The DARK MESA Experiment

MENU 2023

Future Facilities and Directions

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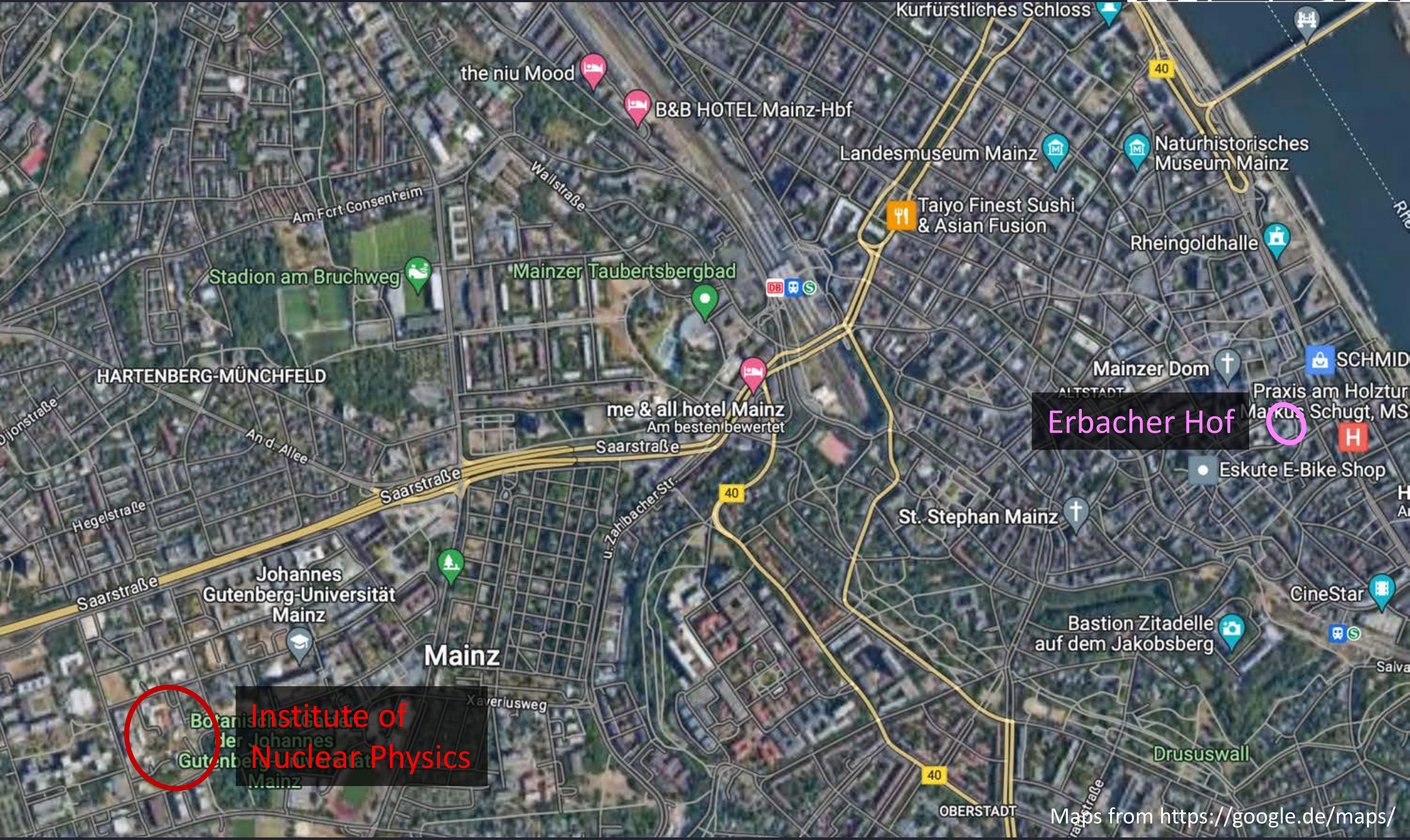
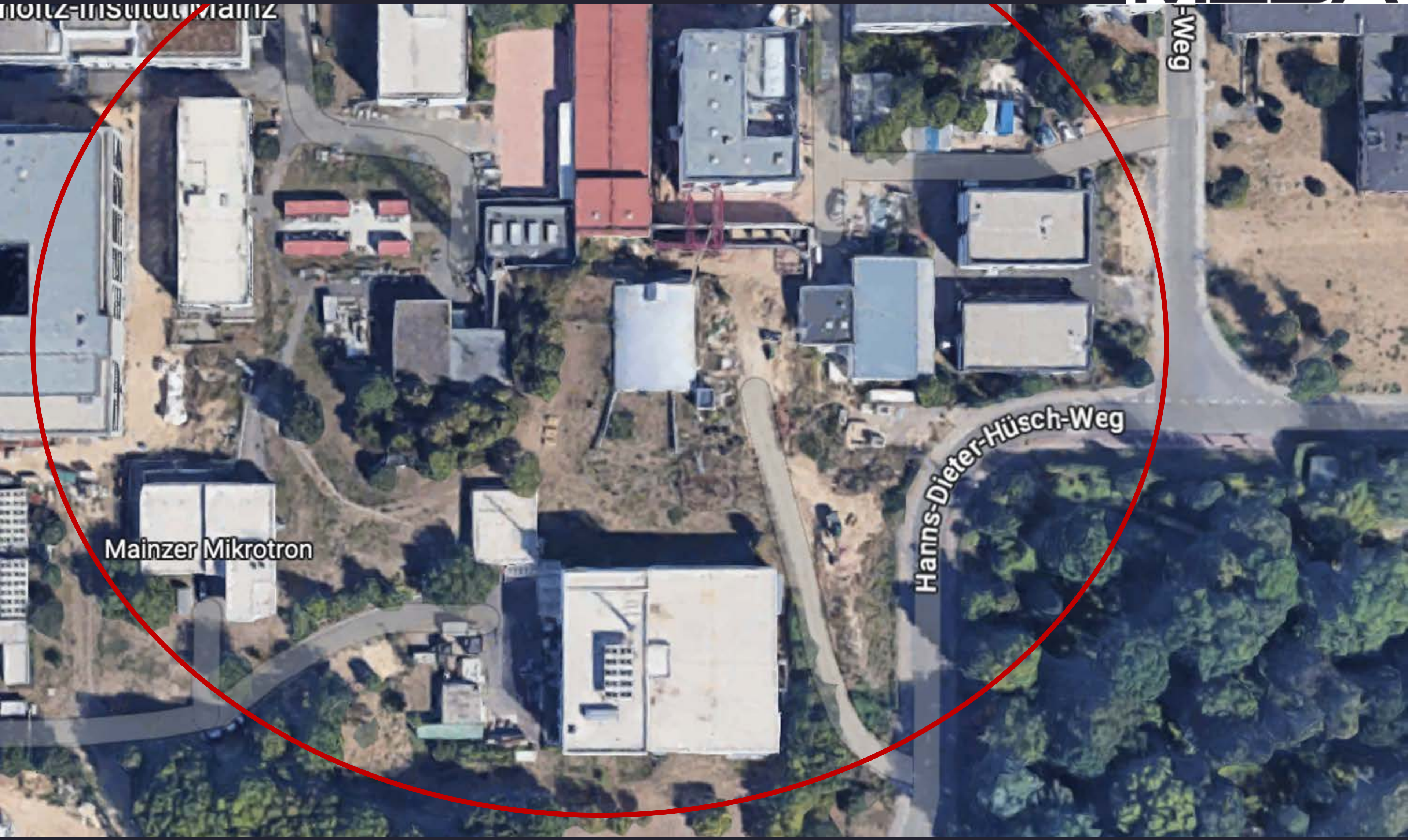
M. Biroth for the MAGIX collaboration, Mainz - mbiroth@uni-mainz.de

Map of Mainz

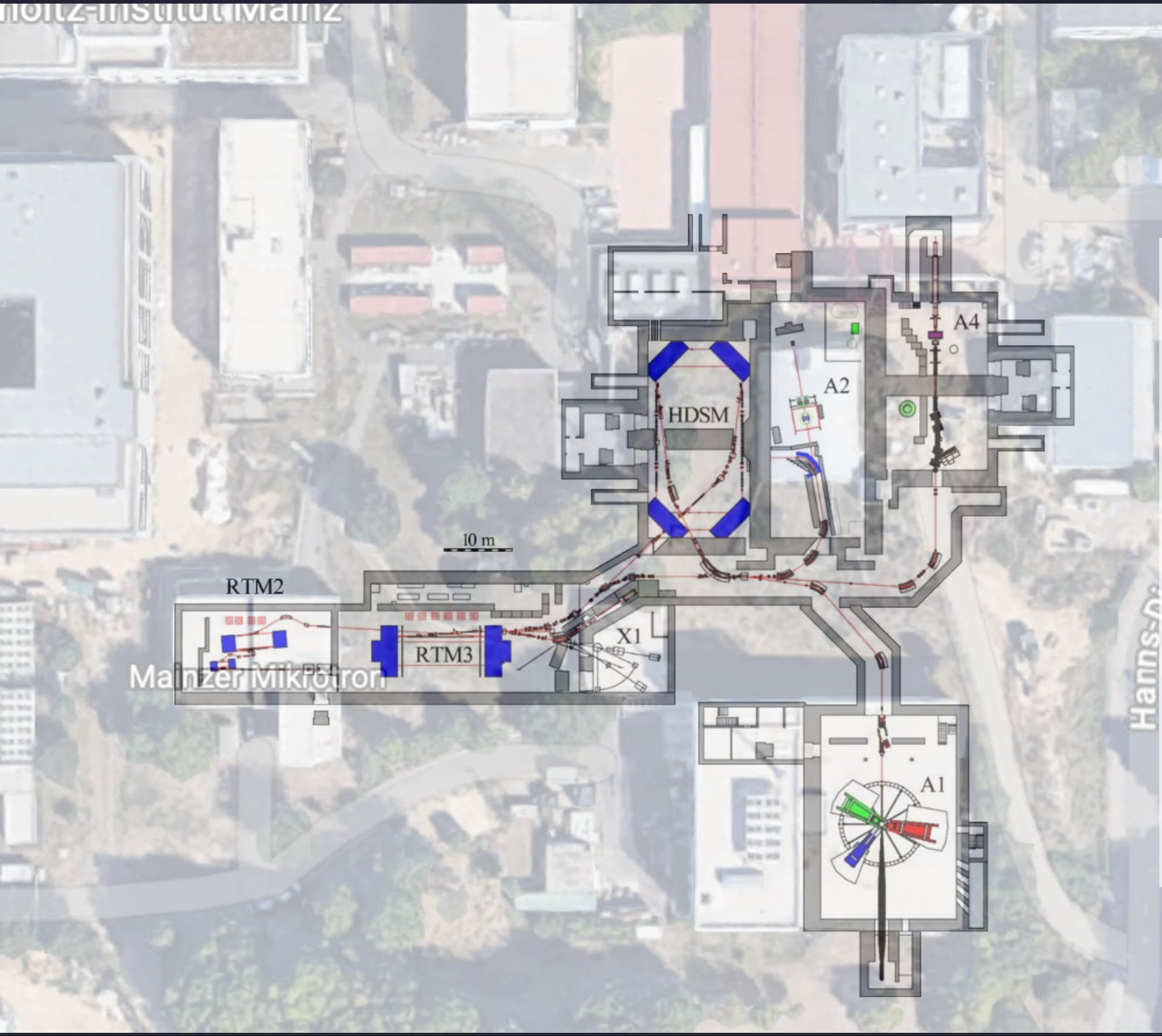

Kurfürstliches Schloss
the niu Mood
B&B HOTEL Mainz-Hbf
Landesmuseum Mainz
Naturhistorisches Museum Mainz
Taiyo Finest Sushi & Asian Fusion
Rheingoldhalle
Wallstraße
Am Fort Consenheim
Stadion am Bruchweg
Mainzer Taubertsbergbad
HARTENBERG-MÜNCHFELD
Mainzer Dom
ALTSTADT
Praxis am Holztur
me & all hotel Mainz
Am besten bewertet
Saarstraße
Erbacher Hof
Eskute E-Bike Shop
An d. Allee
Dijonstraße
Hegelstraße
St. Stephan Mainz
Johannes Gutenberg-Universität Mainz
CineStar
Bastion Zitadelle auf dem Jakobsberg
Mainz
Institute of Nuclear Physics
Xaveriusweg
Drususwall
40
OBERSTADT
Maps from https://google.de/maps/

Institute of Nuclear Physics

DARK MESA



Electron Accelerator MAMI



Linear electron accelerator Mainz Mikrotron (MAMI):

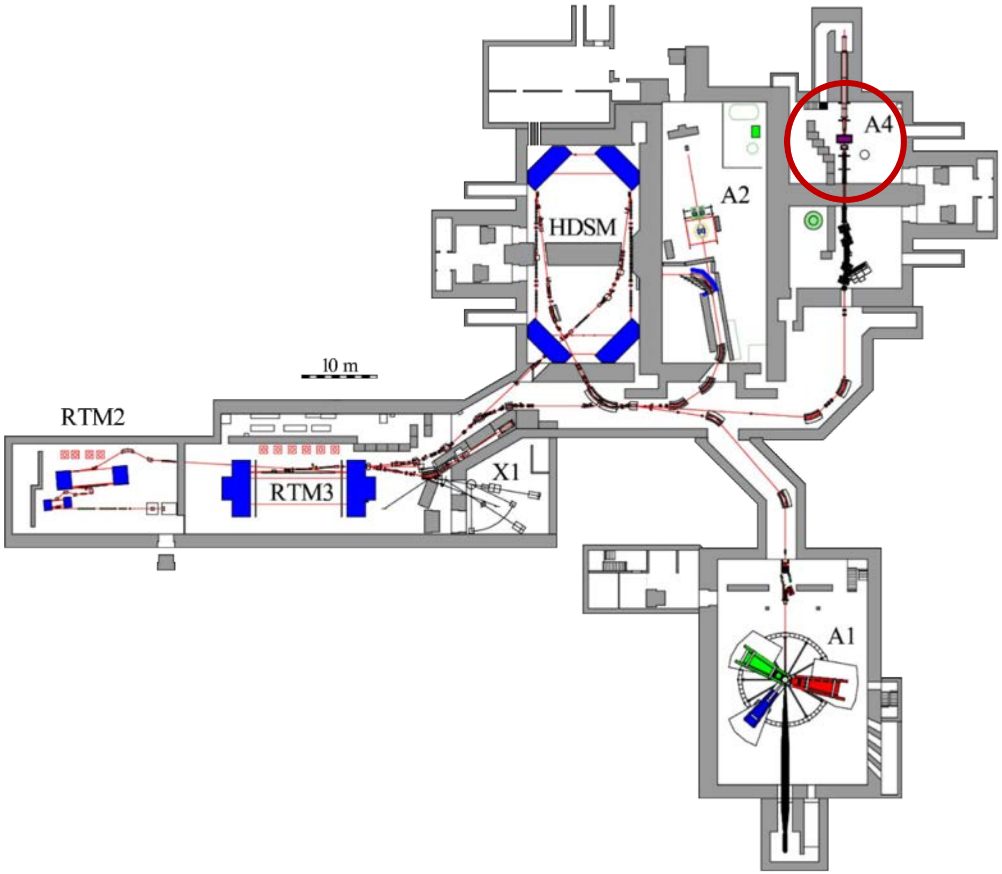
- Energy: $E_e \leq 1.6\ \mathrm{GeV}$
- Current: $I_e \leq 100\ \mu\mathrm{A}$

Ongoing Experiments: A1, A2, X1

Former experiment: A4

Recycling of the A4 Experiment

- Former A4 experiment measured parity violating asymmetries



1000 PbF_2 crystals and PMTs

Recycling of the A4 Experiment

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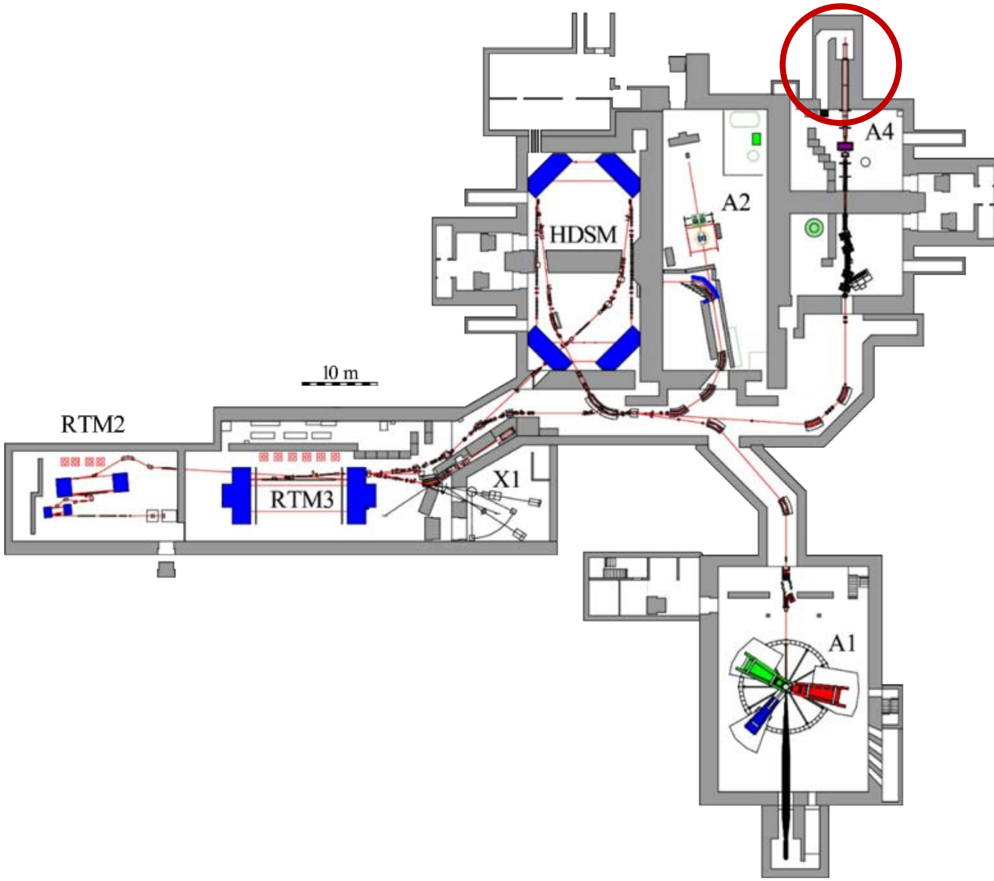
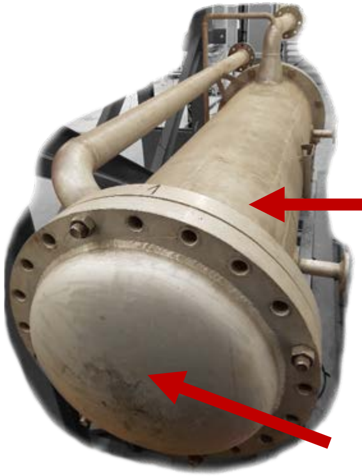


