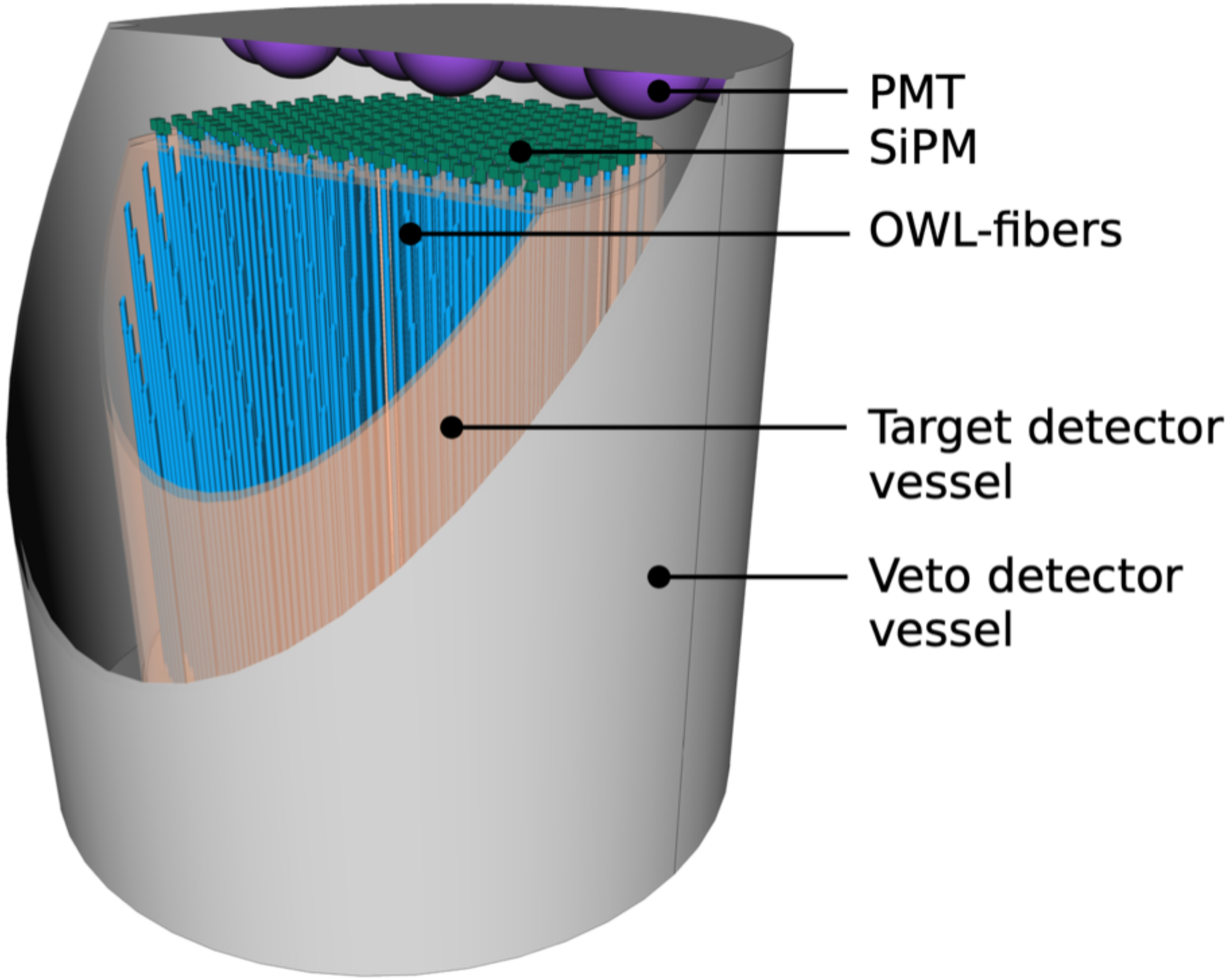
<u>Prototype of a $0\nu\beta\beta$ experiment (NuDoubt^{++})</u>
Test isotopes: ^{78}Ke, ^{124}Xe, ^{106}Cd
Aim: observe $0\nu\beta\beta+$ in p-rich isotopes:



No only a detector test: <u>DarkMESA</u> .

