

European Nuclear Physics Conference,  
September 21-26, 2025  
Caen/France



# Lepton Facilities in Europe – Status and Perspectives

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Achim Denig – JGU & HIM Mainz  
PRISMA<sup>+</sup> Cluster of Excellence



JOHANNES GUTENBERG  
UNIVERSITÄT MAINZ

European Nuclear Physics Conference,  
September 21-26, 2025  
Caen/France

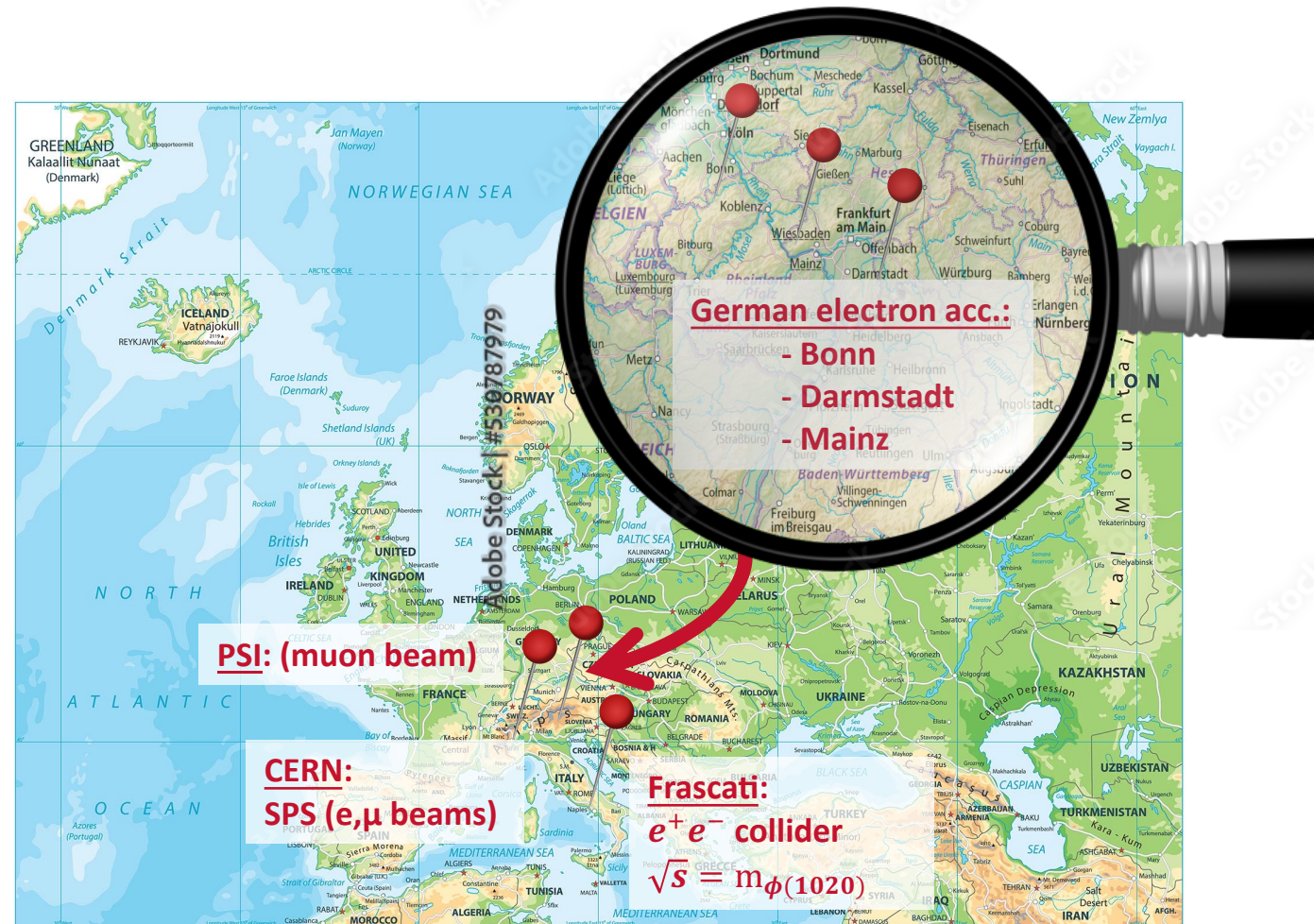


# Lepton Facilities in Europe – Status and Perspectives

- Focus in this talk on the research in the field of nuclear/hadron/particle physics
- Running accelerators & future directions, concentrate on fixed-target machines, only one running  $e^+e^-$  collider: DAΦNE

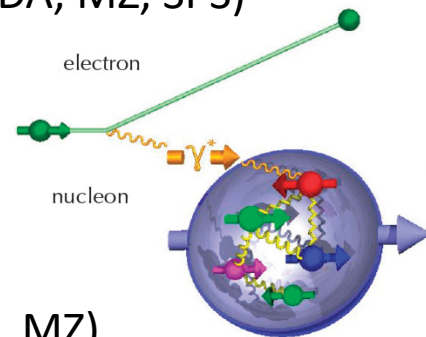


# Overview European Lepton Accelerators

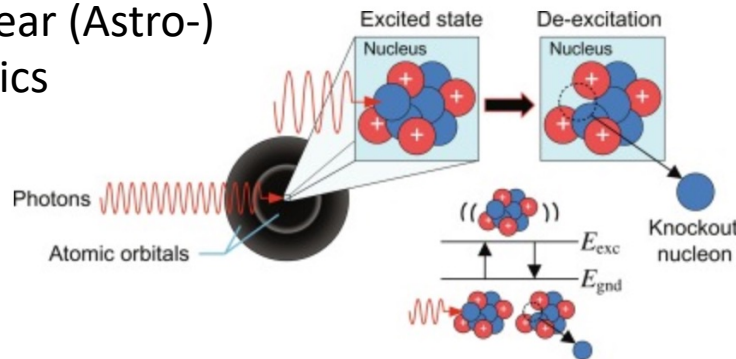


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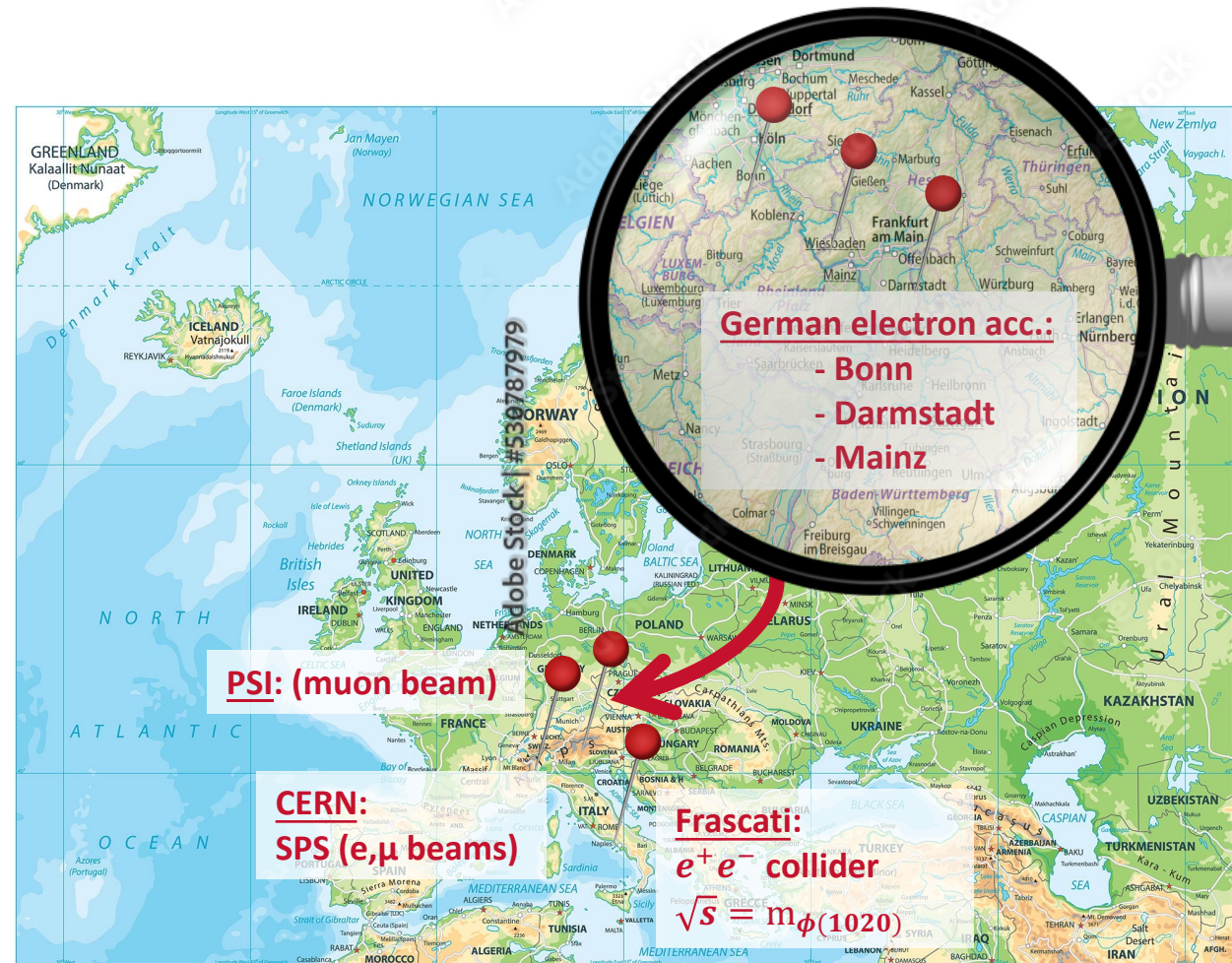
- Electron/Muon scattering (DA, MZ, SPS)  
→ Form factors,  
structure functions



- Photon beam lines (BN, DA, MZ)  
→ Baryon spectroscopy, polarizabilities  
→ Nuclear (Astro-) physics

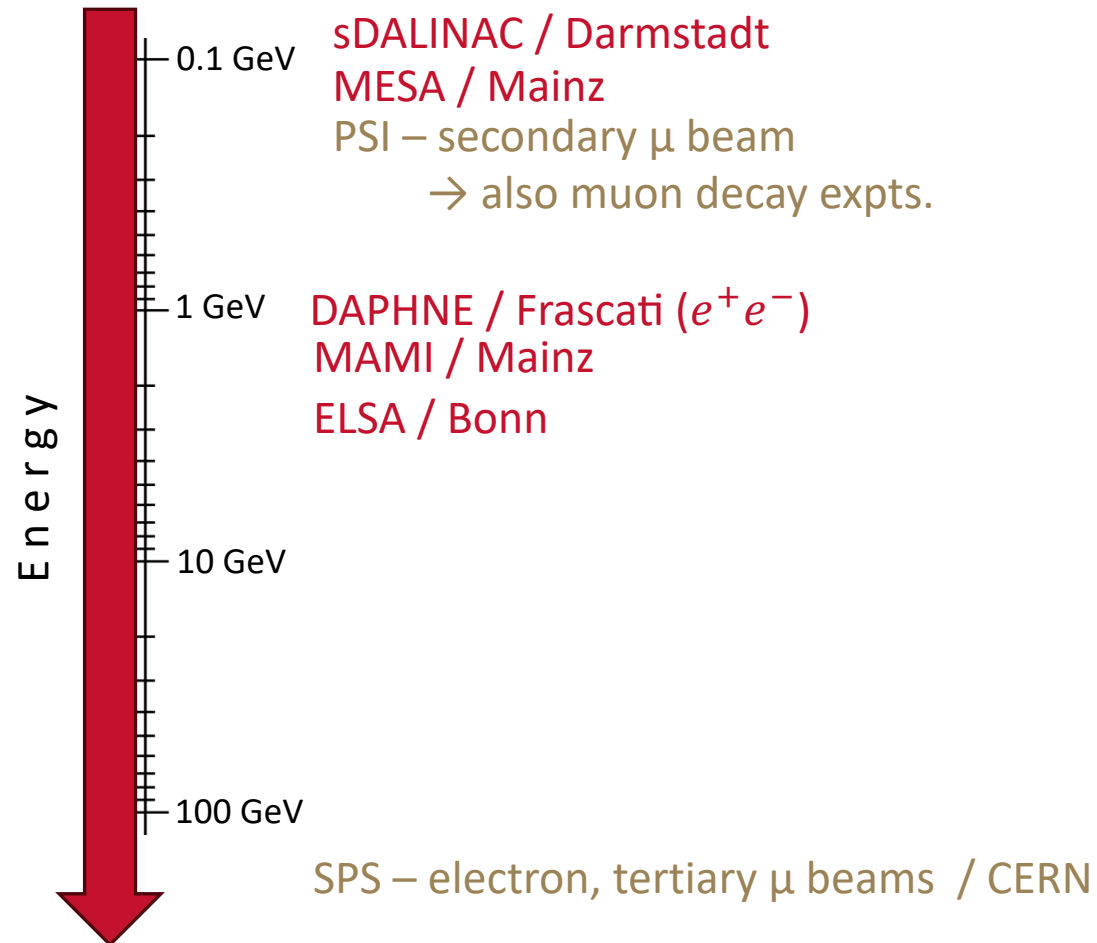


- Low-energy muon beam lines (PSI)  
→ LFV, muonic atoms,  $\mu p$  scattering



# Overview European Lepton Accelerators

$E > O(100 \text{ MeV})$





# Overview European Lepton Accelerators

$E > O(100 \text{ MeV})$

Nuclear physics

SDALINAC / Darmstadt  
MESA / Mainz  
PSI – secondary  $\mu$  beam  
→ also muon decay expts.