High-power beam dump

- Thickness: $2\ \mathrm{m} \sim 26\ X_0$

Copper end cap: $9.5\ X_0$

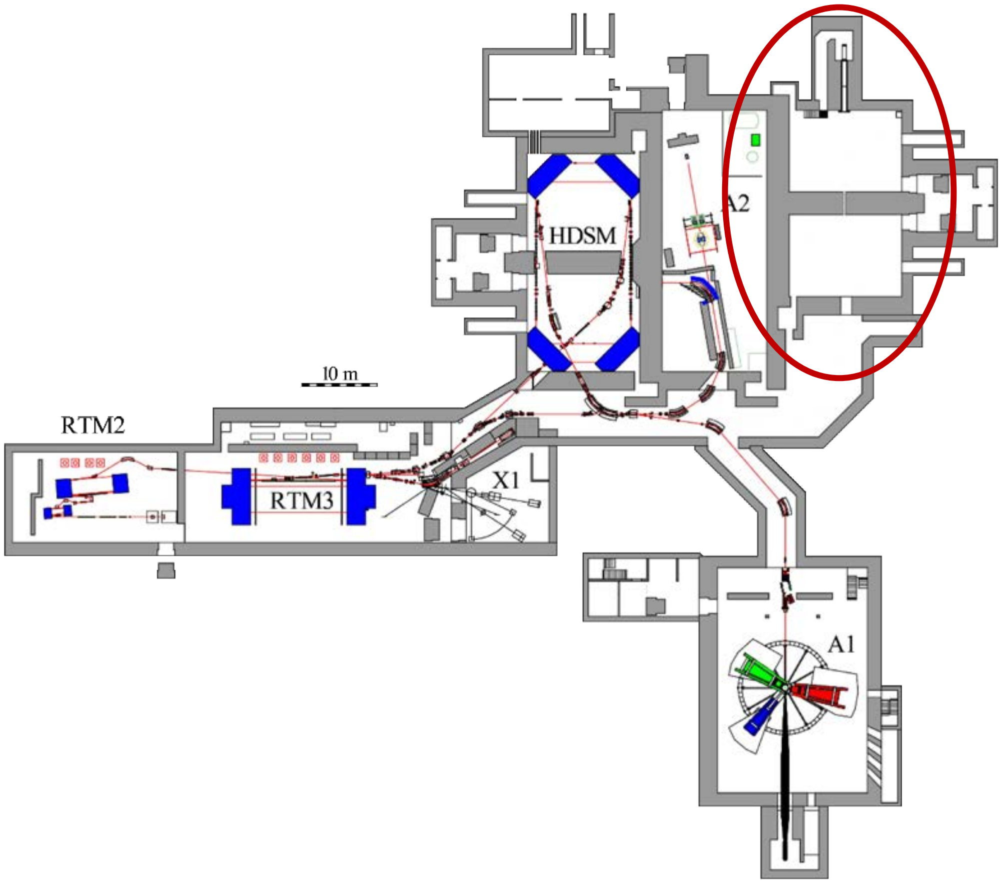


Aluminum absorber: $16.5\ X_0$

Cooling water reservoir: $0.4\ X_0$

Recycling of the A4 Experiment

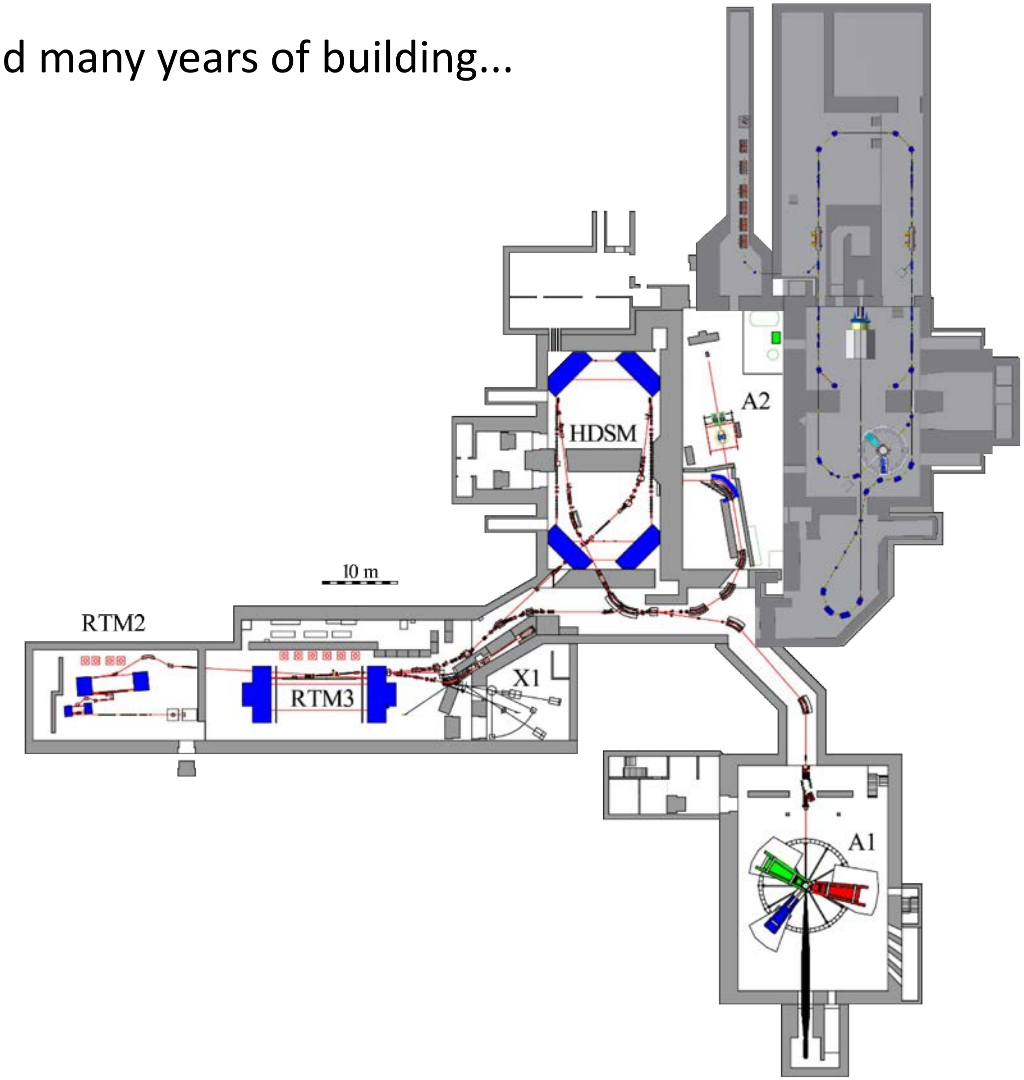
...and after clearing the hall...



Recycling of the A4 Experiment

DARK MESA

...and many years of building...

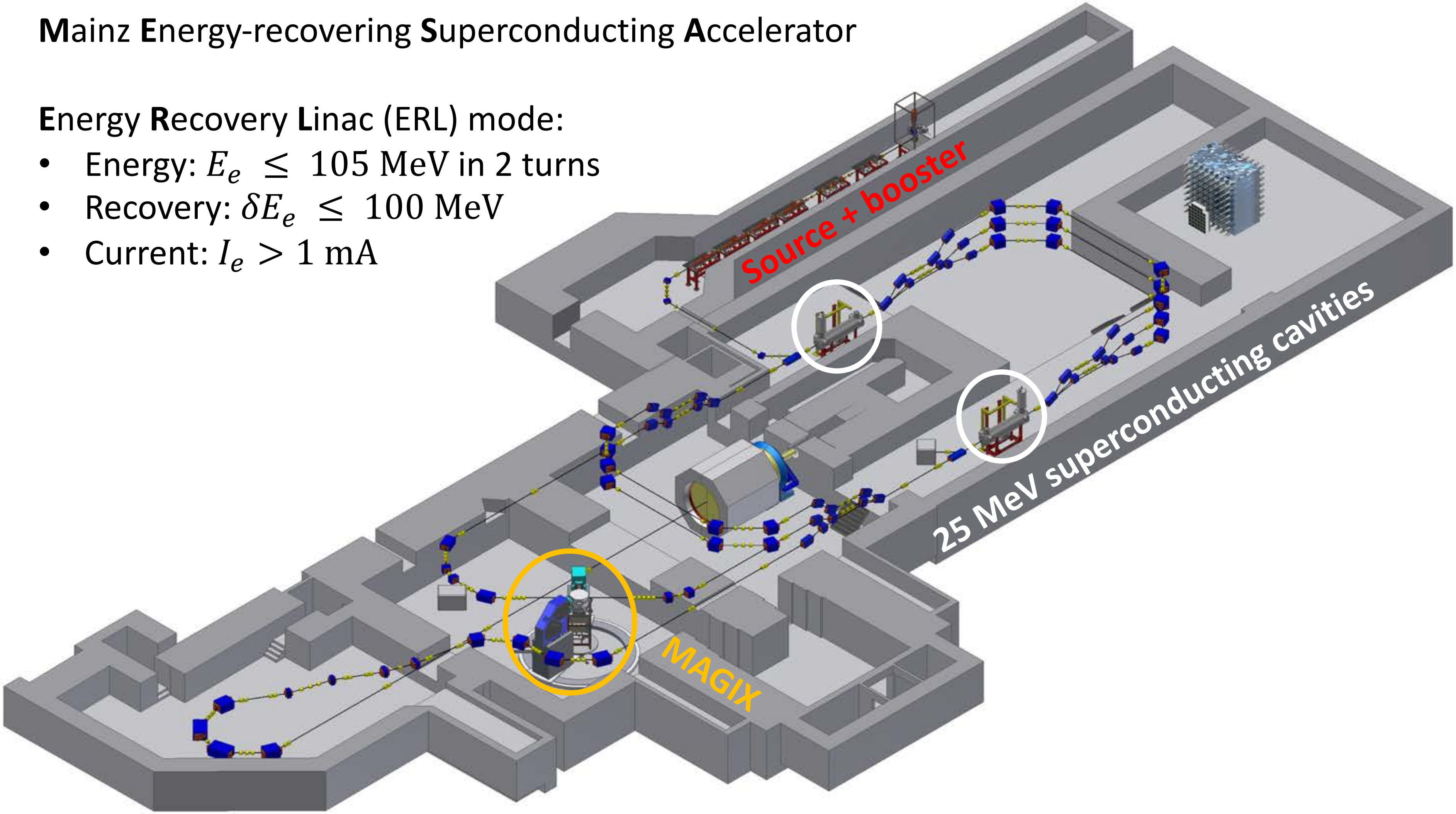


Electron Accelerator MESA

Mainz **E**nergy-recovering **S**uperconducting **A**ccelerator

Energy **R**ecovery **L**inac (ERL) mode:

- Energy: $E_e \leq 105\,\text{MeV}$ in 2 turns
- Recovery: $\delta E_e \leq 100\,\text{MeV}$
- Current: $I_e > 1\,\text{mA}$



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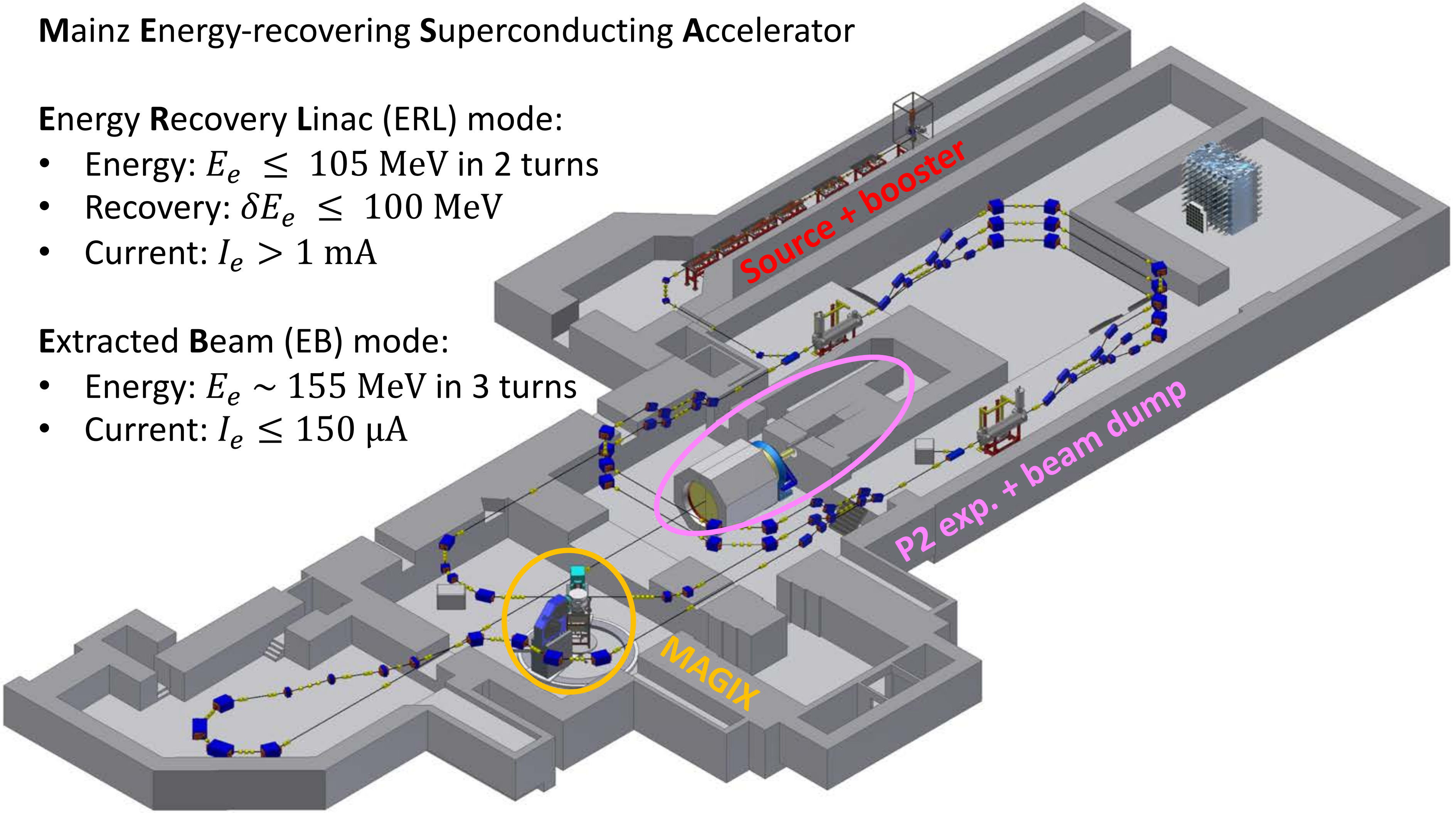
Extracted **B**eam (EB) mode:
- Energy: $E_e \sim 155$ MeV in 3 turns
- Current: $I_e \leq 150$ μA