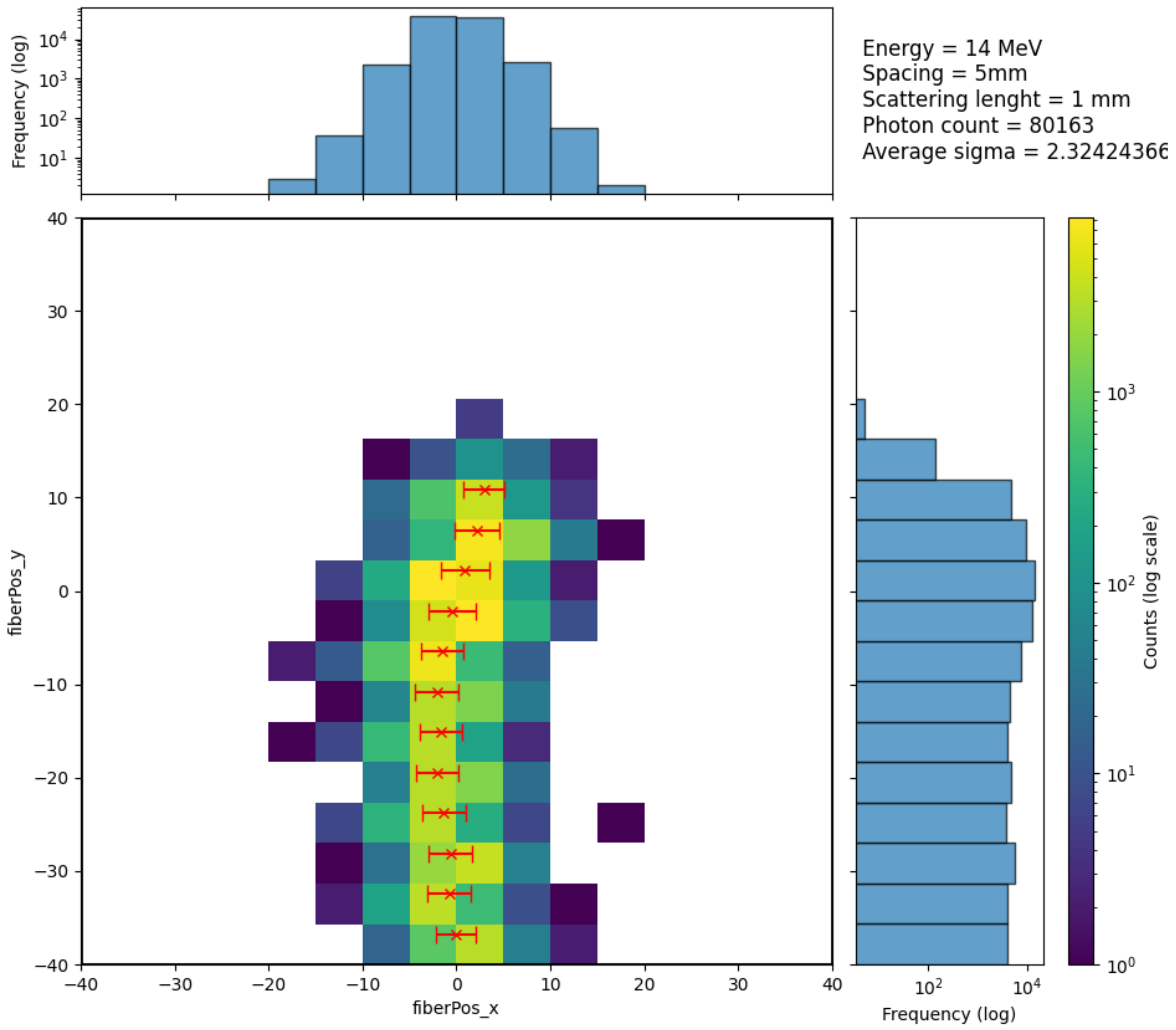
<u>Technology</u>:
Liquid Scintillator (Opaque/W-based)
Optimised WLS Fibres (OWL)
Readout: SiPMs

