MAMI/MESA: future perspectives

Marc Vanderhaeghen (Univ. Mainz)

Present and future perspectives in Hadron Physics,

LNF (Frascati, Italy), June 17-19, 2024

PRISMA+

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JGU

Hadrons Nuclei CRC 1660

Outline

- Introduction: QCD 50 years
  where do we stand, where do we go?

- MAMI and MESA accelerators

- Future physics program at MAMI and MESA

1974: QCD asymptotic freedom

Nobel Prize Physics 2004:
D.J. Gross, H.D. Politzer, F.Wilczek

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50 Years of Quantum Chromodynamics

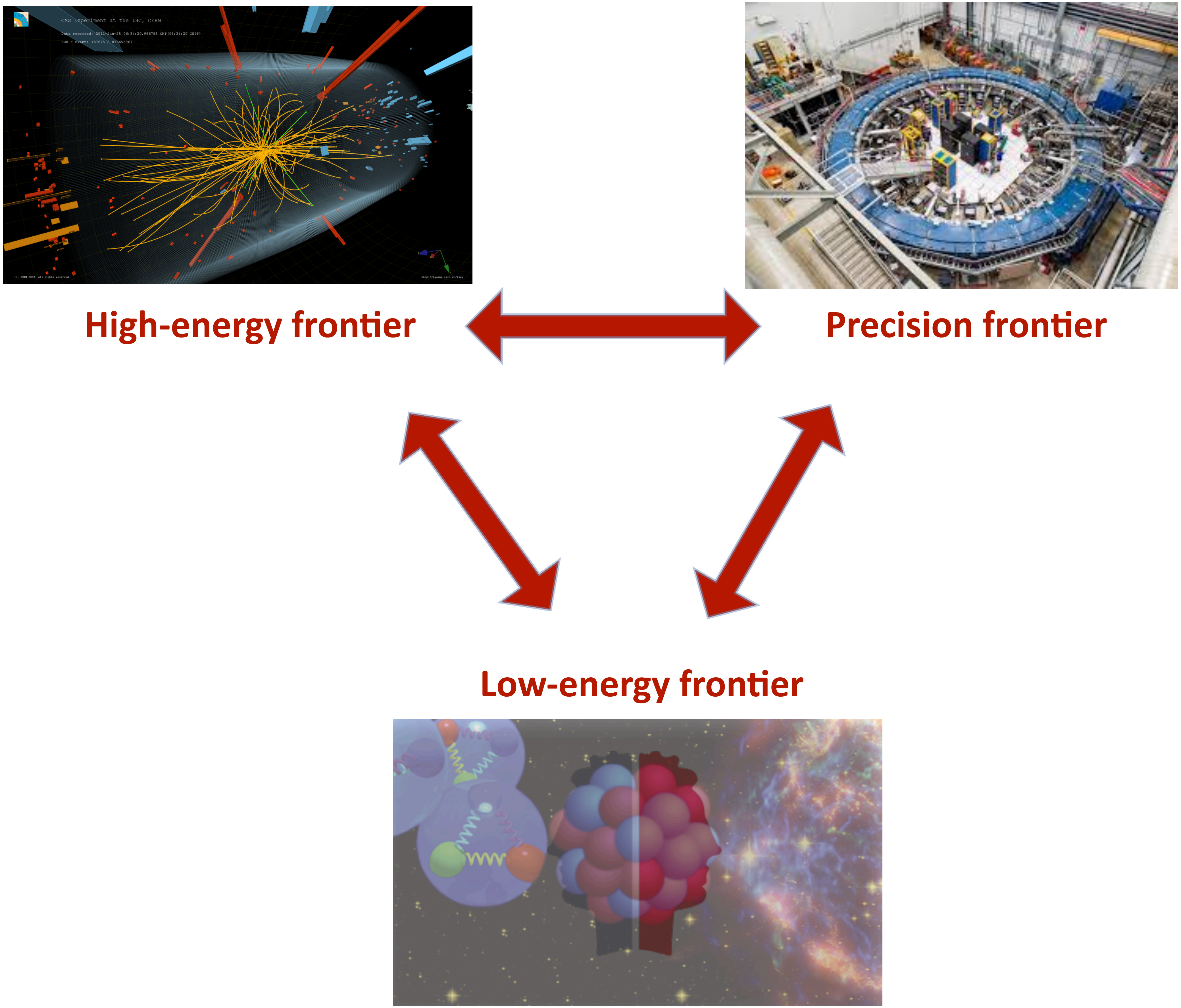
Franz Gross ,[1,2], Eberhard Klempt[b,3],

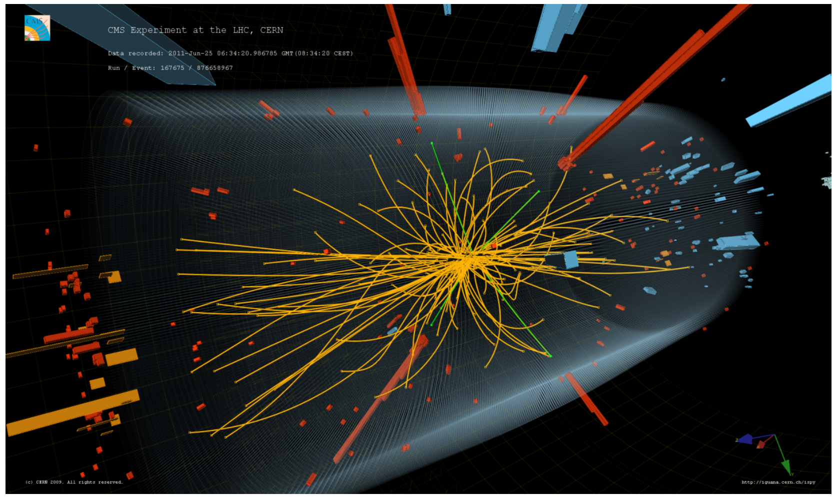
Stanley J. Brodsky[c,4], ndrzej J. Buras[c,5], Volker D. Burkert[c,1], Gudrun Heinrich[c,6], Karl Jakobs[c,7], Curtis . Meyer[c,8], Kostas Orginos[c,1,2], Michael Strickland[c,9], Johanna Stachel[c,10], Giulia Zanderighi[c,11,12],

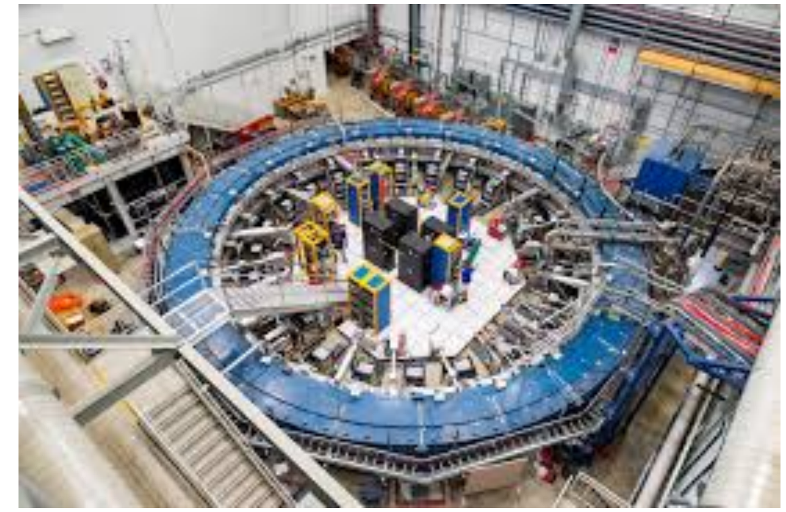
Nora Brambilla[5,12,13], Peter Braun-Munzinger[10,14], Daniel Britzger[11], Simon Capstick[15], Tom Cohen[16], Volker Crede[15], Martha Constantinou[17], Christine Davies[18], Luigi Del Debbio[19], chim Denig[20], Carleton DeTar[21], lexandre Deur[1], Yuri Dokshitzer[22,23], Hans Günter Dosch[10] Jozef Dudek[1,2], Monica Dunford[24], Evgeny Epelbaum[25], Miguel . Escobedo[26], Harald Fritzsch[d,27], Kenji Fukushima[28], Paolo Gambino[11,29], Dag Gillberg[30,31], Steven Gottlieb[32], Per Grafstrom[33], Massimiliano Grazzini[34], Boris Grube[1], lexey Guskov[35], Toru Iijima[36], Xiangdong Ji[16], Frithjof Karsch[37], Stefan Kluth[11], John B. Kogut[38,39], Frank Krauss[40], Shunzo Kumano[41,42], Derek Leinweber[43], Heinrich Leutwyler[44], Hai-Bo Li[45], Yang Li[46], Bogdan Malaescu[47], Chiara Mariotti[48], Pieter Maris[49], Simone Marzani[50], Wally Melnitchouk[1], Johan Messchendorp[51], Harvey Meyer[20], Ryan Edward Mitchell[52], Chandan Mondal[53], Frank Nerling[51,54,55], Sebastian Neubert[3], Marco Pappagallo[56], Saori Pastore[57], José R. Peláez[58], ndrew Puckett[59], Jianwei Qiu[1,2], Klaus Rabbertz[60], lberto Ramos[61], Patrizia Rossi[1,62], nar Rustamov[51,63], ndreas Schäfer[64], Stefan Scherer[65], Matthias Schindler[66], Steven Schramm[67], Mikhail Shifman[68], Edward Shuryak[69], Torbjörn Sjöstrand[70], George Sterman[71], Iain W. Stewart[72], Joachim Stroth[51,54,55], Eric Swanson[73], Guy F. de Téramond[74], Ulrike Thoma[3], ntonio Vairo[75], Danny van Dyk[40], James Vary[49], Javier Virto[76,77], Marcel Vos[78], Christian Weiss[1], Markus Wobisch[79] Sau Lan Wu[80], Christopher Young[81], Feng Yuan[82], Xingbo Zhao[53], Xiaorong Zhou[46]

arXiv 2212.11107 [hep-ph]

Quo vadis?

