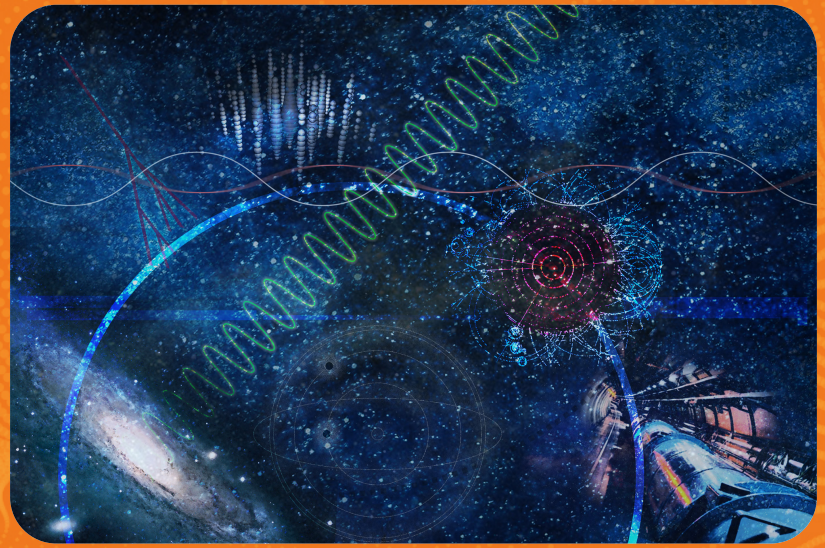
HELMHOLTZ

RESEARCH FOR
GRAND CHALLENGES

Cosmic Matter in the Laboratory

Highlights

Tetyana Galatyuk & Frank Maas



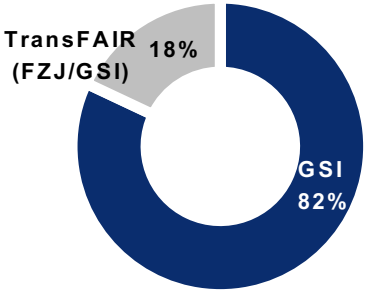
DESY. JÜLICH Forschungszentrum GSI HI JENA HELMHOLTZ HIM HELMHOLTZ Helmholtz-Institut Mainz HZB Helmholtz Zentrum Berlin HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF Helmholtz-Zentrum Geesthacht Zentrum für Material- und Küstenforschung IPP KIT Karlsruhe Institute of Technology

Who we are

MU CML
MATTER AND THE UNIVERSE

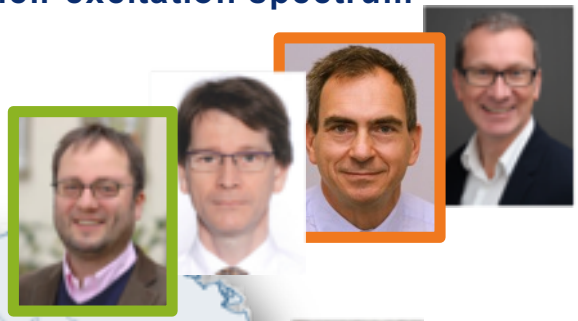
Budget: 18.9 Mio €/y

People:
82 FTE core-funded scientists
64 FTE doctoral students
22 FTE scientific support



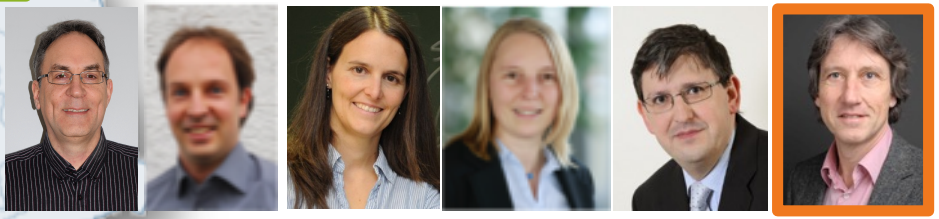
6 ERC Grants
20 joint positions with universities
3 female former HYIG promoted to university professor
6 (co)spokespersons of large international collaborations

Properties of hadrons and their excitation spectrum



Nuclear structure, nuclear reactions, and superheavy elements

Theory



QCD phase structure and properties of QCD matter

Test of fundamental symmetries

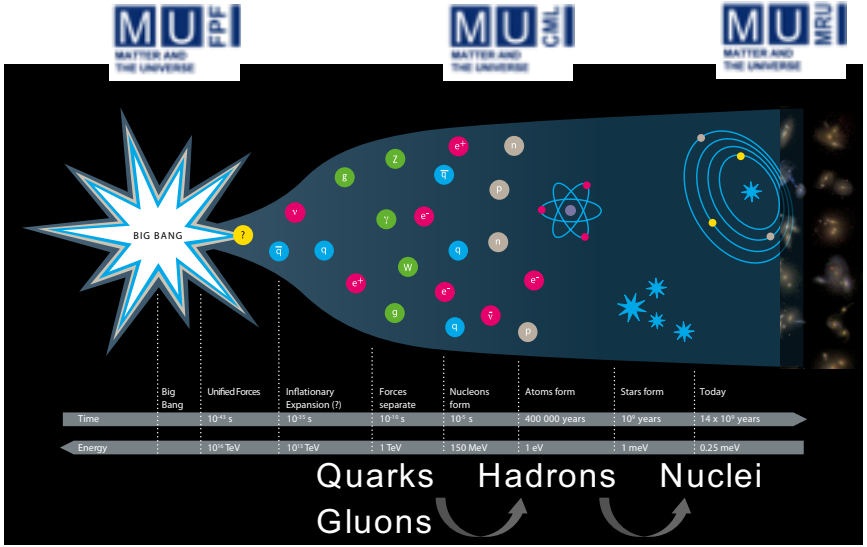
Cosmic Matter in the Laboratory within MU