Hadron physics

DAPHNE / Frascati ( $e^+e^-$ )  
MAMI / Mainz  
ELSA / Bonn

Energy

10 GeV

Deep Inelastic Scattering

AMBER  
Apparatus for Meson and Baryon  
Experimental Research



SPS – electron, tertiary  $\mu$  beams / CERN  
→ nucleon structure (DIS), dark sector



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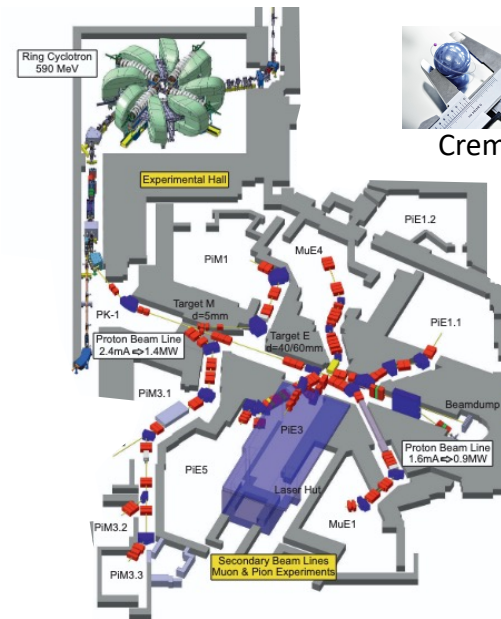
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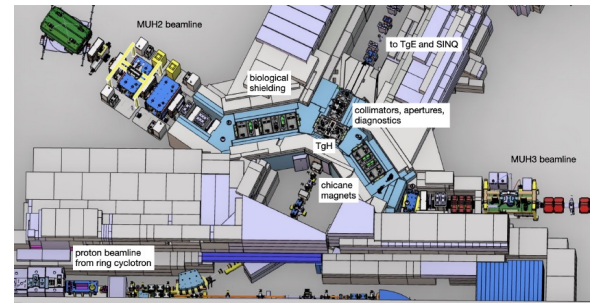
A00BER  
Apparatus for Meson and Baryon  
Experimental Research



PSI proton cyclotron with secondary beam lines:  
 $\mu$  rate  $O(<100 \text{ MeV/c}) \rightarrow$  most intense continuous low momentum muon beam in the world up to few  $\times 10^8 \mu/s$

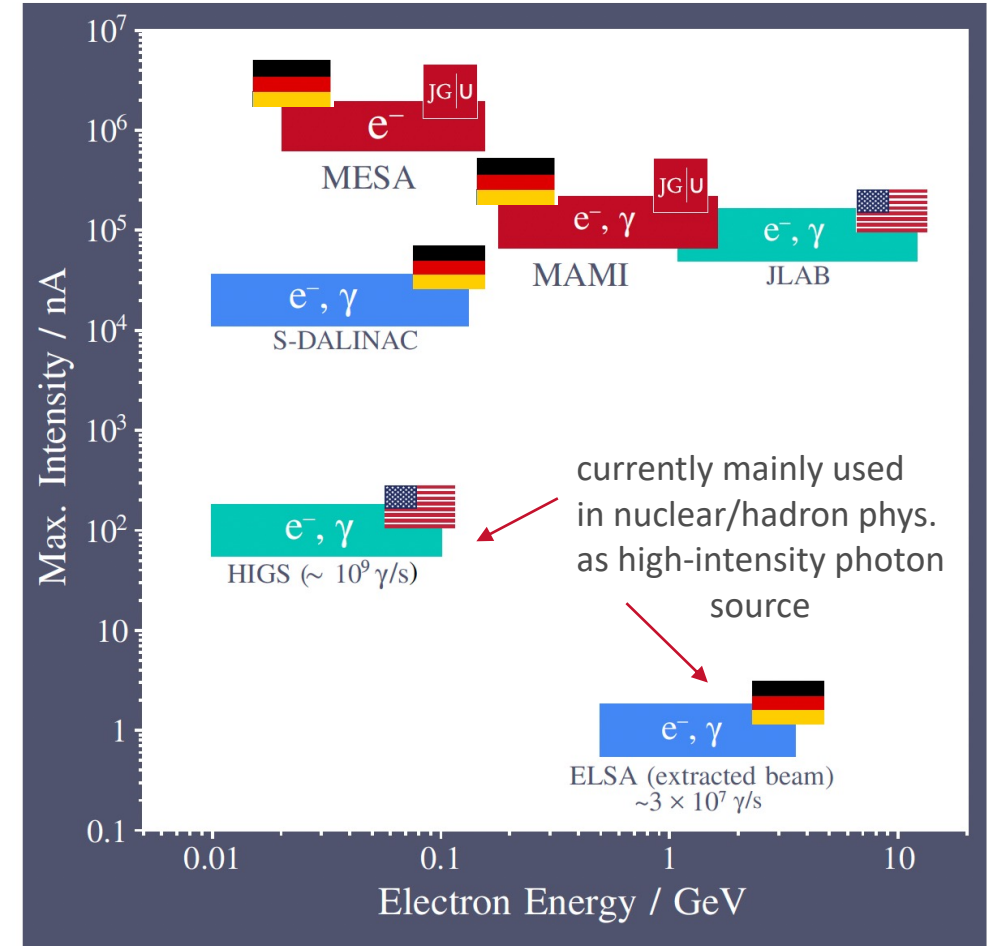
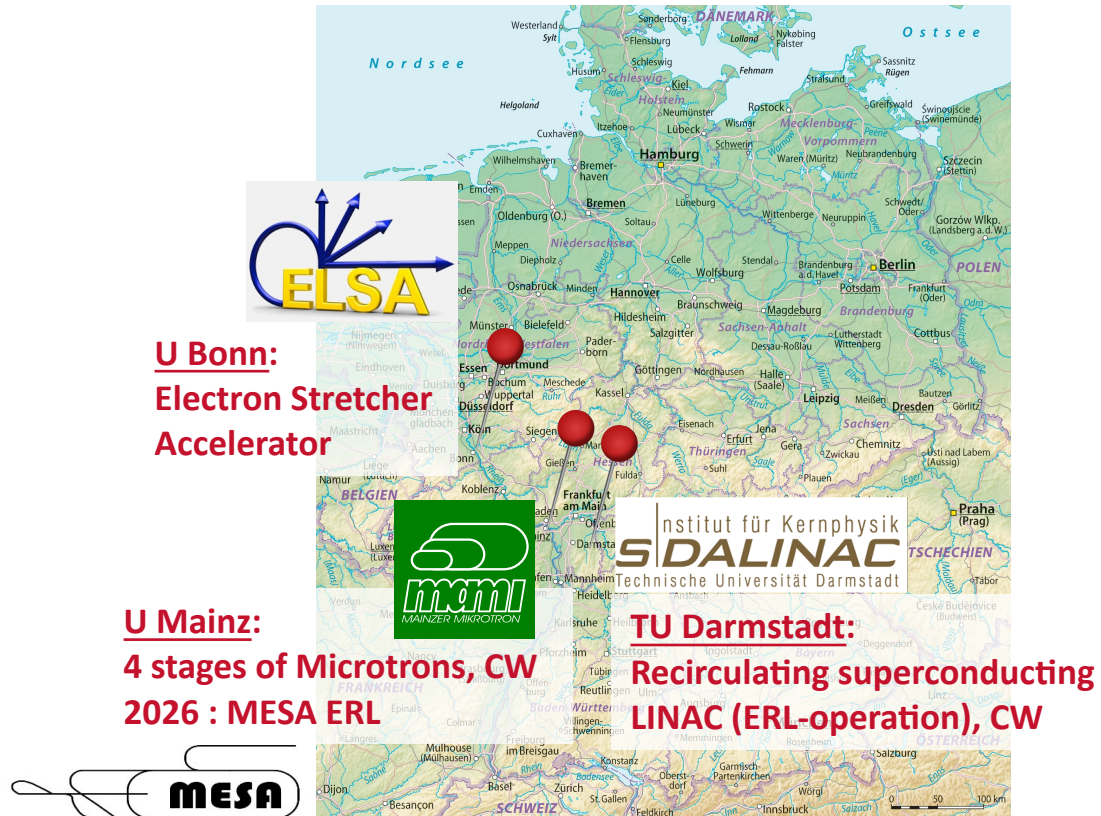


Klaus Kirch (Wed Plenary)



High Intensity Muon Beamline HIMB project (2029+):  
New target station and muon beam line  
→ increase of  $\mu$  intensity by 2 orders of magnitude

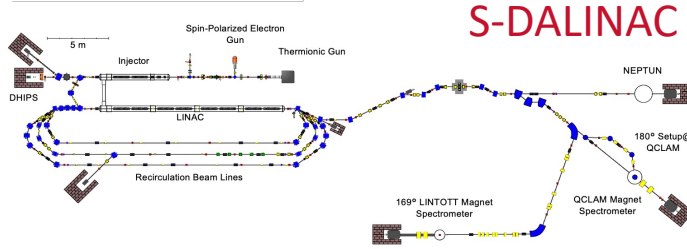
# Fixed-Target Electron Accelerators in Germany



# „University Accelerators“ S-DALINAC, ELSA, MAMI

## Main Focus on:

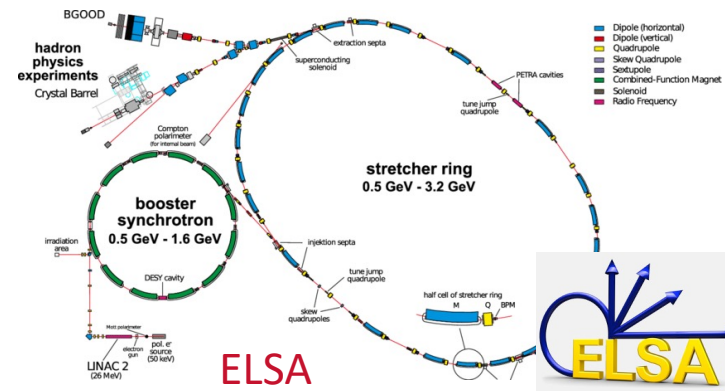
Institut für Kernphysik  
**S-DALINAC**  
Technische Universität Darmstadt



**S-DALINAC**

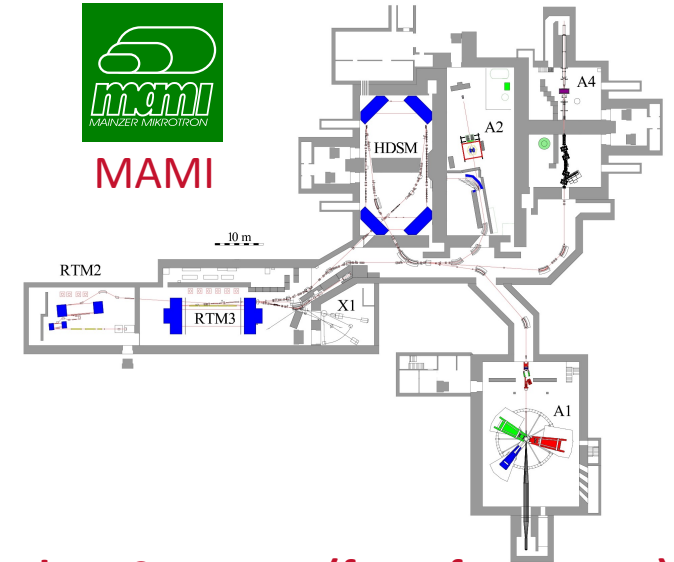
**Nuclear (Astro-)physics**  
**Energy-Recovering Linac R&D**