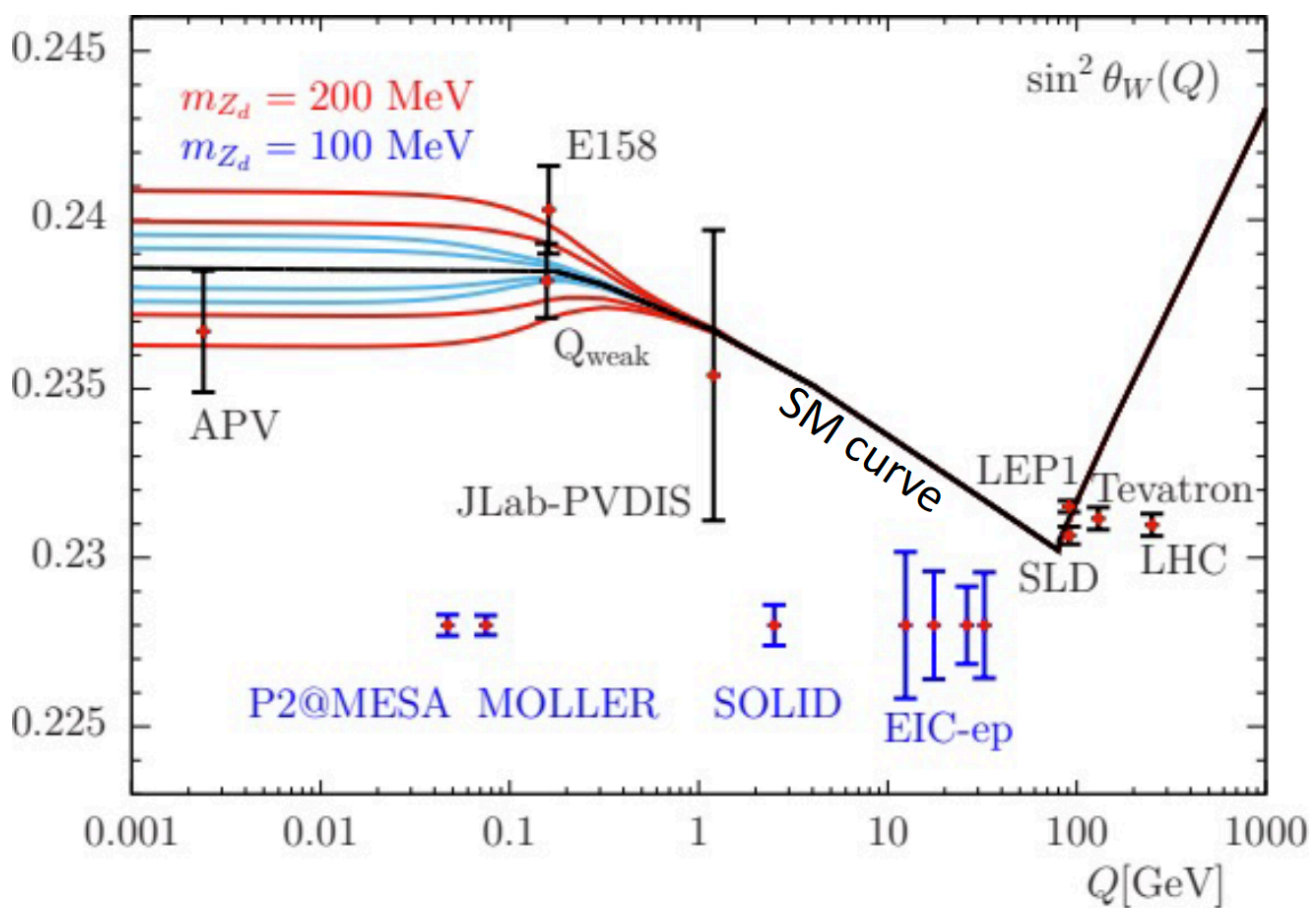

High-energy frontier
Precision frontier
Low-energy frontier





High-energy frontier **Precision frontier**

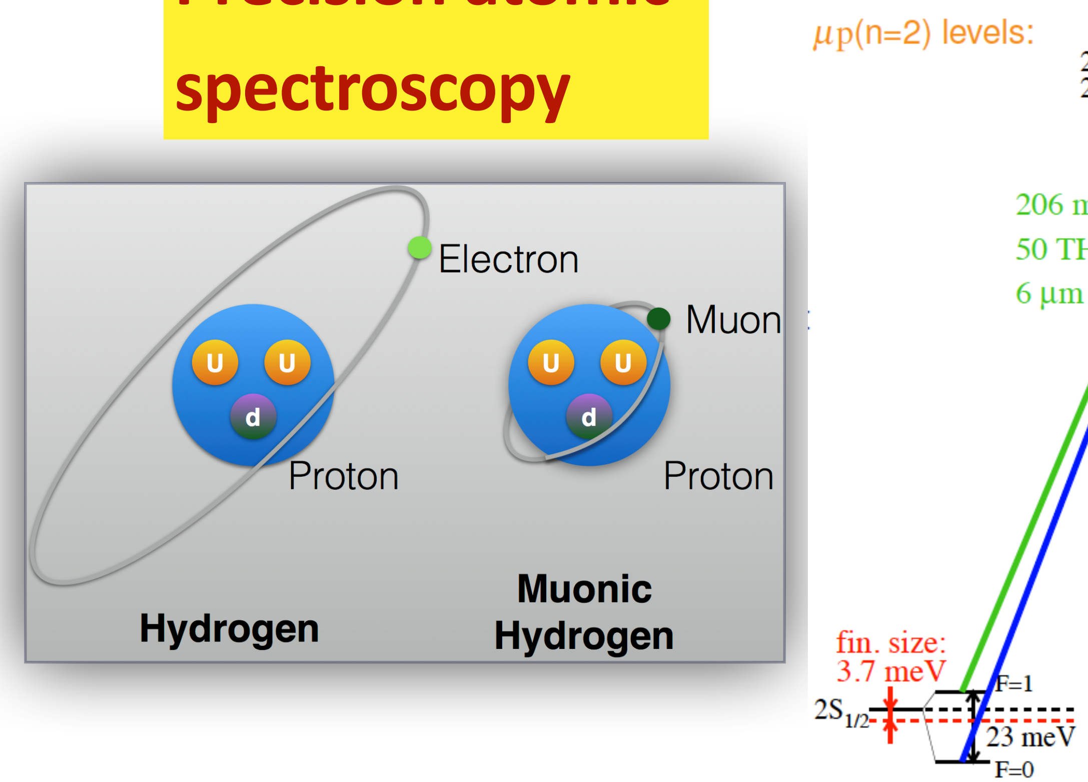
Running of $\sin^2 \theta_W$

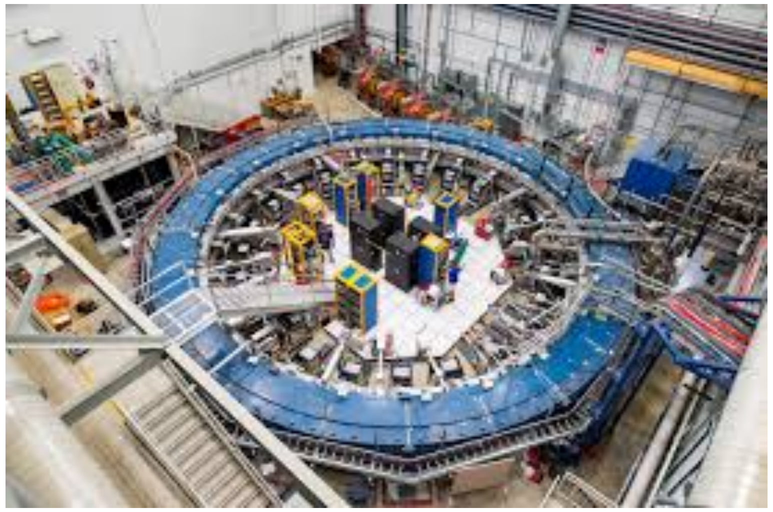


Precision low Q^2 expt.

-> complementing high-energy experiments
-> reaches new physics scale of ~50 TeV !

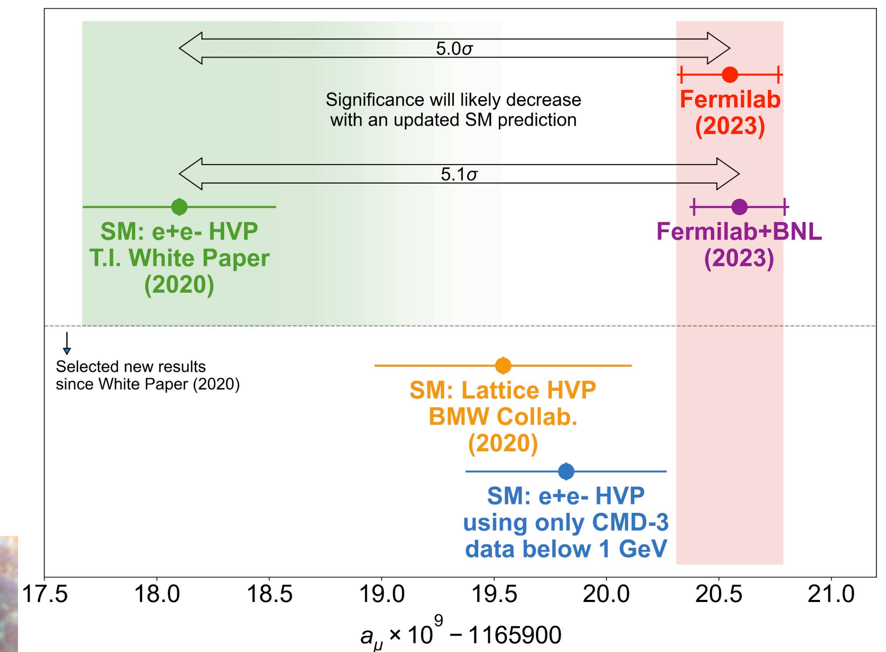
Precision atomic spectroscopy



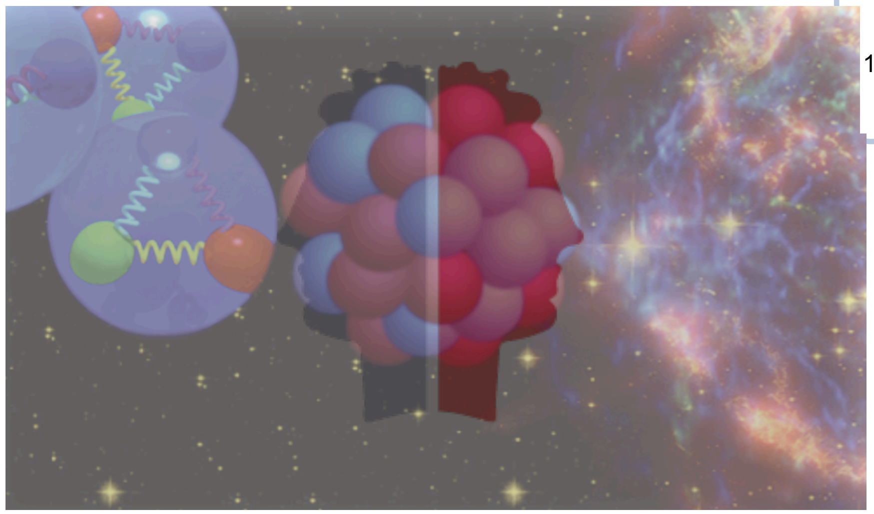


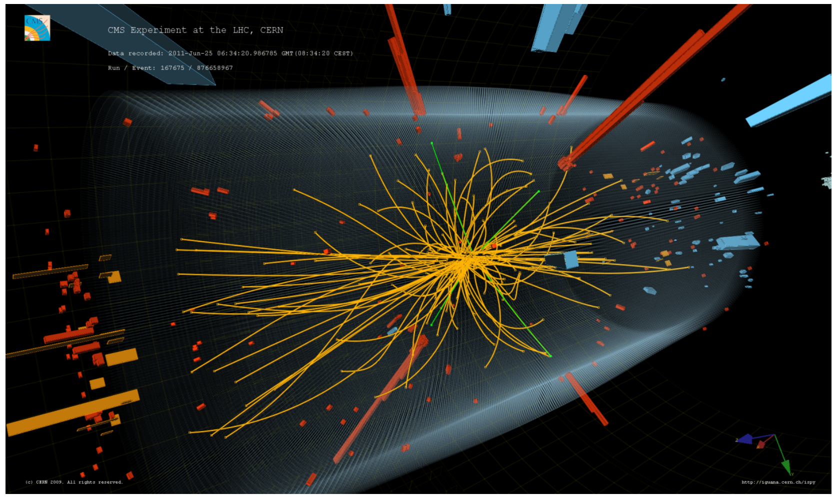
Precision frontier

$(g\text{-}2)_\mu$

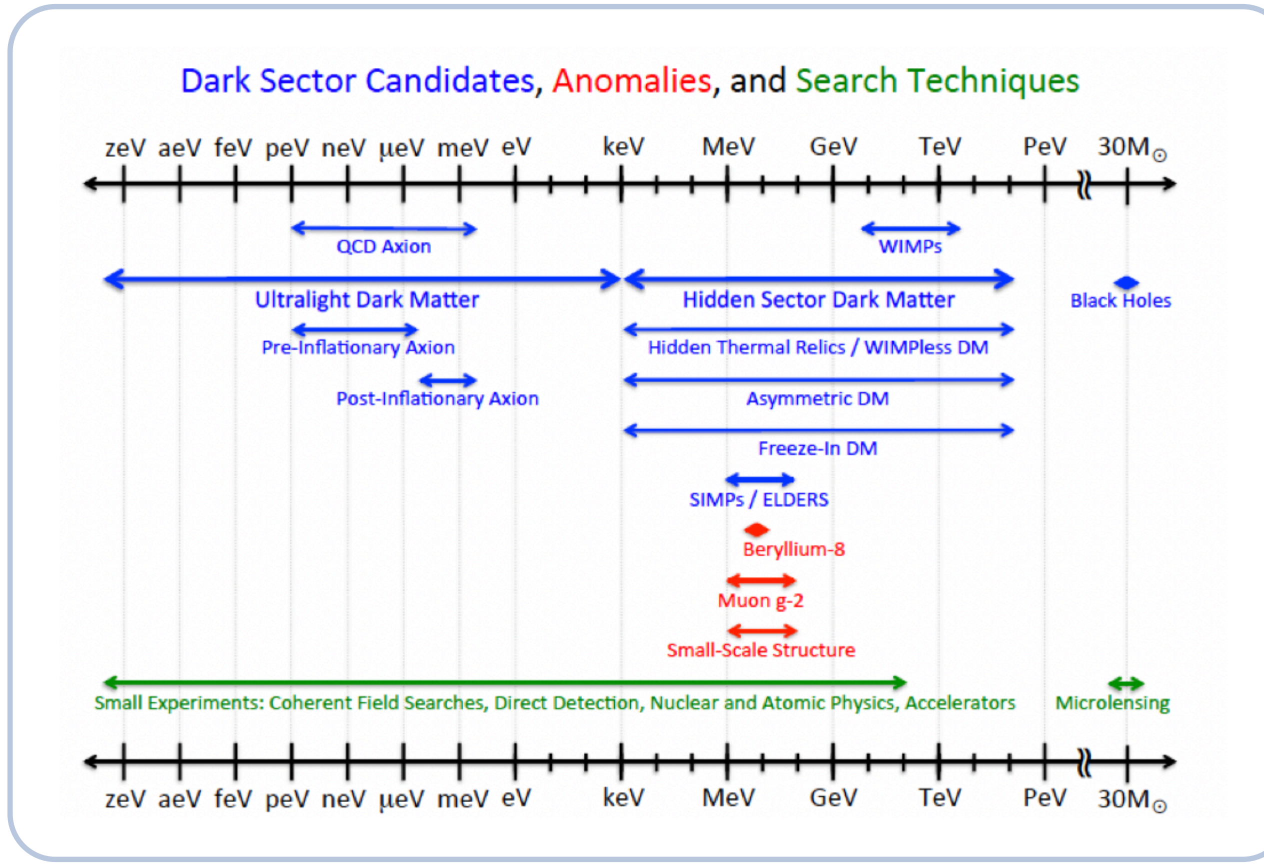


Low-energy frontier

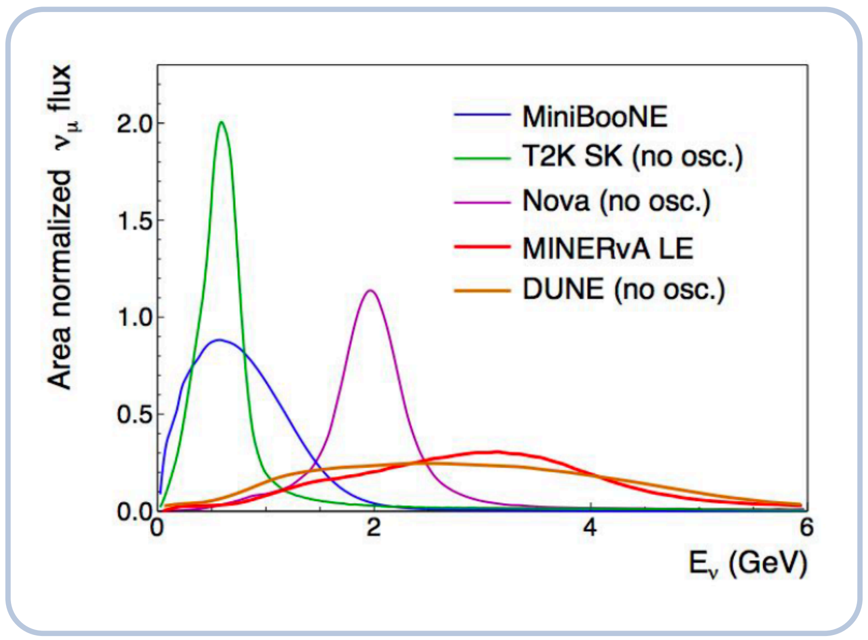




High-energy frontier

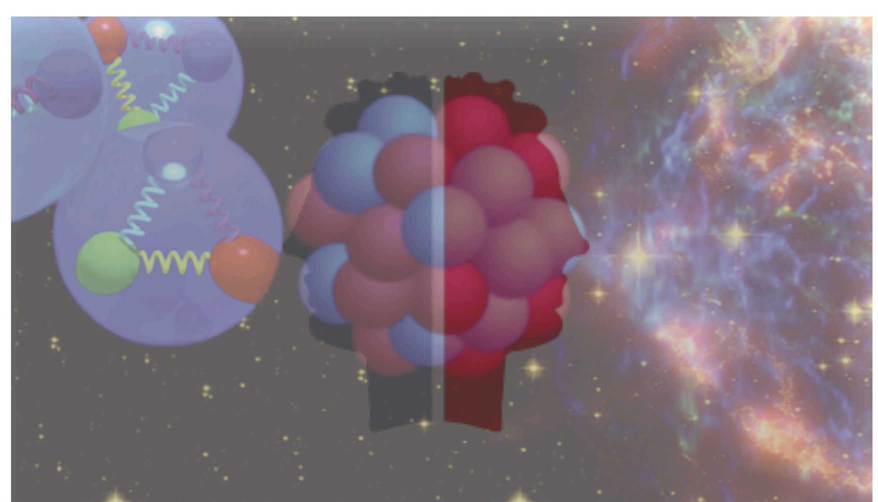


Dark matter could be lighter than previously thought, **MeV - GeV mass range**: ALPs, dark photon, X17, …