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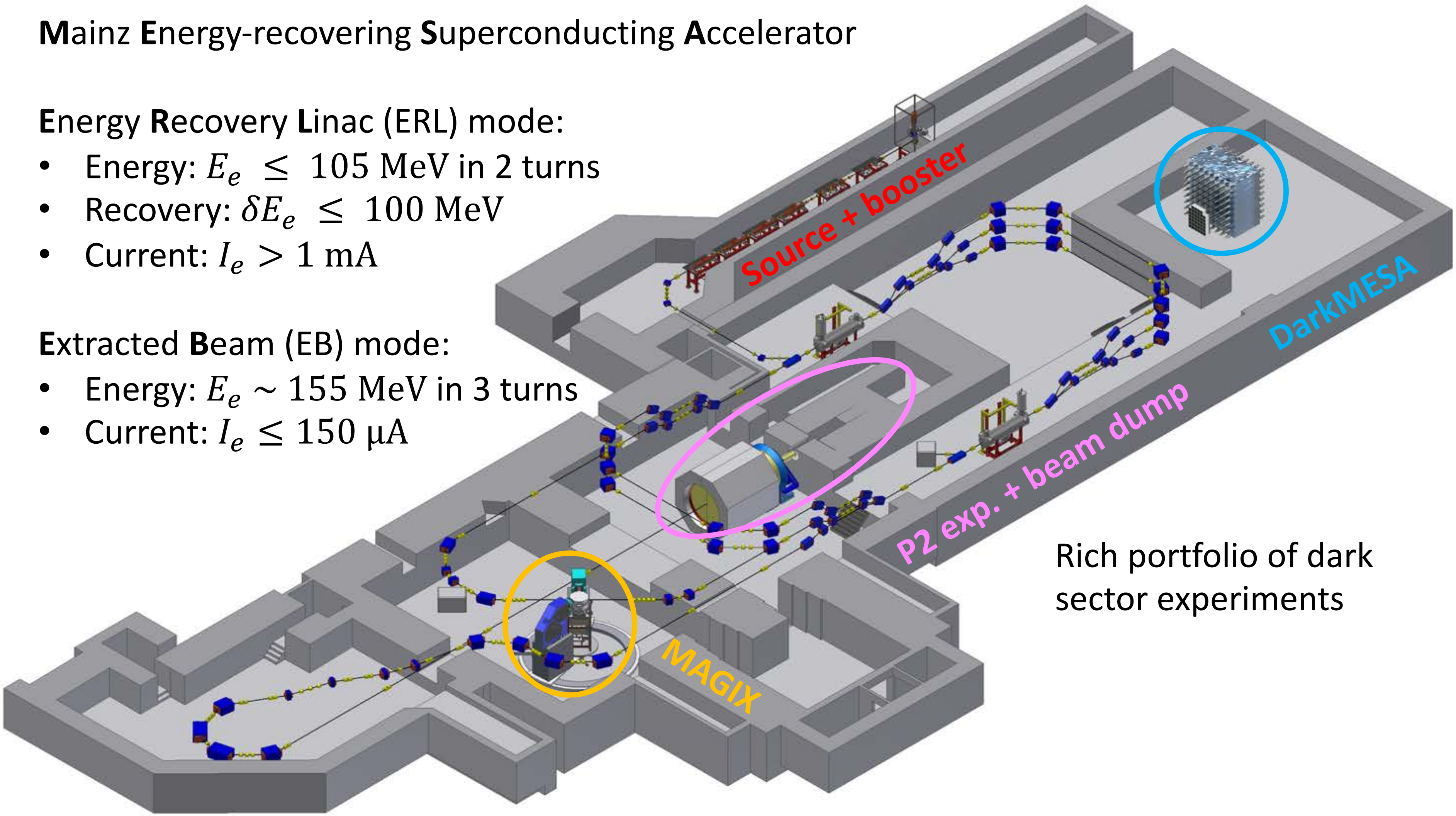
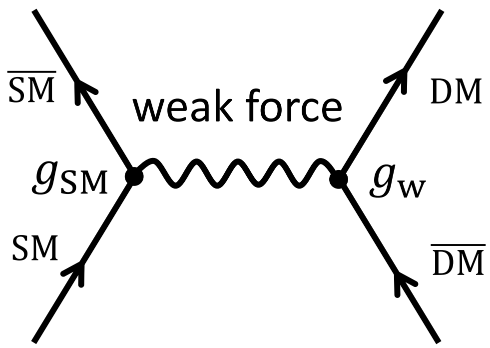


Rich portfolio of dark sector experiments

WIMPs and Light Dark Matter

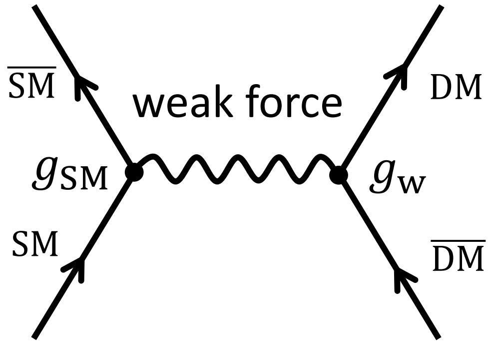
Weakly Interacting Massive Particles



- Matching relic abundance for the electroweak mass scale
- WIMPs require only SM interaction
- No positive evidence after LHC and galactic DM searches

WIMPs and Light Dark Matter

Weakly Interacting Massive Particles



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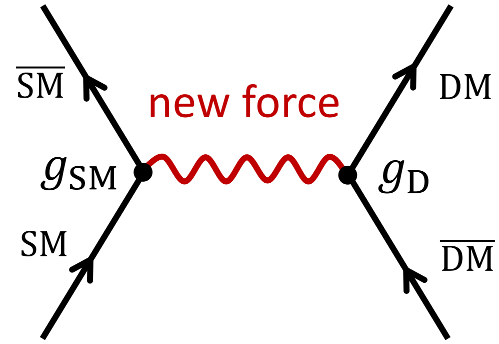
Light Dark Matter

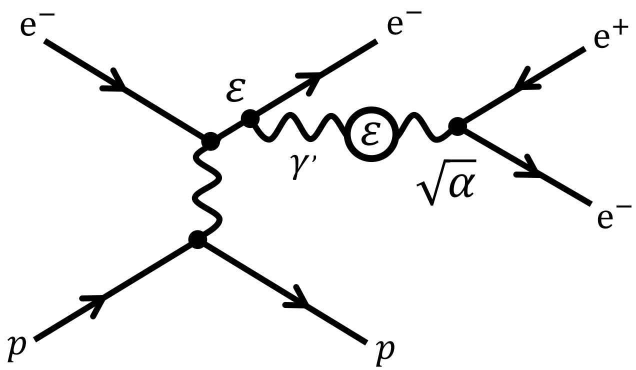


- Thermal relic targets exist for the MeV-GeV mass scale
- LDM requires a beyond SM force
- Rich phenomenology of portals: vector, higgs, neutrino, axion

Investigating the Vector Portal

- Dark photon γ' is the vector mediator
- Coupling to ordinary photons by kinetic mixing $\varepsilon = g_{\mathrm{D}}/g_{\mathrm{SM}} = \sqrt{\alpha_{\mathrm{D}}/\alpha}$
- Decay modes to both sectors

Visible decay: $m_{\gamma'} \ll m_{\chi}$



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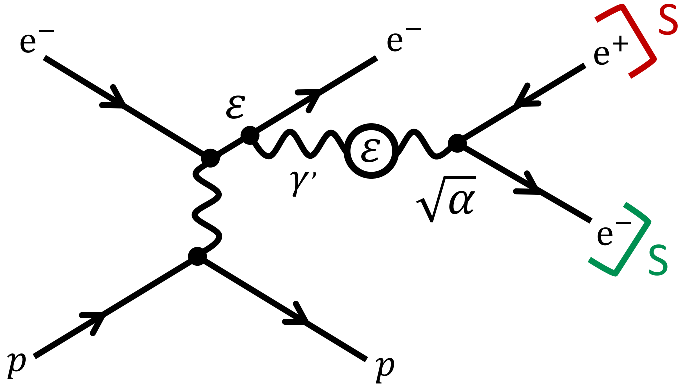
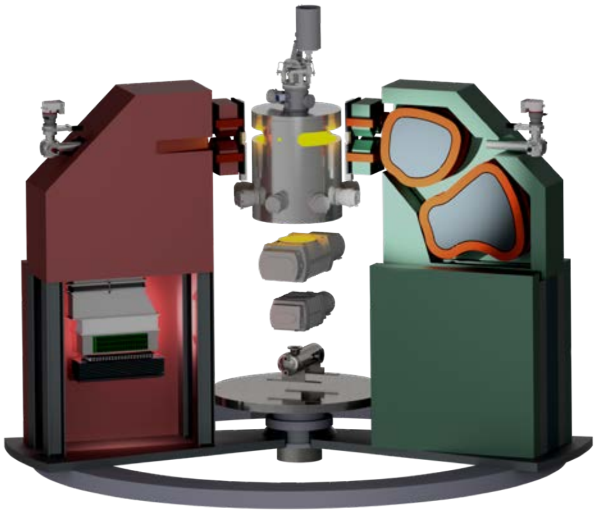


- MESA in the ERL mode
- Supersonic gas jet target
- Magnetic spectrometers



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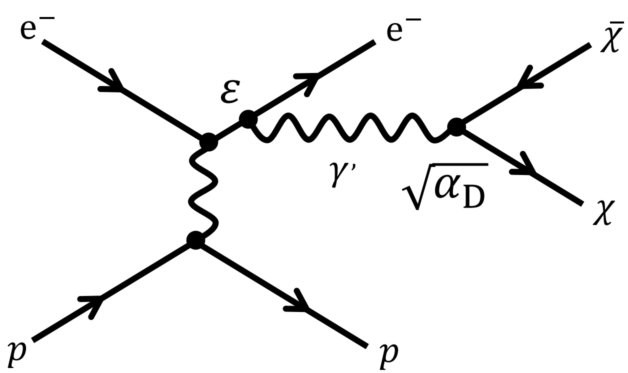

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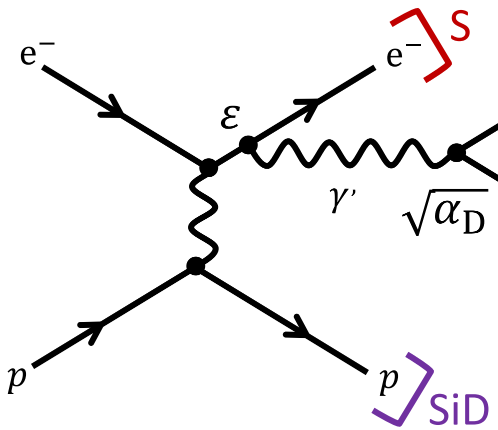
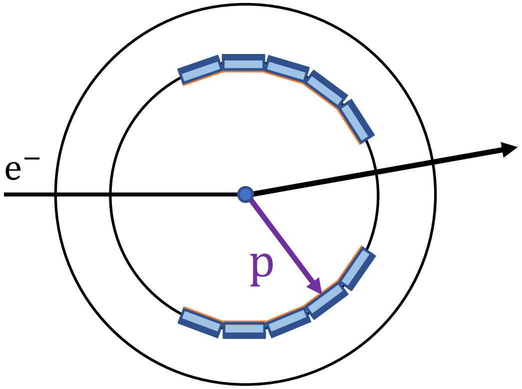


- Silicon strip recoil detectors $16{\times}3$ mm
- Scintillator telescope layer for PID

Circular arrangement:



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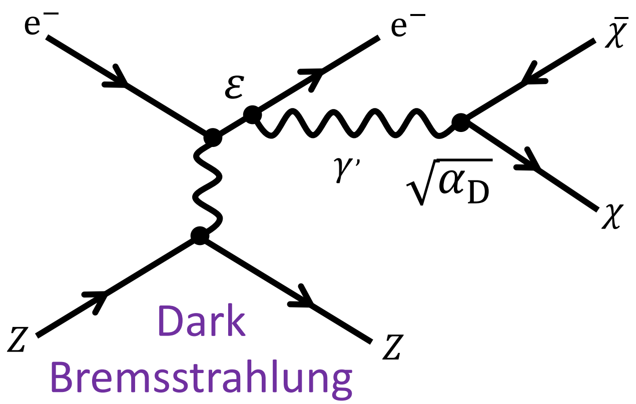

$$\sigma_{\mathrm{DBS}} \propto Z^2 \left(\frac{\varepsilon}{m_{\gamma'}}\right)^2$$

P2 experiment (runtime 20,000 h)

- MESA in the EB mode
- Liquid hydrogen target
  60 cm $\rightarrow$ $\mathrm{d}E/\mathrm{d}x \sim 17$ MeV

- Dumped electrons: 6.74×10^{22}

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

Investigating the Vector Portal

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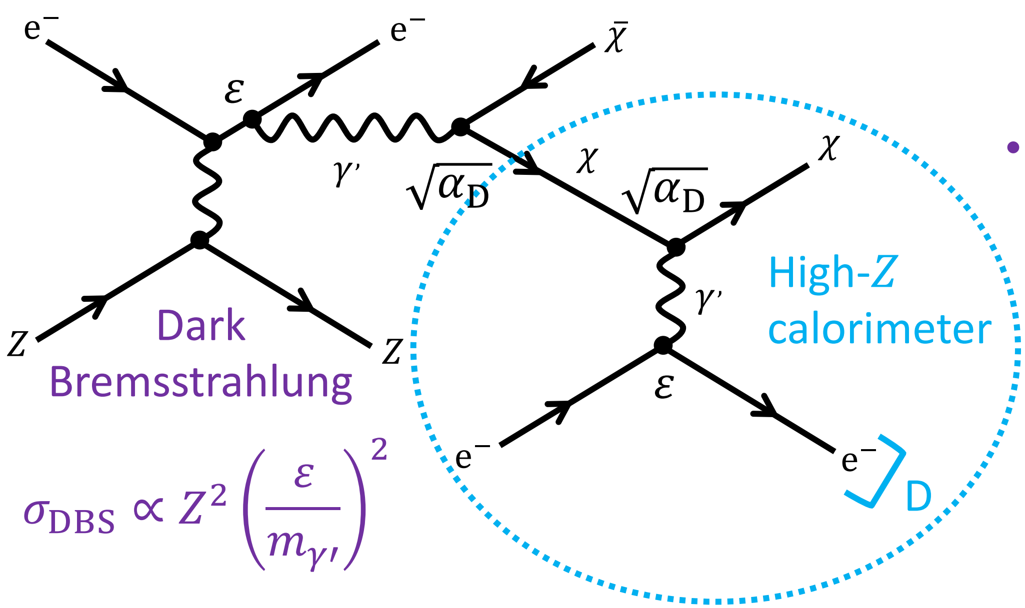

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Direct LDM measurement!

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

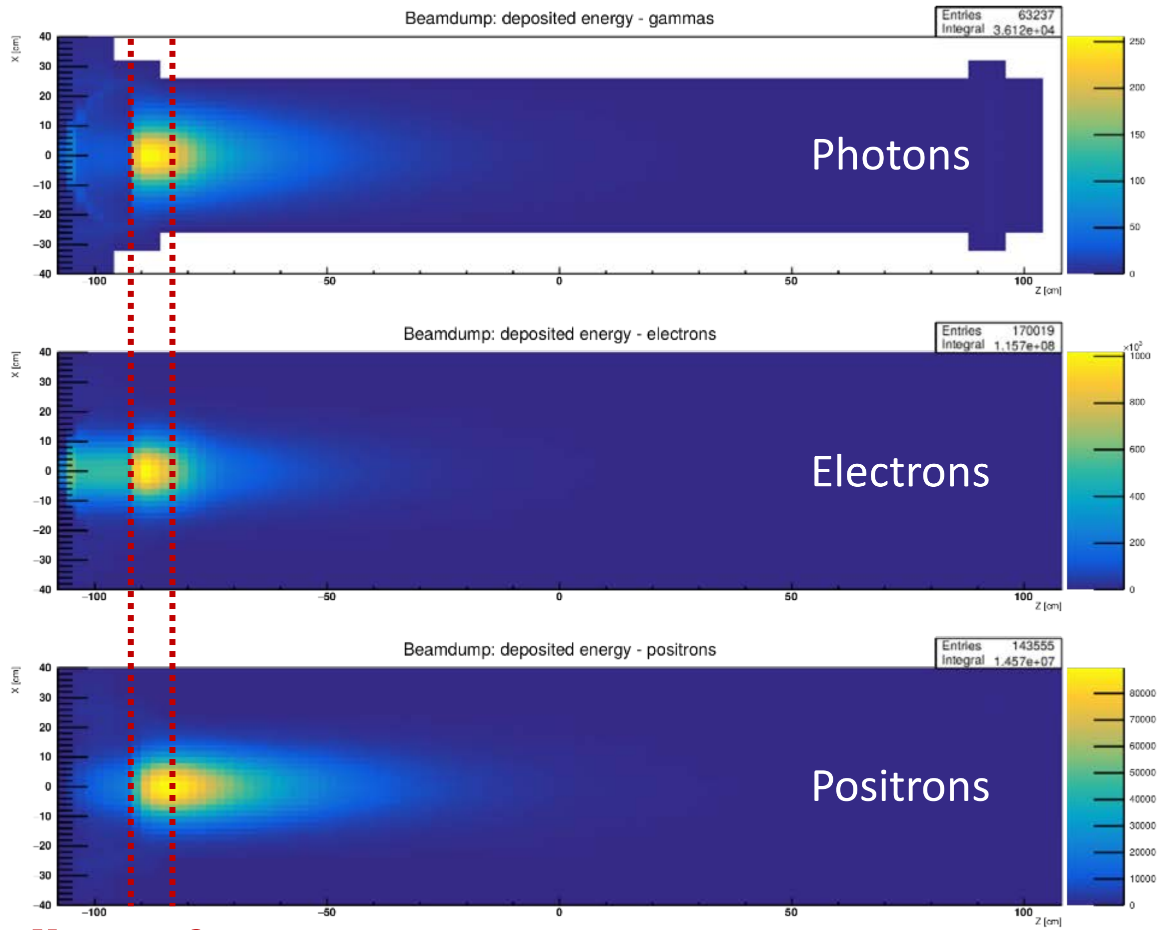
Simulation: Dark Photons

DARK MESA

GEANT4 simulation:

- 155 MeV electron beam interacts with P2 target
- Residual beam is stopped within one radiation length X_0
- On average 1 hard photon and 3 charged particles per electron are produced:
  - Dark Bremsstrahlung
  - Dark annihilation

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

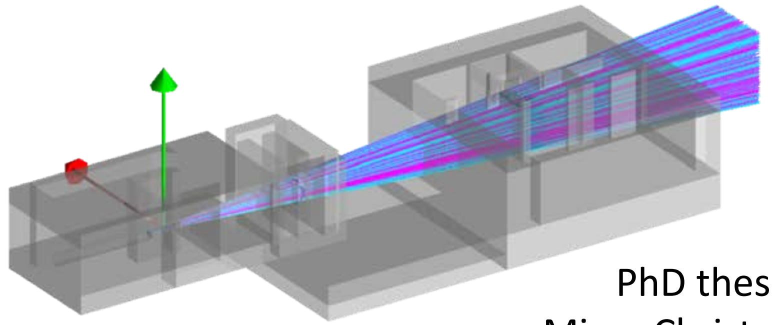


$X_{0,\mathrm{Al}} = 9\ \mathrm{cm}$

PhD thesis of Mirco Christmann

MadGraph simulation:

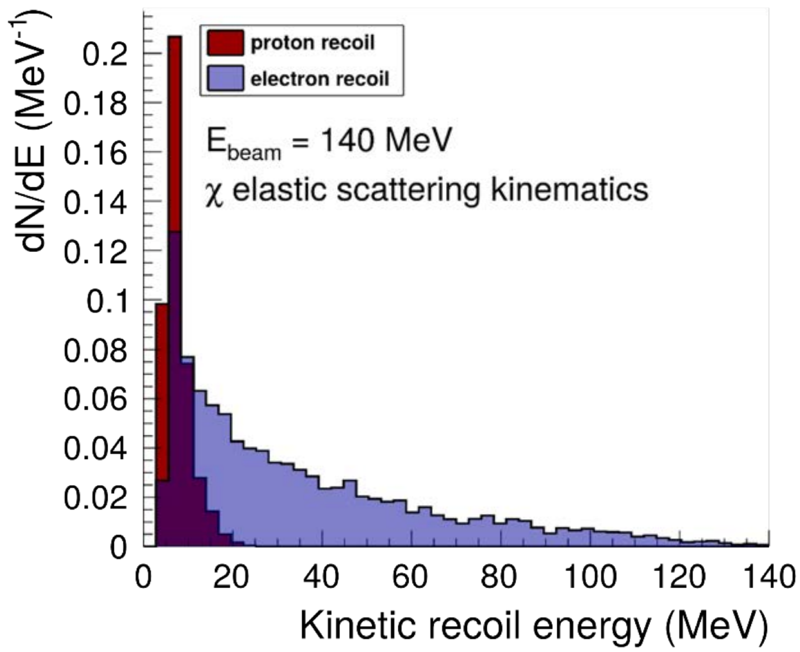
- Calculation of physical dark photon decays into DM pairs $\chi\bar{\chi}$
- Assumptions: $m_{\gamma'} := 3\, m_\chi \,, \alpha_\mathrm{D} := 0.5$



PhD thesis of
Mirco Christmann

Back in GEANT4:

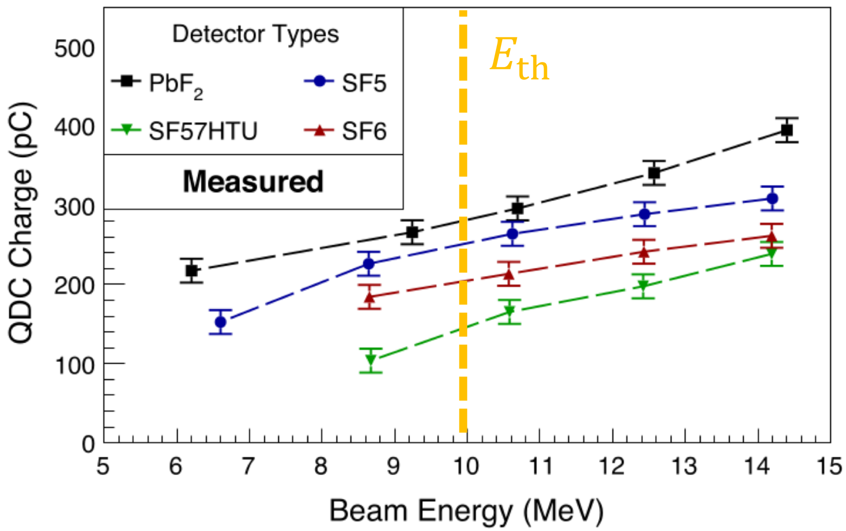
- Dark matter particles knock out electrons with energies as low as $E_\mathrm{th} \sim 10\ \mathrm{MeV}$
- A Calorimeter is perfectly suited to detect low-energetic electrons
- Different Cherenkov glasses were tested for their sensitivity



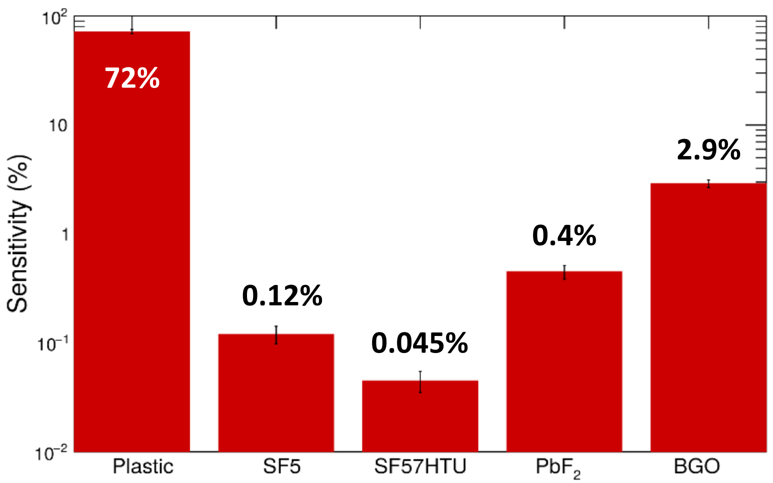
Detector Sensitivity Study

PbF$_2$ and the Pb-glass SF5 offer proper electron sensitivity and neutron insensitivity

Electron sensitivity study



Neutron sensitivity study

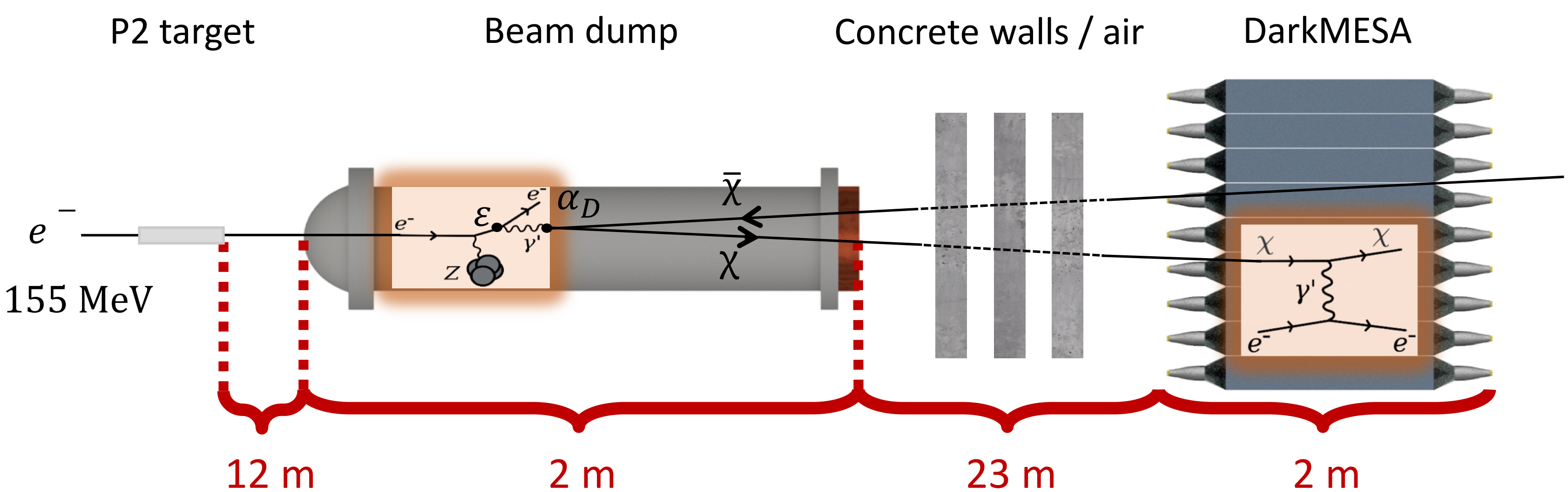


Electron beam test, read:
Mirco Christmann, et al.

- NIM A 958 (2020) 162398
- NIM A 960 (2020) 163665

Bachelor thesis of Paul Burger:
Neutron sensitivity study with an AmBe source

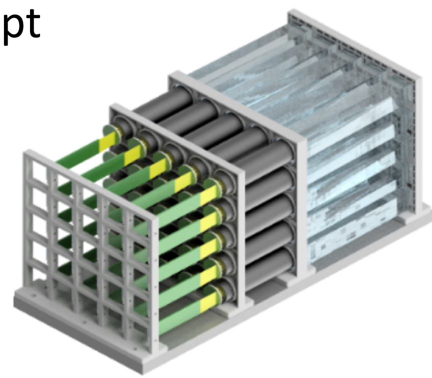
Modular Calorimeter Concept



- Modular calorimeter concept

PbF_2 module
5×5 matrix of PbF_2
Volume: 4 l

1000 crystals: A4@Mainz
each $(18\times3\times3)\ \mathrm{cm}^3$

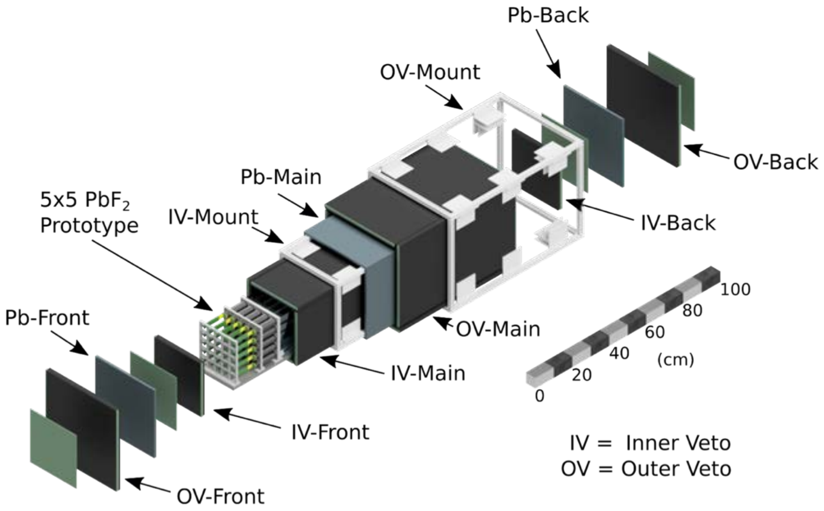


SF5 module
4×4 matrix of SF5 Pb-glasses
Volume: 9 l

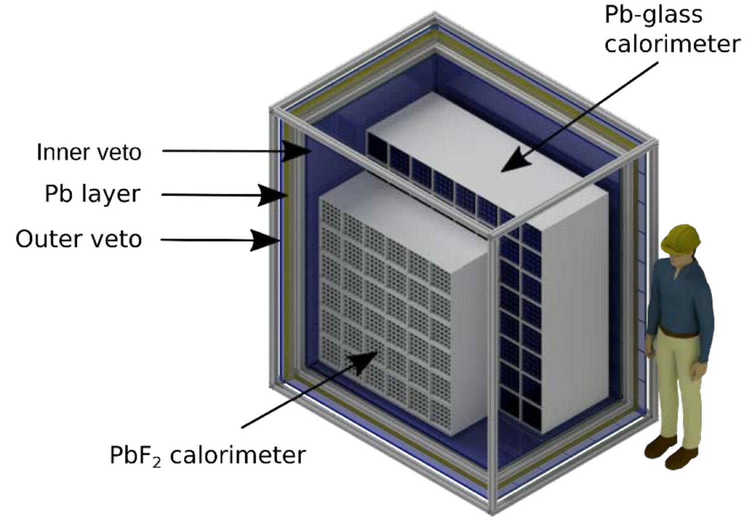
2000 glasses: WA98@CERN
each $(46\times3.5\times3.5)\ \mathrm{cm}^3$

Active Volume Expansion

- Phase A: 1 PbF_2 module, active volume of $0.004\ \mathrm{m}^3$



- Phase B: 30 PbF_2 and 64 SF5 modules, active volume $0.7\ \mathrm{m}^3$



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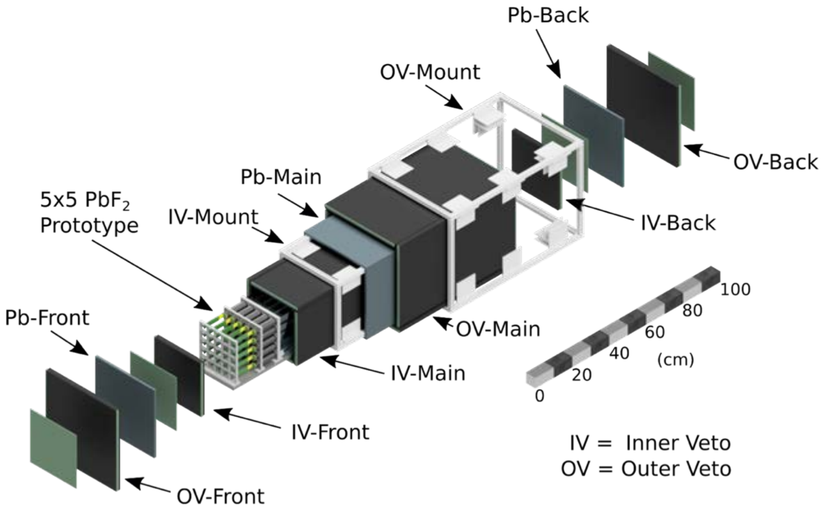

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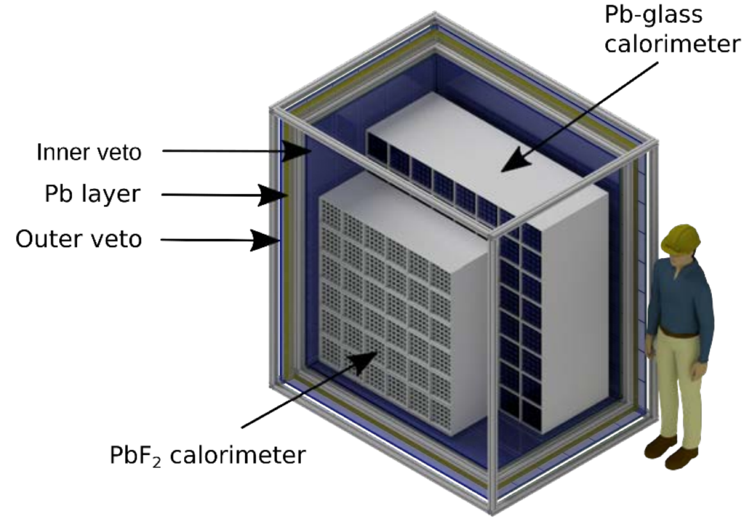


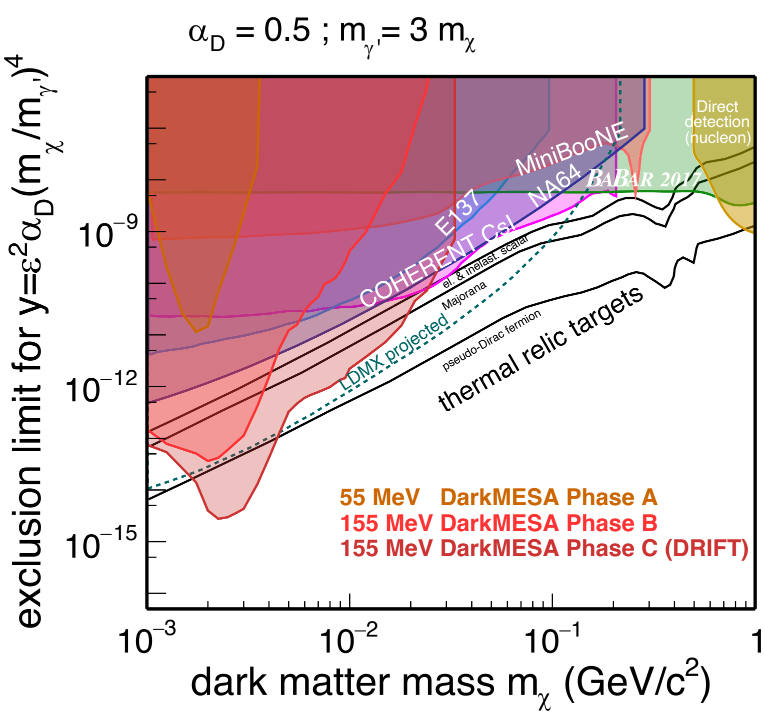
- Phase C: Long term plans
  - DarkMESA DRIFT: $1\ \mathrm{m}^3$ negative ion TPC as complimentary detection method
  - Calorimeter upgrade: Volume expansion up to 9 m^3