Mission and objectives

Key contribution to the Helmholtz-Mission:

Emergence of complex phenomena in strong interaction

Role of the strong interaction in the evolution of our universe



Mission

- Unravel the properties of hadrons; access and understand the QCD spectrum
- Explore strongly interacting systems under extreme conditions of temperature, density, isospin

Strategy

- Study cosmic matter in the laboratory
- Use primary and secondary ion beams from (anti-)protons to uranium
- Apply forefront technologies

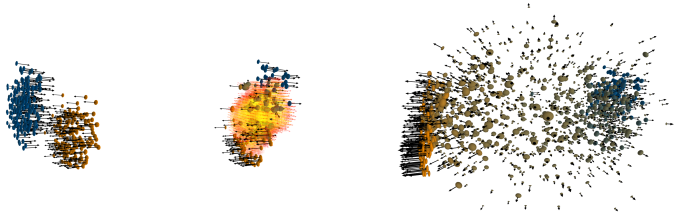
Strong link to MT MATTER AND TECHNOLOGIES

Uniqueness

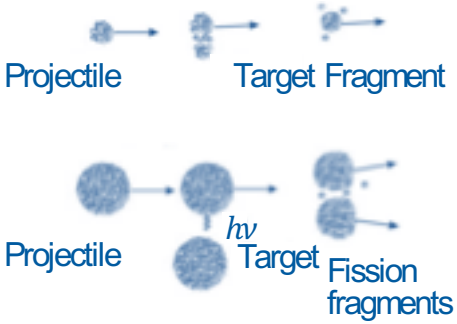
- Relativistic ion beams of highest intensities
- Storage rings for cooled (secondary) beams
- Innovative experiment instrumentation

Experiment and Theory Methods

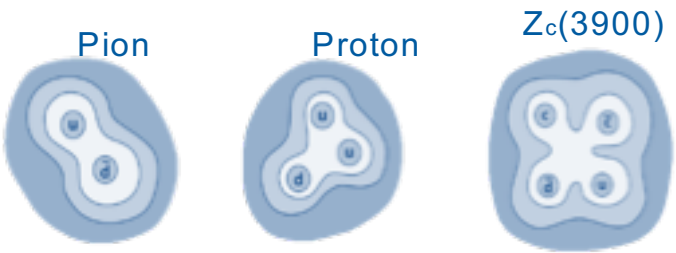
Collision of heavy-ions at (ultra-)relativistic energies



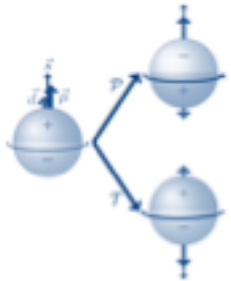
In-flight fragmentation, separation and storage of ions at relativistic energies



Matter-antimatter annihilation



Test of fundamental symmetries



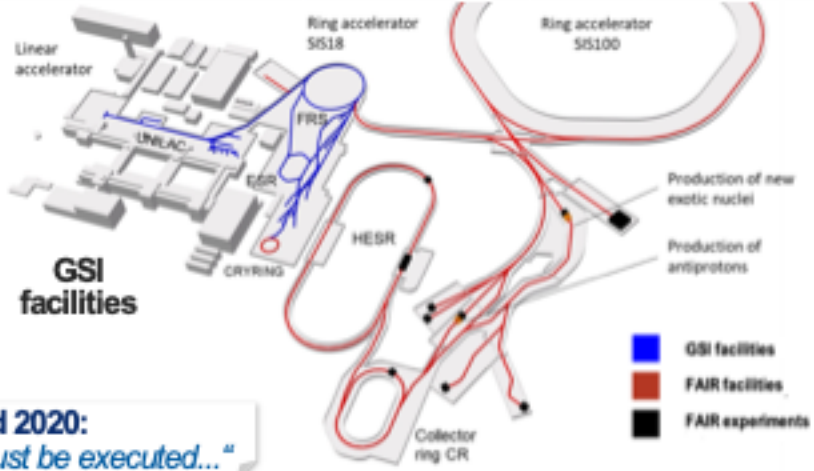
Strong link to MT

Where we stand and where we want to go

2021 → 2022 → 2023 → 2024 → 2025 → 2026 → 2027 → 2028

FAIR Phase 0:

Since 2018: Intermediate forefront research program at GSI with improved beams and FAIR detectors: Y. Leifels



GSI facilities

FAIR: 2025 early science, start of FAIR operation and physics exploration, see talk by T. Galatyukl

POF Center evaluation 2017 and 2020:
"...The FAIR Phase 0 program must be executed..."

Preparation for unique measurements addressing fundamental symmetries with polarized beams