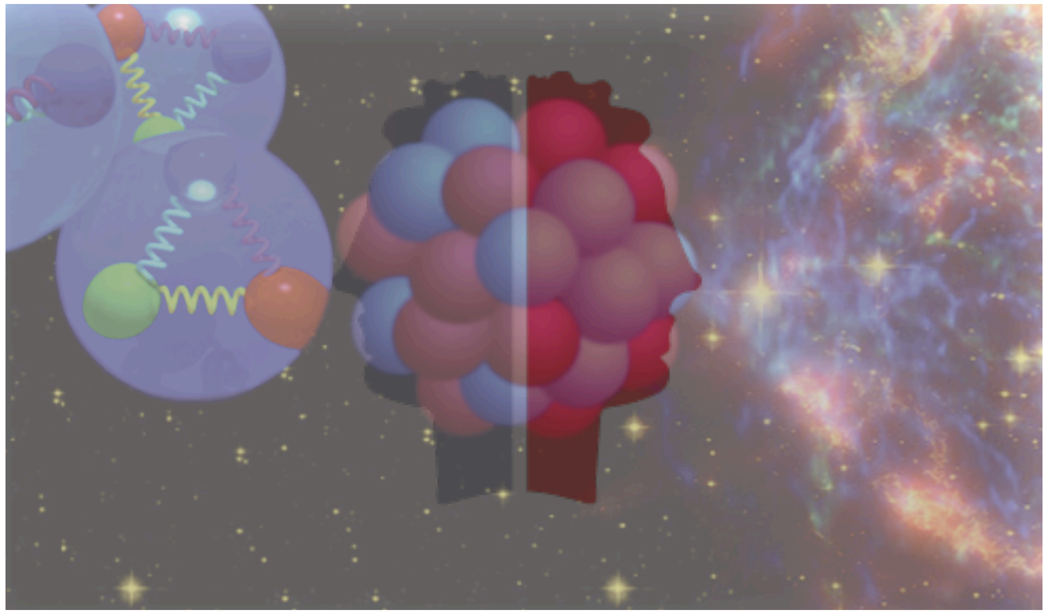
nuclear physics input needed for long-baseline neutrino facilities

Low-energy frontier

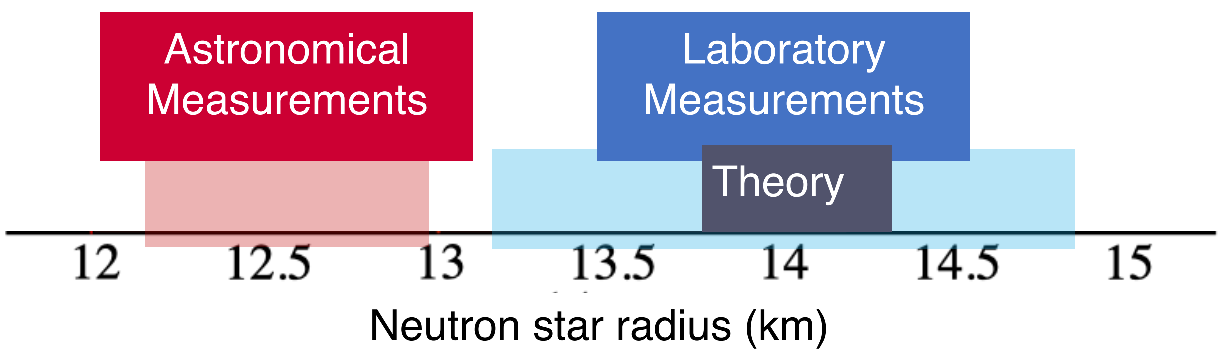


New opportunities:
PADME, Belle II, …
MESA, BDX@JLab, …

arXiv:1901.09966

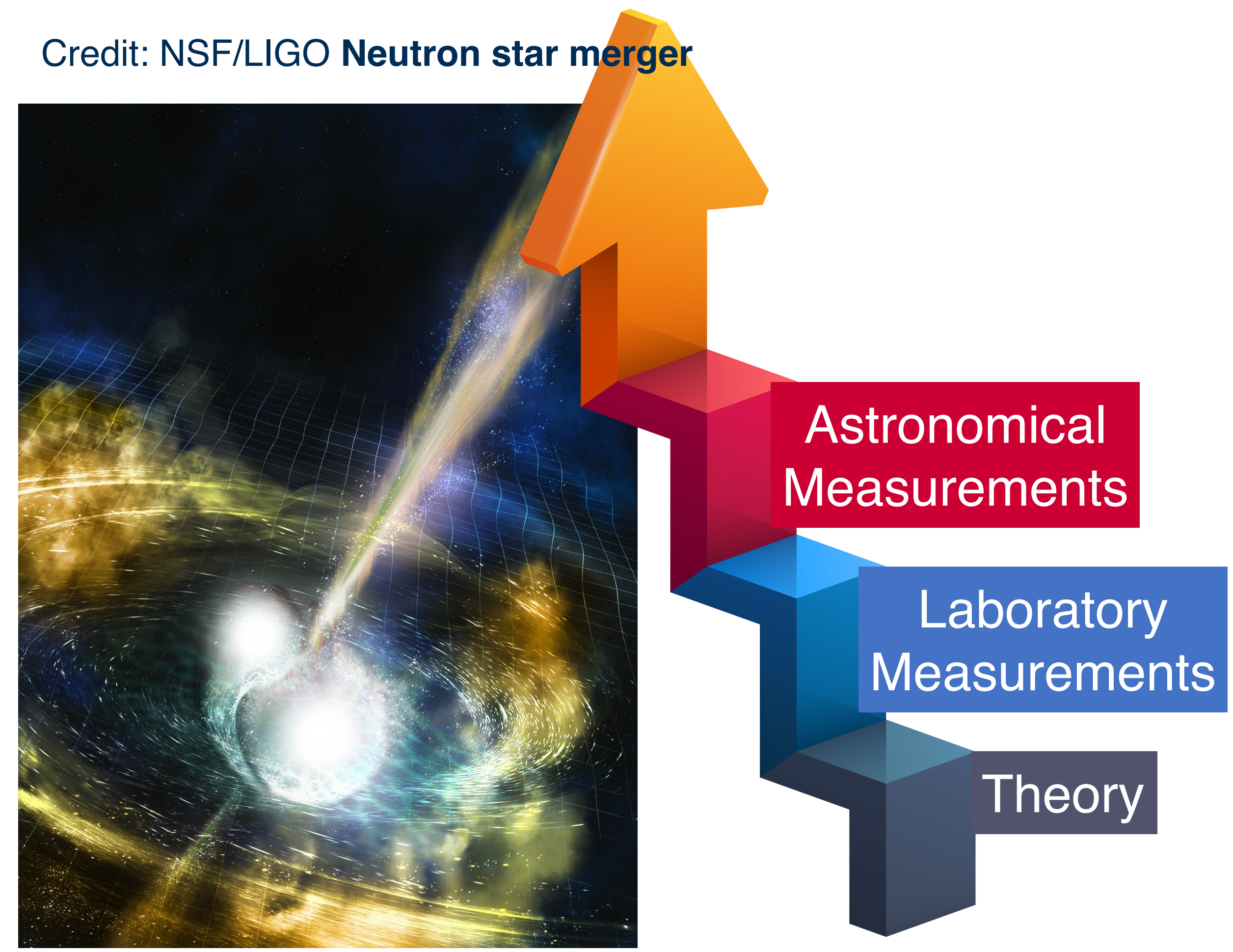


Low-energy frontier allows to connect the LAB to the astrophysical domain



- Astronomical measurement from gravitational wave (LIGO/Virgo) in **neutron star merger** and pulse profile (NICER) in pulsar measurements
- Laboratory measurement from neutron skin of nuclei and heavy ion reactions

Credit: NSF/LIGO **Neutron star merger**



Are discrepancies hinting at scale-specific phenomena or gaps in our understanding of nuclear matter?

Key physics programs at the low-energy frontier

➡ **Low-energy high-intensity experiments** take center stage in the **search for new, beyond SM particles**

- Low-energy precision determination of the **weak charge** of the **electron** and **proton**
- **Muon's (g-2)**
- Search for **dark sector** and **dark matter** particles in the MeV - GeV mass range

➡ **Understanding of hadronic processes to high precision** drives discoveries in different fields of physics

- **neutrino matter-antimatter symmetry violating phase** requires neutrino-nucleus cross sections
- **laser spectroscopy of light muonic atoms:** order-of-magnitude improvement in the proton and light-nuclei structure quantities

➡ Recent developments in **multi-messenger astronomy** -> **need for new precision experiments in low-energy nuclear physics**

- Precision probes of the **nuclear EOS ->** better understanding of structures in neutron-rich matter
- Key reaction cross sections relevant to **nuclear astrophysics** require low-energy high-intensity nuclear physics facilities
- Precision electron scattering to benchmark state-of-art **nuclear effective field theory** calculations

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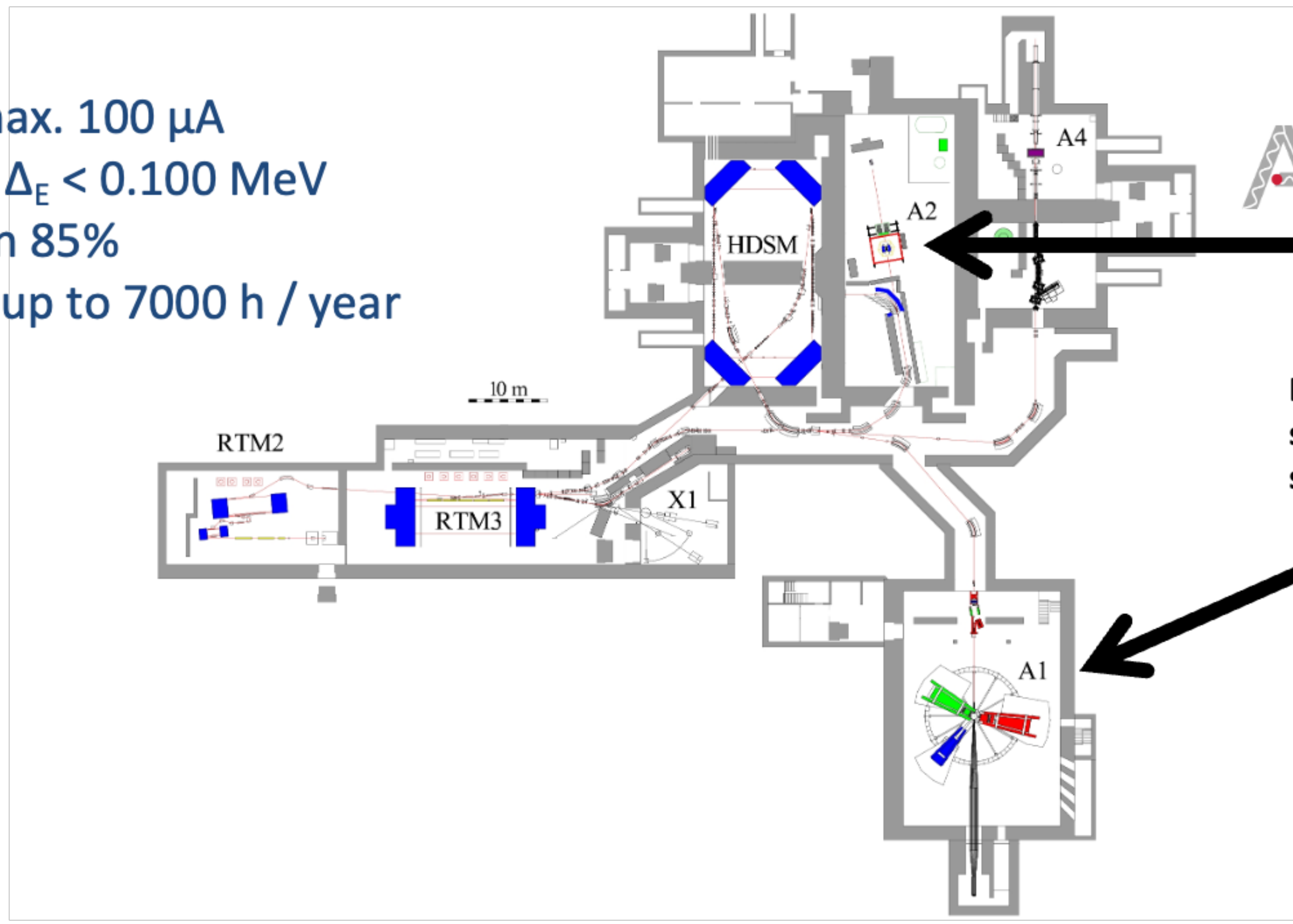
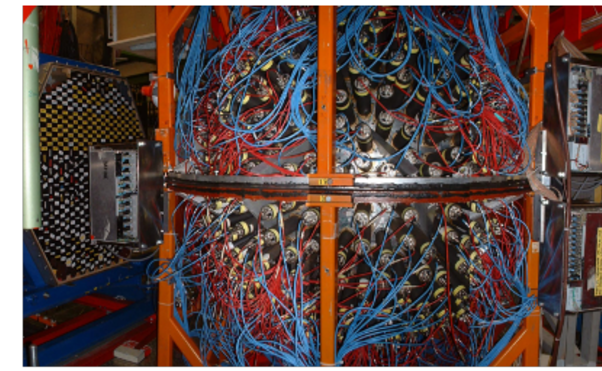
MAMI in combination with new accelerator MESA: tailored to address these physics questions

The Mainz Microtron MAMI

Electron Accelerator E = 0.185 GeV - 1.6 GeV (CW)
operated at JGU Mainz
Hallmarks

