

Cosmic Matter in the Laboratory

SPOKES-
PERSONS



Tetyana
Galatyuk



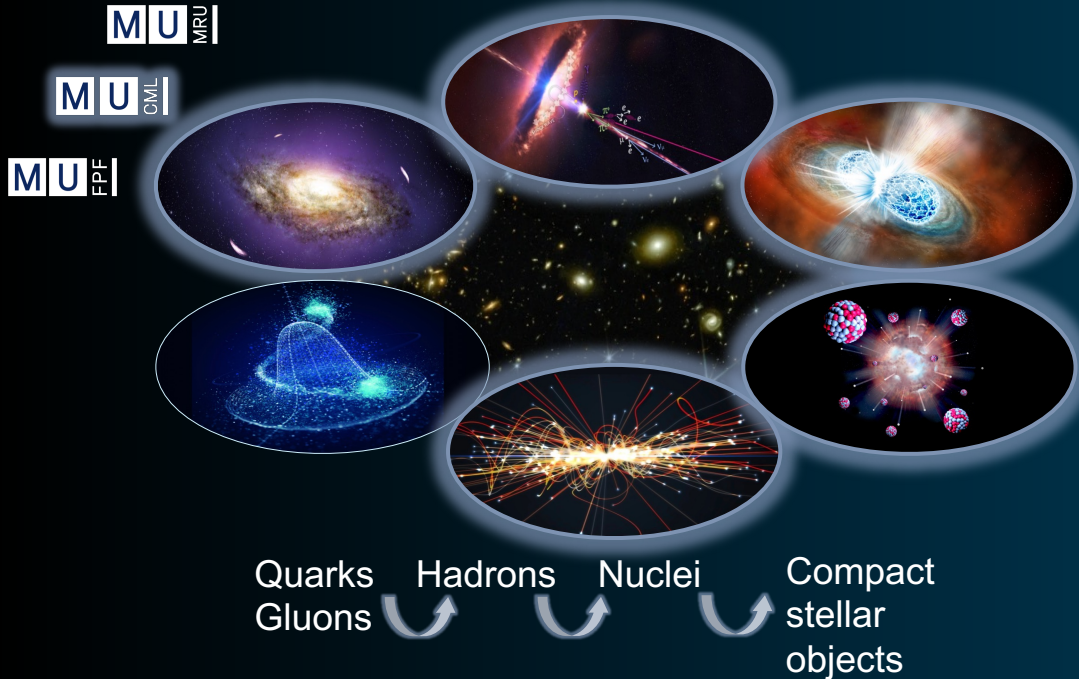
Michael
Block



Research for grand challenges.

Our mission

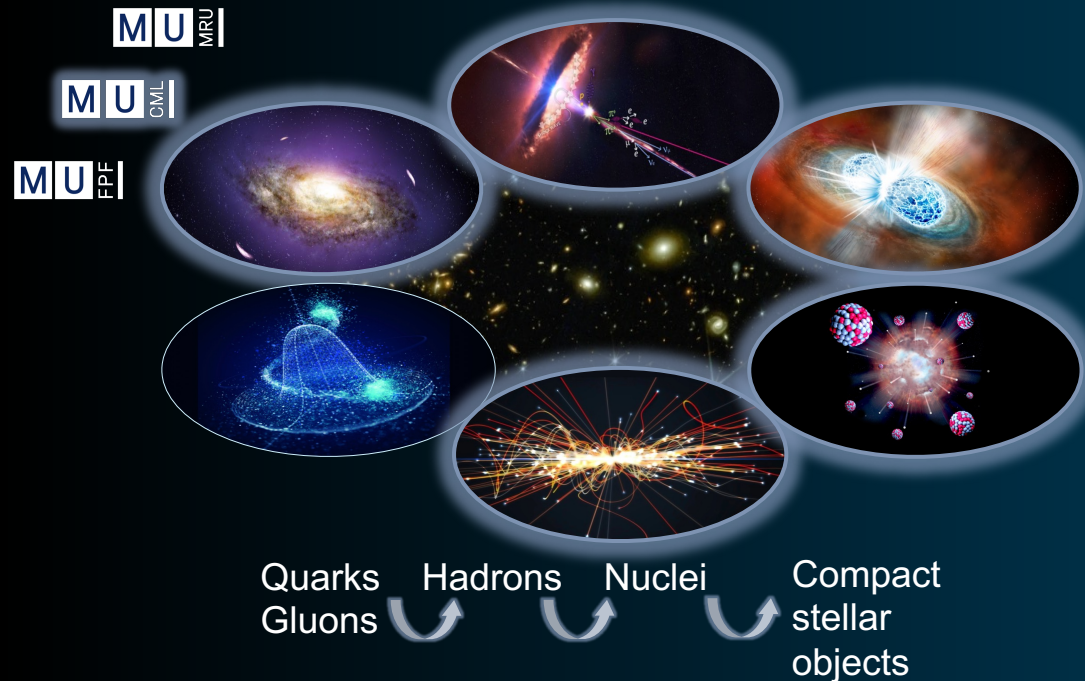
Understand the complex phenomena governed by the strong interaction in the non-perturbative regime of Quantum Chromodynamics (QCD)