- Electron scattering facilities
- Photon beam lines



**ELSA**

**Hadron Spectroscopy**  
→ Photon beam lines



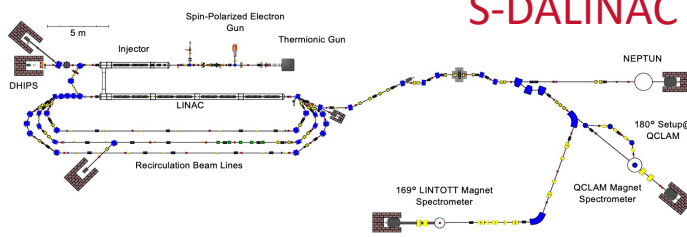
**MAMI**

**Hadron Structure (form factors, ....)**  
**Hadron Spectroscopy**  
**Nuclear (Astro-)physics**  
**New Physics Searches**  
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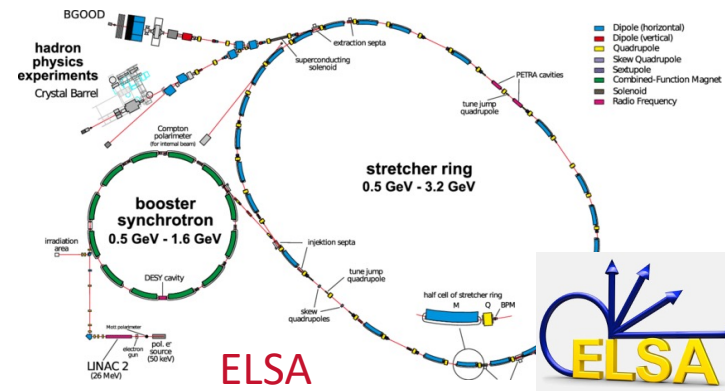
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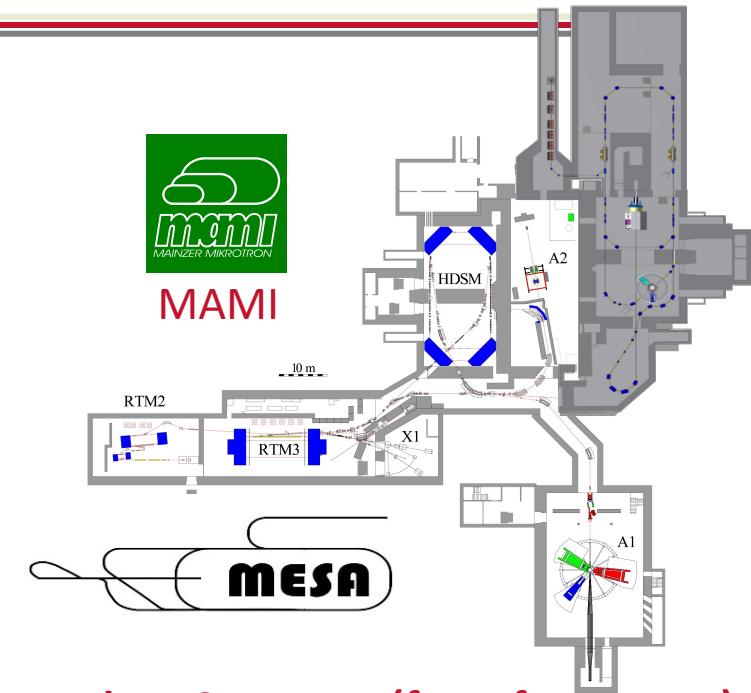
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**MAMI**  
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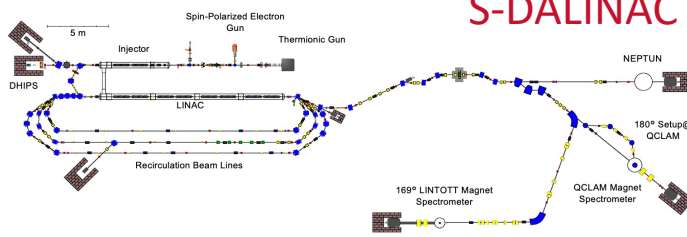


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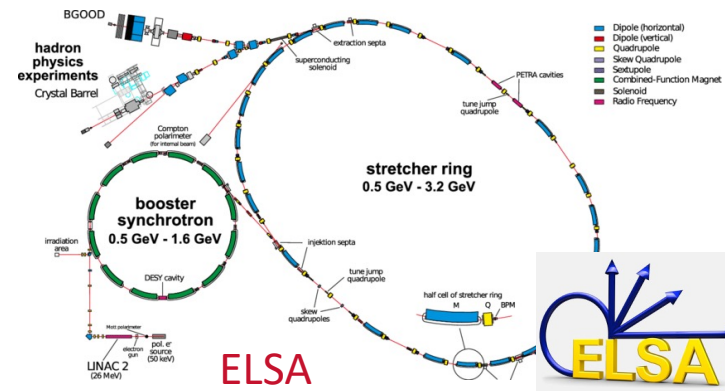
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S-DALINAC

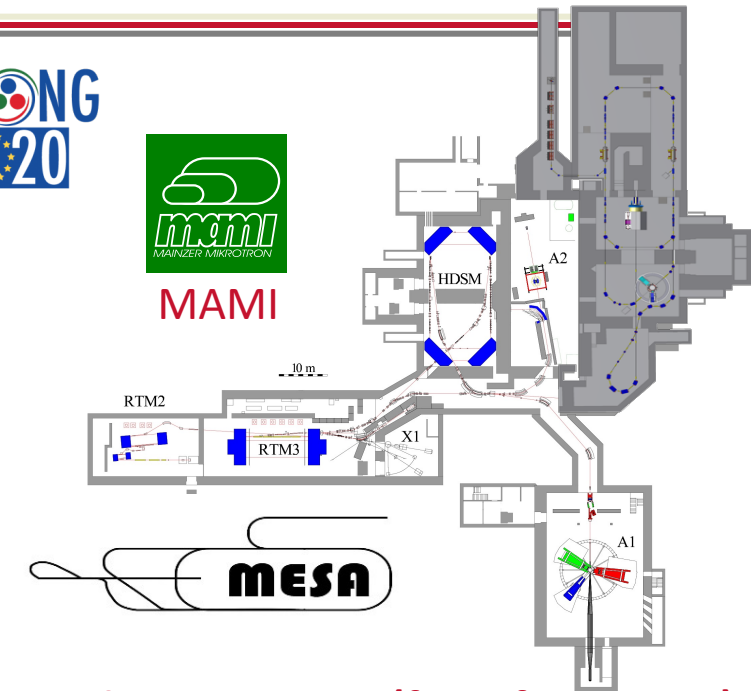
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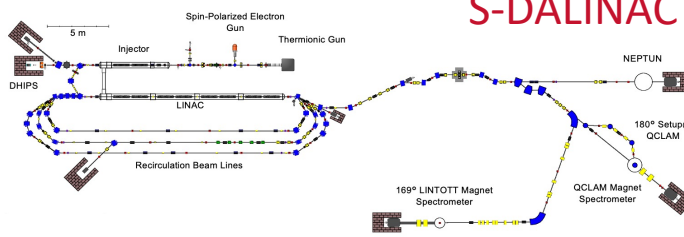
→ World-class competitiveness demonstrated by successes in obtaining 3rd part funding, most recently in German Excellence Strategy successes for Bonn and Mainz

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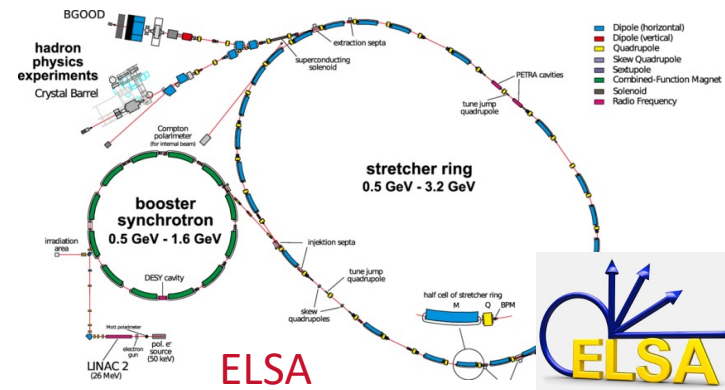
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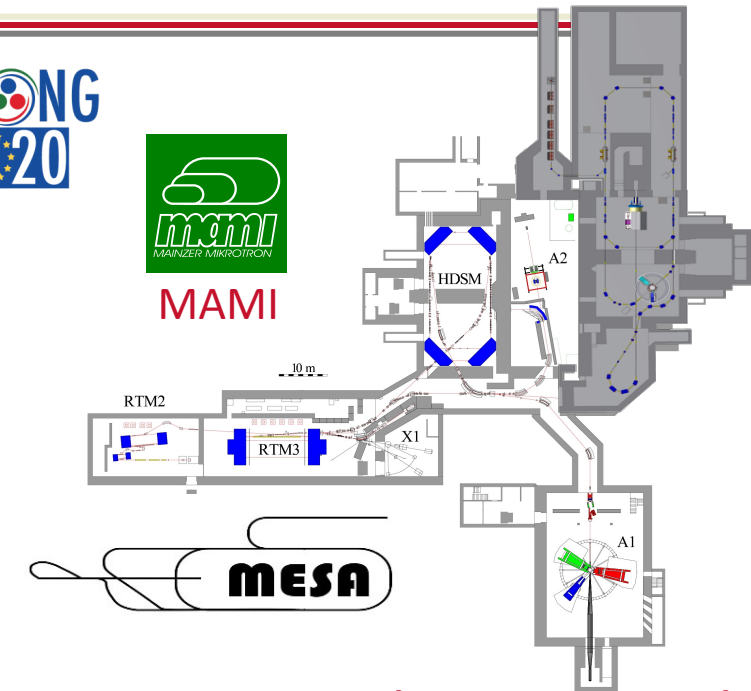
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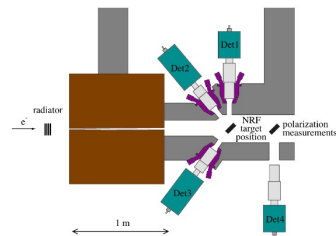
- Electron scattering facilities
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→ **World-class competitiveness demonstrated by successes in obtaining 3rd part funding, most recently in German Excellence Strategy successes for Bonn and Mainz**

# Nuclear (Astro-)Physics at the S-DALINAC

## Electron and Photon beams :

- **Lintott high resolution spectrometer**
- **QCLAM coincidence spectrometer for electron scattering**
  - high acceptance w. possibility to operate under  $180^\circ$
  - commissioning of  $(e, e'\gamma)$  electrophotoproduction set-up DAGOBERT  
[B.Hesbacher et al., NIM A 1078, 170574 \(2025\)](#)
  - program launched for electrofission studies
- **Neptun tagged photon beam**
- **DHIPS low energy, high intensity photon beam**
  - Role of chiral two-body currents in light nuclei:  ${}^6\text{Li}$ ,  ${}^{10}\text{B}$ ,  ${}^{14}\text{N}$

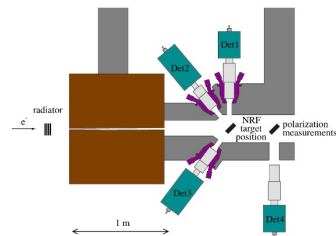


Darmstadt High Intens.  
Photon Setup (DHIPS)

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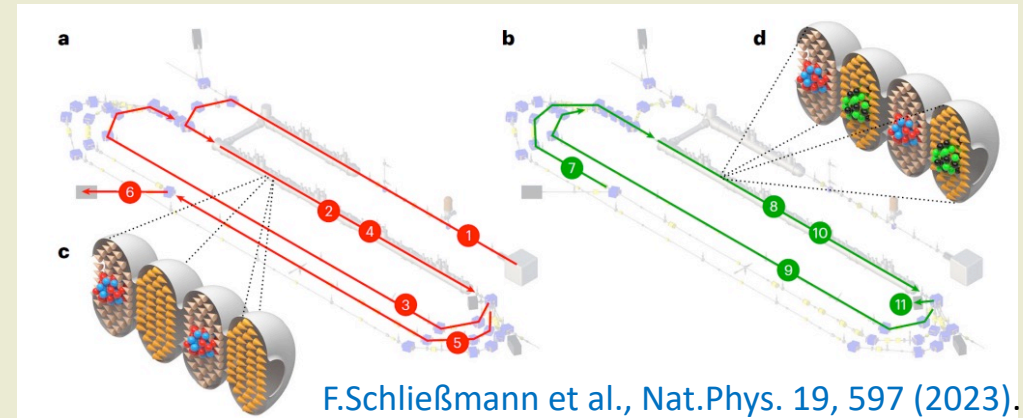
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Darmstadt High Intens.  
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## First demonstration of Energy-Recycling in a multi-turn Energy-Recovery LINAC (ERL) (2022)



- >99% energy recycling achieved at high energy

nature physics

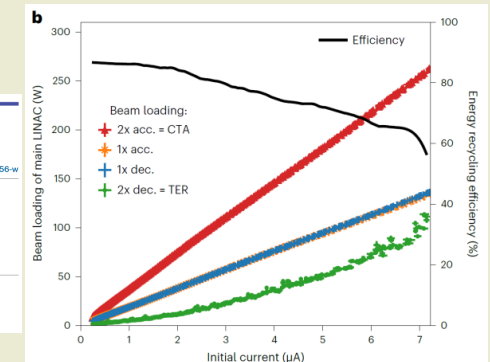
### Article Realization of a multi-turn energy recovery accelerator