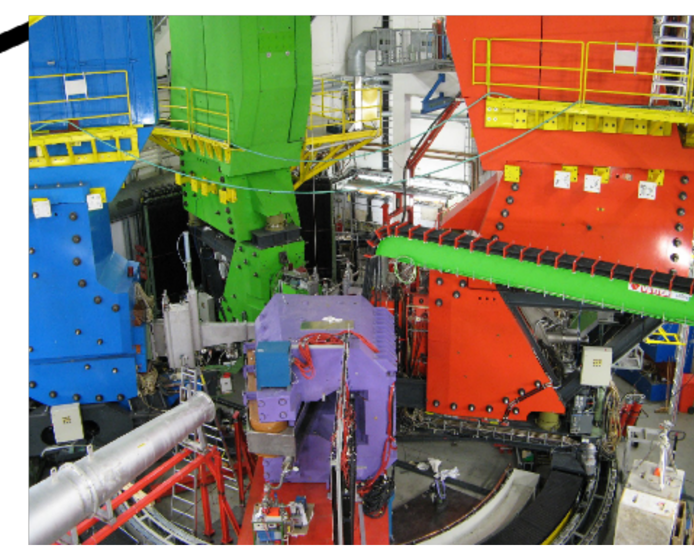
- Intensity max. 100 µA
- Resolution Δ_E < 0.100 MeV
- Polarization 85%
- Reliability: up to 7000 h / year





Photon scattering (A2 hall) (Crystal Ball / TAPS calorimeters; Polarized frozen-spin target ⍰ currently at Univ. Bonn)

Electron scattering (high resolution spectrometer setup)



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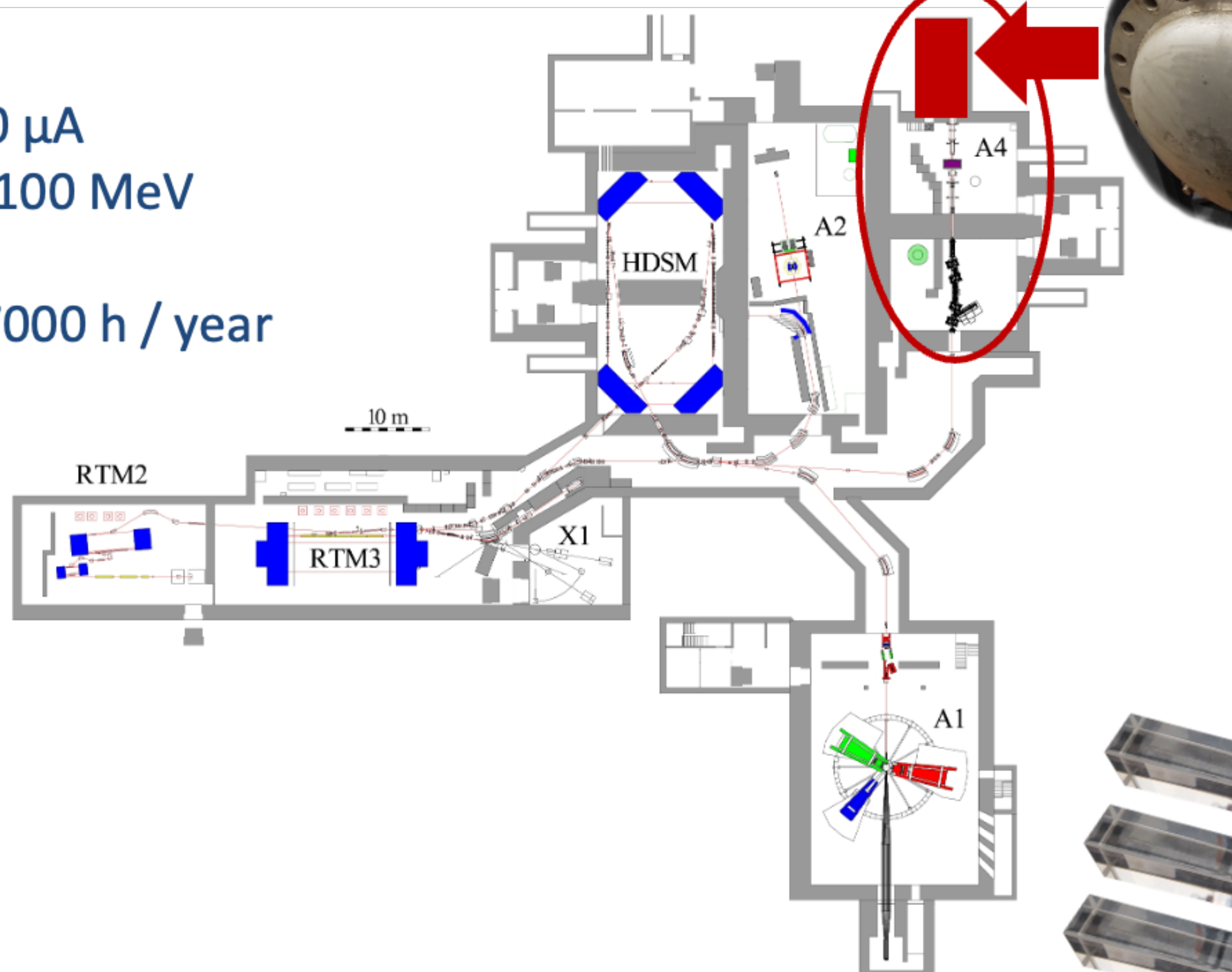
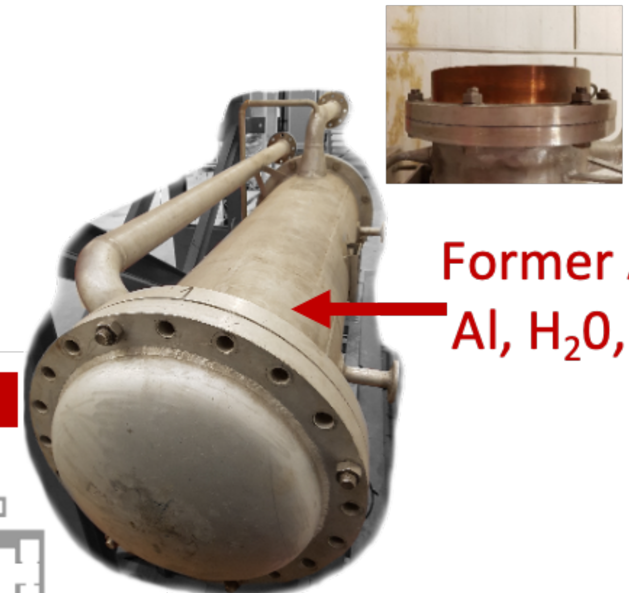
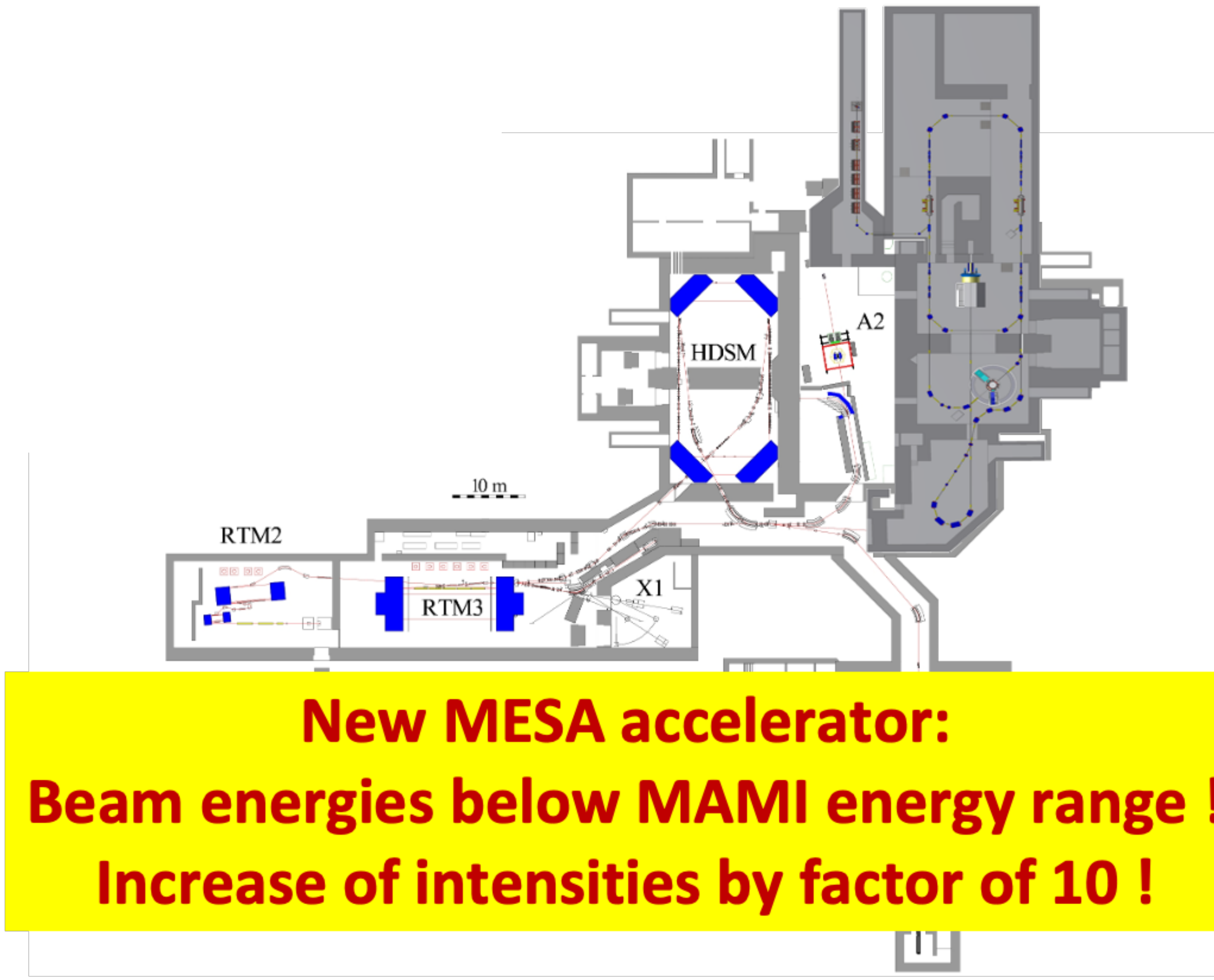




Former A4 beam dump:
Al, H_20, Cu ⍰ 20 X_0

Former A4 experiment:
1000 PbF_2 crystals
and PMTs

Mainz Energy-Recovering Superconducting Accelerator MESA



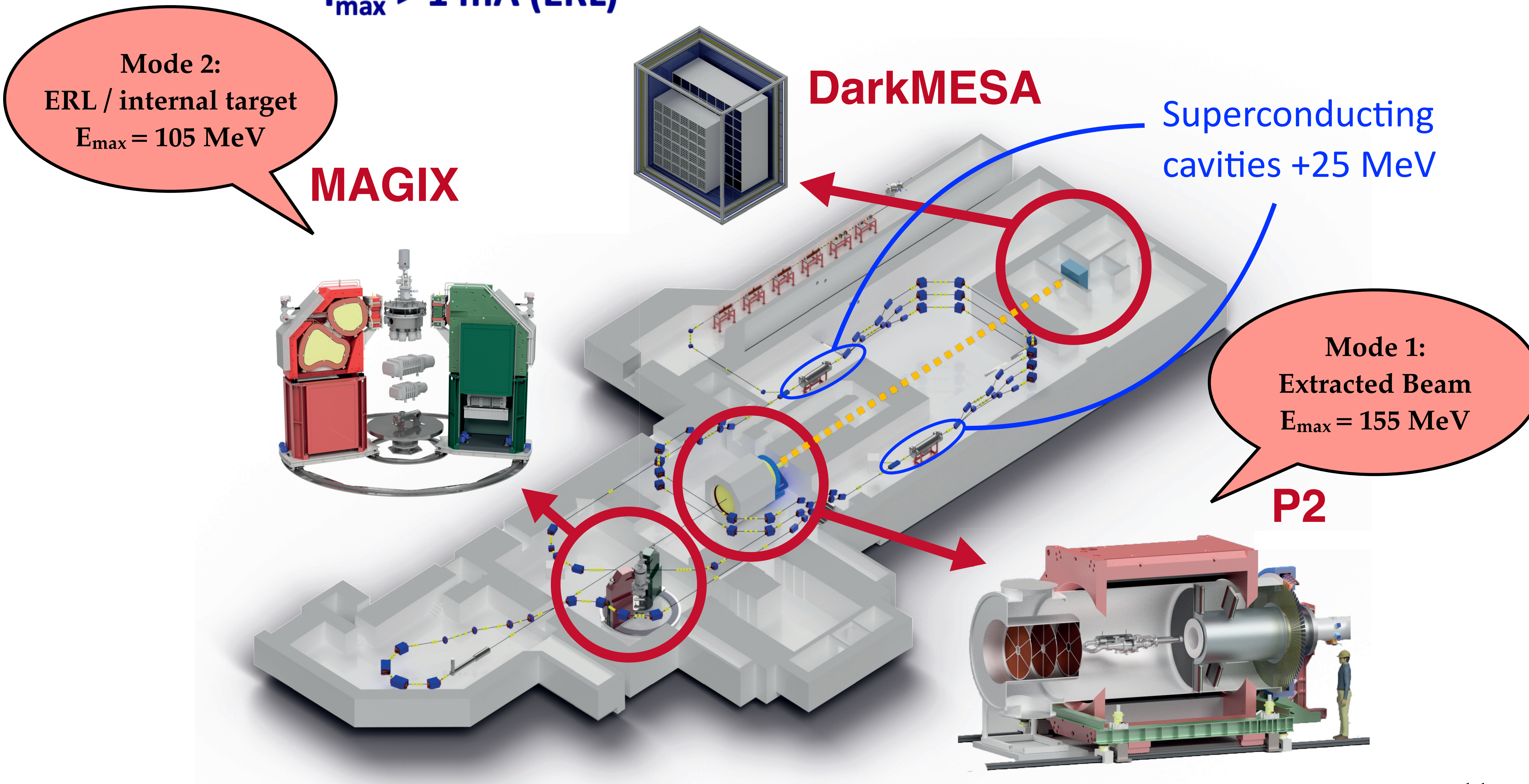
New MESA accelerator:
Beam energies below MAMI energy range !
Increase of intensities by factor of 10 !