From microscopic to macroscopic scales

Our mission

Understand the complex phenomena governed by the strong interaction in the non-perturbative regime of Quantum Chromodynamics (QCD)



- Understand the **properties of matter** arising from the **strong interaction**
- Explain the **nucleosynthesis of the elements** in the Universe
- Search for physics **beyond the Standard Model** through low-energy precision experiments

From microscopic to macroscopic scales

Our competences

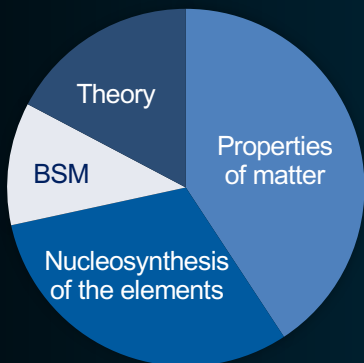
Experimental, theoretical, and technical expertise

81 scientists, 59 doctoral students,
16 support personnel, 30.7 M€ (plan for 2028)



HIM
HELMHOLTZ
Helmholtz Institute Mainz

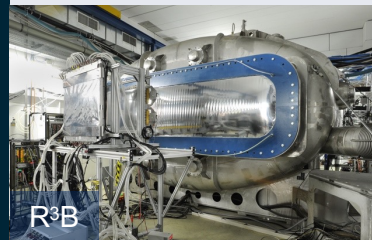
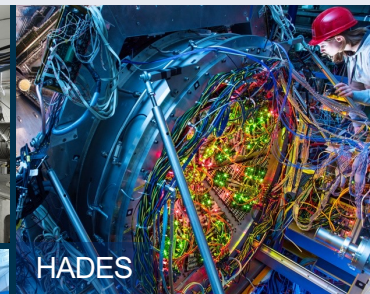
HZDR
HELMHOLTZ ZENTRUM
DRESDEN ROSENDOERF



Team excellence:

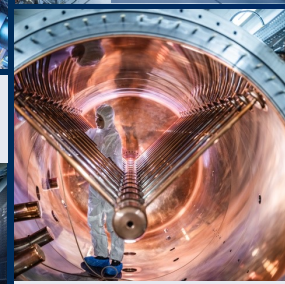
8 ERC grants, Helmholtz investigator group,
Gottfried Wilhelm Leibniz Prize 2022,
21 joint faculty positions with universities,
leading roles in large international collaborations