Received: 28 March 2022

Accepted: 26 October 2022

Published online: 26 January 2023

Felix Schließmann, Michaela Arnold, Lars Juergensen, Norbert Pietrala, Manuel Dutine, Marco Fischer, Ruben Grewe, Manuel Steinhilber, Lennart Stobbe & Simon Weil

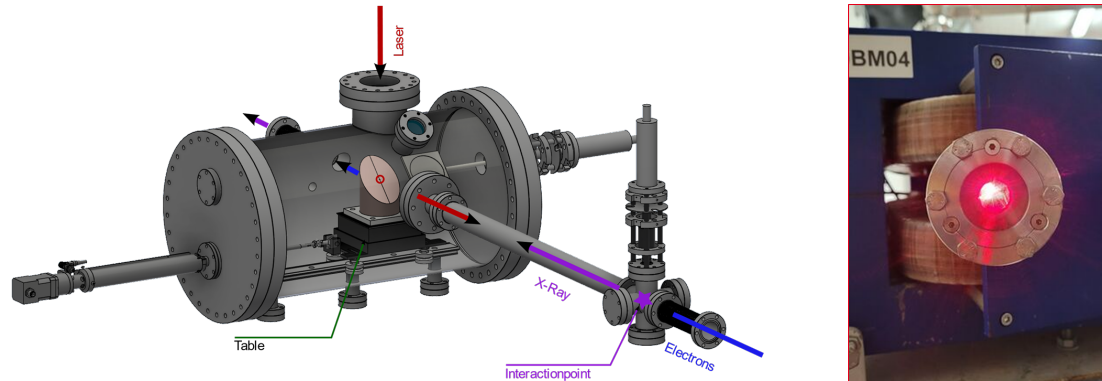




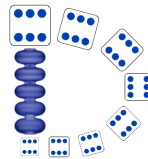
# Future Directions S-DALINAC @ Darmstadt

## Development of ERL operation for photon beams

- Artificial  $\gamma$ -ray beams from Laser-Compton Backscattering (LCB) in multi-turn ERL operation

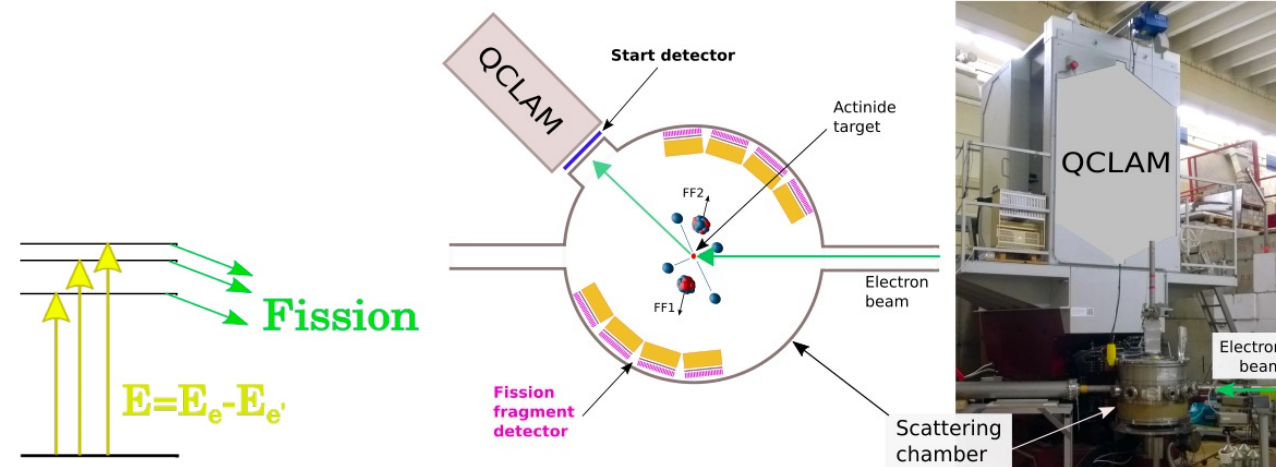


- Possible future: DICE (Darmstadt Individually-Circulating Compact ERL)
  - complementary to MESA
  - further requirements of community



## New electrofission setup “DEFERA” for the S-DALINAC

→ new information on properties of transuranium actinides that provide constraints for the fission cycle of the r-process of nucleosynthesis in neutron star mergers



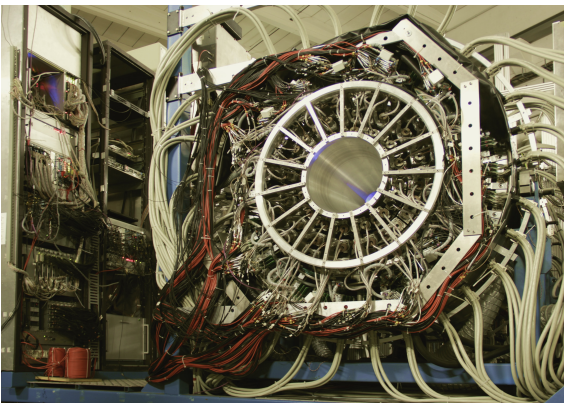
- use of electrons to **excite the nucleus**
- excited states **decay promptly via fission**
- **Coincidence** of scattered electrons and fission fragments
- funding approval for DEFERA in Jan. 2025; set-up started

# Photon-induced Baryon Physics at ELSA

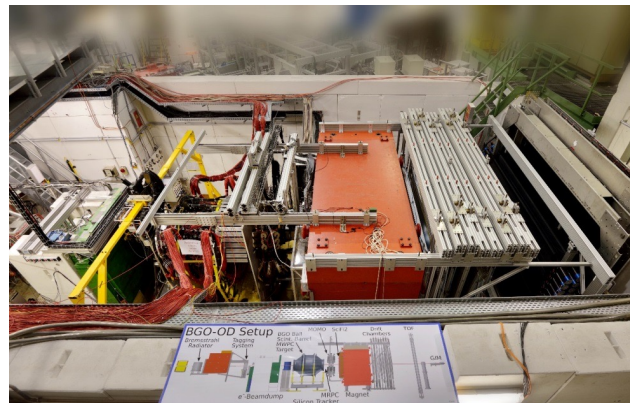


## Photon beam (linear & circular polarization):

- **CB-ELSA** 4 $\pi$  detector + **TAPS** + polarized target
  - Double polarization experiments:  $\vec{\gamma}\vec{p} \rightarrow \pi^0 p, \eta p, \pi^0 \pi^0 p, \dots$
  - Full kinem. coverage of asymmetries  $\Sigma, E, G, H, \dots$
- **BGOOD** detector (charged final states)
  - BGO 4 $\pi$  calorimeter combined with forward spectrometer
  - Strangeness photoproduction at low momentum transfer and coherent photoproduction off the deuteron

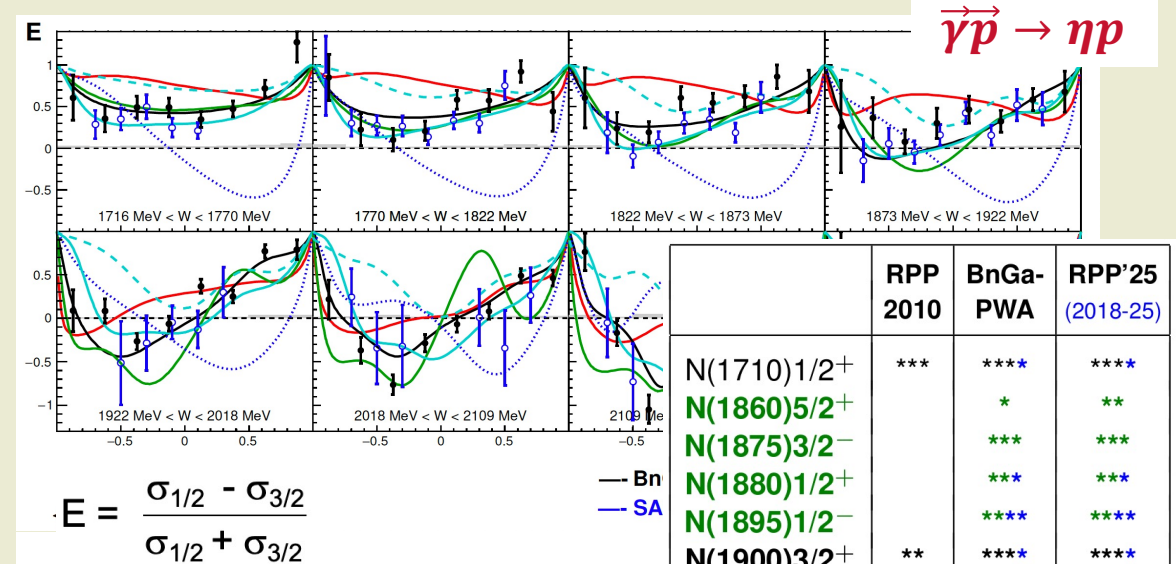


Crystal Barrel/TAPS



BGOOD

## Polarization d.o.f.: key to resolve the baryon spectrum



→ huge impact on knowledge of resonances in the second and third resonance region

Farah Afzal (Tue Plenary)

	RPP 2010	BnGa- PWA	RPP'25 (2018-25)
N(1710)1/2+	***	****	****
<b>N(1860)5/2+</b>		*	**
<b>N(1875)3/2-</b>		***	***
<b>N(1880)1/2+</b>		***	***
<b>N(1895)1/2-</b>		****	****
<b>N(1900)3/2+</b>	**	****	****
<b>N(2060)5/2-</b>		***	***
<b>N(2100)1/2+</b>	*	***	***
<b>N(2120)3/2-</b>		***	***
<b>Δ(1600)3/2+</b>	***	***	****
<b>Δ(1900)1/2-</b>	*	***	***
<b>Δ(1940)3/2-</b>	*	**	**
<b>Δ(2200)7/2-</b>	*	***	***

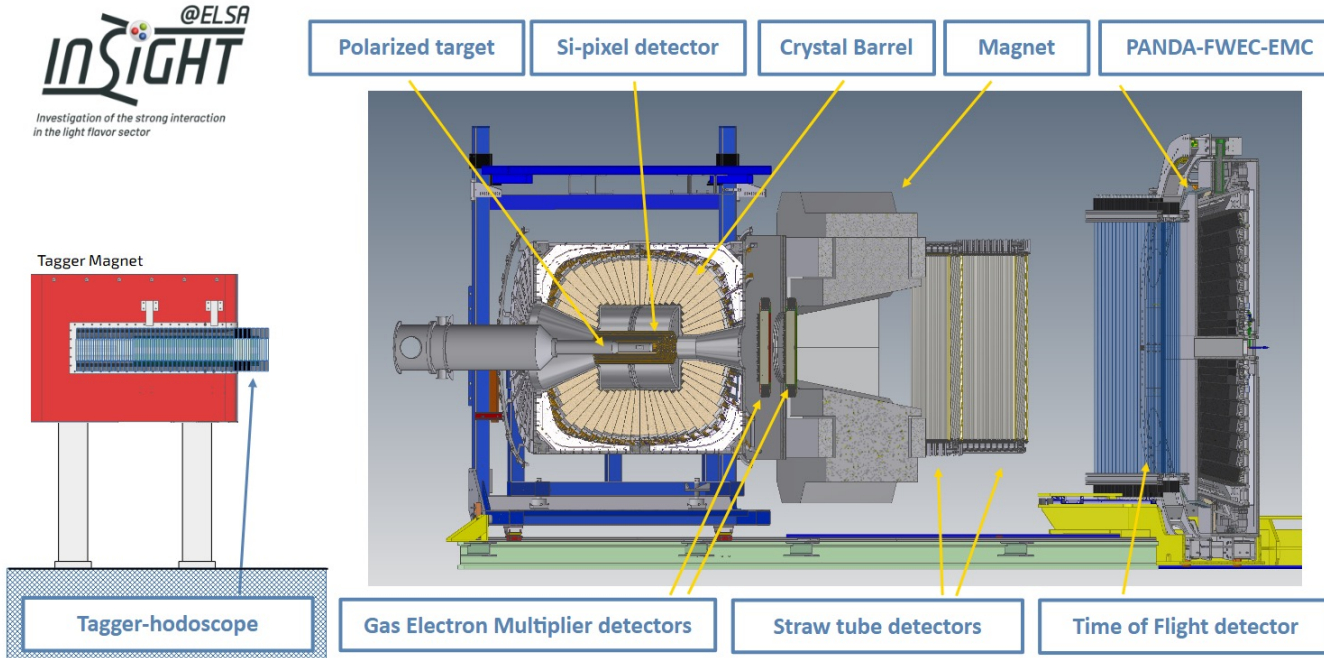
only examples shown



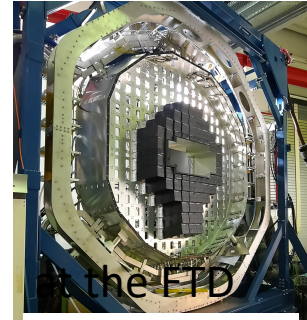
# Future Directions ELSA @ Bonn



A new experiment as part of the new Cluster of Excellence „Color meets Flavor“:



Arrival of the PANDA forward endcap calorimeter in Bonn:



- Over almost the entire  $4\pi$ -solid angle:
- High resolution photon measurements
  - Precise charged particle detection
- Polarized beam and polarized target

→ unique possibilities!