New experimental hall

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

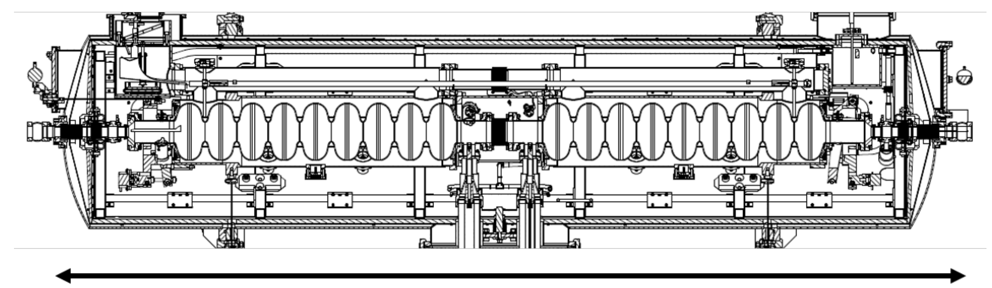
The MESA accelerator

Superconducting technology
Recirculating ERL
E_{max} = 105/155 MeV
I_{max} > 1 mA (ERL)



The MESA accelerator

Installation ongoing, commissioning foreseen in 2025



3.5 meter

MESA-main component: SRF-Cryomudule

Both MESA Cryo-Modules fulfill specifications:

25MV Acceleration voltage at <40 Watt thermal loss at 2Kelvin

Physics program at MAMI and MESA embedded in newly established Collaborative Research Center CRC1660

CRC1660

Hadrons and Nuclei as Discovery Tools

B
Beyond Standard Model Searches involving Hadrons

H
Interface between Hadron and Nuclear Physics

N
Nuclei and Astrophysics

- Strong **discovery** potential for new physics phenomena
- Powerful **tools** to sharpen our understanding of strongly interacting systems

CRC1660: Hadrons and Nuclei as Discovery Tools

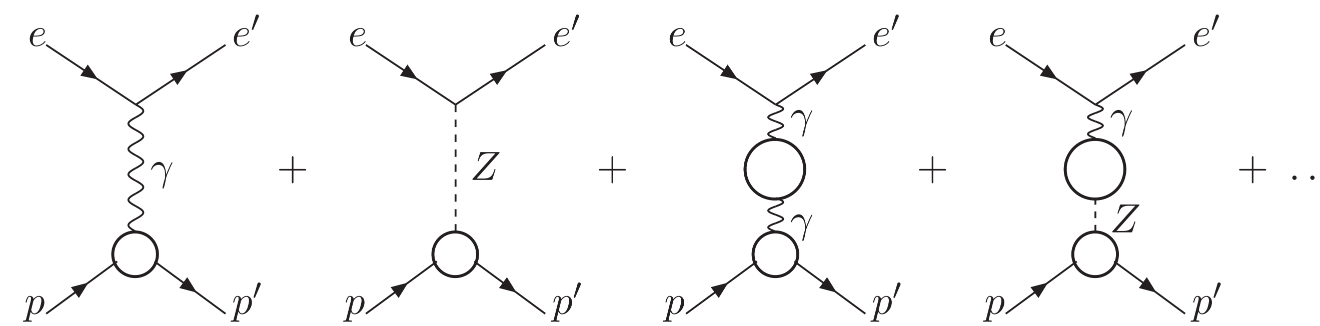
Hadrons Nuclei
CRC 1660

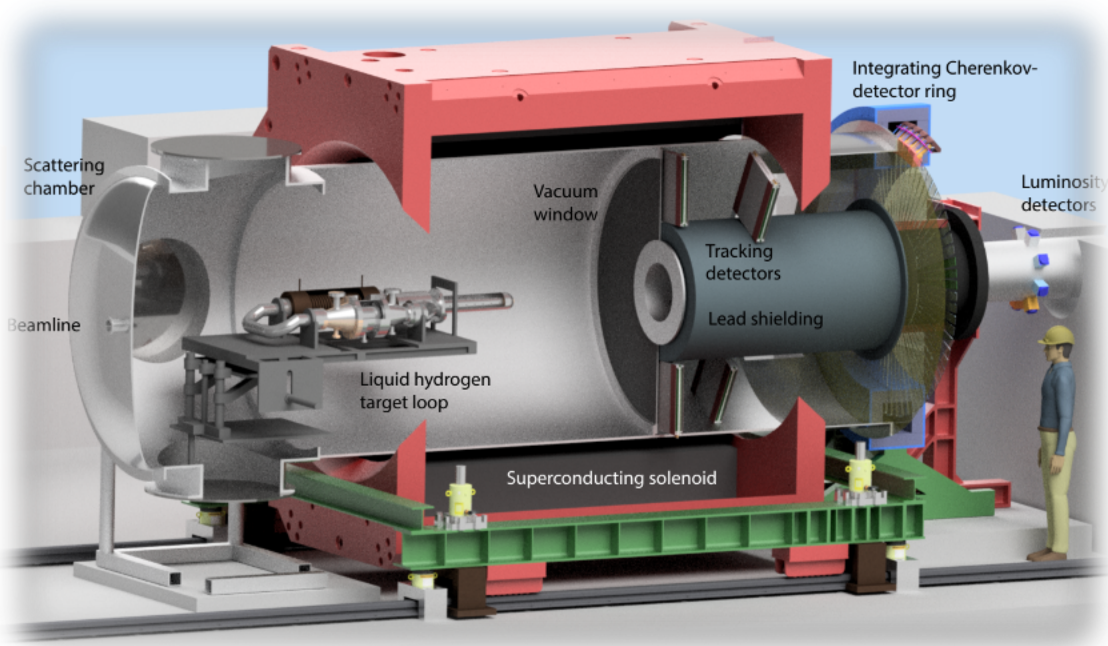
- **13 projects: 26 PIs (24 JGU Mainz + PI Uni-Frankfurt + PI Uni-Münster)**
- **Interdisciplinary:** atomic, nuclear and hadron physics
- Close collaboration between **theory** and **experiment**
- 2 main infrastructures: **MAMI** and **MESA**
- **Integrated Graduate school**
- **DFG funding: ca 10 MEuro (2024 - 2028),** 12 year funding perspective
- **28 PhD + 6.5 PD** positions

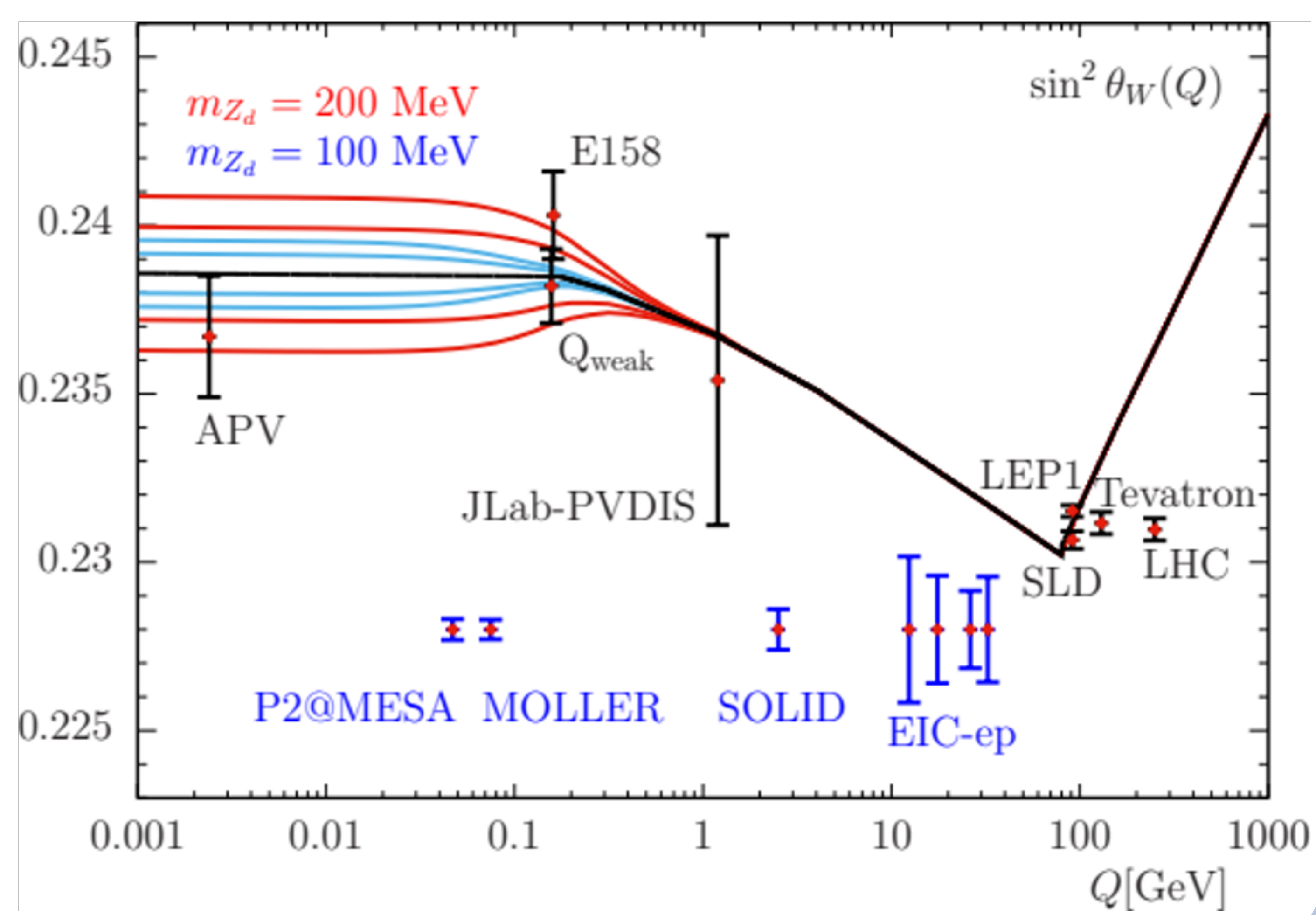
Spokespersons: C. Sfienti & M. Vdh

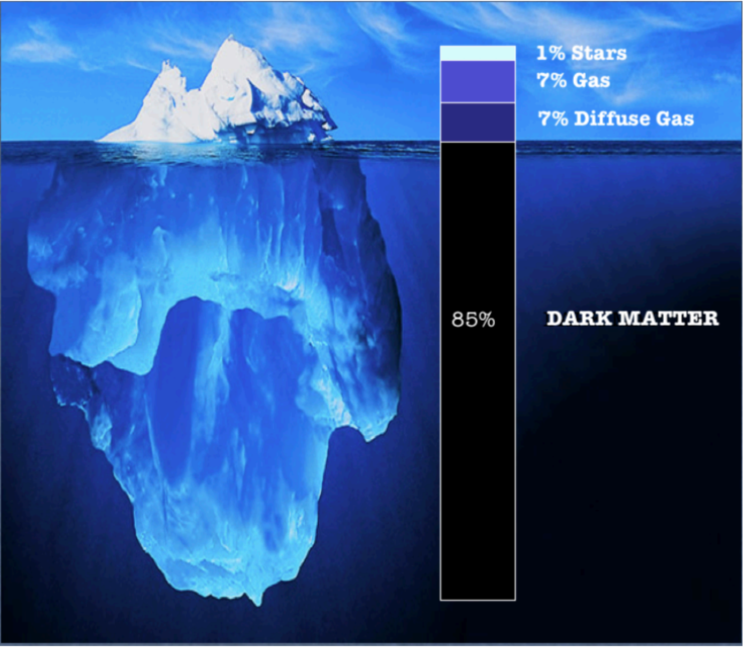
P2: Parity violating electron scattering at MESA

- P2@MESA measurement of proton **weak mixing angle sin² θ_W** at low scale to precision of 0.14%
- Precision test of Standard Model
- Complementary to LHC measurements at Z-boson mass
- dedicated theory radiative corrections
- **Sensitive to BSM physics at scales ~ 50 TeV**
- Extension to **nuclear targets** planned