COSY at Jülich

LHC at CERN ALICE

Operation of central tracking detector with continuous readout

ALICE records Pb-Pb data at 50 kHz collision rate

Crucial contributions to the operation, detector calibration, physics program

User facilities and instruments available for FAIR Phase 0

MU ion facilities and experimental setups talk by Y.Leifels

Nuclear structure, nuclear reactions, and super-heavy elements

UNILAC p to U beams up to 11.4 MeV/u

heavy ion storage ring ESR
fragment separator FRS
heavy-ion synchrotron SIS18

Properties of hadrons and their excitation spectrum

SIS18 π, p beams up to 4.5 GeV

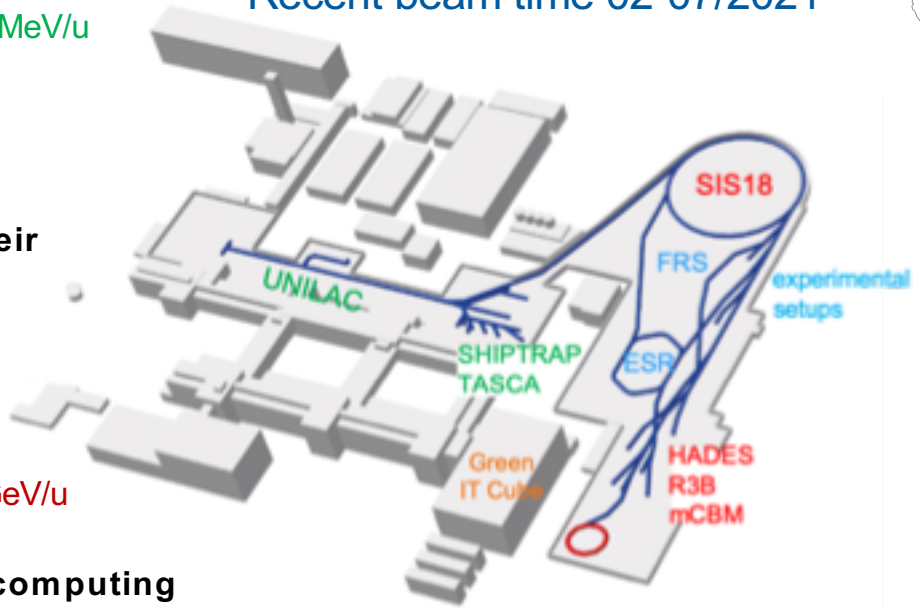
QCD phase structure and properties of QCD matter

SIS18 heavy-ion beams up to 1 GeV/u

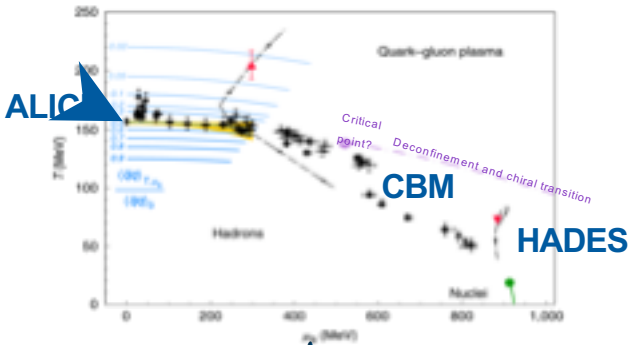
Scientific high-performance computing

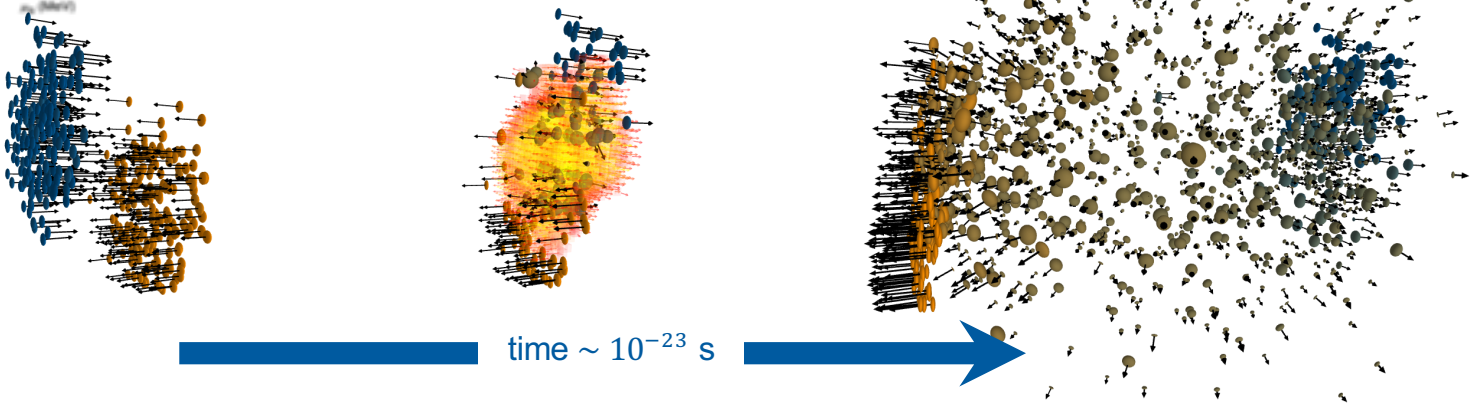
GSI, HIM, FZ Jülich, KIT

Recent beam time 02-07/2021



FAIR Phase 0 outside campus:
LHC / CERN
AD / CERN
BEPCII / China
GANIL / France
COSY / Germany
MAMI / Germany
TRIGA / Germany
RIKEN / Japan
Nuclotron / Russia
CEBAF / USA
RHIC / USA





Collision of heavy-ions at (ultra-)relativistic energies

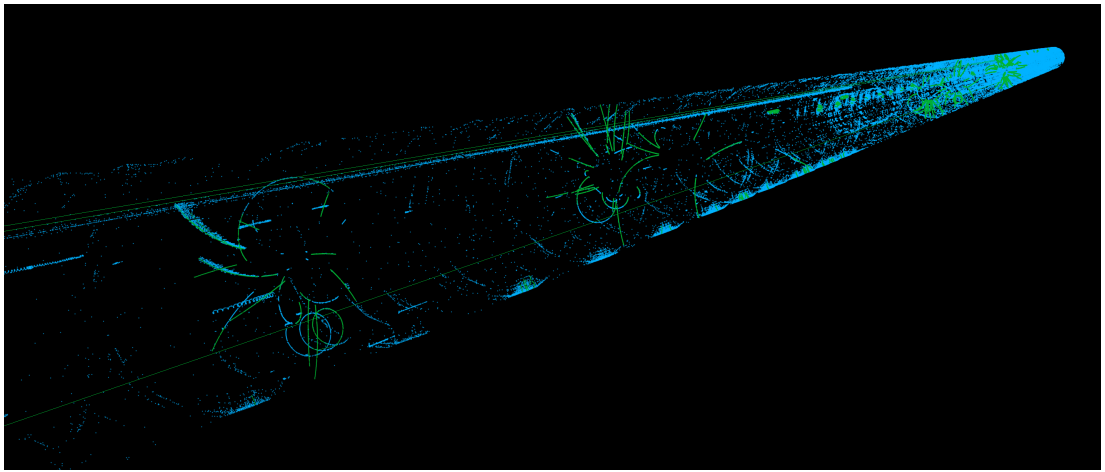
→ produce and investigate transient states of QCD matter under extreme conditions of temperature and density