Concept for NuDoubt^{++}/DarkMESA



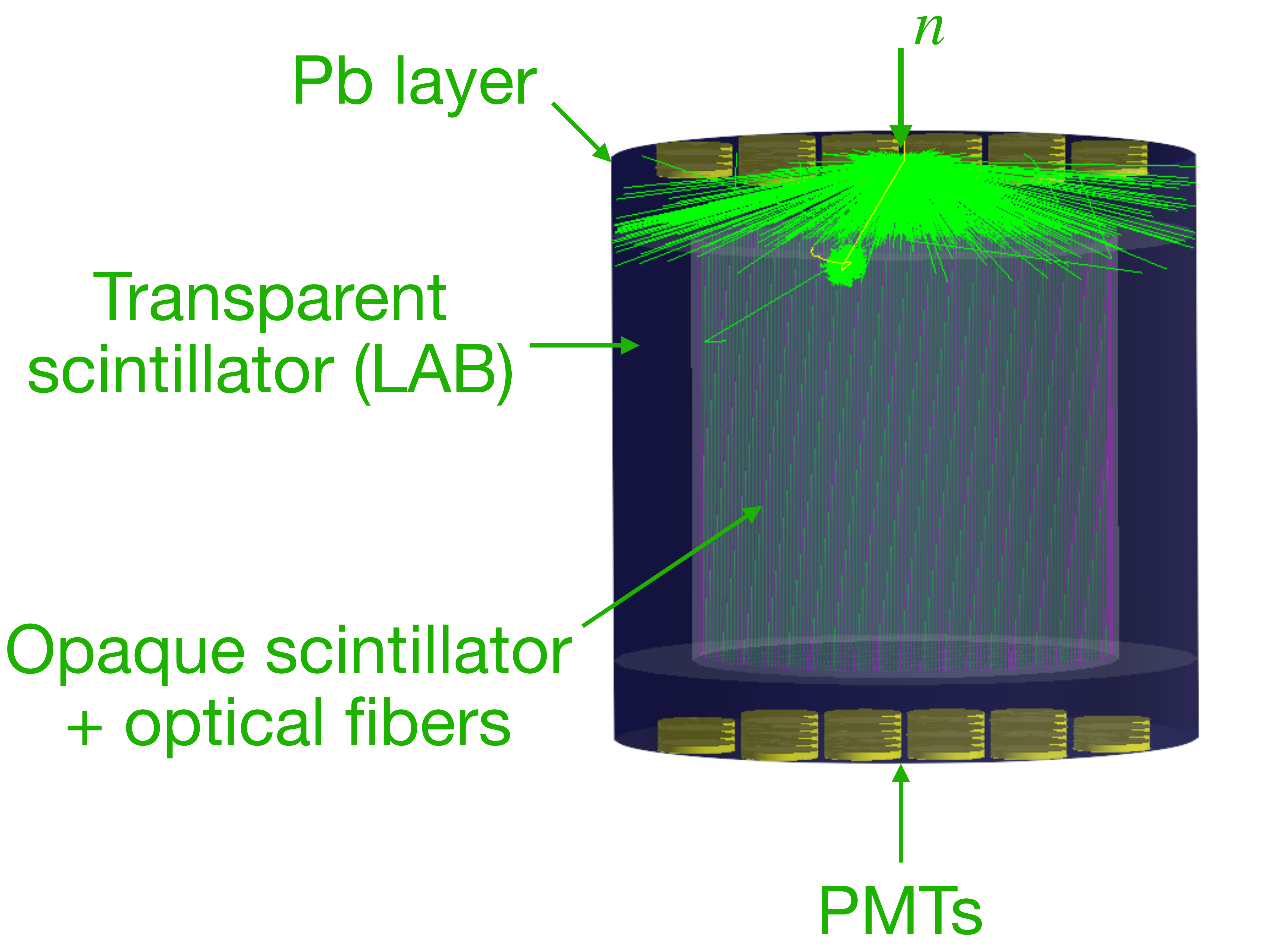
Detector Concept

Simulation towards a ~10cm^3 prototype.
To be tested at MAMI accelerator (JGU).
Key point: threshold, tracking, PID.