Design, R&D, construction, operation of cutting-edge experiments



Storage, cooling,
manipulation of rare ion
beams

Analysis of multi-
Petabyte-size data sets



Relativistic ion
beams of highest
intensities

Our strategy

Address key observables across all scales

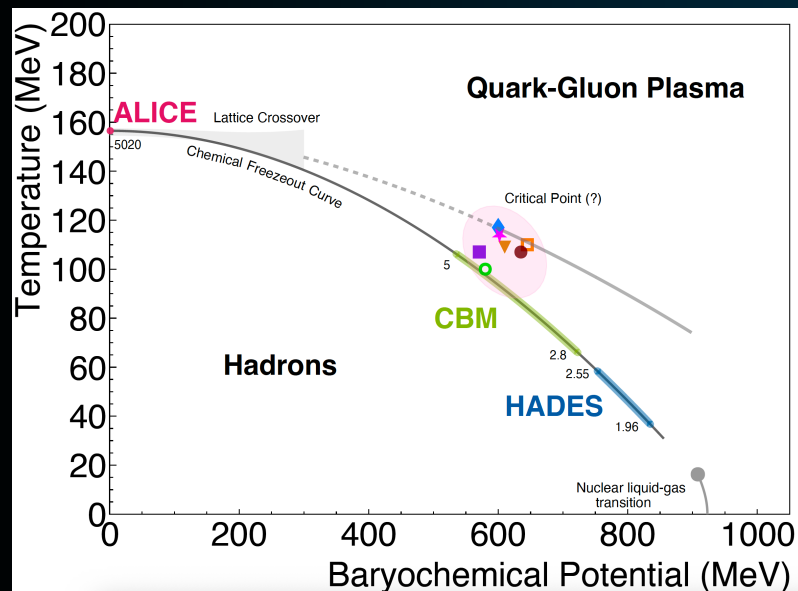
- Realize the full physics potential of the new FAIR facility leveraging the outstanding capabilities of the **Super-FRS** and **SIS100**
- Continue to conduct comprehensive research using the existing research infrastructures at **GSI** and facilities at the **HI Mainz** (MESA, TRIGA ...), **BEPC-II**, **JUNO**
- Perform high precision measurements at **HZDR Felsenkeller** and the new underground nuclear astrophysics laboratory with German Center for Astrophysics (DZA)
- Exploit the **high luminosity** potential of the **LHC** for ions in **ALICE Run 4**, provide technical and scientific contributions to the ALICE 3 project



QCD matter at the extremes

Unraveling the grand features of the QCD phase structure

Collision energies from GeV to TeV, high interaction rate detectors from 50 kHz to 10 MHz

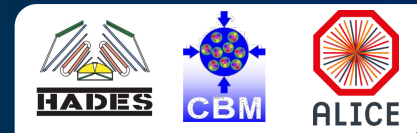


PoF IV arXiv:2508.18879 [nucl-th]
PRC 106 (2022) 014904

PoF V

- Realize unique science program with **CBM**:
Unprecedentedly high statistics $\leadsto$ access to rare probes
- Deployment of **ALICE** inner tracker upgrade and HL-LHC:
 $\times 100$ more statistics, excellent vertexing capabilities
 $\leadsto$ QGP diagnostics with charm- and beauty quarks
- **Theory**: Connecting non-perturbative QCD to observables

Goals for PoF V: Search for 1st order chiral and deconfinement phase transition and QCD critical point. Extract transport properties of matter. Understand hadronization mechanism.

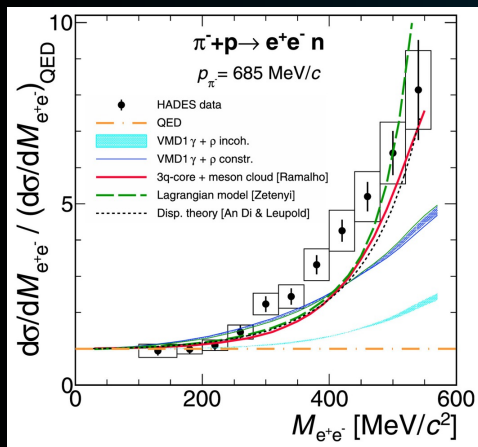


Hadrons, their properties, and interactions

How do the complex spectra of hadrons arise from QCD?

PoF IV

Revealing the nature of baryon virtual-photon coupling in the timelike region



PLB 875 (2026) 140338
Nat. Phys. 17 (2021) 1200

PoF V

- Fully exploit world-unique combination of
 - GSI secondary **pion beam** and **HADES**
 - SIS100 **proton beam** and **CBM**
- Unprecedented studies of exotic hadrons with heavy quarks
 - BESIII** at the BEPC-II e^+e^- collider
 - Complementary studies in pp collisions with **ALICE**
- Theory:** Study meson–baryon scattering using Lattice QCD and coupled-channel EFT



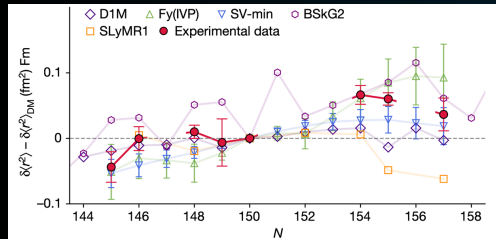
Goals for PoF V : Study structure, spectroscopy and electromagnetic transition form factors of mesons, baryons and hyperons. Explore exotic hadrons, multi-strangeness and charm degrees of freedom.