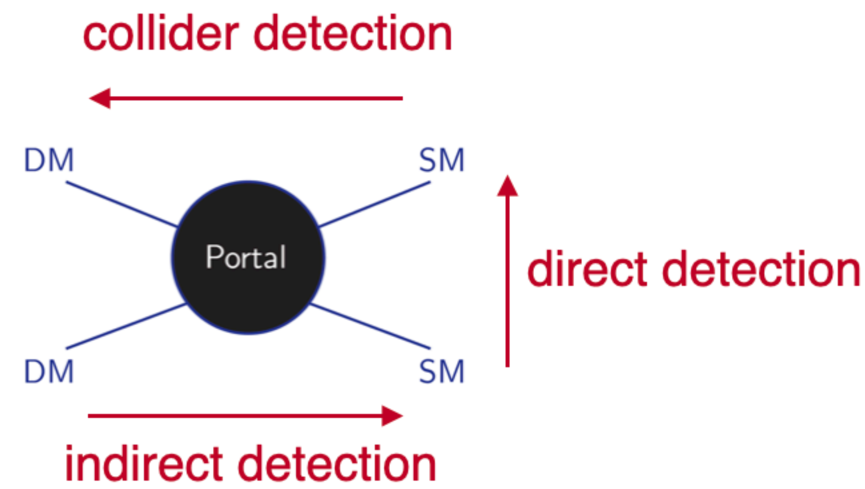








Dark sector searches at MESA



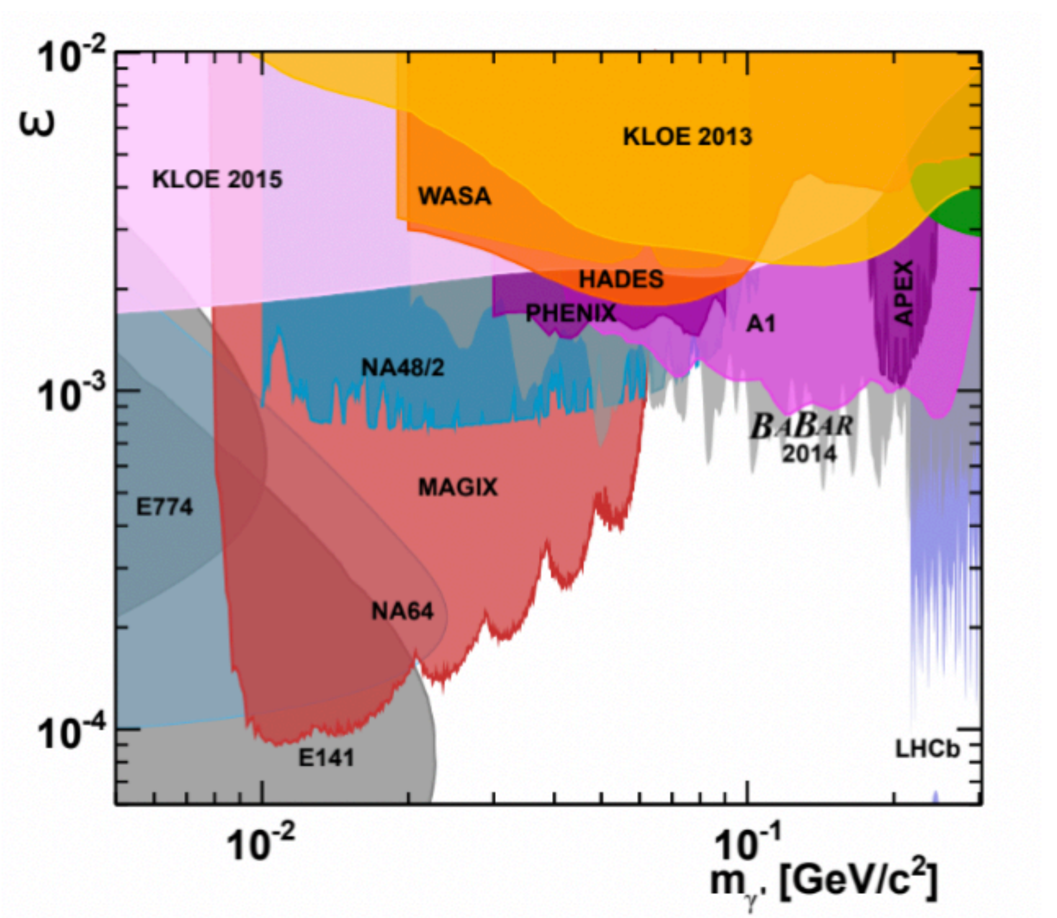
WIMPs

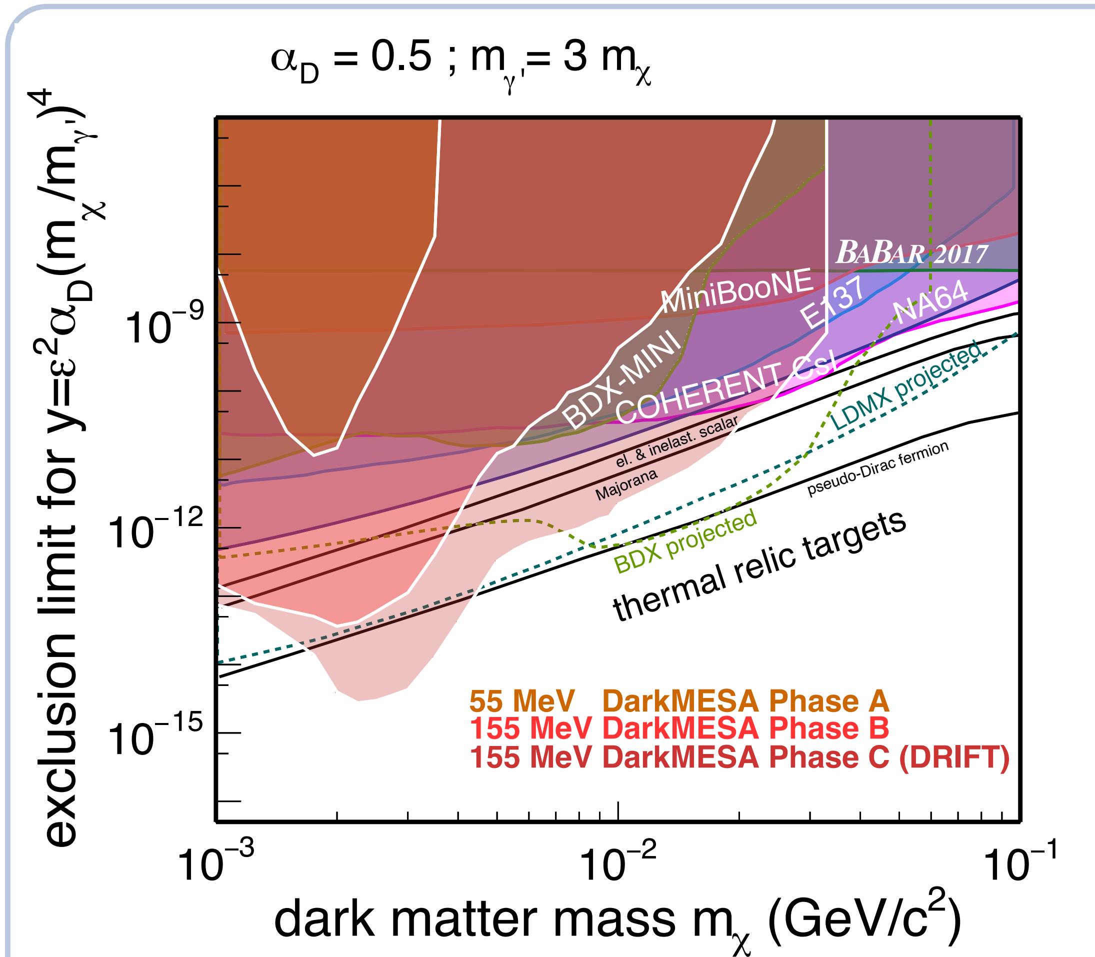
~ GeV < m_{DM} < ~ TeV

Light dark matter

~ MeV < m_{DM} < ~ GeV

- Search for **dark sector messenger particle(s)** in electron scattering with MAGIX@MESA
- Search for **light dark matter** using extracted MESA beam at DarkMESA

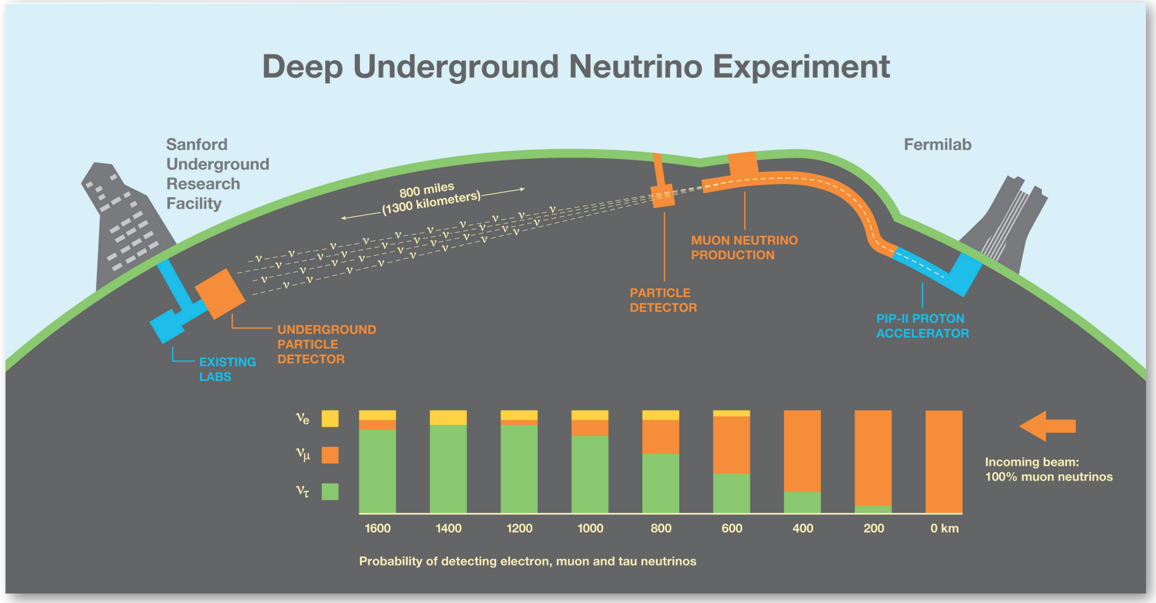




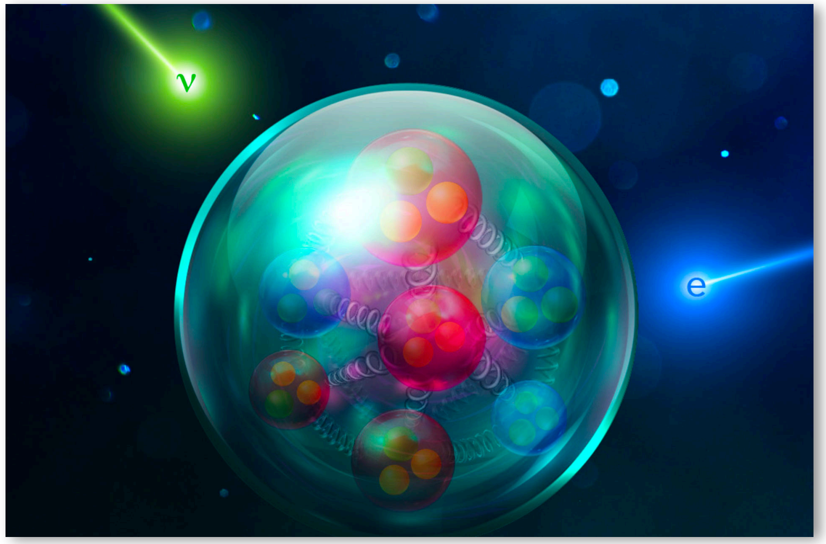
Electrons for neutrino program at MAMI

- Neutrino oscillations ➡ neutrinos are massive
- Next generation of **long-baseline neutrino experiments** (DUNE, T2HK): oscillation parameters at 1% level
- Interpretation requires precise **neutrino-nucleus cross sections** as input

- e⁻ scattering off medium-mass nuclei at MAMI to reduce uncertainties from nuclear structure
- Complemented by lattice QCD program to determine nucleon axial form factors

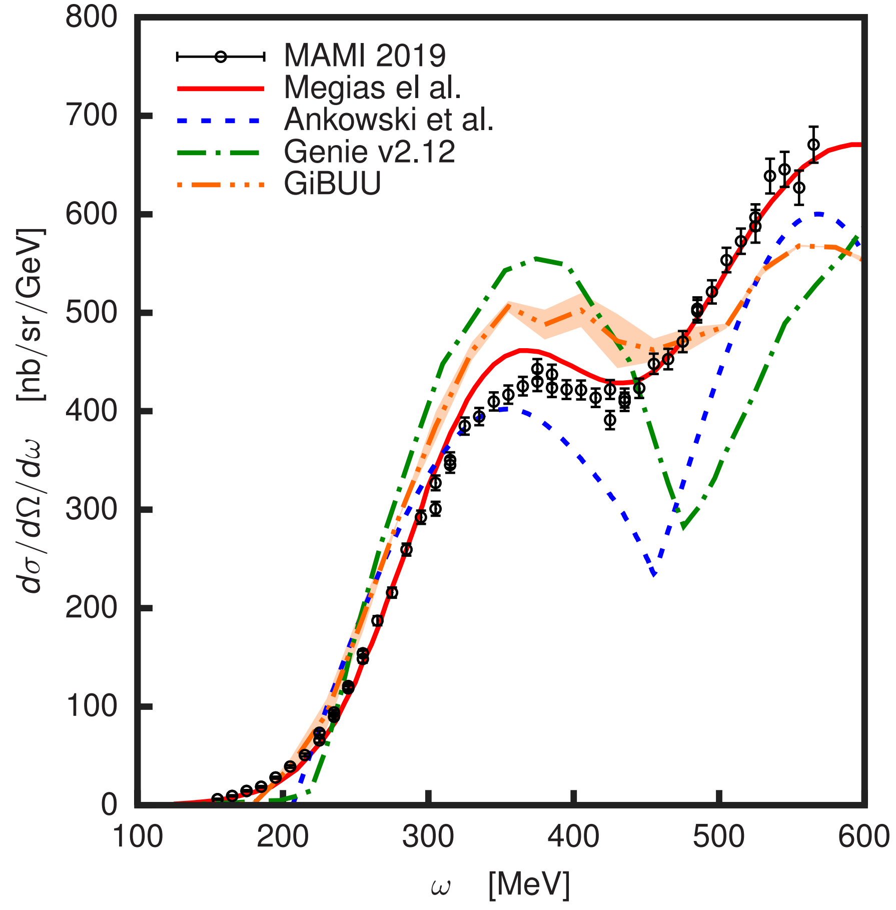


Source: www.dunescience.org



Credit: JLAB/**Neutrino-nucleus interaction**

^{12}C(e,e') @ MAMI (855 MeV)



Precision nucleon structure from muonic atoms and e⁻-scattering

- **Muonic atom spectroscopy:** allowed for 10-fold improvement in proton radius determination, **benchmark for nucleon/nuclear structure theory**

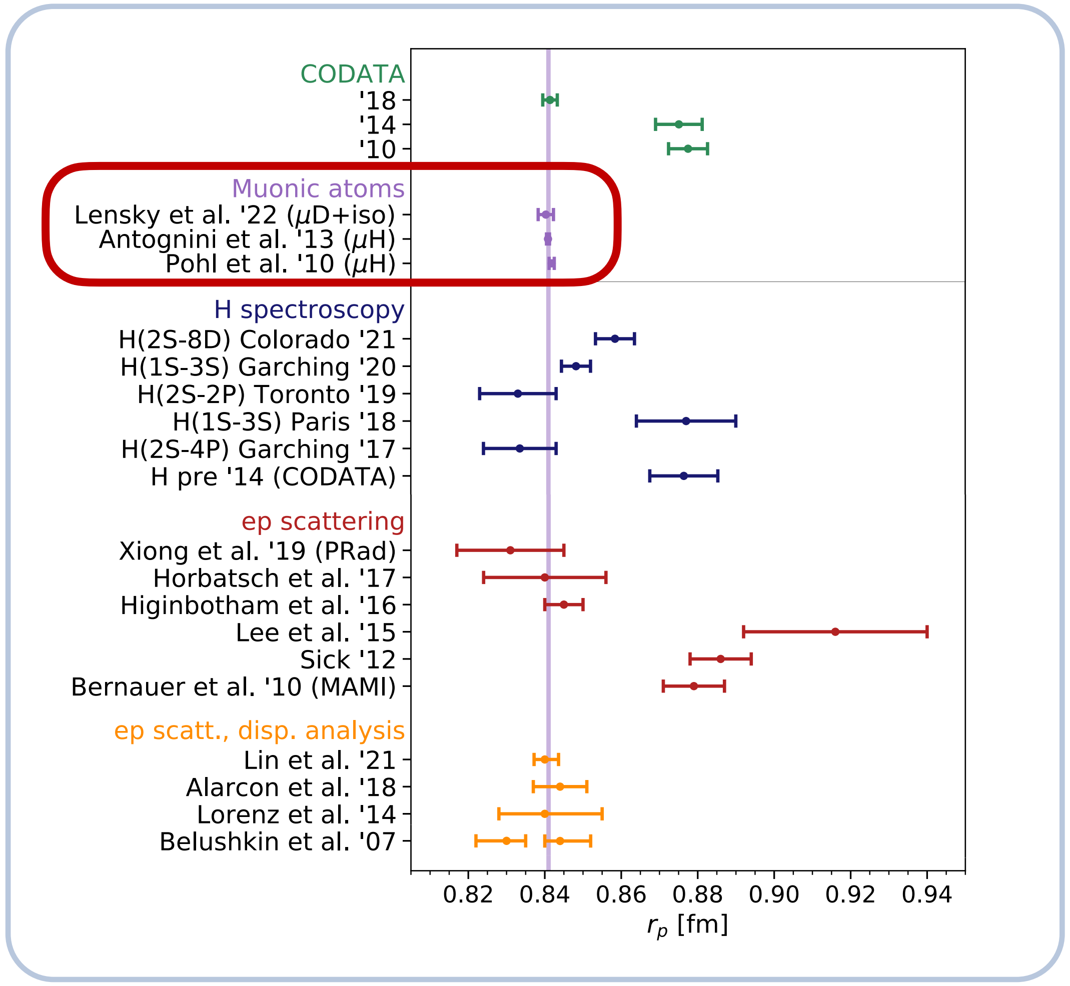
- Next generation of μ-atom experiments @PSI