# Future Directions ELSA @ Bonn



After ELSA shutdown in 2026/27:

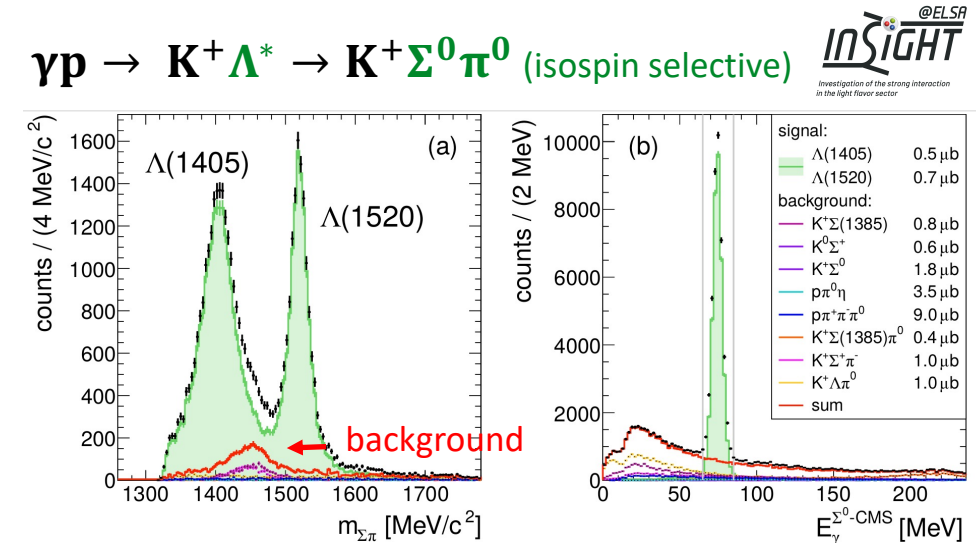
- **INSIGHT@ELSA: Non-strange and strange baryon spectroscopy:**

Gain a complete picture of the  $N^*$ ,  $\Delta^*$  - baryon spectrum:

⇔ Polarized photoproduction off the polarized proton and neutron!  
(unambiguous PWA not possible without polarization obs.)

Spectrum and properties of  $\Lambda^*$ ,  $\Sigma^*$  ⇔ “.. field is starved for data”

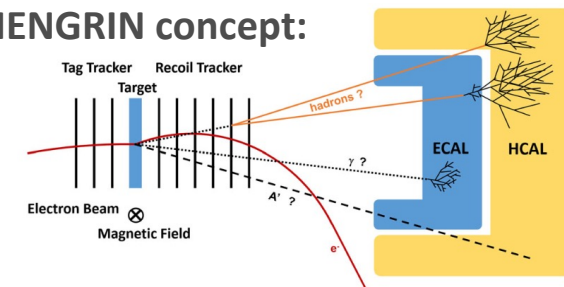
⇔ multi-quark states? molecules? 2-pole structures?



- **LOHENGRIN proposal:** Search for Light Dark Matter via dark bremsstrahlung  
– need  $10^{15}$  Electrons on Target via ELSA slow extraction @ 500 MHz  
(EPJC 85 (2025) 5, 600)

- **ELSA also a key facility** (test beam)  
for the FTD (Forschungs- und Technologiezentrum Detektorphysik) at University of Bonn

LOHENGRIN concept:





# Nucleon Structure and Spectroscopy at MAMI

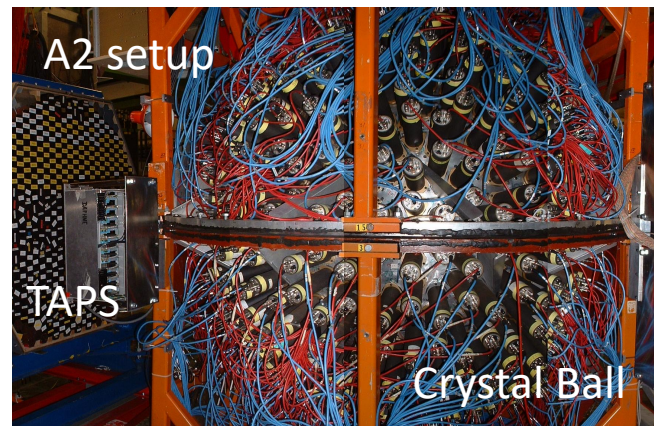
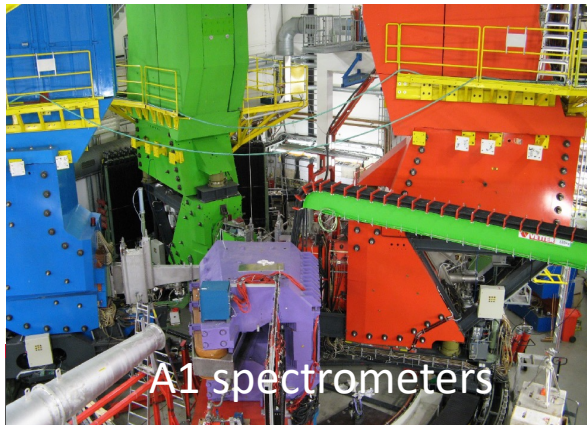
## Electron and Photon beams (linear & circular polar.):

### ■ A1 high-resolution spectrometer setup (incl. KAOS)

- Nucleon electromagnetic form factors
- Transverse asymmetries as input to neutron skin determination
- Hypernuclear physics
- Detection of neutron-rich isotope  ${}^6\text{H}$

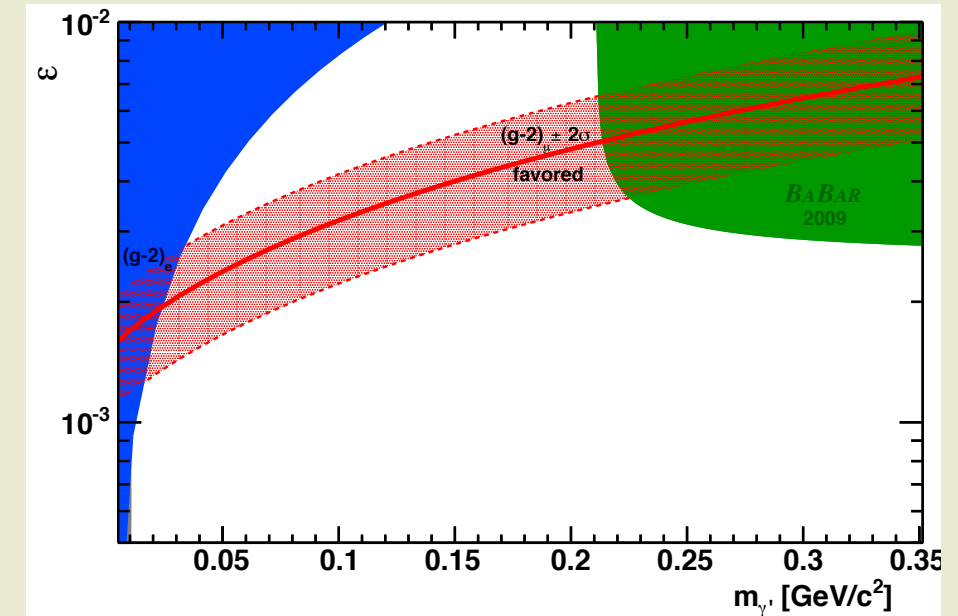
### - A2: Crystal Ball $4\pi$ detector + TAPS + polarized target

- Baryon spectrum via double-polarization experiments
- Nucleon Polarizabilities via Compton scattering  $\vec{\gamma}\vec{p} \rightarrow \gamma'p'$
- Meson Transition Form Factors as input to HLbL  $(g-2)_\mu$



## Unique possibilities also beyond Hadron Physics, e.g. Dark Photon $\gamma'$ searches at A1/MAMI

- Force carrier of a dark sector
- Could explain astrophysical anomalies
- Could explain  $(g-2)_\mu$  puzzle



# Nucleon Structure and Spectroscopy at MAMI

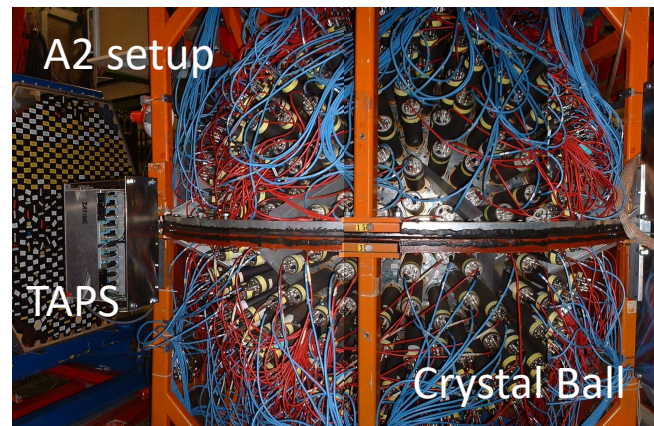
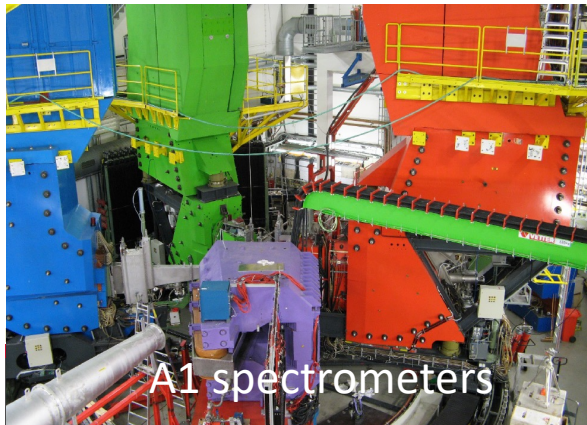
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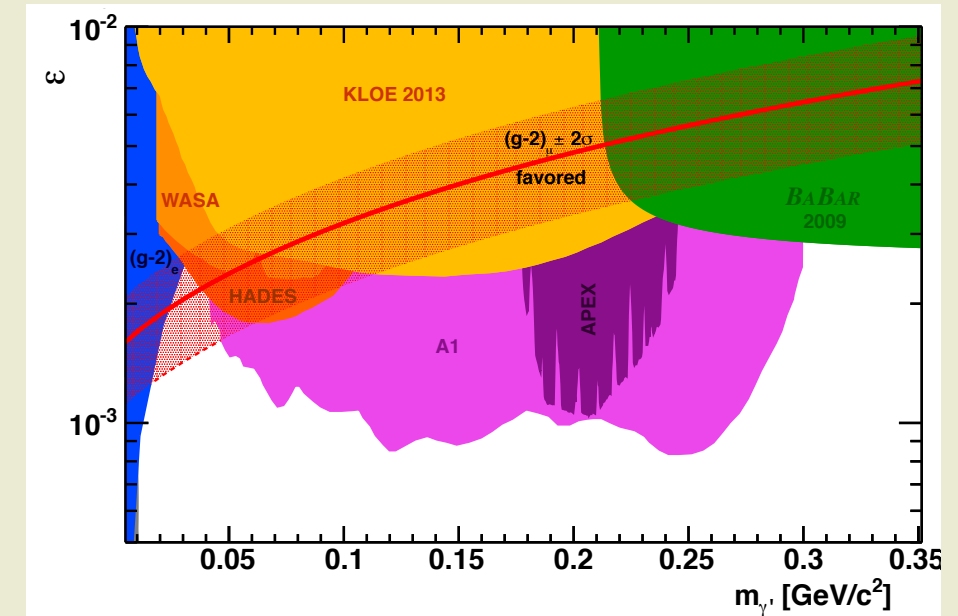
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# Future Directions MAMI @ Mainz

## Continuation of operation of A1 and A2 setup

### ■ A1 high-resolution spectrometer setup

- Operation of supersonic **gas jet target** constructed with U Münster (A. Khoukaz) for MAGIX experiment at MESA
- Improved **MAMI energy measurements**