DarkMESA Expected Reach

Phase	Detector	Period	Time	EOT
A	Prototype	1.-4. year	2,200 h	$7.42 \cdot 10^{21}$
B	PbF_2, SF5	4.-6. year	6,600 h	$2.22 \cdot 10^{22}$
C	+TPC	7.-12. year	13,200 h	$4.45 \cdot 10^{22}$

Simulation by M. Christmann, Saskia Plura

Limits given as $y \propto m_\chi^2 \langle \sigma_A v \rangle$
$\sigma_A \sim$ cross section of $\chi\bar{\chi} \to SM$



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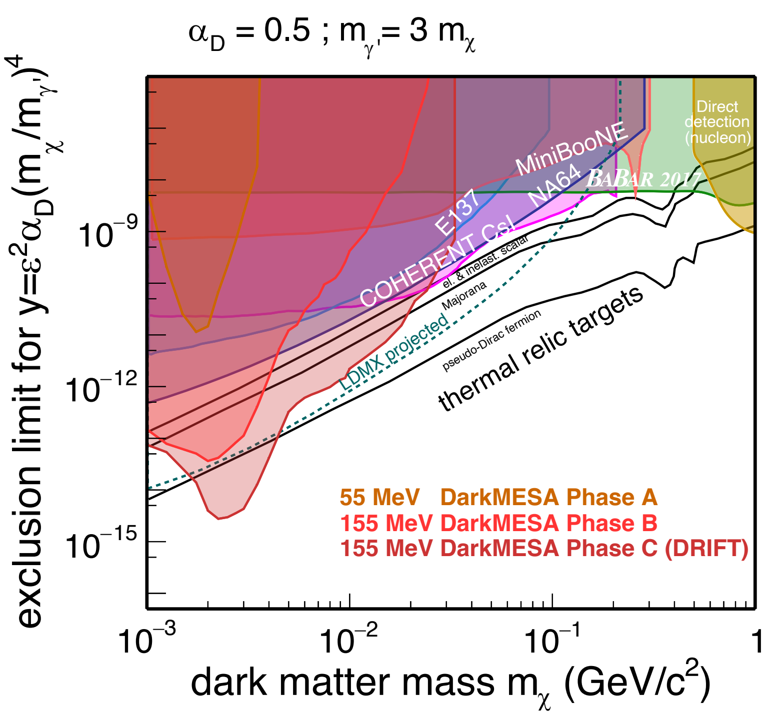
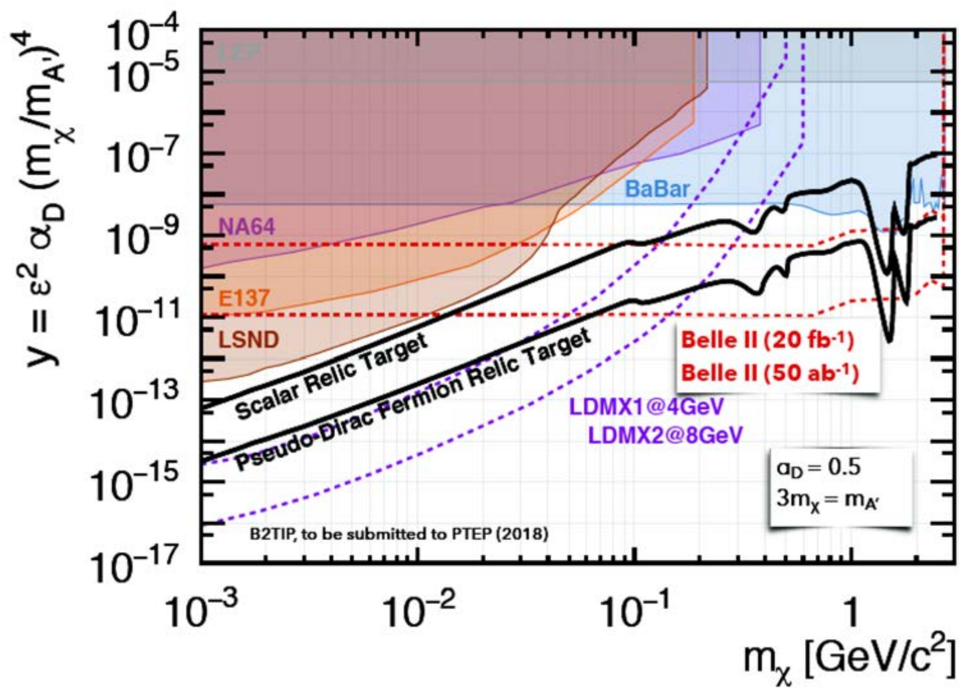
Main Competitors:

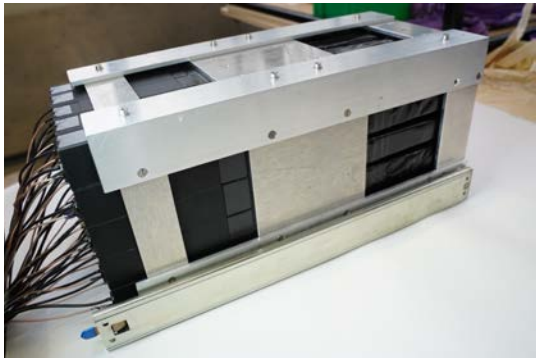
- LDMX
- Future NA64
- Belle II at high masses



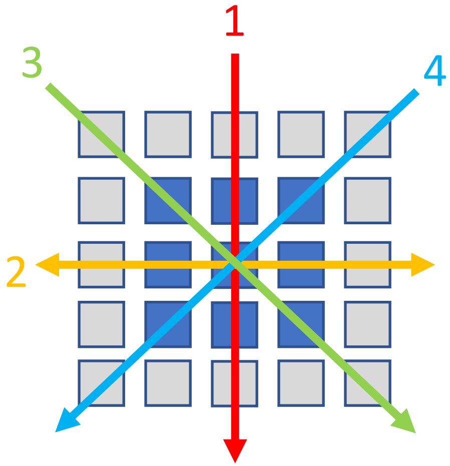


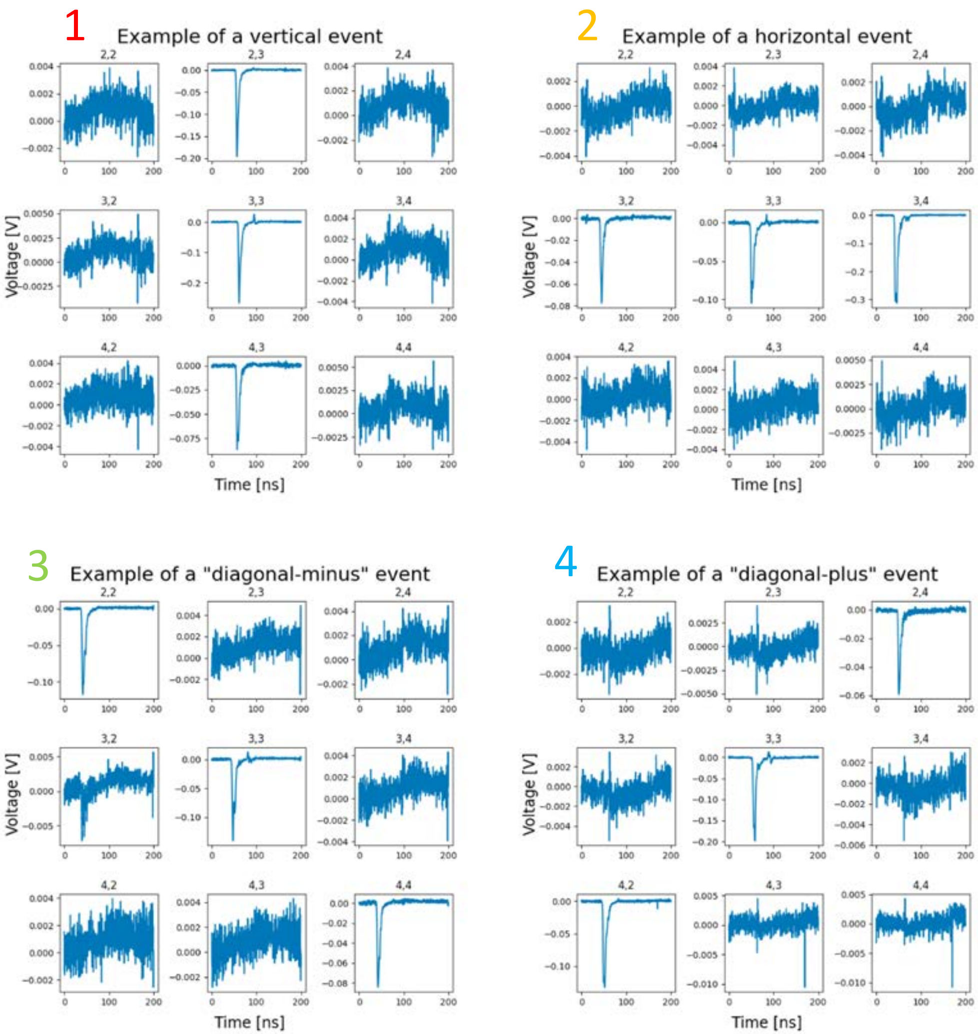
Phase-A Calorimeter Response

Phase A calorimeter (5x5 PbF_2):



Response to 4 different cosmic tracks:



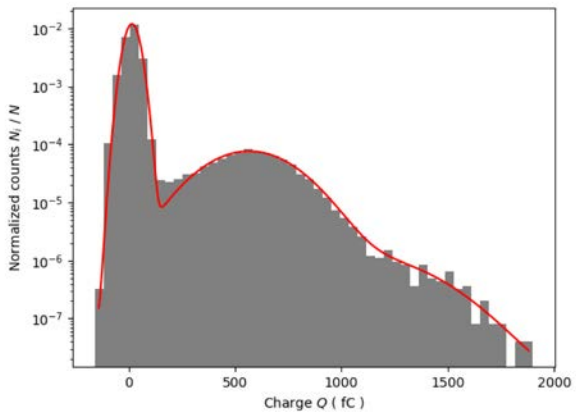


Bachelor thesis of Jonas Pätschke

Calorimeter Crystal Calibration

Gain calibration of the PMTs

- Curve-fitting of charge spectra under short laser pulses



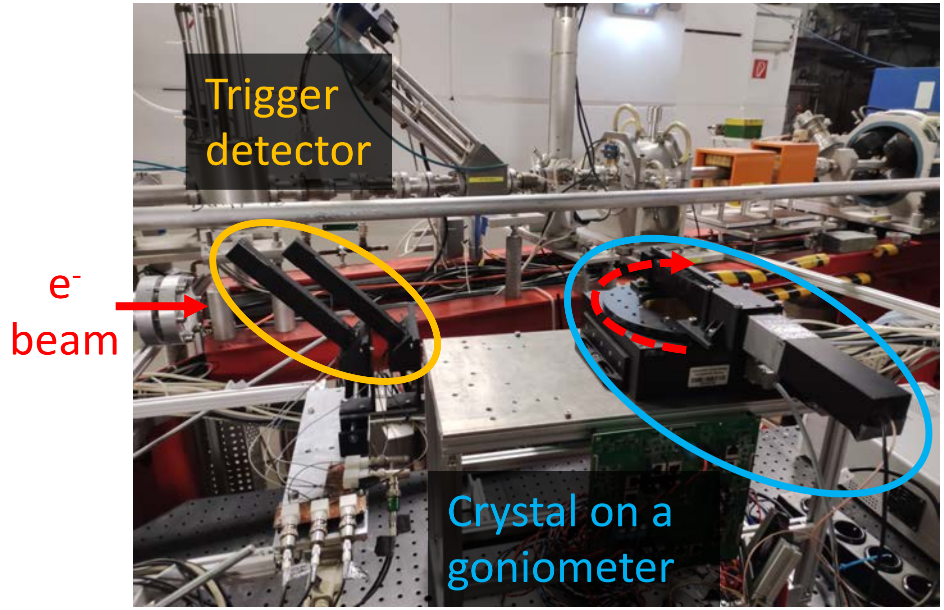
Bachelor thesis of Jonas Pätschke

Light output calibration of the crystals:

- Sensitivity to particle tracks with respect to the Cherenkov angle:

$$\cos\theta = 1/n\beta$$

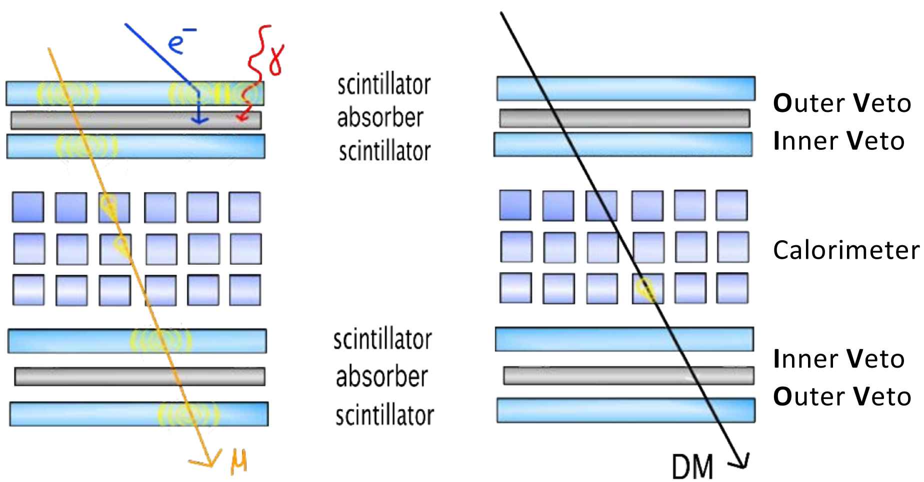
- Beam test data is under analysis



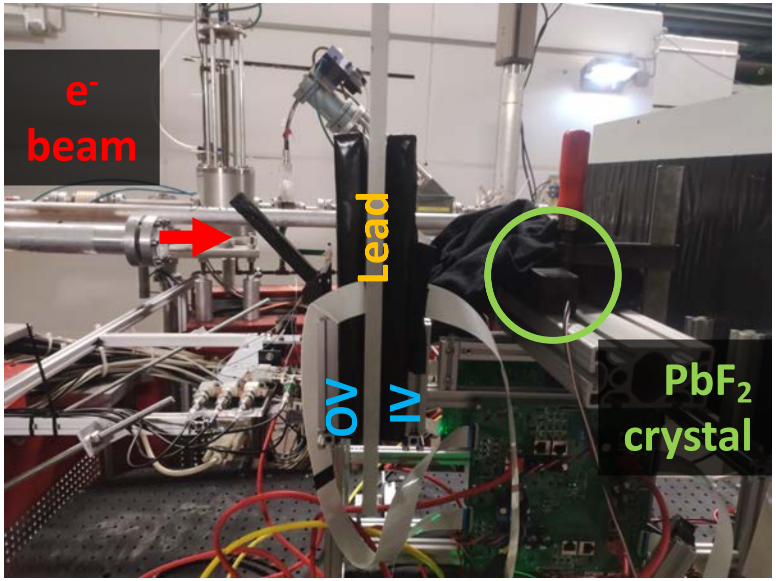
PhD thesis of Matteo Lauß

Cosmic Particles Veto Concept

- Veto layers from double plastic scintillator-absorber sandwiches
- Heavy absorber shields electrons and converts photons, neutrons
- Muons produce a signal in opposite veto layers
- DM is assumed to pass the veto detector