Nuclear properties at the extremes

Reaching yet inaccessible region of the nuclear chart

PoF IV

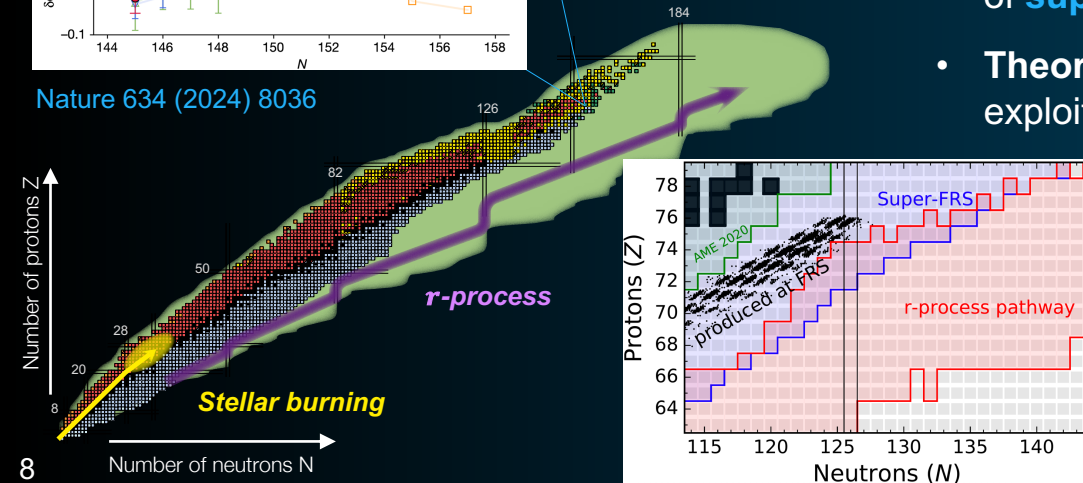
Smooth trends in fermium charge radii and the impact of shell effects



Nature 634 (2024) 8036

PoF V

- Utilize the full suite of detection systems of the **NUSTAR** at the **Super-FRS**
- Study masses, electromagnetic and weak properties of **nuclei far off stability**
- Investigate atomic, chemical and nuclear properties of **superheavy elements**
- Theory:** interpret measured data and exploit their astrophysical implications



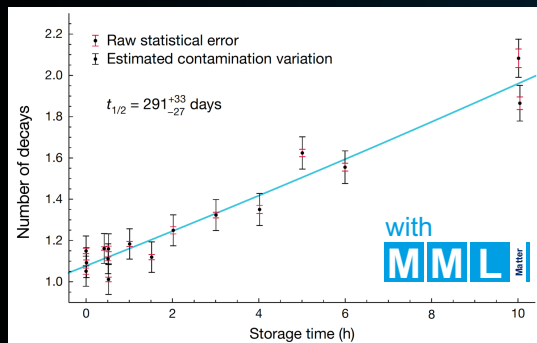
Goals for PoF V: Unravel the nuclear physics of the *r*-process in the laboratory. Extend the nuclear chart to the neutron-rich side, study evolution of shell structure and nuclear shapes.

Nucleosynthesis of chemical elements

Nuclear reactions for astrophysical processes

PoF IV

Bound-state beta decay of thallium-205 helps to determine timescale for the Sun's birth



Nature 635 (2024) 8038

PoF V

- Unique combination of **FRS – ESR – CRYRING**: Measure reactions at relevant astrophysical energies utilizing **stored radioactive-ion beams**
- Complementary measurements with **stable-particle beams** at underground laboratory **Felsenkeller**
- High-precision measurement of **neutrino oscillation parameters** at **JUNO** observatory



Goals for PoF V : Study key nuclear reactions for big bang, stellar burning, and explosive processes. Determine the neutrino mass hierarchy, understand neutrino flavor transformation in astrophysical environments.

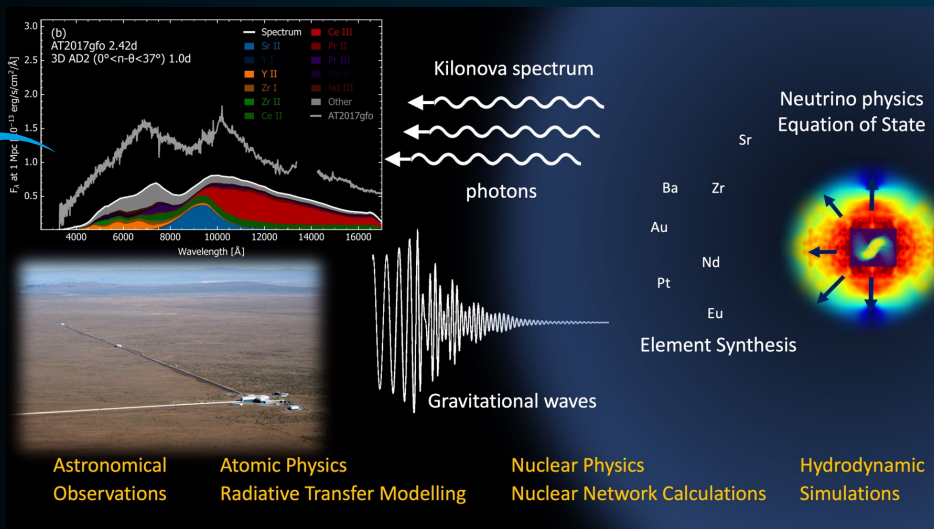
Multi-messenger signals from neutron star merger