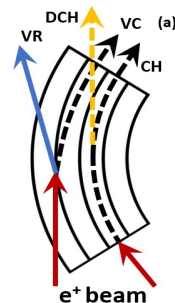


### ■ A2 Crystal Ball/TAPS setup

- **Neutron polarizability** program
- Searches for **hexaquark  $d^*(2380)$**

### ■ Positron beam line (X1 area) for channeling experiments

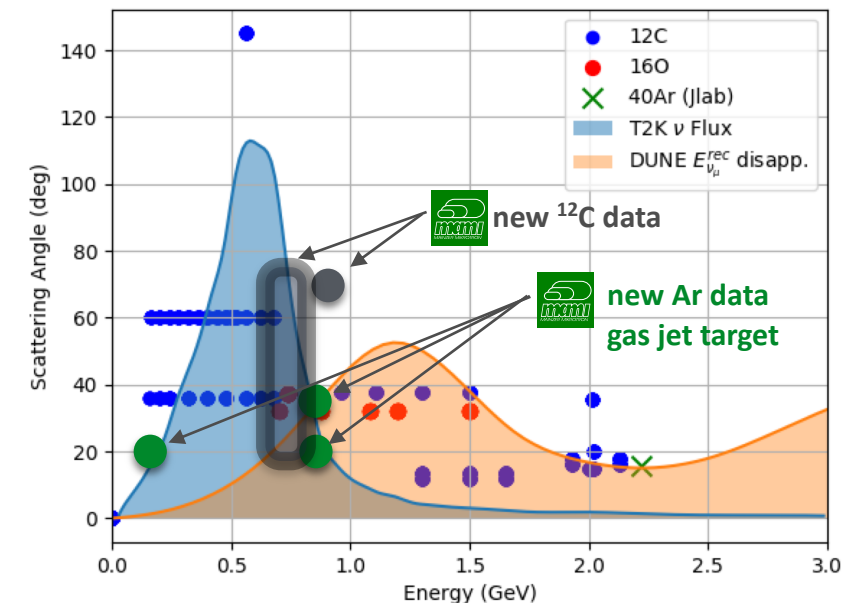
First highly efficient deflection of sub-GeV positrons in bent crystal worldwide !



## Electrons for Neutrinos (A1 experiment)

Interpretation of **neutrino experiments** (DUNE, T2K, Hyper-K, Mini-Boone, ...) requires knowledge of **neutrino-nucleus interaction** ( $^{12}\text{C}$ ,  $^{16}\text{O}$ ,  $^{40}\text{Ar}$ )

→ **Check and calibrate MC-programs** via dedicated program of **electron-nucleus measurements**





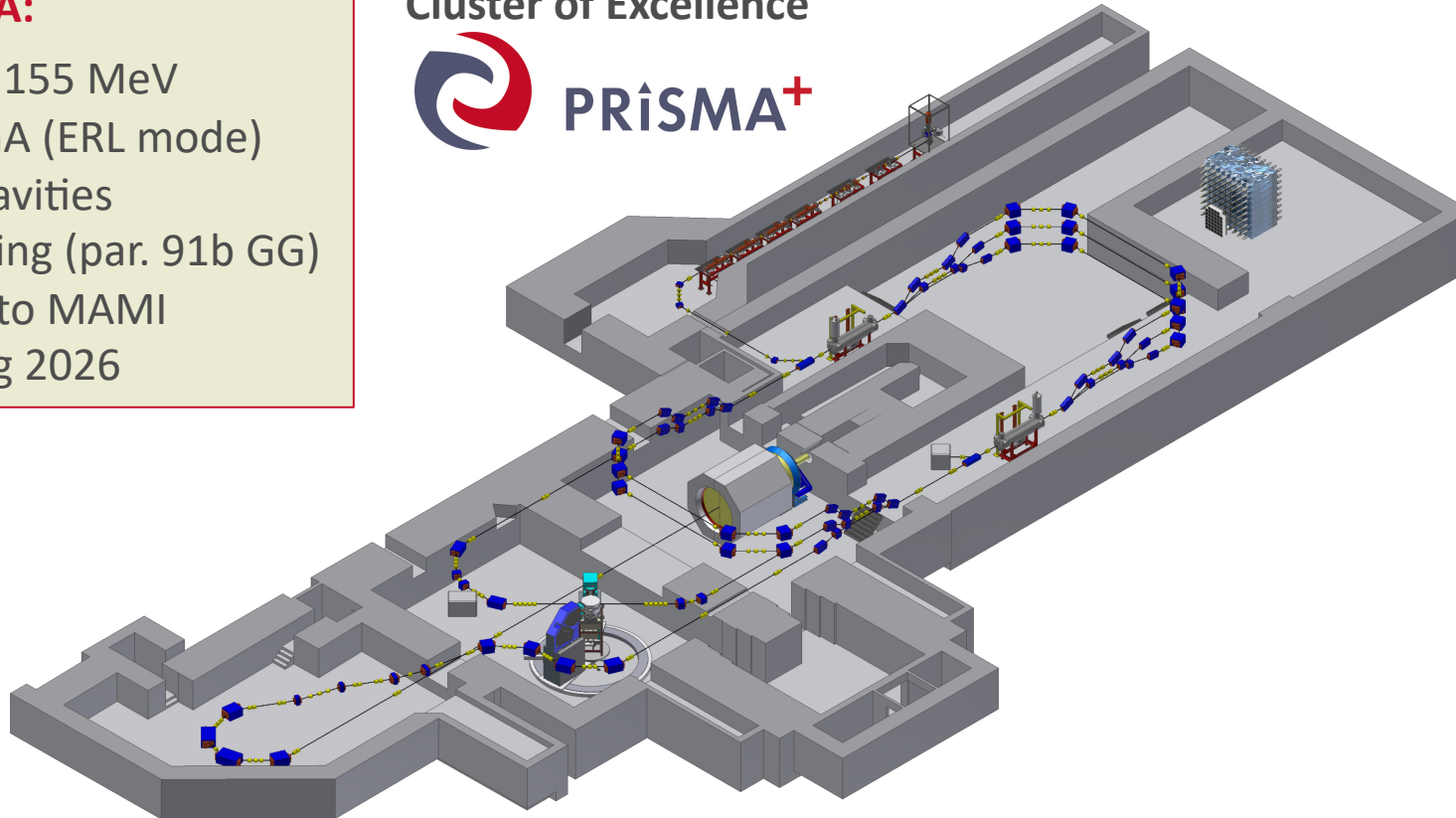
# Future directions at Mainz: MESA

## Mainz Energy-Recovering Superconducting Accelerator

### Key parameters MESA:

- Max. beam energy 155 MeV
- Beam current >1 mA (ERL mode)
- Superconducting cavities
- New research building (par. 91b GG)
- Can run in parallel to MAMI
- Start commissioning 2026

Cluster of Excellence





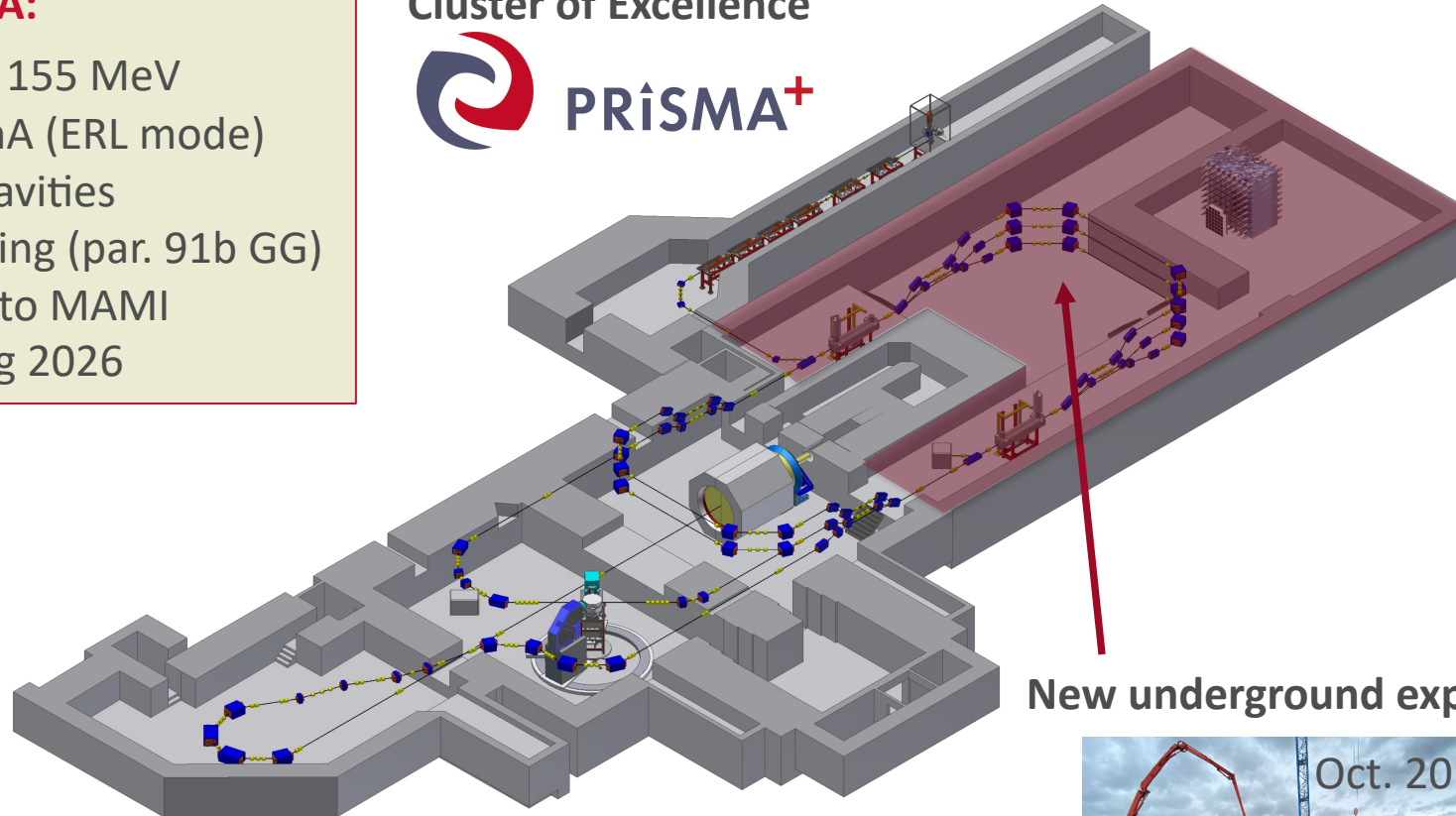
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Cluster of Excellence



New underground experimental hall (par. 91b GG)



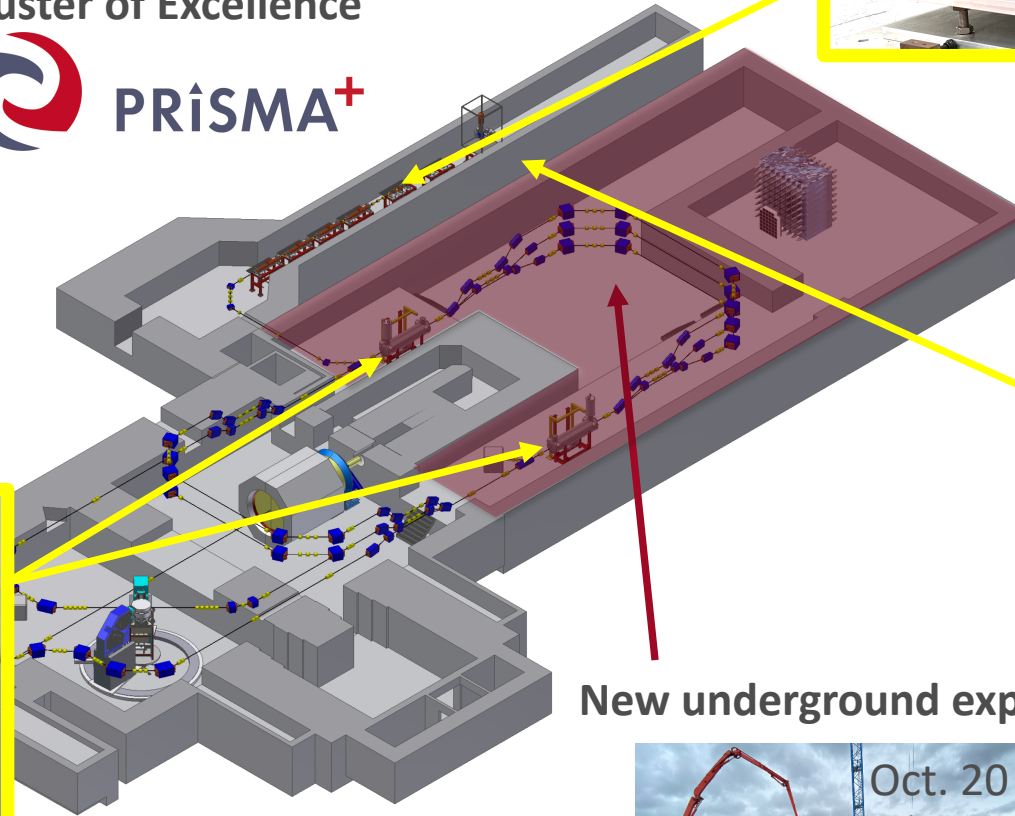
# Future directions at Mainz: MESA

## Mainz Energy-Recovering Superconducting Accelerator

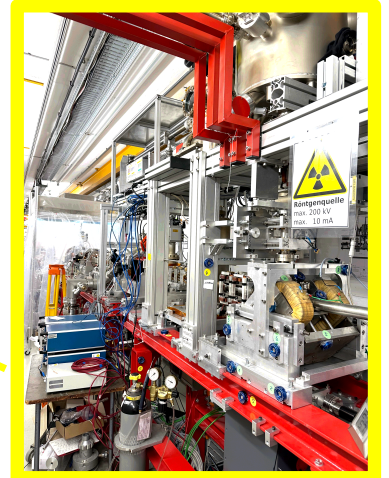
### Key parameters MESA:

- Max. beam energy 155 MeV
- Beam current >1 mA (ERL mode)
- Superconducting cavities
- New research building (par. 91b GG)
- Can run in parallel to MAMI
- Start commissioning 2026

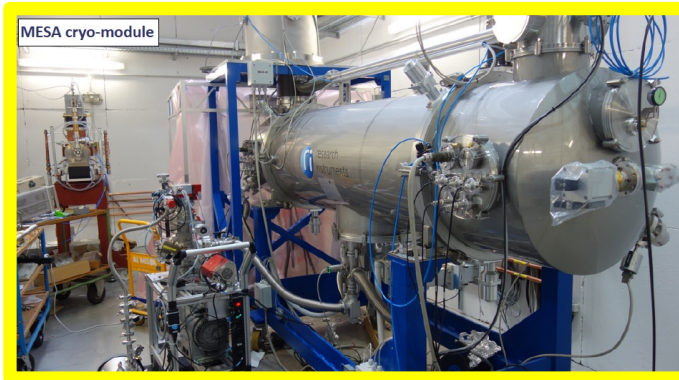
Cluster of Excellence



Normal conducting LINAC



Polarized Source Test Setup



Cryomodules successfully tested

New underground experimental hall (par. 91b GG)

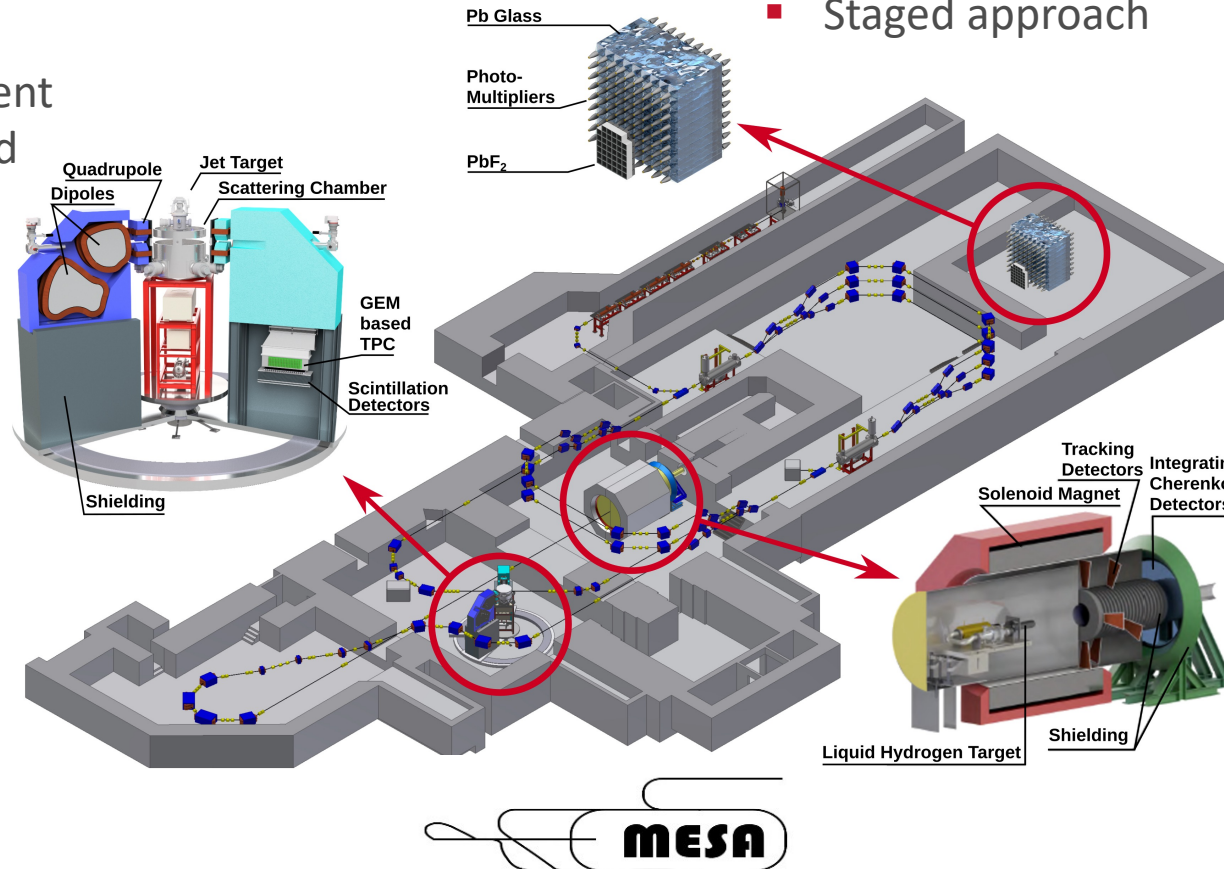




# MESA Experiments

## MAGIX experiment

- Operated in ERL mode of MESA
- Double-arm spectrometers
- Internal gas target experiment
- Gas jet target commissioned in 2017/18



## DarkMESA

- Beam dump experiment
- Direct detection of light dark matter
- PbF<sub>2</sub> and lead glass Cerenkov calorimeter
- Staged approach

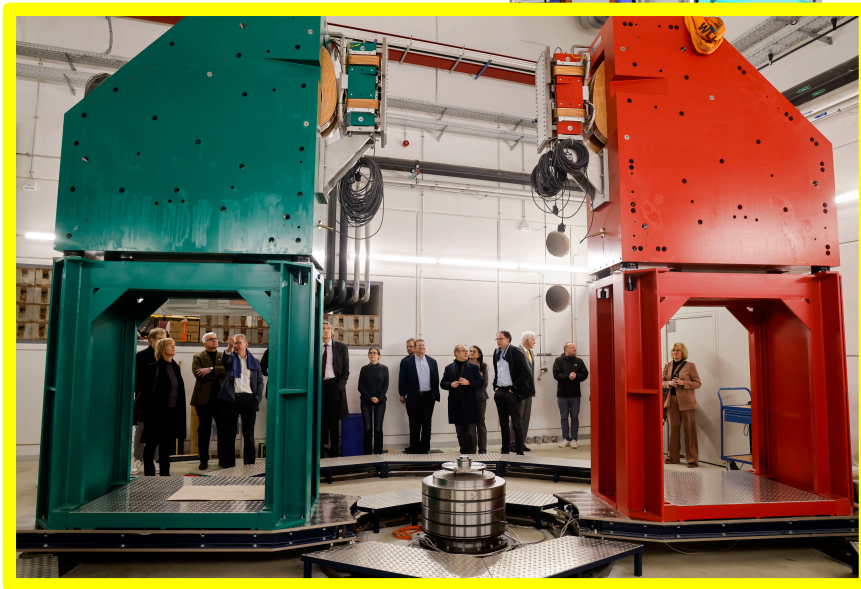
## P2

- Extracted beam mode
- Parity violation experiment
- $10^{22}$  Electrons / a
- $\sin^2 \theta_W$  and neutron skin

# MESA Experiments

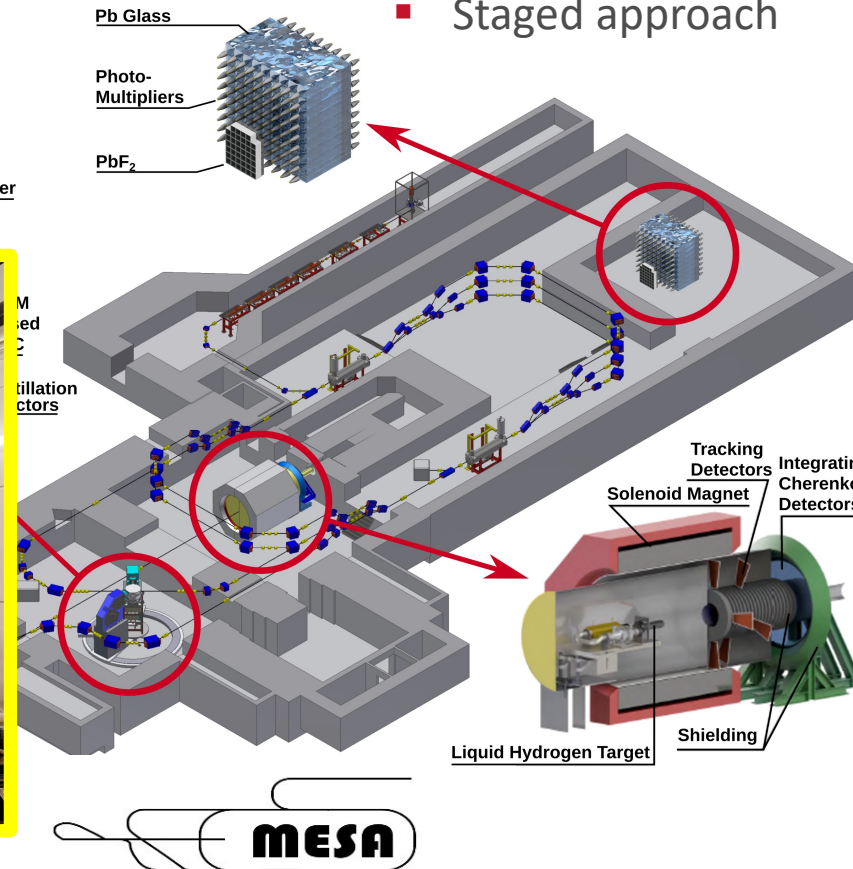
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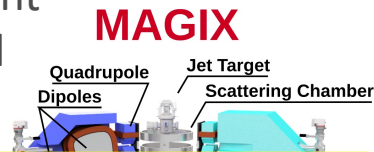
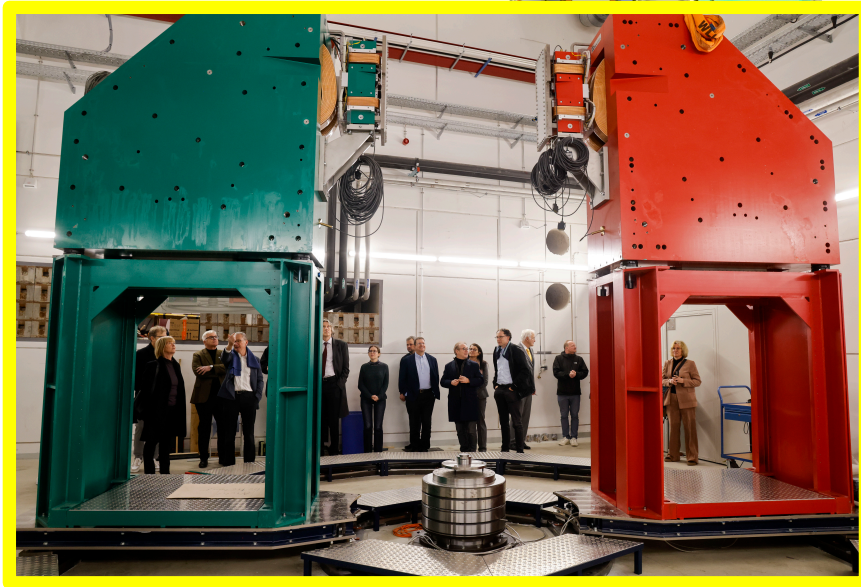
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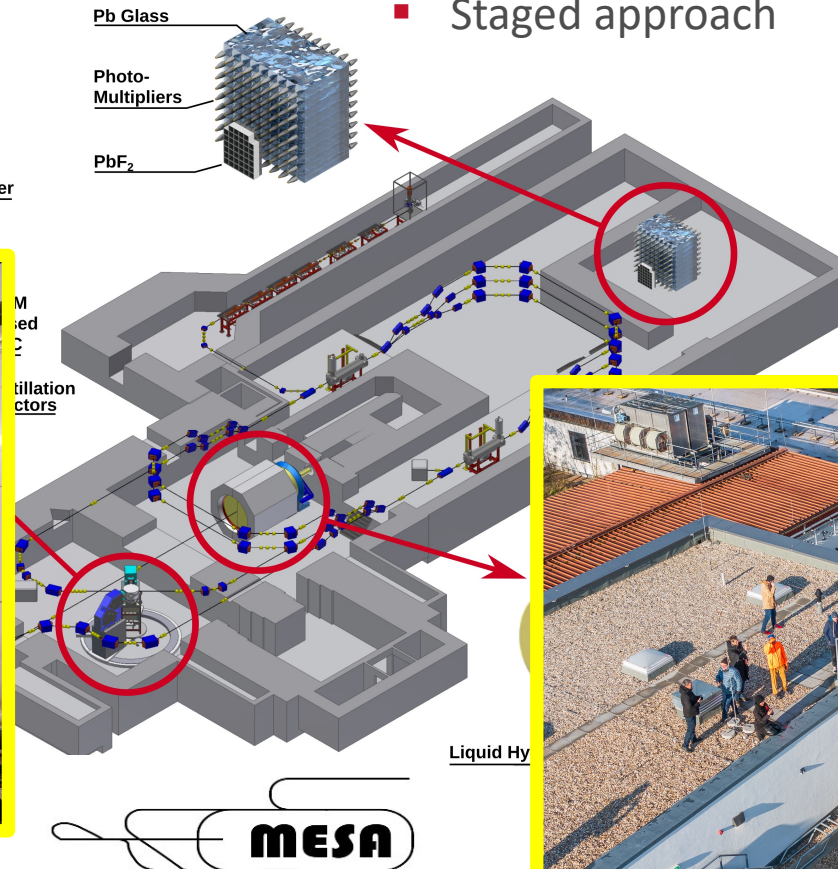
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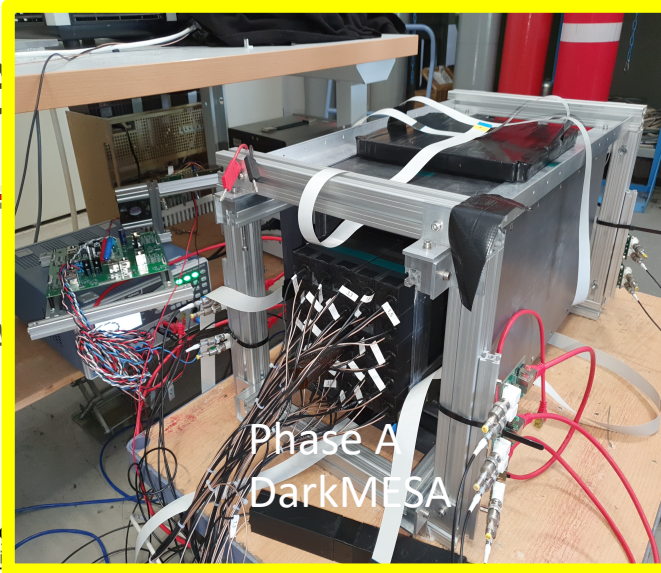