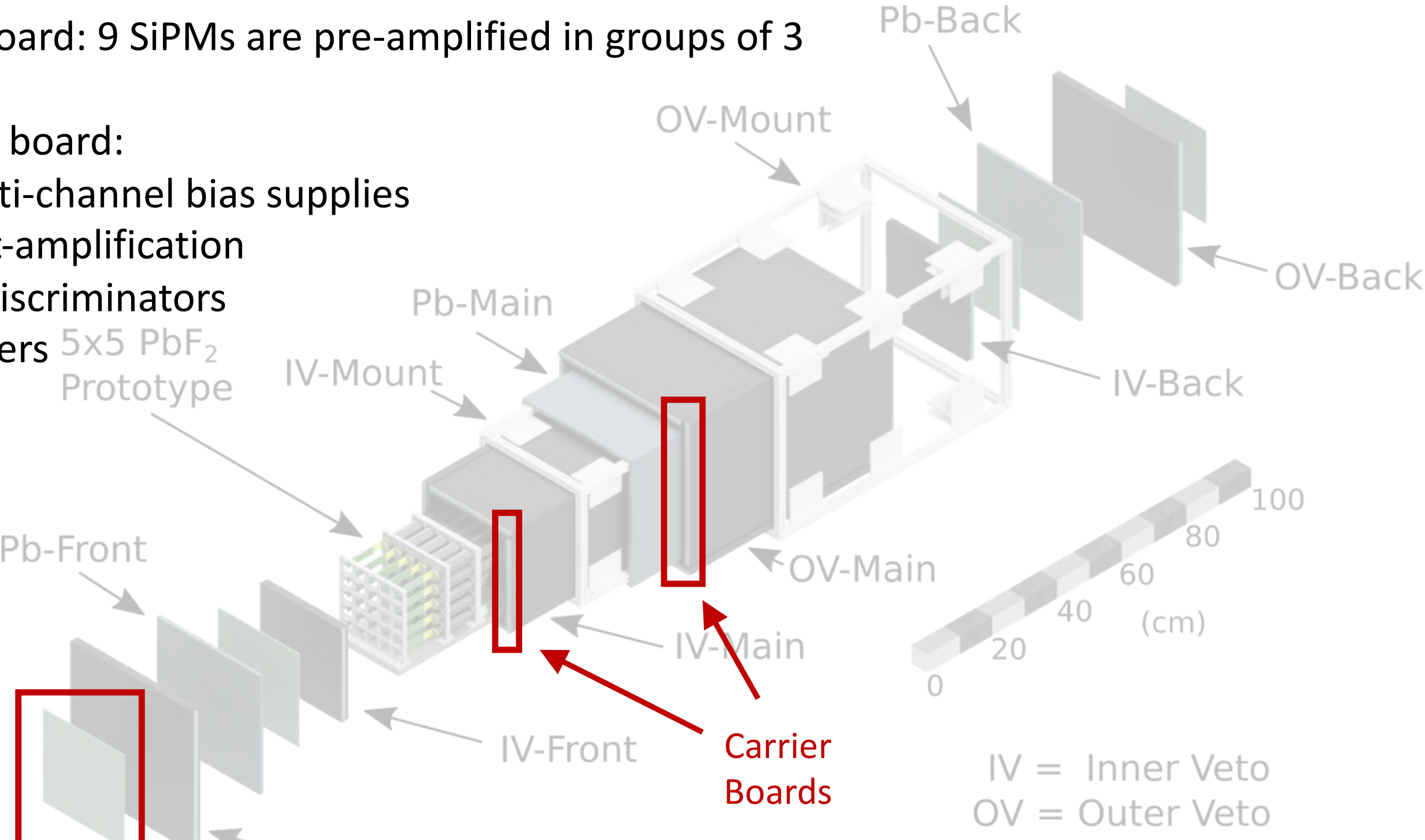
Beam test data under analysis



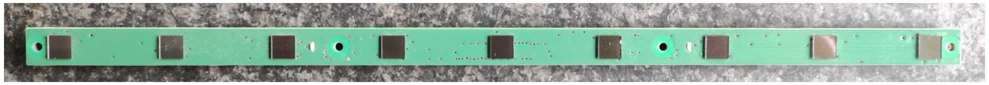
PhD thesis of Matteo Lauß

Phase-A Veto Readout

- Carrier board: 9 SiPMs are pre-amplified in groups of 3
- Collector board:
  - Multi-channel bias supplies
  - Post-amplification
  - LE discriminators
  - Scalers



Collector Board



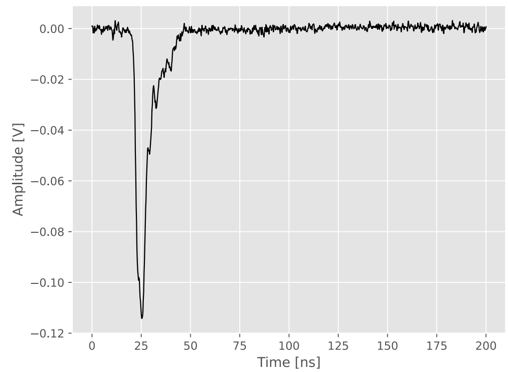
Further reading: M. Lauß, *et al.*, NIM A 1012 (2021) 165617

Detector Signal Processing

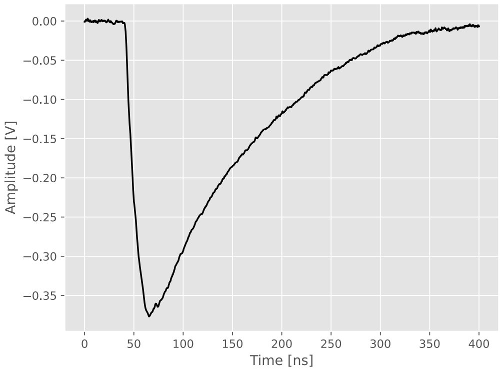
- Signals are sampled for documentation purposes
- Ongoing study of pulse shaping to match ADC characteristics
- PANDA SADC
  - Channel count: 64
  - Voltage resolution: 14 bit
  - Sampling frequency: $80\ \mathrm{MHz} = 1/12.5\ \mathrm{ns}$

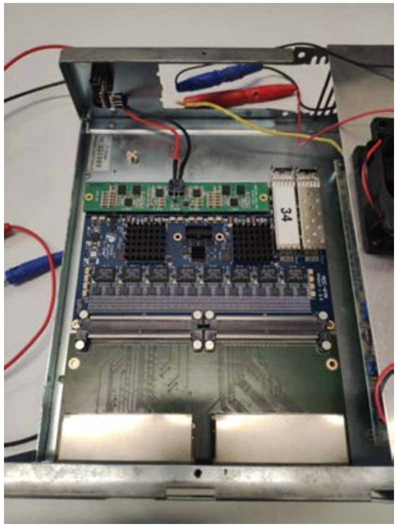
See: PhD thesis of E.J.O. Noll (2020) Digital Signal Processing for the Measurement of Particle Properties with the PANDA Electromagnetic Calorimeter

Narrow calorimeter PMT signal:



Broad Veto SiPM signal:





Thank you!

DARK MESA

Additional information:

- S. Plura (today 16:51) Search for Light Dark Matter with the DarkMESA Experiment
- S. Schlimme (Thursday 11:00) The MESA physics programme

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

WESTFÄLISCHE WILHELMS-UNIVERSITÄT MÜNSTER

Massachusetts Institute of Technology

Univerza v Ljubljani

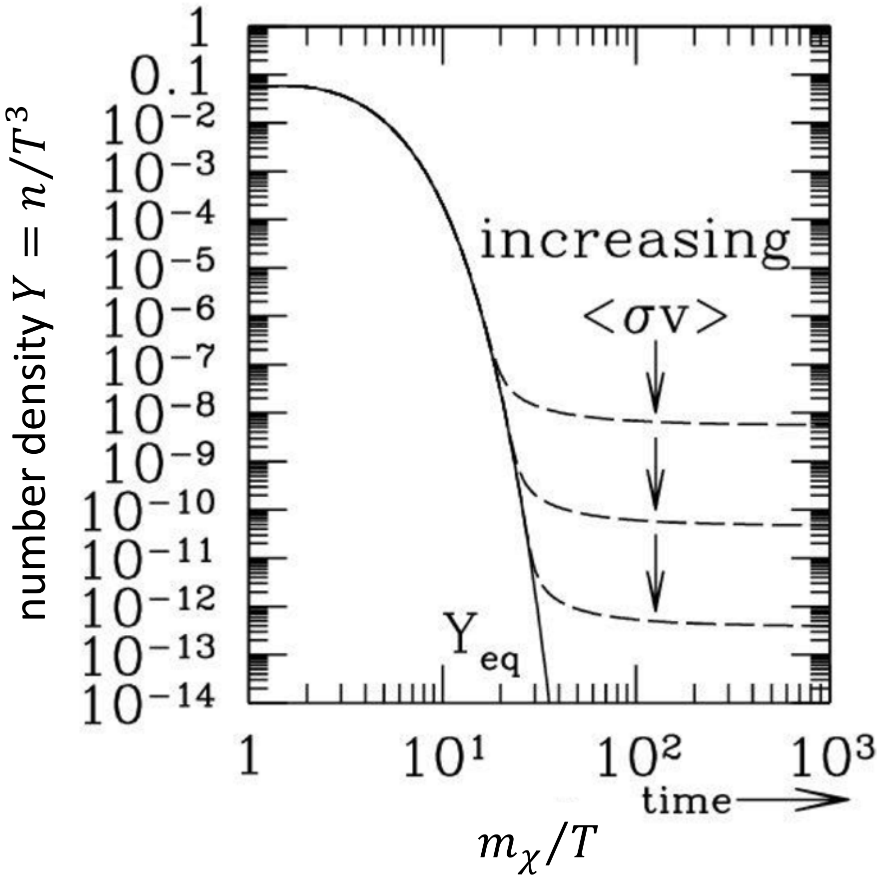
PRISMA+

MAGIX

HIM Helmholtz-Institut Mainz

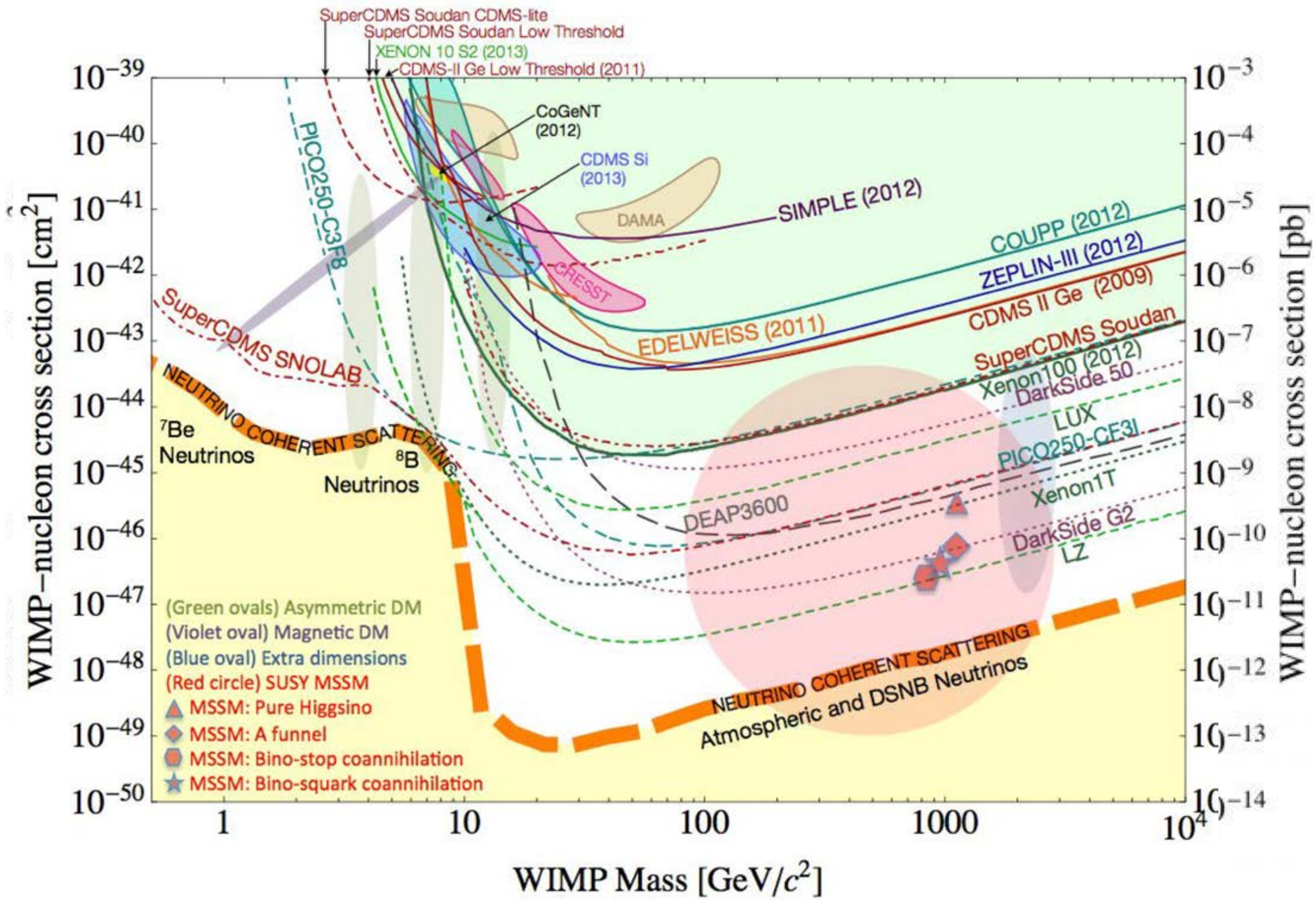
Thermal Dark Matter

- Early universe $T > m_\chi$: Dark Matter (DM) is hold in thermal equilibrium by interaction with Standard Model (SM) matter
- During cooling down $T < m_\chi$: Number density dropped $n \propto \mathrm{e}^{-m_\chi/T}$
- Finally $T \ll m_\chi$: Number density froze out at $n_{\mathrm{FO}} \approx H/\langle \sigma_{\mathrm{A}} v \rangle$
- Increased annihilation cross-section σ_{A} would lead to decreased relic abundance and later freeze-out



Hubble constant H, thermally averaged annihilation cross-section $\langle \sigma_{\mathrm{A}} v \rangle$

WIMPs Expected Reach



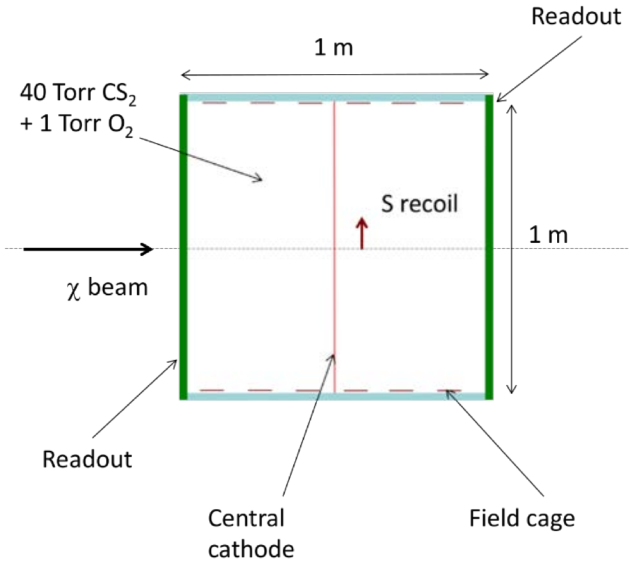
DarkMESA DRIFT

- Negative ion time projection chamber filled with Carbon Disulfide at 0.05 bar, see: D.P. Snowden-Ifft, et al., arXiv:1809:06809

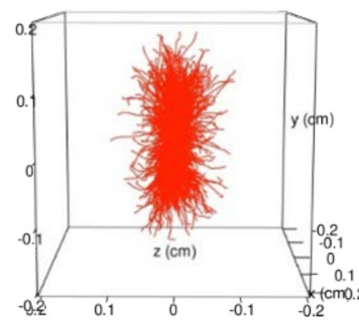
- Lowers the nuclear recoil detection threshold: $E_{\mathrm{th}} \sim 35\ \mathrm{keV}$

- Requires Gadolinium-doped scintillators as cosmic Neutron veto detectors

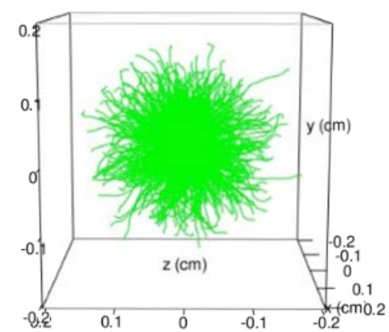
  - Started cooperation with Philip Cole, Lamar University, Texas, US



Signal



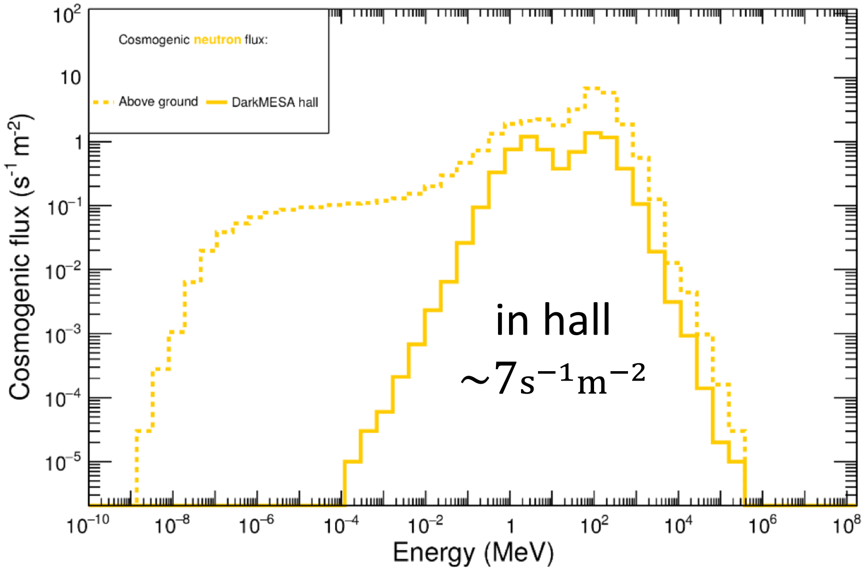
Isotropic background



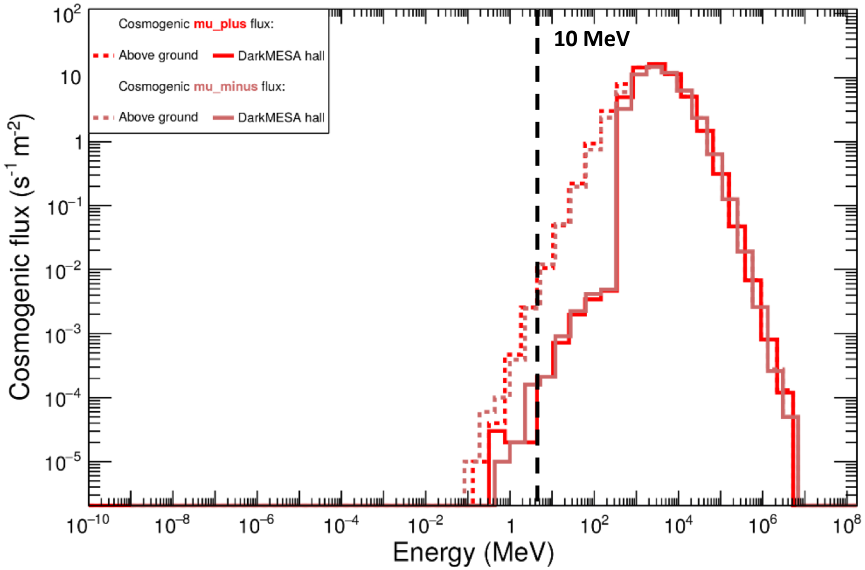
Cosmic Particles Background

- Simulation of cosmogenic background based on the **C**osmic-**R**ay shower librar**Y**