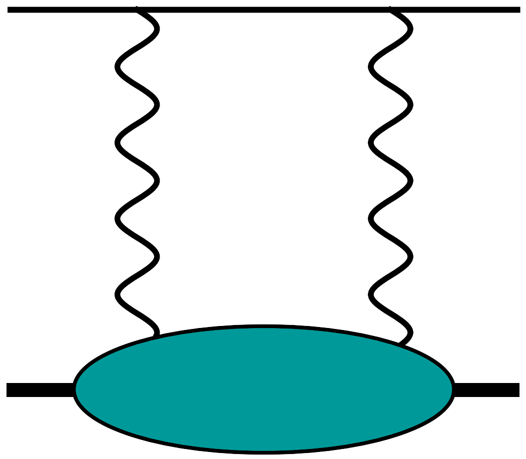
➡ First measurement of 1S hyperfine splitting in μH to two orders of magnitude better than theory

➡ Improvement of Lamb shift in μH by factor 5

➡ X-ray spectroscopy precision nuclear radii

- Dedicated theory to improve hadronic corrections to muonic atom spectroscopy using EFTs and dispersive techniques: **two-photon exchange**
- Framework for interpretation of electron and Compton scattering experiments
- Dedicated precision e⁻ scattering program to measure **proton form factors at MAGIX@MESA**
- **Compton scattering** program at **MAMI** will yield world's best determination of **neutron polarizabilities**

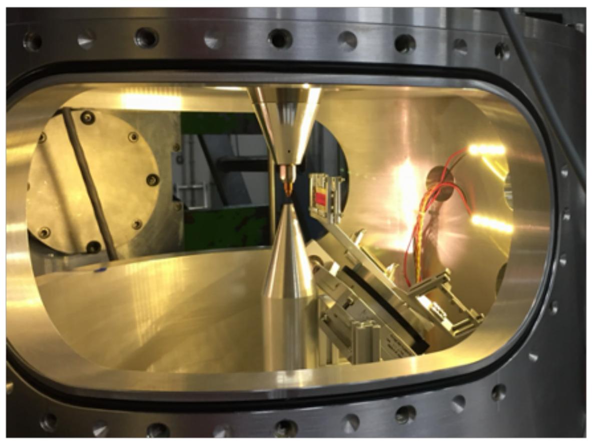




Electron scattering program with MAGIX @ MESA

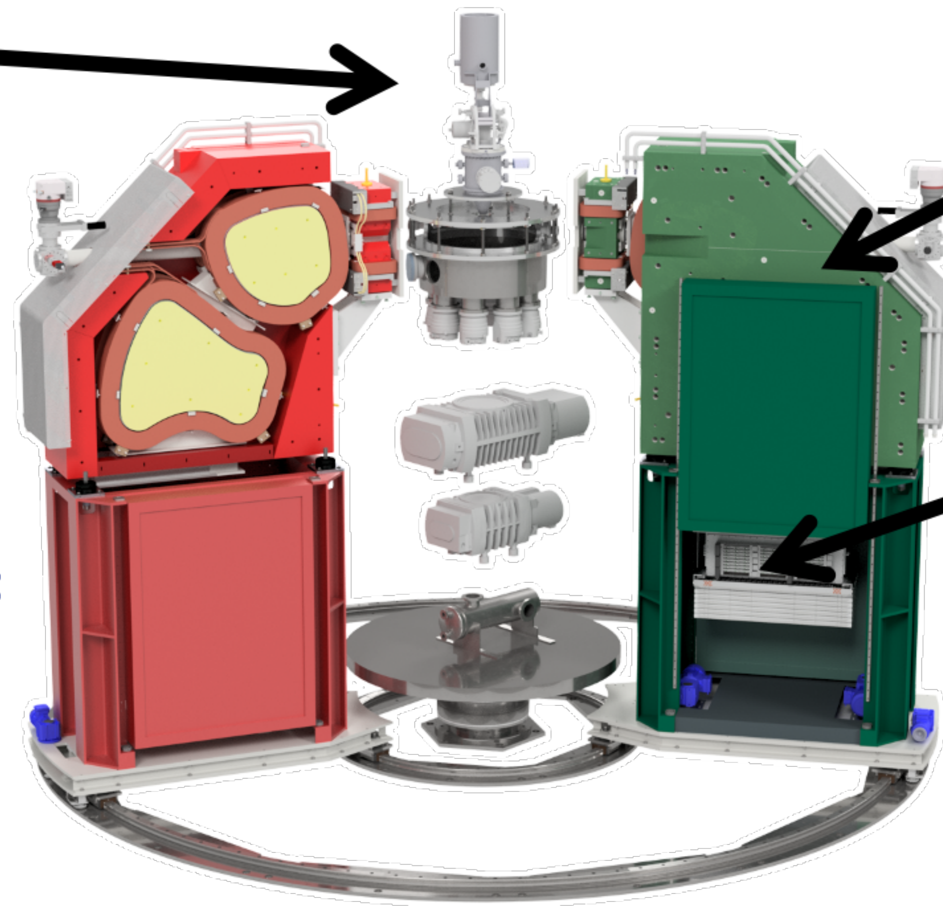
Operation of a high-intensity (polarized) ERL beam in conjunction with light internal target
→ a novel technique in nuclear and particle physics

NIM A1013 (2021)



Supersonic crygenic gas jet target

- Windowless environment
- Commissioned at A1/MAMI
- Design density $10^{19}/cm^2$



Two identical spectrometers

- Two dipoles each
- One quadrupole each

TPC-based focal plane detector

- 10^{-4} momentum resolution
- Requires spatial resolution of O(100 μm)
- Open field cage
- GEM readout

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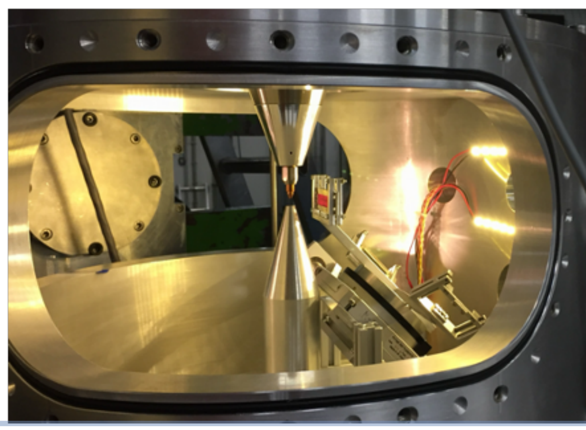

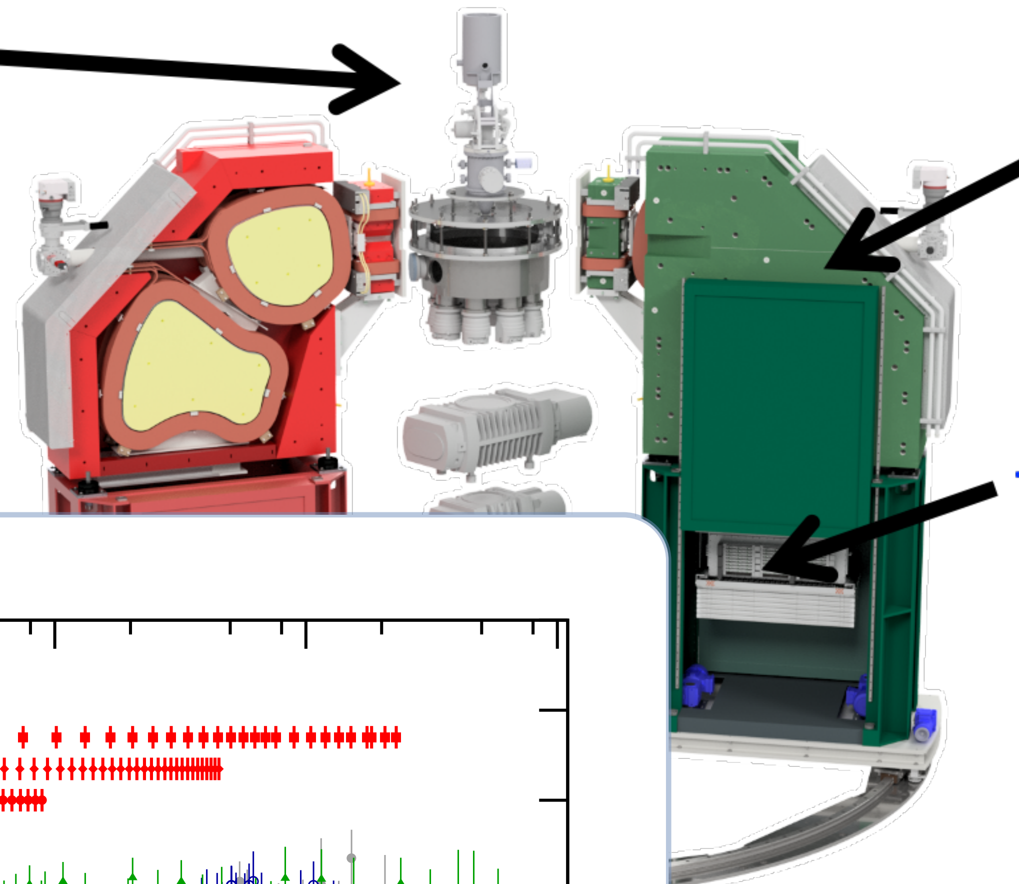

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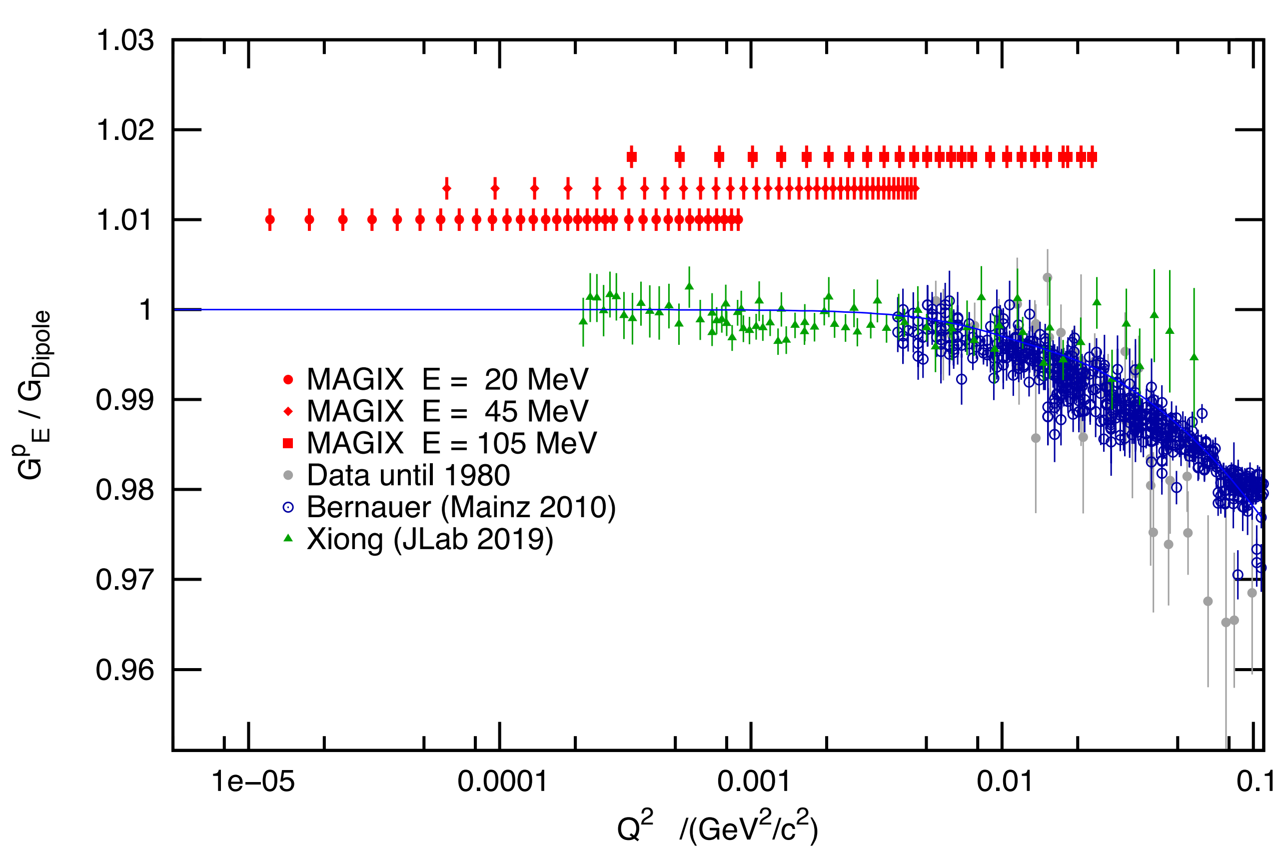
- GEM readout