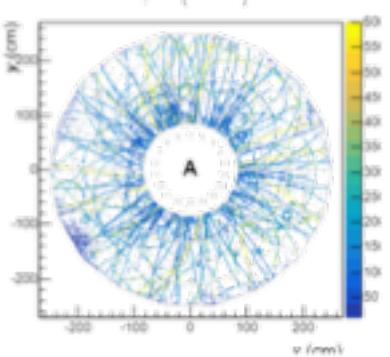
→ See flash talk by S. Spies, W. Esmail

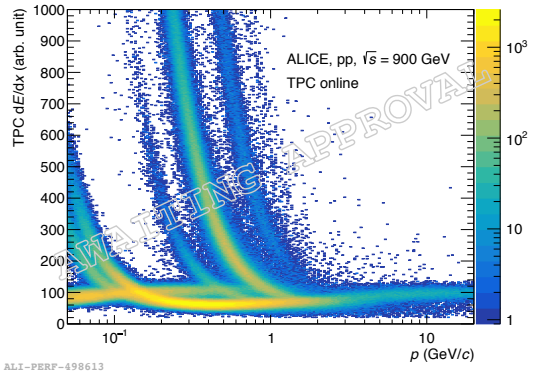
QCD phase structure and properties of QCD matter

ALICE Experimemnt at LHC: First test with proton-proton collisions (Oct 21 – Nov 1 /2021) at injection energy (900 GeV), Operation in **continuous readout mode!**

First steps towards Run 3 physics!







CML:

- Time Projection Chamber TPC Upgrade
- Online-Offline Analysis framework
- HGF-project “Full exploitation of the LHC”

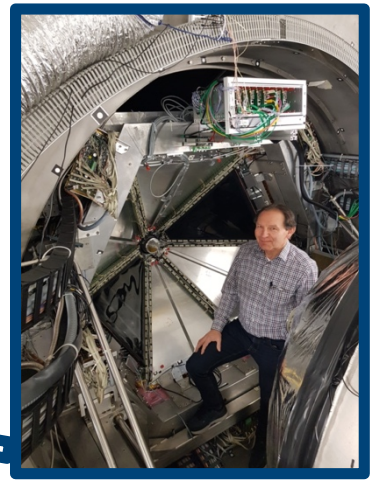
Upgrades for the FAIR Phase-0 beam time in 2022

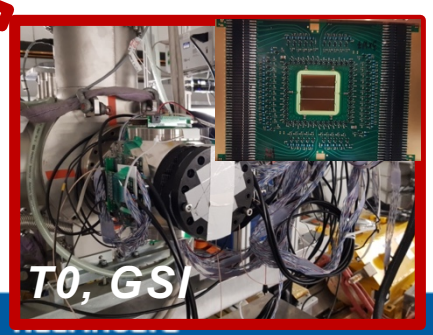
- Improved physics performance through instrumentation of the very forward hemisphere using FAIR technology.
- Dedicated to the joint HADES-PANDA physics program on electromagnetic properties of hyperons.

iTOF

TransFAIR, Jülich

- APD read-out
- Enhances trigger purity



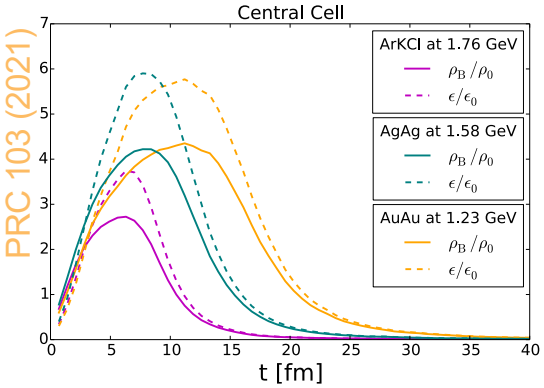


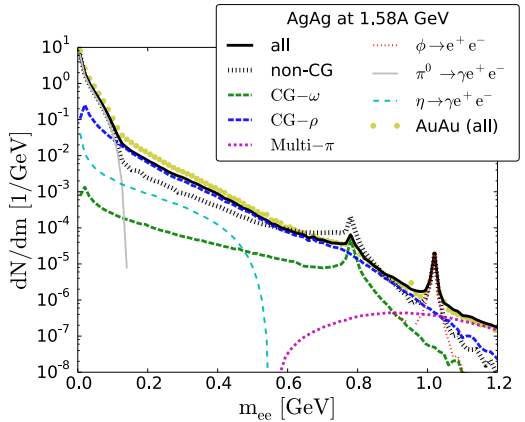
First Tests
in Feb. 2021

System
in operation

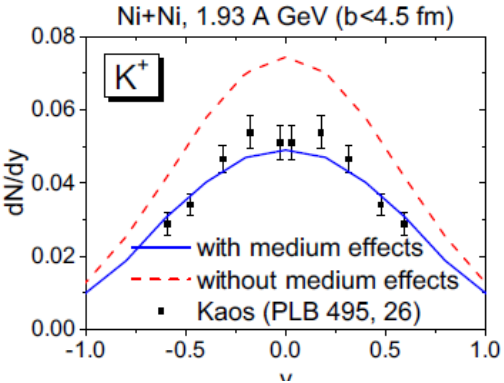
Theory of Hot and Dense QCD Matter - Observables for Medium Modifications