Neutron flux: Sea level (dashed), Hall (solid)



Muon flux: Sea level (dashed), Hall (solid)

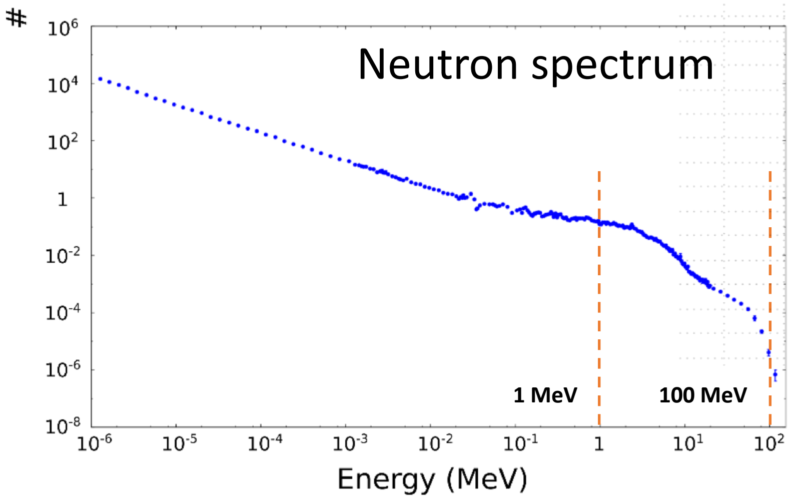


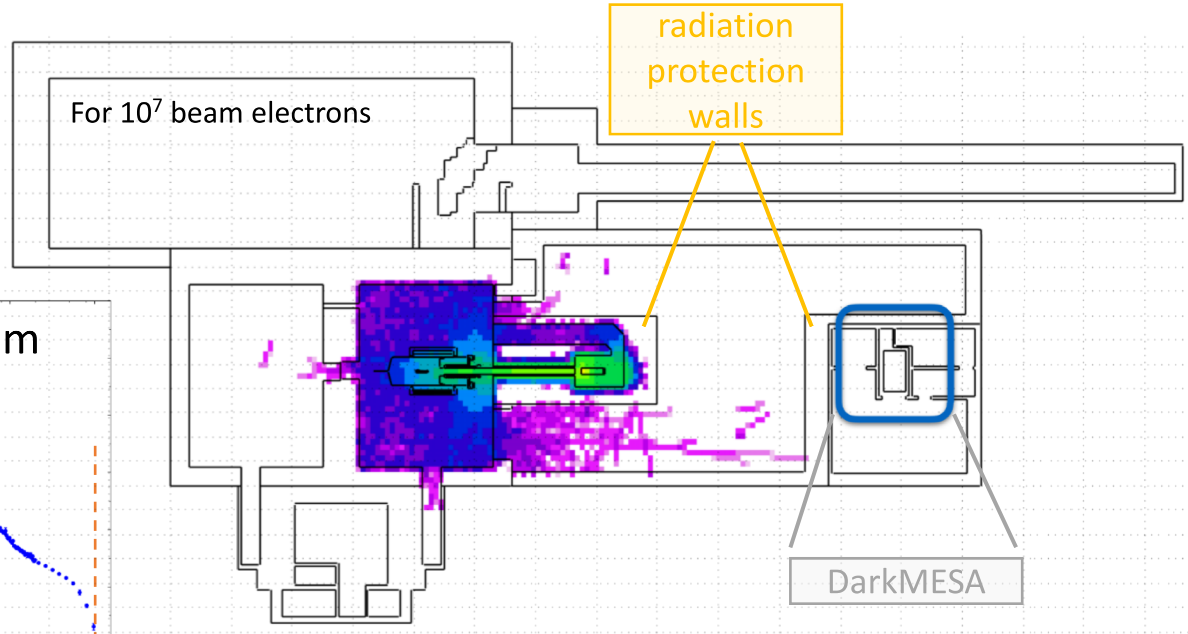
- Cosmogenic particles have to be vetoed with high efficiency

35

Beam Neutrons Background

- FLUKA simulation of beam-induced neutrons

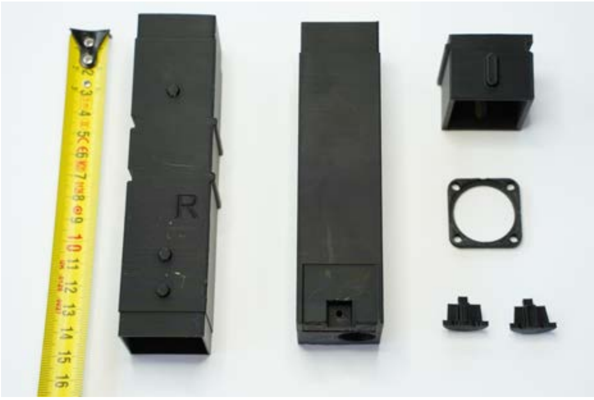




- No significant background
- Work in progress

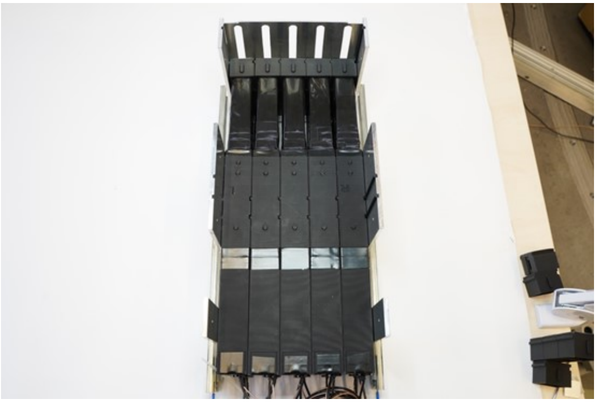
PbF_2 Module Assembly

3D printed housing with locking points

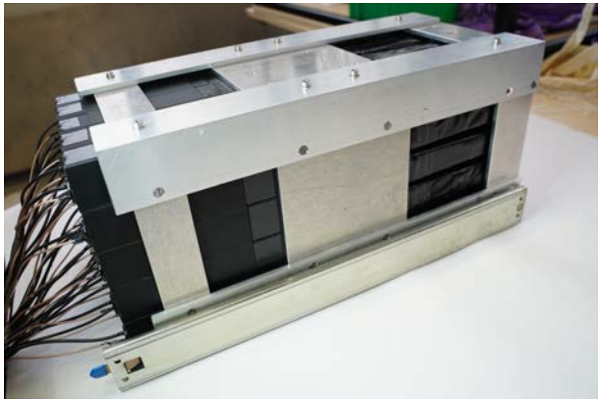


Single-detector assembly

First layer assembly



Complete prototype



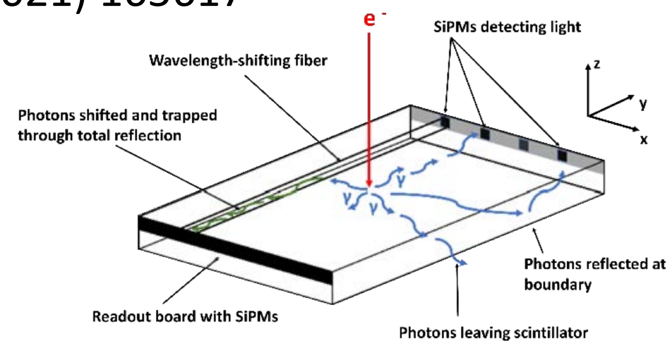
Bachelor thesis of Jonas Pätschke

Veto Scintillator Properties

DARK MESA

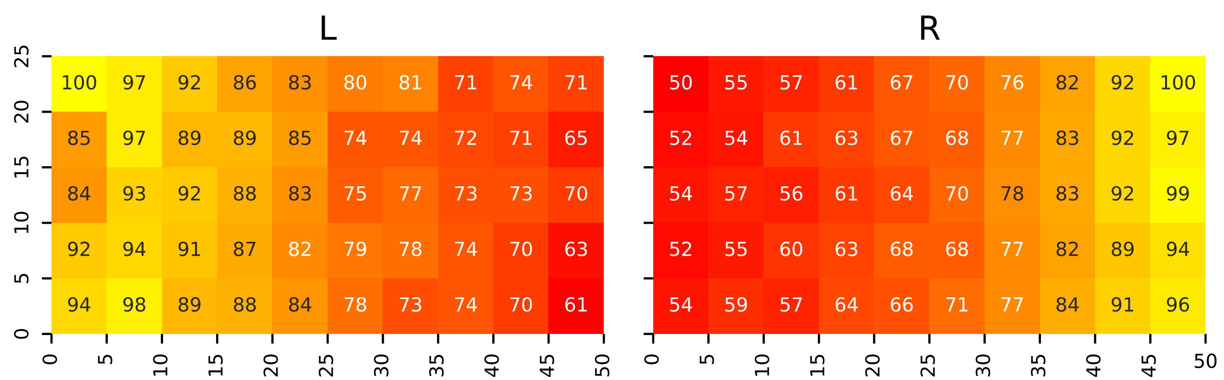
- Veto scintillators tested with cosmic particles and in the electron beam
- Wavelength shifting fibers increased light output but also the inhomogeneity
- Further reading: M. Lauß, *et al.*, NIM A 1012 (2021) 165617

- Ongoing study of
  - Readout electronics
  - Attenuation length $< \ 10\,\%/\mathrm{cm}$
  - Homogeneity



$50 \times 25 \times 2\ \mathrm{cm}^3$

L  R

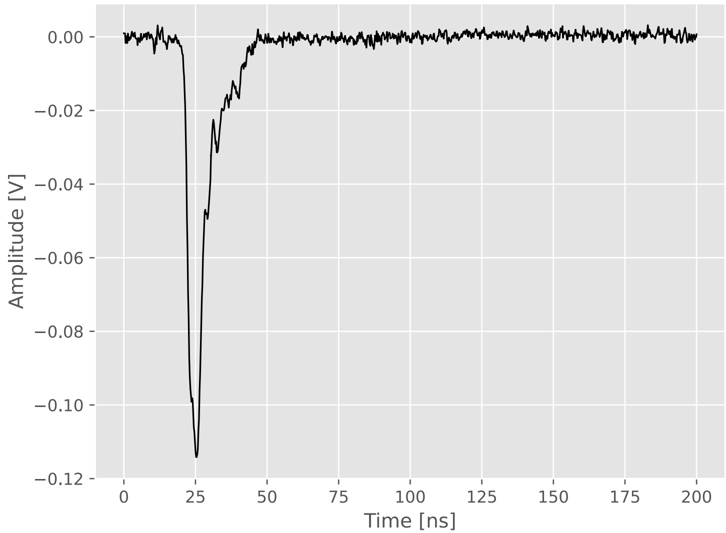


PhD and master thesis of Matteo Lauß

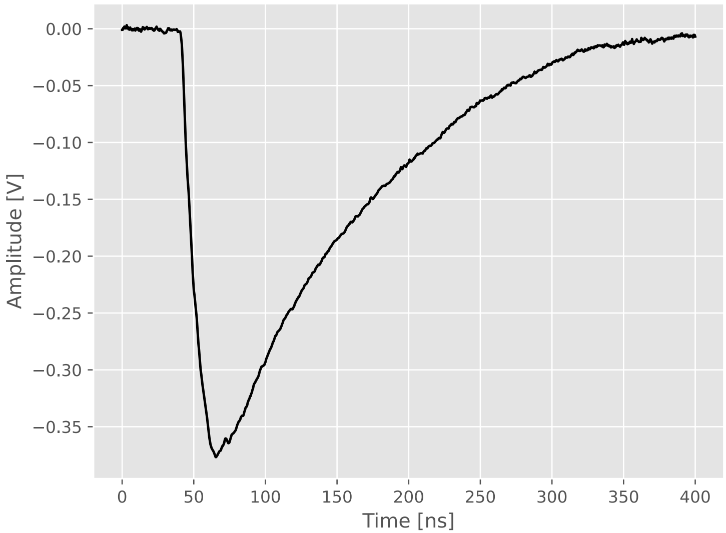
Detector Signal Shapes

- Waveforms of calorimeter and veto detectors are differently shaped

Narrow calorimeter PMT signal:



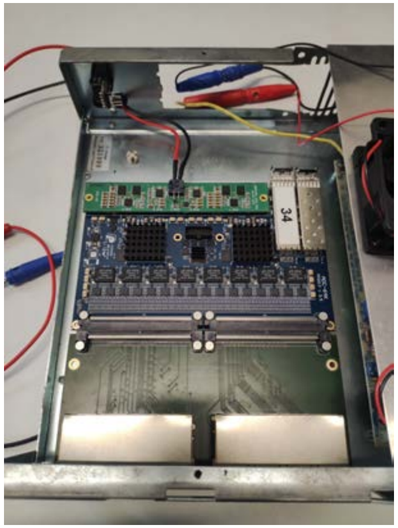
Broad Veto SiPM signal:



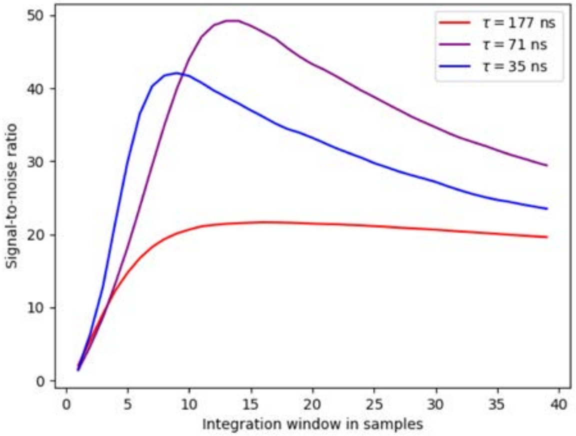
- For documentation purposes the waveforms of rare events should be stored
- Budged per channel is limited in case of a total count of 2000 in phase B

Detector Signal Processing

- PANDA SADC
  - Channel count: 64
  - Voltage resolution: 14 bit
  - Sampling frequency: $80\ \mathrm{MHz} = 1/12.5\ \mathrm{ns}$
  - See: PhD thesis of E.J.O. Noll (2020) Digital Signal Processing for the Measurement of Particle Properties with the PANDA Electromagnetic Calorimeter