Jonas Pätschke

Simulation of neutron background



Michail Kontogoulas

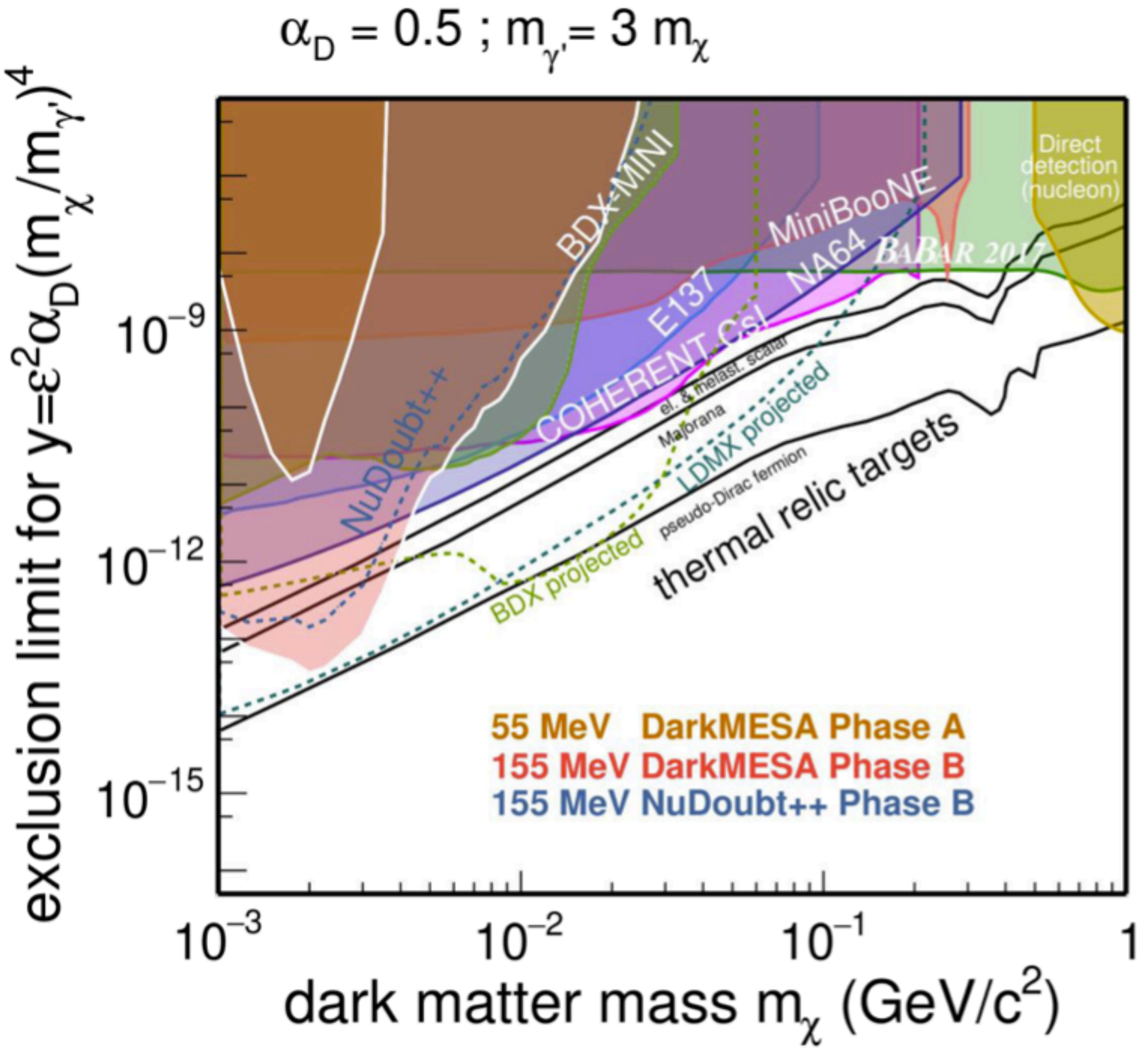
Projected Limits

* Moving from G4+MadGraph to full G4 simulation (A. Celentano, INFN Genova).