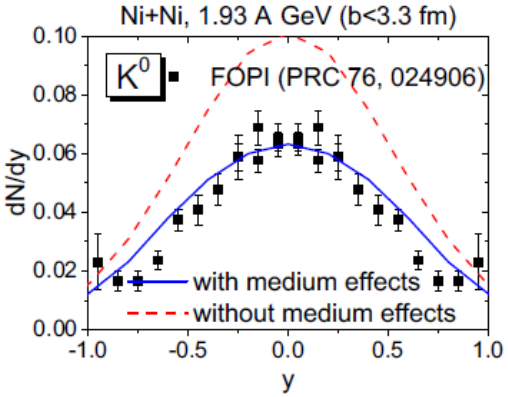
PRC 103 (2021)

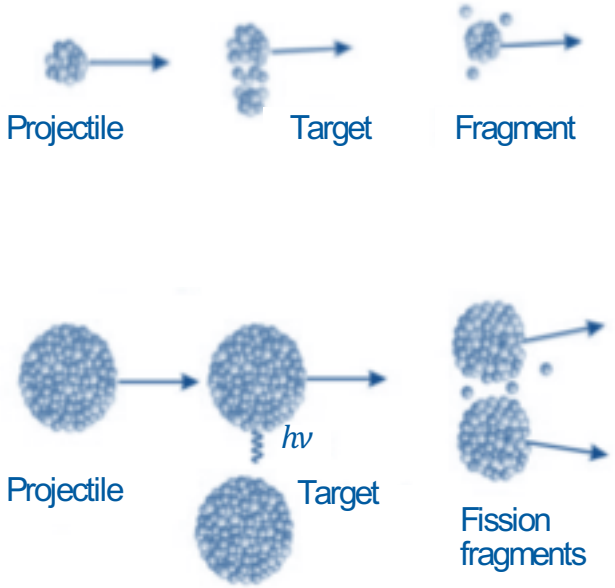




- In heavy-ion collisions at GSI high densities are reached over extended time period
- Predictions for HADES AgAg dilepton spectra surprisingly similar to Au+Au results
- G-matrix approach for in-medium potentials for kaons indicates significant effects for strangeness production
- Collective flow is also affected







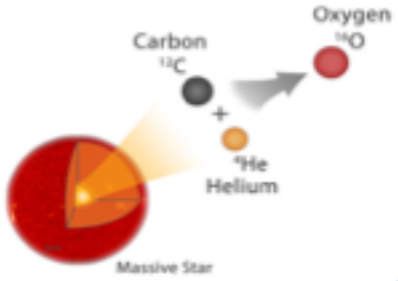
In-flight fragmentation, separation and storage of ions at relativistic energies

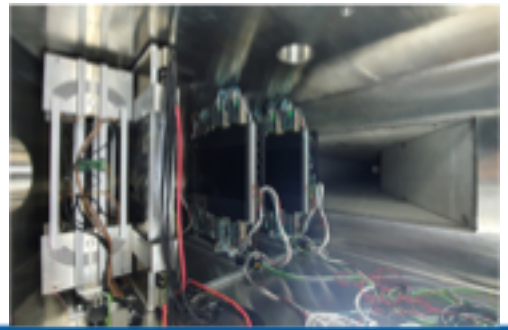
→ investigate exotic r-process isotopes with high selectivity and sensitivity

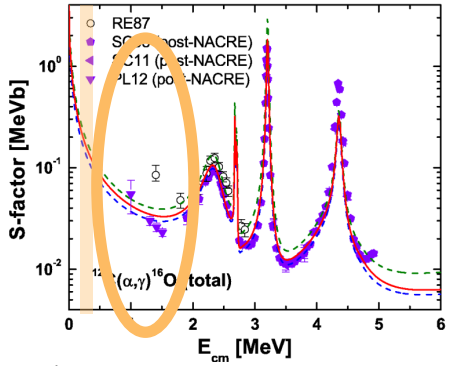
→ See flash talk by Oliver Just, K. Wimmer

Nuclear Reactions R3B
Coulomb dissociation of 16O into 12C and 4He

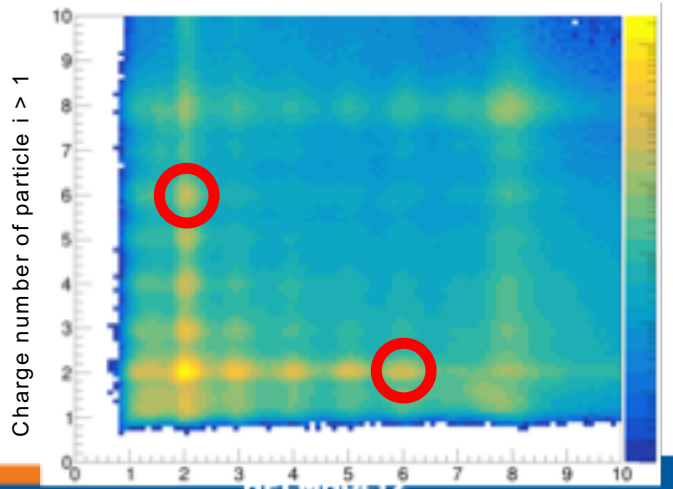
- $^{12}C(\alpha,\gamma)^{16}O$ is critical reaction of helium burning in massive stars, rate is insufficiently known
- Determines the ratio of $^{12}C/^{16}O$ in the universe
- Goal: measure cross section of fusion reaction of Helium and Carbon at small relative energies (below E_{cm} = 1MeV) by Coulomb dissociation of ^{16}O
- Demanding detector setup for beam intensities of up to 10^9 oxygen ions / second
- Collected 67 TB of data during beam time in 2021