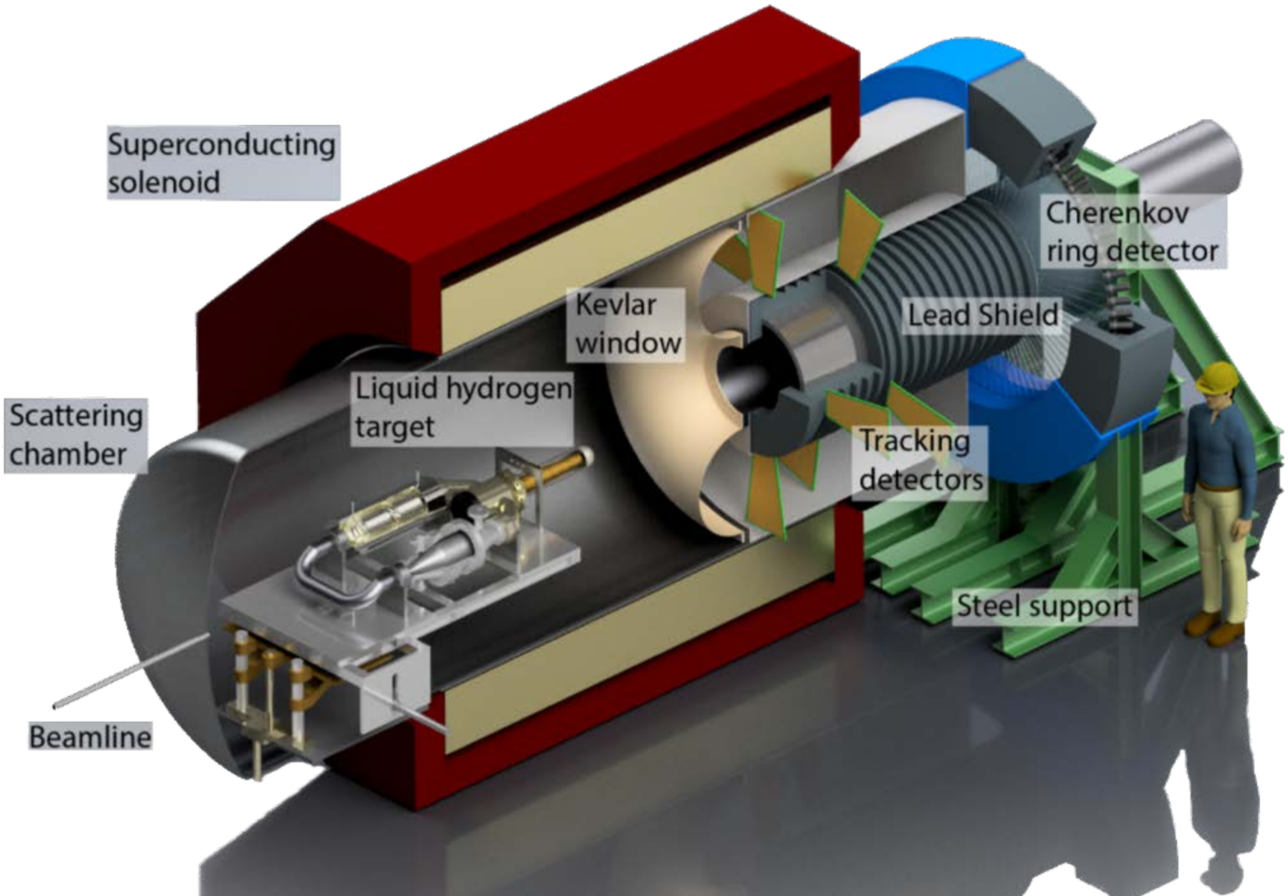


- Energy signals of the fast PMTs have to be bandwidth limited to match the slow sampling rate
- Investigation of the optimum time constant τ:
  - Require sample in the rising edge (Phase error)
  - Optimize the charge integral SNR



P2 Experiment at MESA

The weak mixing angle: Measurement of the parity violating asymmetry in the elastic scattering of polarized electrons off unpolarized nuclei



Measurement time:
20,000 h

Beam current:
150 μA

Dumped electrons:
6.74×10^{22}

Target:
LH 60 cm

Dumped energy:
≤ 140 MeV

Competitors Overview

- Beam dump experiments similar to DarkMESA
  - BDX@JeffersonLAB, e^{-}beam (future unclear)
  - SHiP@SPS/CERN, p beam (future unclear)
  - MiniBooNE@FermiLAB, ν beam (ongoing)

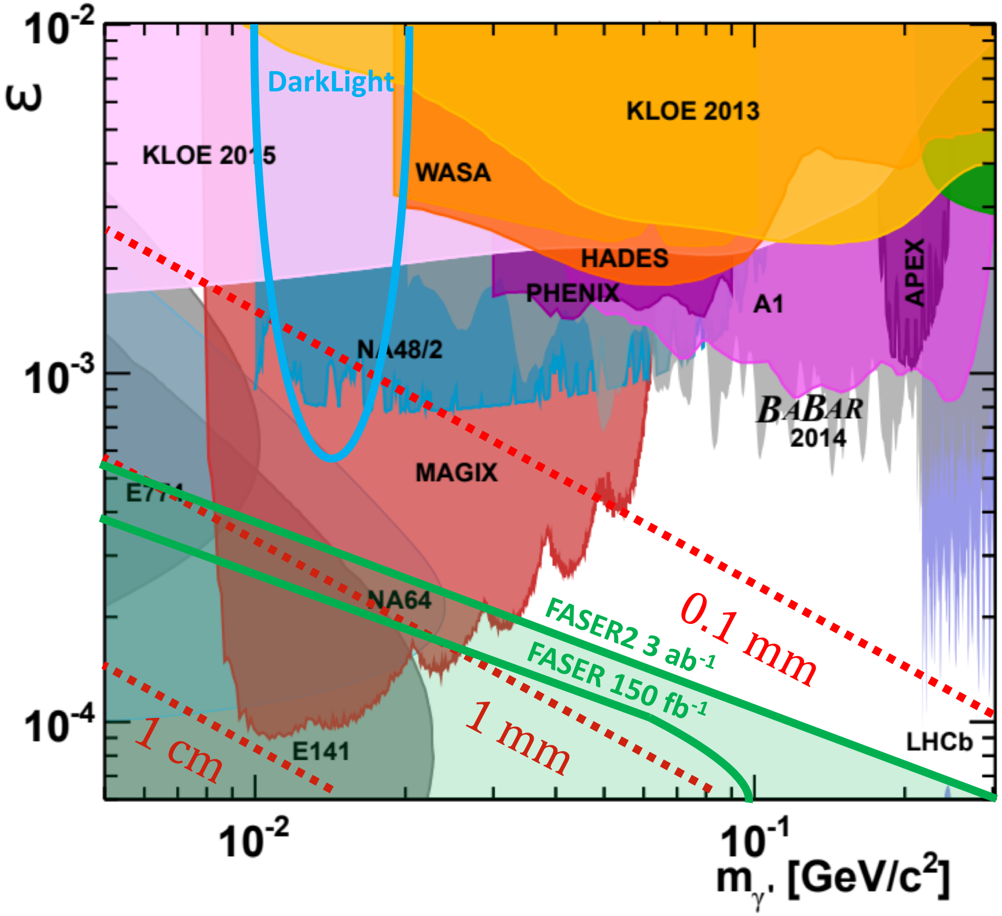
- Missing mass experiments similar to MAGIX
  - PADME@INFN,Frascati, e^{+} beam on e^{-} (ongoing)
  - DarkLight@ARIEL/TRIUMF, e^{-} beam (30 MeV in 2024, 50 MeV in 2025)

- Missing momentum/energy experiments
  - LDMX@SLAC,Stanford, e^{-} beam (4 GeV in 2025, 8 GeV in 2027)
  - NA64@SPS/CERN, e^{-} beam (upgrade)
  - Lohengrin@ELSA,Bonn, e^{-} beam (future)

- Collider experiments
  - FASER@LHC/CERN, pp collisions (ongoing)
  - BaBar, BES III, ISR in $\mathrm{e}^{+}\mathrm{e}^{-}$ collisions (future: Belle II)

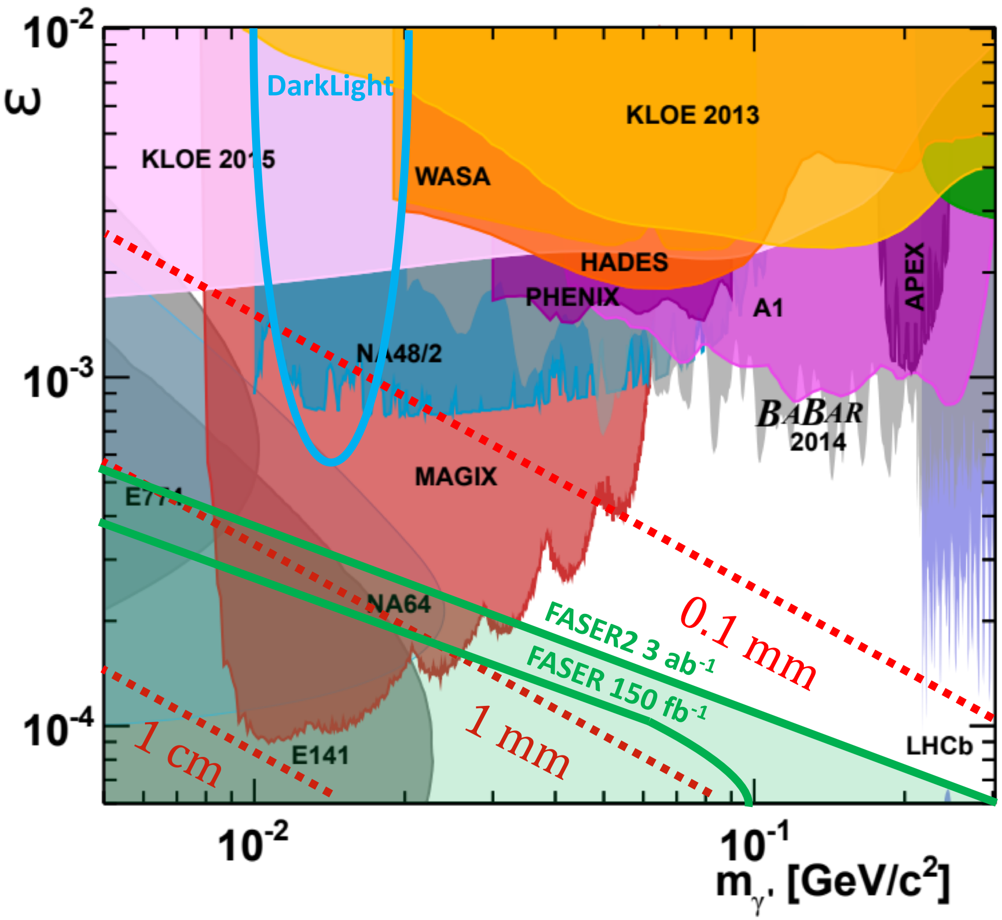
Visible Decay Expected Reach

- Decay length $l = \gamma c \tau \leq 8\ \mathrm{mm}$ requires vertex reconstruction
- Search for a sharp invariant mass peak: $m^2_{\gamma'} = (\mathrm{e}^+ + \mathrm{e}^-)^2$
- Simulation by H. Merkel
- Competitors:
  - DarkLight
  - FASER
  - NA64



Visible Decay Expected Reach

- Decay length $l = \gamma c \tau \leq 8\ \mathrm{mm}$ requires vertex reconstruction
- Search for a sharp invariant mass peak: $m_{\gamma'}^2 = (\mathrm{e}^+ + \mathrm{e}^-)^2$
- Simulation by H. Merkel
- Competitors:
  - DarkLight
  - FASER
  - NA64
- Sensitivity enables the search for the vector boson candidate X17 in excited states of He, Be and C

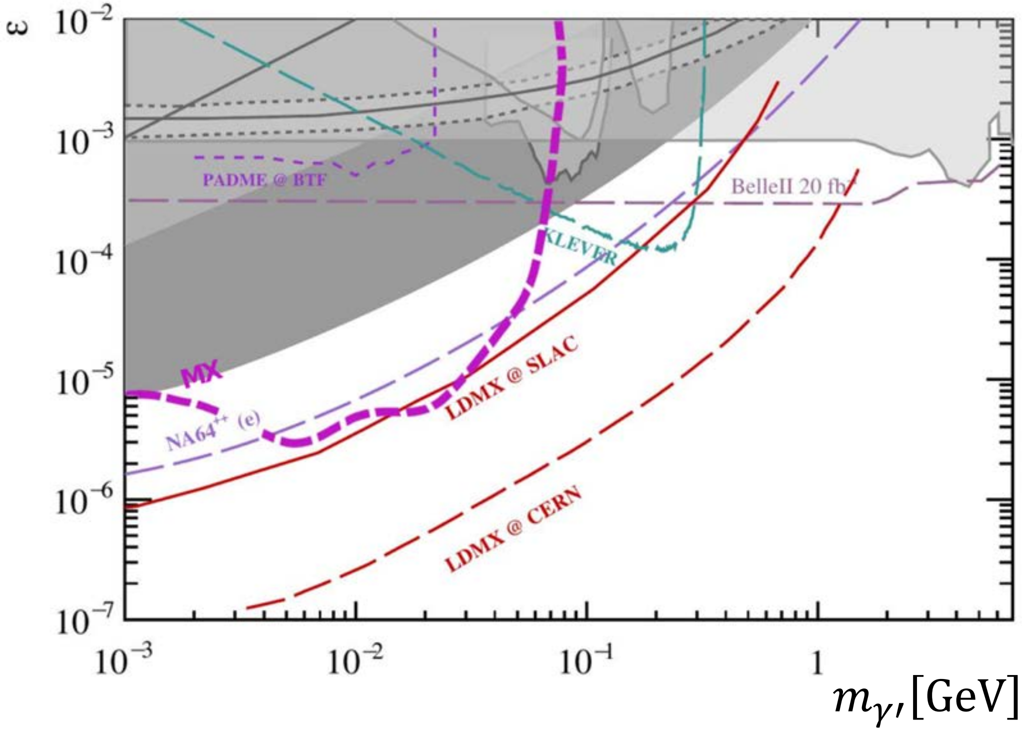


Invisible Decay Expected Reach

- Missing mass:
  $m_{\gamma'}^2 = (e^{o-} - e^- + p^o - p)^2$

- Simulation by P. Gülker

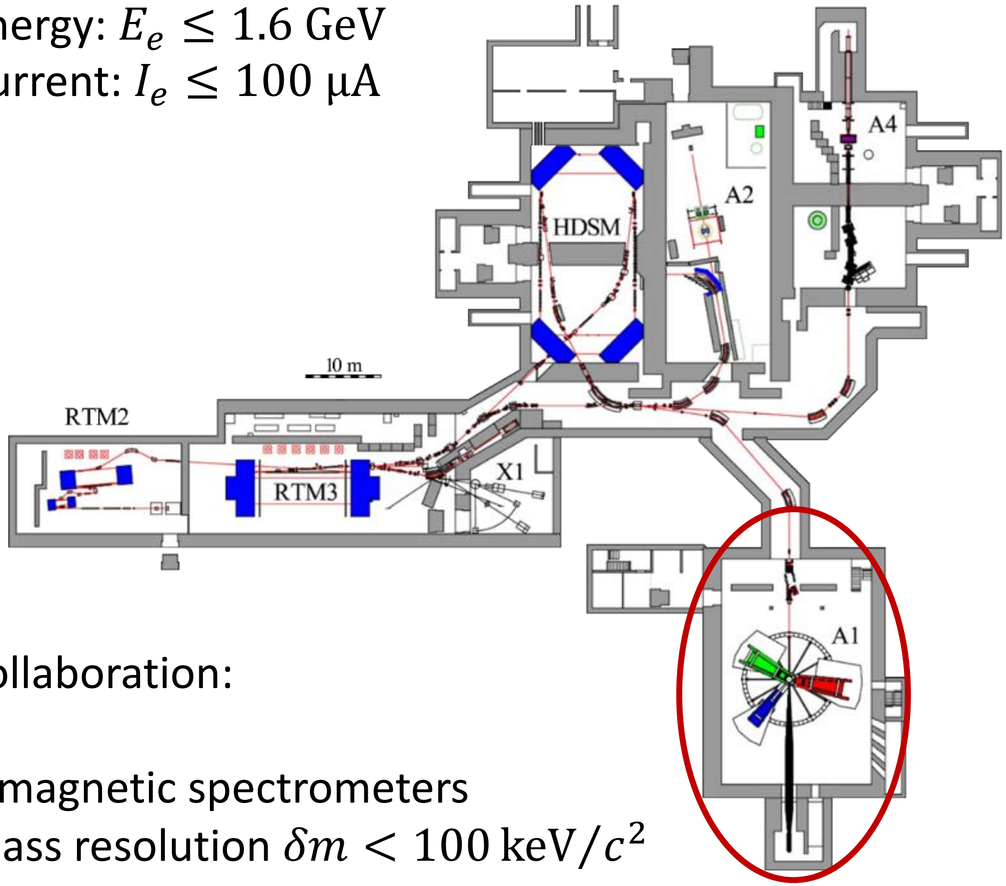
- Competitors:
  - LDMX@SLAC 8 GeV
  - Future NA64
  - Future Belle II at high masses



Visible Decay at MAMI

Linear electron accelerator
Mainz Mikrotron (MAMI):

- Energy: $E_e \leq 1.6\,\mathrm{GeV}$
- Current: $I_e \leq 100\,\mu\mathrm{A}$



A1 collaboration:

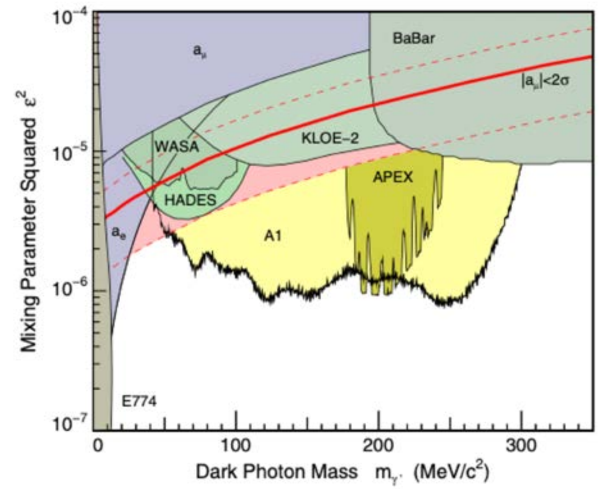
- 3 magnetic spectrometers
- Mass resolution $\delta m < 100\,\mathrm{keV}/c^2$

Experiment:

- Beam: $E_e \in [180, 855]\,\mathrm{MeV}$
- Target: tantalum foil

Exclusion limits:

- $m_{\gamma'} \in [40, 300]\,\mathrm{MeV}/c^2$
- $\varepsilon \geq 8 \cdot 10^{-7}$



H. Merkel, et al., Phys. Rev. Let. 112 (2014) 221802