Connecting GSI/FAIR data to astronomical observations

PoF IV

Understanding the origin of spectral features of kilonovae

Astrophys.J.Lett.
954 (2023) L41



Perspective: potential discrepancies between observations and laboratory experiments can point to BSM physics, e.g. axion-like particles or dark matter components

PoF V

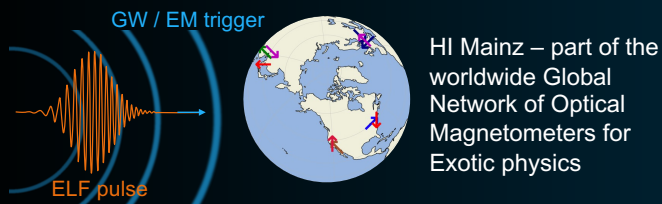
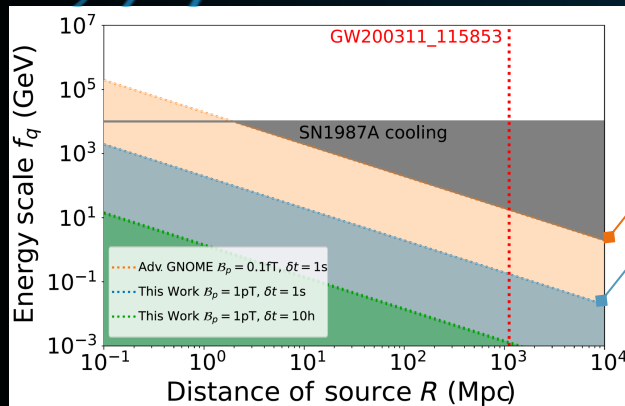
- Identify signatures of non-nucleonic degrees of freedom in high-density matter combining gravitational and electromagnetic radiation with CBM data
- Microscopic input for supernova and neutron star merger simulations provided by NUSTAR

Goal for PoF V: Enhance the science impact of astronomical observations like GW, neutrinos, and EM radiation, e.g., from neutron star mergers, through advanced theoretical models based on GSI/FAIR data.

BSM searches

Precision tests of fundamental symmetries at low energy

Goal: Search for BSM particles emitted in stellar mergers, with a trigger provided by the gravitational wave interferometer LIGO.



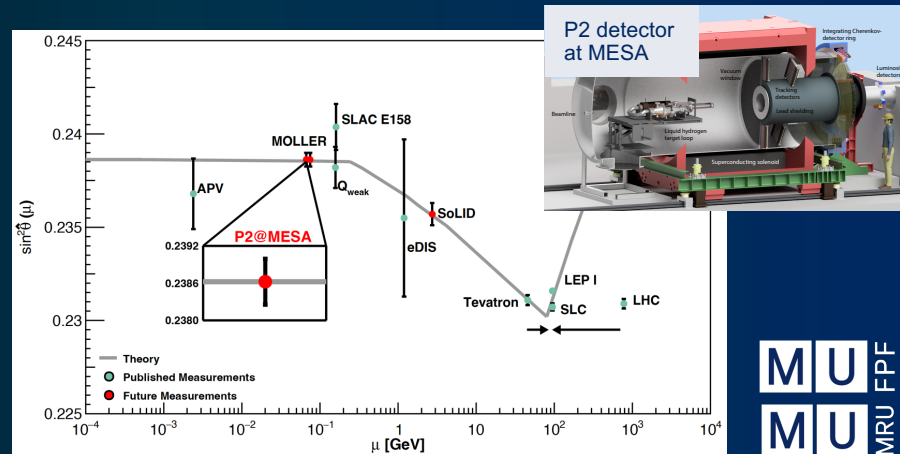
PoF V

PoF IV

PRX 15 (2025)
031048

Goal: Determination of $\sin^2 \theta_W$ at low-energy with highest precision (0%). Test SM by comparing to ab-initio theoretical predictions.