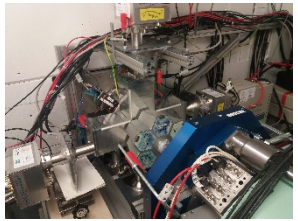
Pairs of Helium and Carbon in the data



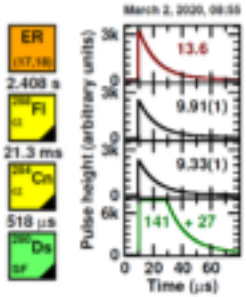
NUSTAR – Superheavy Elements

Pinpointing the center of the Island of Stability: it is not at Z = 114

Heavier elements move into the spotlight

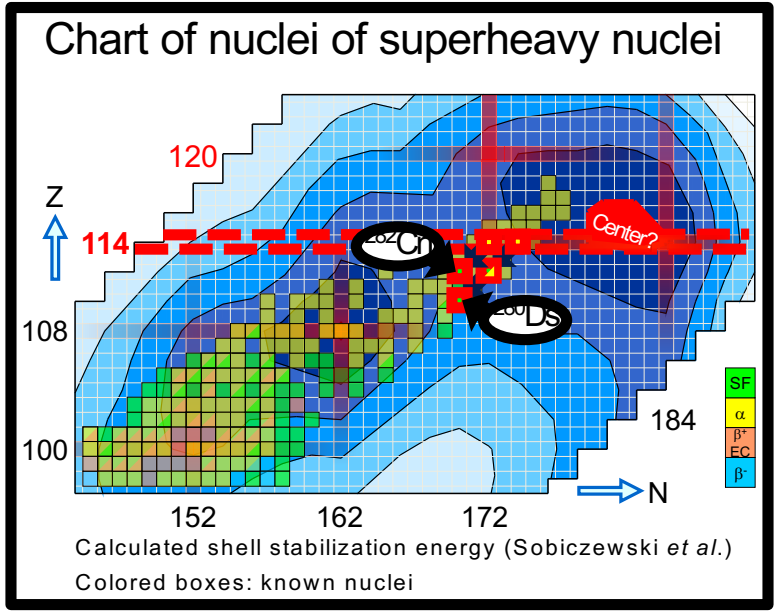


TASISpec+



Fully digital DAQ

- High-resolution **α-photon nuclear spectroscopy** of 14 flerovium (element 114) decay chains with TASISpec+ at **TASCA** recoil separator at GSI: first detailed nuclear structure studies of even-Z element near the "island"
- Discovery of **new isotope ^{280}Ds** provides first **sequence of α-decay energies across Z=114** shell gap
- Discovery of **excited 0+ state** in ^{282}Cn: **shape coexistence**
- Both observations, together with extensive triaxial beyond mean-field theory indicate that there is **no pronounced shell gap at proton number Z=114**
- Focus shifts to **heavier elements: 120? 126?**



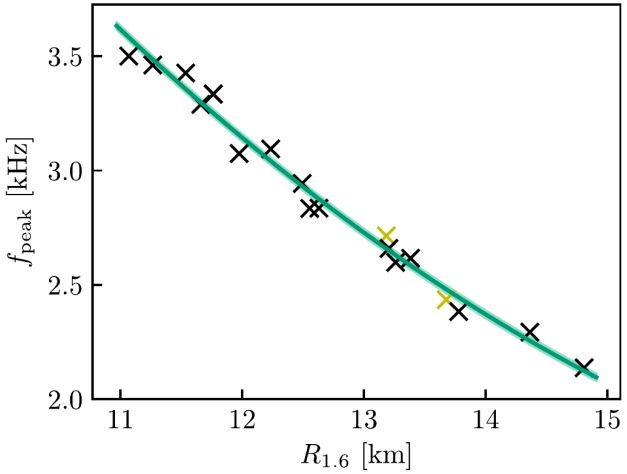
A. Såmark-Roth *et al.*, Phys. Rev. Lett. 126 (2021) 032503
J.L. Egido & A. Jungclaus, Phys. Rev. Lett. 125 (2020) 192504; *ibid.*, 126 (2021) 192501

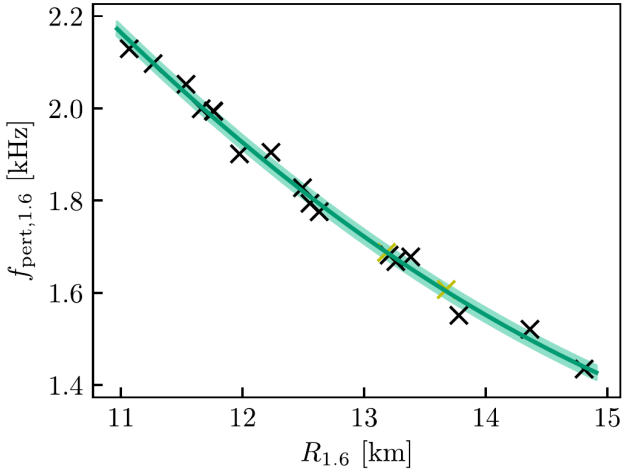
Spokesperson: D. Rudolph, Lund. Univ.