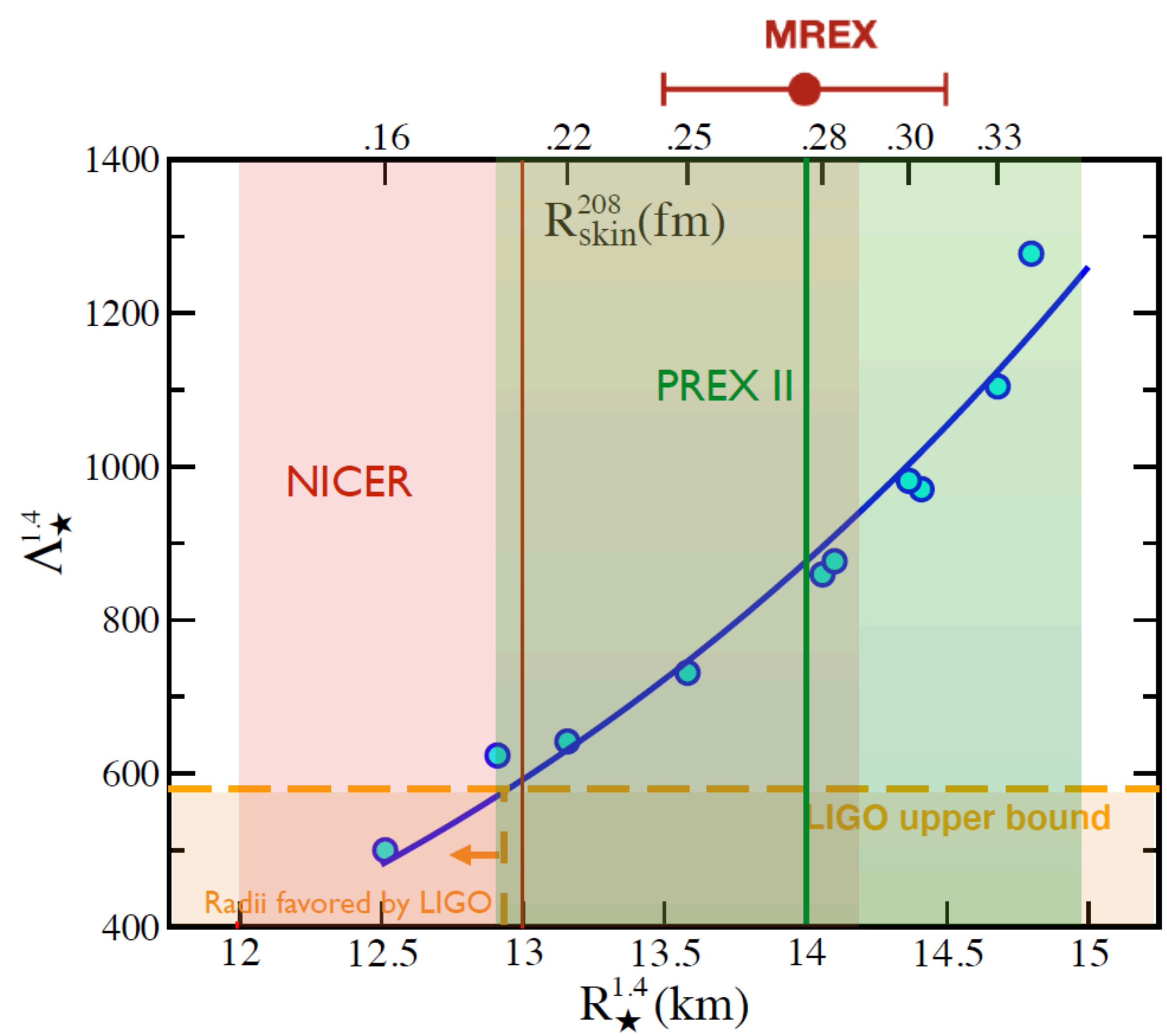
- Will allow for high-precision measurement of **structure quantities of nucleon and light nuclei** at lowest momentum transfers

Neutron skin and surface thickness of ^{208}Pb

- **Multi-messenger astronomy**: new window onto neutron-rich matter under extreme conditions
  - ➡ Detection of neutron star mergers by gravitational wave experiments
  - ➡ X-ray observations at ISS

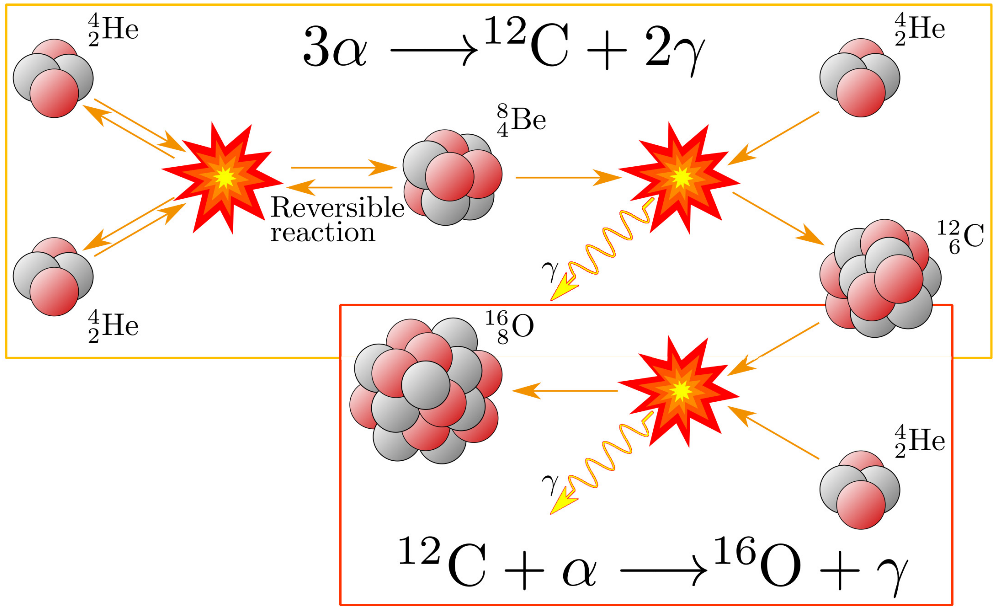
- Need for precision experiments to constrain **nuclear equation of state**

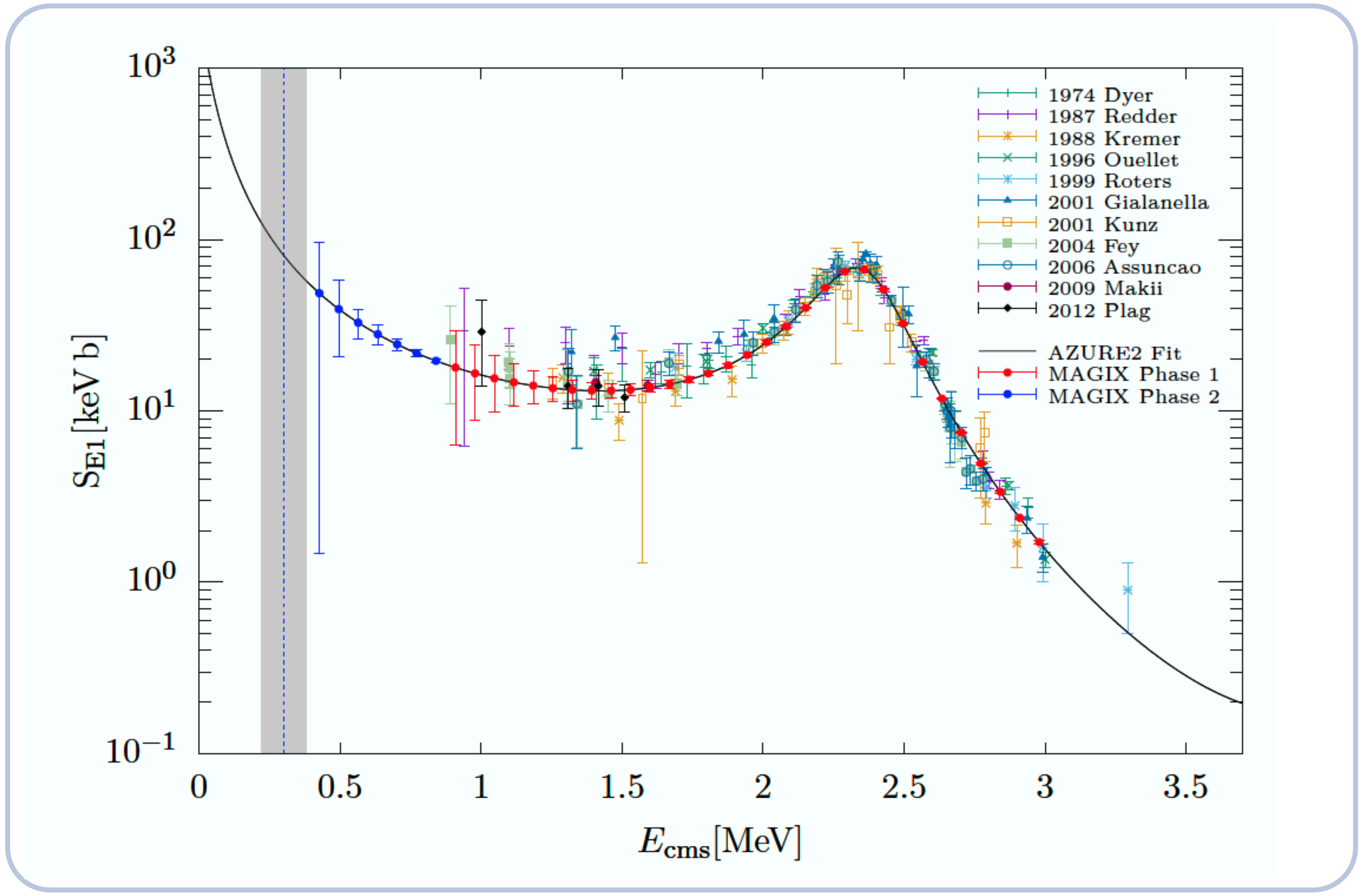
- Clarify by world's best measurement of neutron skin thickness in ^{208}Pb using **parity-violating e^- scattering with P2@MESA**



Reaction cross sections of astrophysical interest at MAGIX

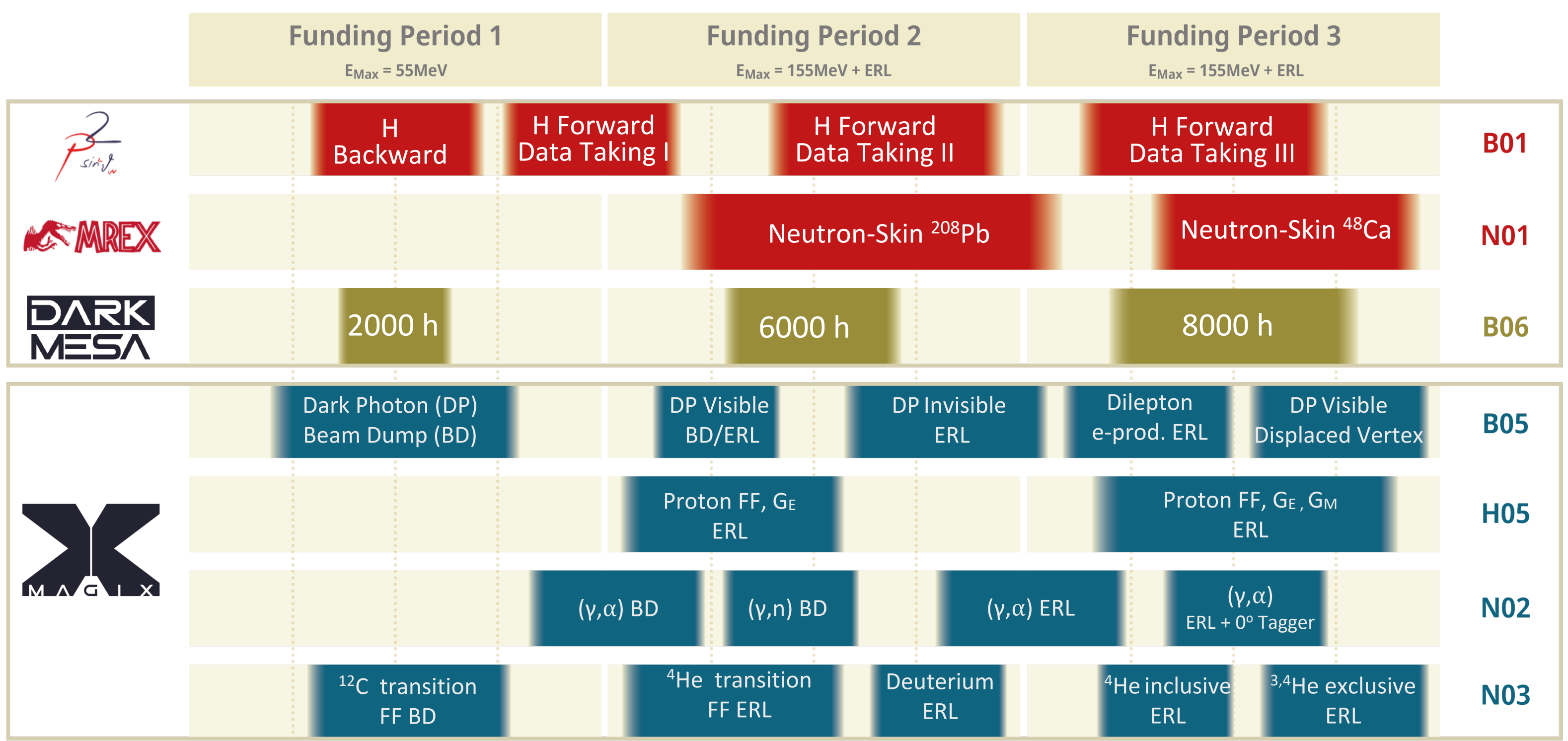
- Nuclear physics input also impacts our understanding of **stellar nucleosynthesis**
- Radiative capture cross sections through measurement of (γ, α) and (γ,n) **inverse reactions**
- MAGIX@MESA will allow measurement to unprecedented low energy
- Theoretical analysis using effective field theory





Summary

- QCD is 50 years of age, but precision physics at femtoscale just started
- Interactions with precision and high-energy frontiers: MAMI and MESA tailored to address these questions
- CRC1660: rich 12 year physics program



- Close synergy theory <-> experiment will move field forward