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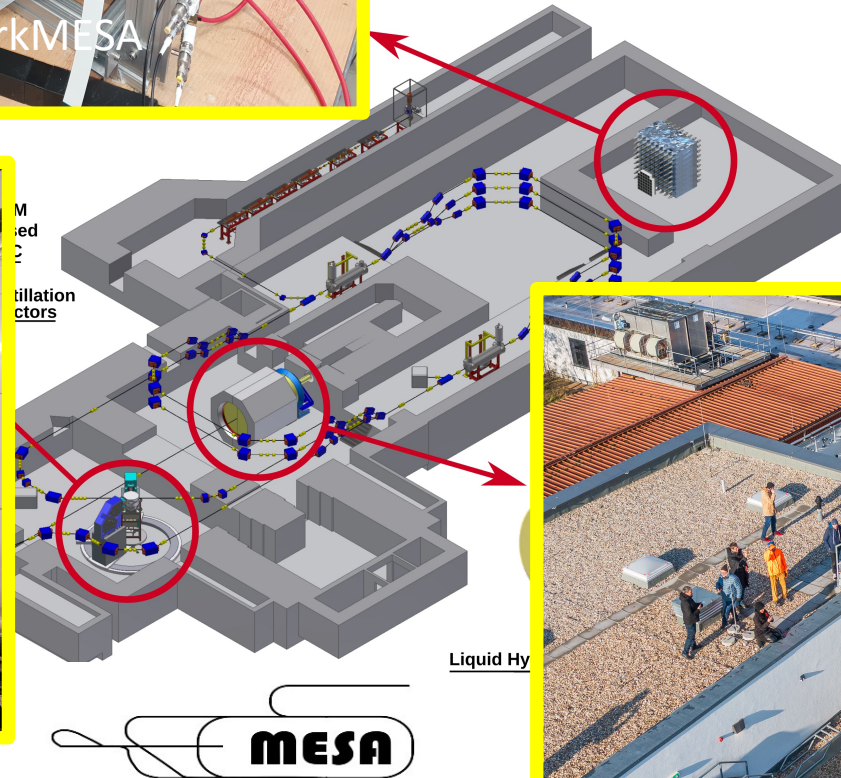
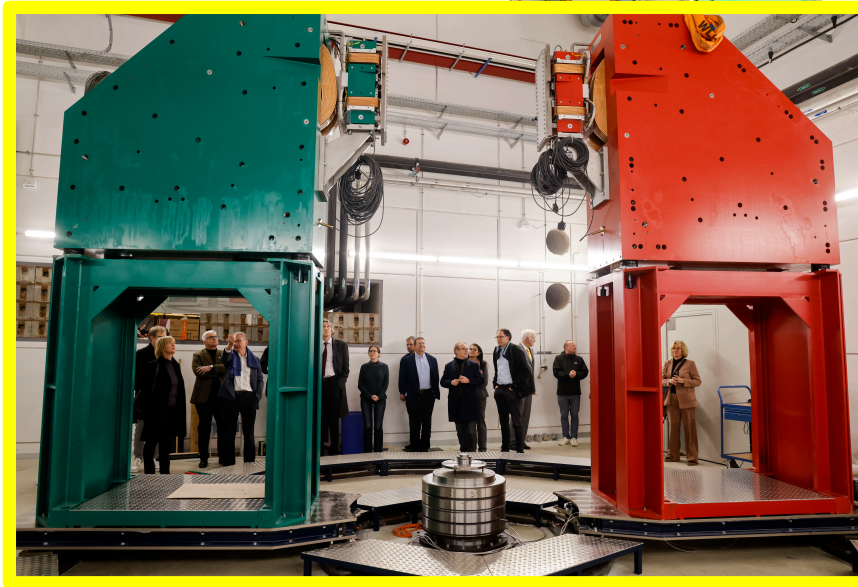
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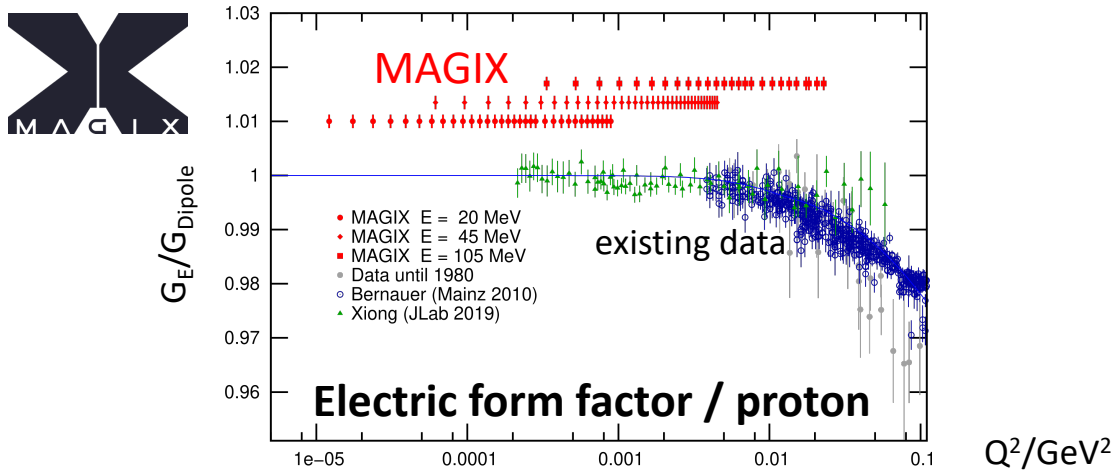
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# Precision Nuclear/Hadron/Physics at MAGIX and P2

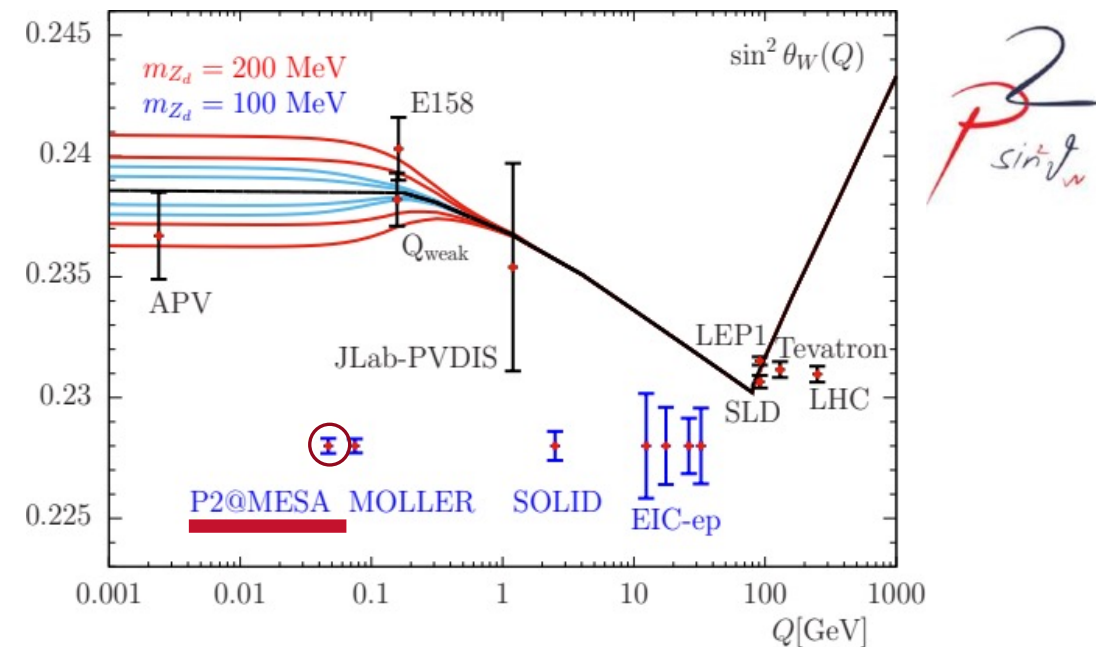
Operation of ERL beam with light internal target  
→ novel technique in nuclear / particle physics



## MAGIX – a versatile electron scattering experiment

- Structure of nucleons and nuclei
- Investigation of few-body systems
- Nuclear astrophysics
- Dark sector searches (dark photons, axions)

Precision test of the SM via determination of  $\sin^2 \Theta_W$   
→ sensitivity from Dark Photons up to 40 TeV BSM



- Longitudinal spin asymmetry on **H** target
- Extraction of  $^{12}\text{C}$  weak charge  **$^{12}\text{C}$**  target
- Sensitivity to neutron skin from **Pb** target



# Conclusions

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- **European lepton facilities at the forefront of research in nuclear/hadron/particle physics**
  - Most intense continuous low-energy muon beam @ PSI
  - Substantial progress in knowledge of baryon spectrum (Bonn, Mainz)
  - investigation of proton structure at all levels, from proton size to internal structure (PSI, Mainz, SPS)
- **Upgrades of existing facilities and new accelerator projects**
  - New MESA accelerator @ Mainz
  - High Intensity Muon Beam line @ PSI
  - More far future: LHeC project for CERN (demonstrator facility PERLE@IJCLab)
- **Europe preparing for the breakthroughs in future accelerator technology**
  - Multi-turn ERL operation @ sDALINAC and operation with gas jet target @ MESA
  - Usage of AI in accelerator development
  - Plasma acceleration (European EuPRAXIA consortium)



# The future: Plasma Acceleration

**EuPRAXIA** is the first European project that develops a dedicated particle accelerator research infrastructure **based on novel plasma acceleration concepts driven by innovative laser and linac technologies.**

1. Building a facility with very high field plasma accelerators, driven by lasers or beams (1 – 100 GV/m field)
2. Producing particles and photons to support several urgent and timely science cases

- Consortium of 54 institutes (18 countries)
- Included in ESFRI road map
- Commissioning of EuPRAXIA@StartLab (Frascati) 2029