Theory: Neutron star asteroseismology

Oscillation frequencies of merger remnants: isolated stars:

- Different absolute frequencies
- Similar scaling with neutron star radius
- Similar frequency **deviations** from universal scaling
- (compare relative location of individual models)
- → EoS constraints





Predictions by simulation data with different EOS models

G. Lioutas et al., PRD 104, 043011 (2020)

Pion

Proton

$Z_c(3900)$

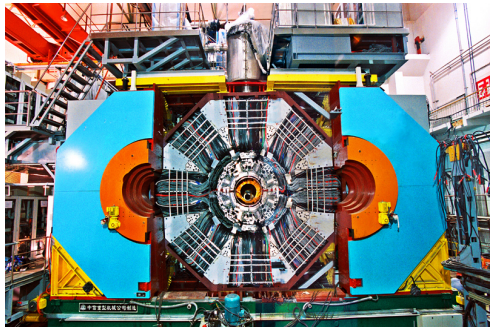
Matter-antimatter annihilation

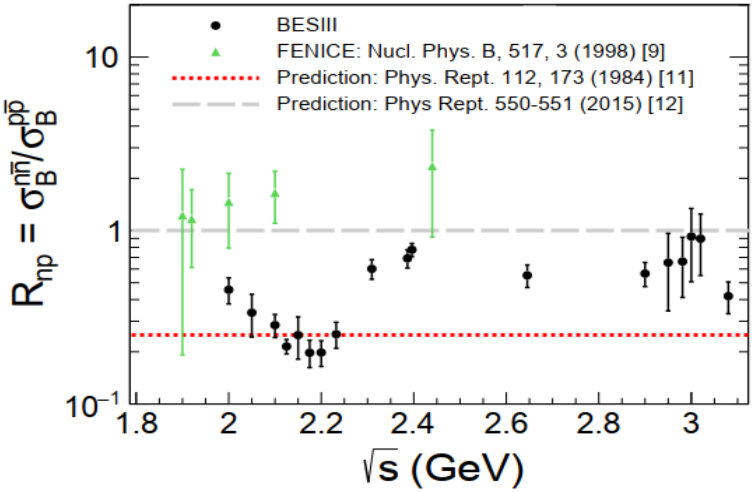
→ produce the QCD excitation spectrum with high resolution and enhanced sensitivity for gluonic degrees of freedom

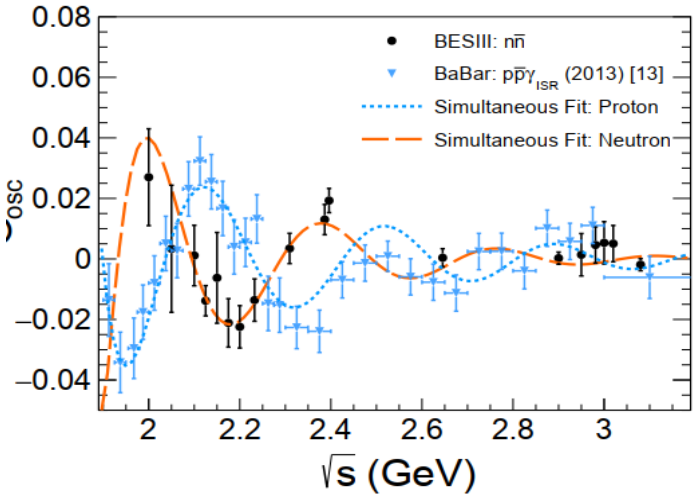
→ See flash talk by W. Esmail, Sahra Wolff, D. Mohler

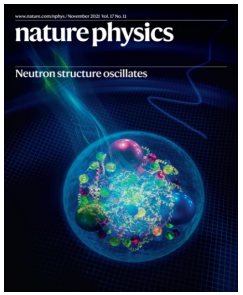
Precise Electromagnetic Structure of the Neutron Measured at BESIII, IHEP Beijing

- Dedicated energy scan in electron positron collisions
- Neutron and Antineutron in final state
- Challenging detection and analysis

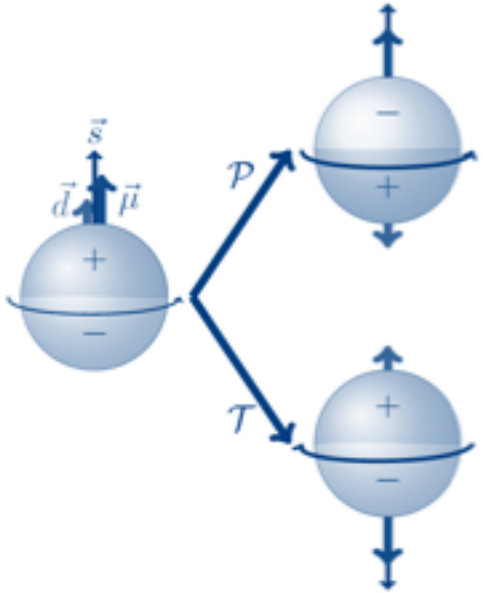








Nat. Phys. 17, 1200–1204 (2021). https://doi.org/10.1038/s41567-021-01345-6



High-precision accelerator experiments

→ search for physics beyond the standard model

→ See flash talk by S. Kumaran

Test of fundamental symmetries

Example: deuteron/proton Electric Dipole Moment (EDM)

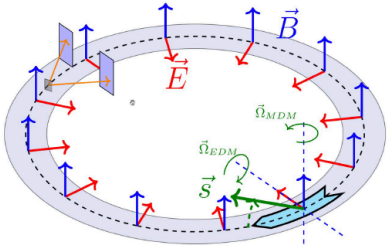
Observed deuteron polarization build-up

COSY at Jülich

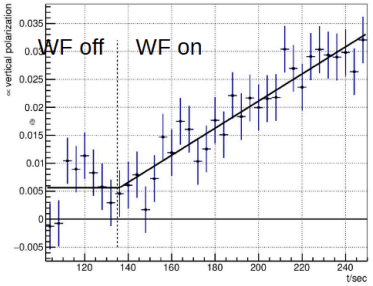
POF Center evaluation 2017:
„ … has an opportunity, unique within the world, to investigate and eventually prove the feasibility of the storage ring EDM method (srEDM) at COSY....“