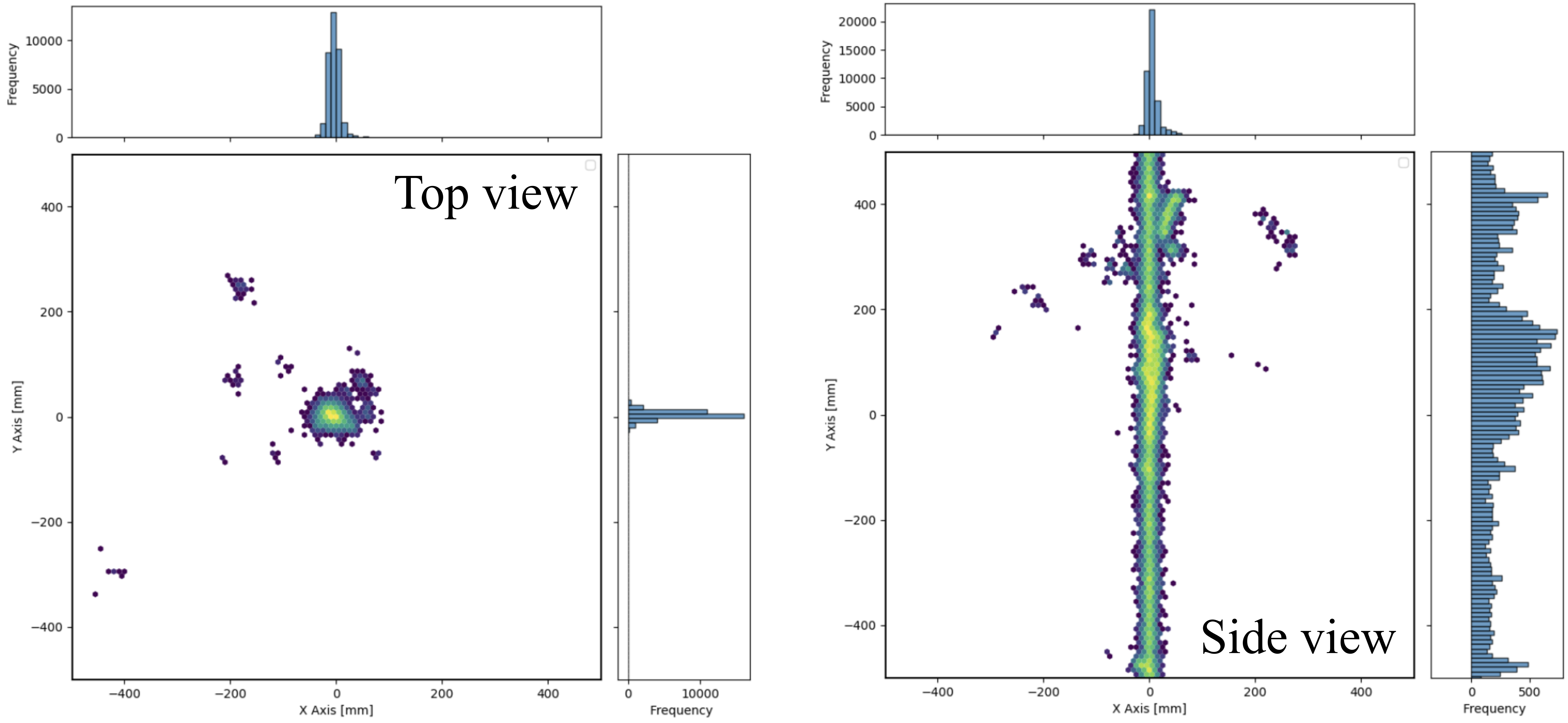
* Add background contributions.

* Simulate other physics models:
- Z'
- axions
- …

Saskia Plura

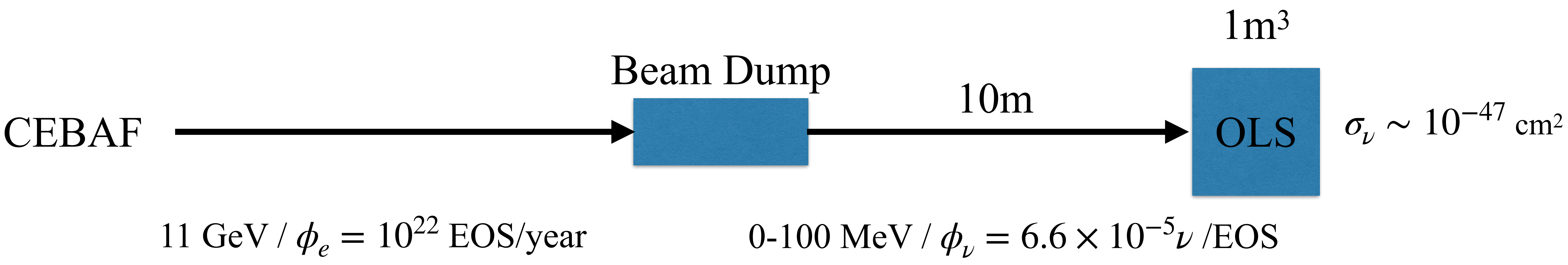


Muon Signal



2 GeV muon through a 1m³ detector filled with OLS and 10mm-pitch fibers

Neutrino Signal (?)



Expected yield:

$N_H \lesssim 1$/year

$N_C \sim 2$/year → Larger Detector

With 22 GeV beam:

~ O(10) improvement for 400-500 MeV neutrinos

Summary

- MESA under construction: first 55 MeV beam in 2025.
- Beam Dump experiments: a lot of EOTs, sensitivity, direct measurement.
- DarkMESA: sensitivity to DM < 10MeV . BDX complementarity.
- Investigation of different technological options underway.
- Potential for applications to DM/muon/neutrino/neutron physics.

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* Thank you!