Electric Dipole Moment @ Storage Rings

precursor experiment on deuteron EDM (PoF milestone CML-2) and axion searches (CML-12) completed a Cosy, analysis/publications are in progress



- EDM observable: build-up of a vertical polarisation
- plot shows build-up observed at Cosy (still dominated by systematic effects)



Work program

Experiment

Deuteron EDM: proof of capability with COSY, accelerator development, completion of deuteron EDM precursor experiment

Indirect axion search via oscillating EDM

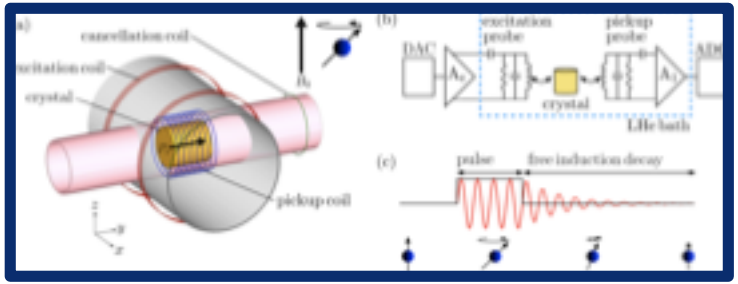
Proton EDM: technical developments and design report for an all-electric storage ring

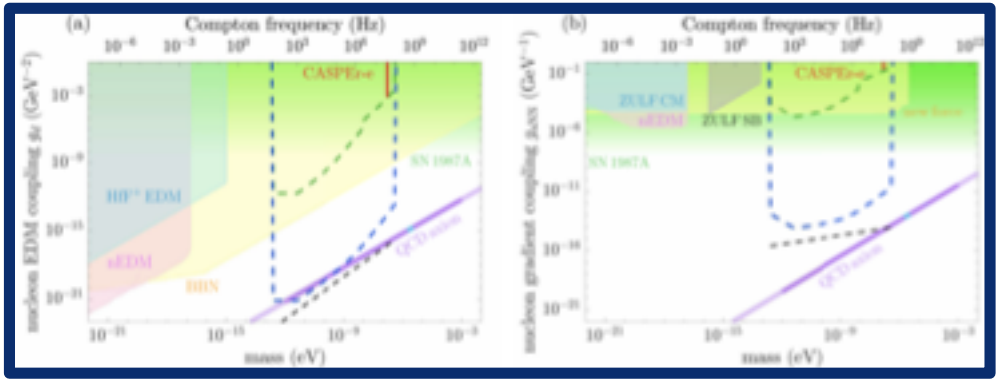
Goal

Search for physics beyond the Standard Model with high precision experiments using nuclear physics methods

HIM MAM Highlight: search for ultralight bosonic DM

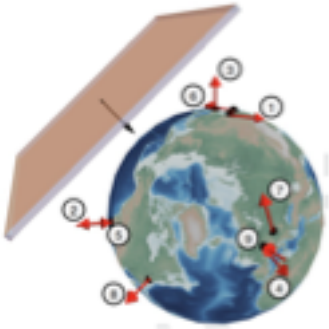
CASPEr: cosmic axion spin-precession experiments; first physics results: 2019-21

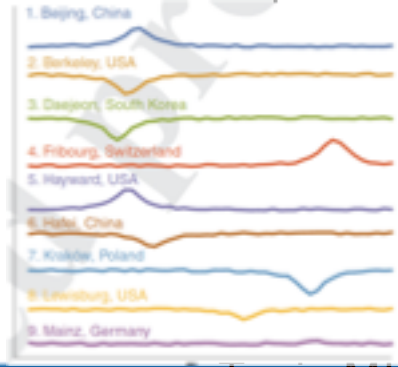


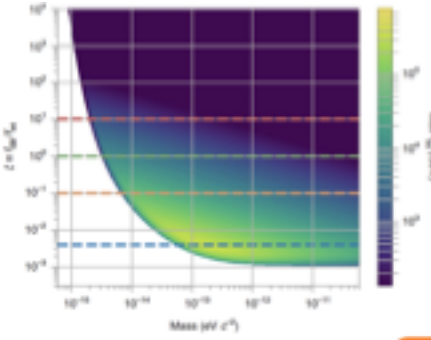


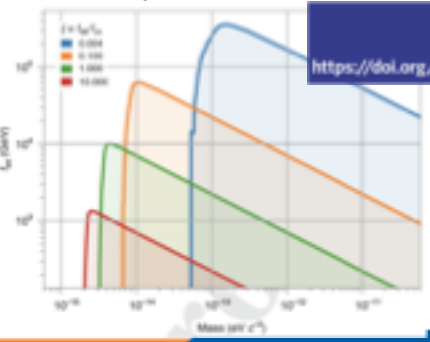
PhysRevLett.126.141802

GNOME: global network of optical magnetometers for exotic physics searches









ARTICLES
https://doi.org/10.1038/s41567-021-01393-y

nature physics

Summary

- Selected highlights from Cosmic Mater in the Laboratory
- FAIR accelerator and physics program is approaching in big steps, see talk by T. Galatyuk
- FAIR Phase 0 program at GSI and abroad: at full swing with exciting new results , see talk by Y. Leifels
- Establish vibrant community performing world-class science with (highly-)relativistic ion beams from (anti-)protons to uranium
- Provide opportunities for young talents to perform fundamental research at the forefront of nuclear science