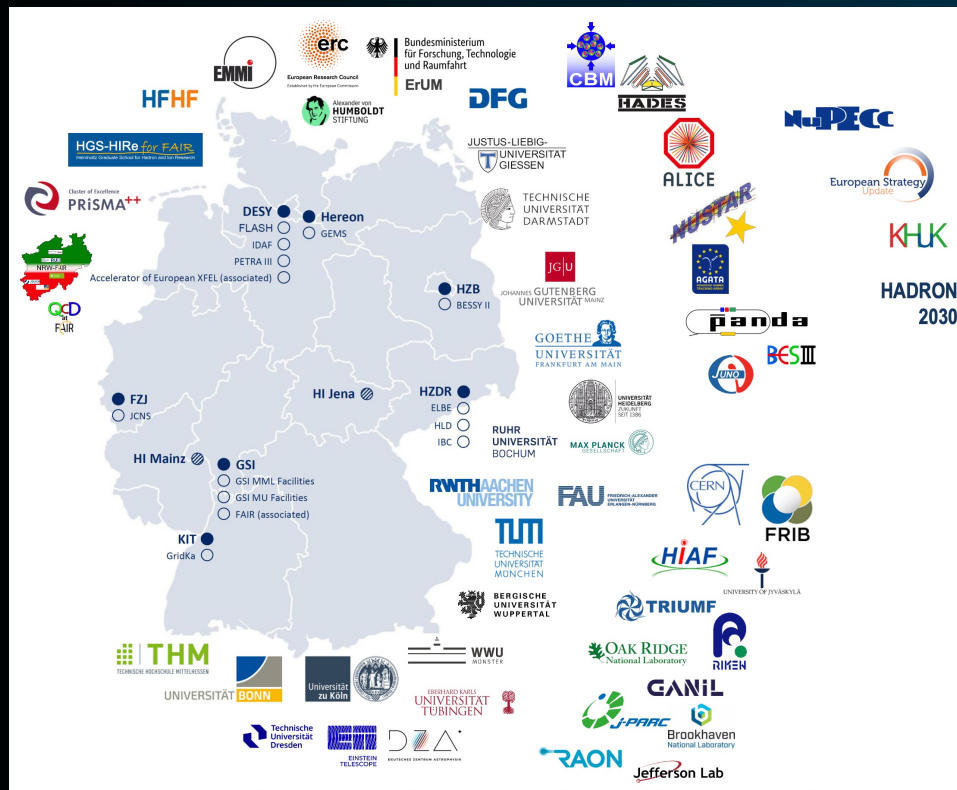
New in PoF V



Combination of **low-energy** and measurements at the Z pole mass (**LHC**) $\leadsto$ probe **new physics** with sensitivity to **mass scales ranging 70 MeV – 50 TeV**

Cooperation and networking

Embedded in strong national and international network



Helmholtz centers and institutes of Matter

- ExtreMe Matter Institute EMMI, Helmholtz Research Academy Hessen for FAIR (HFHF)

National partners

- Universities, graduate schools, collaborative research centers, excellence clusters

European research facilities for hadron and nuclear physics

Large international collaborations, partners and facilities

Priorities aligned with the NuPECC Long Range Plan 2024



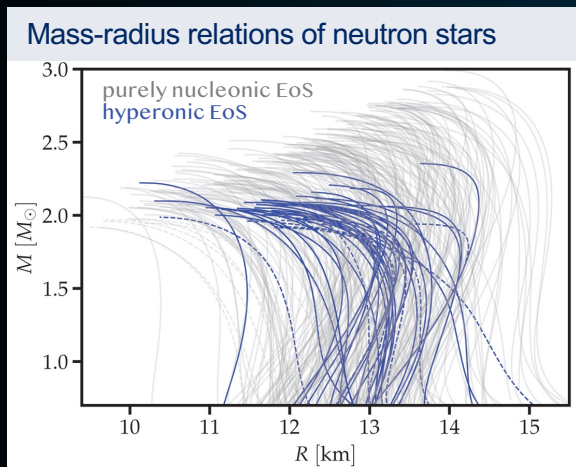
Coherence and synergies

Within MU-CML: Understanding of the high-density equation of state (EoS)

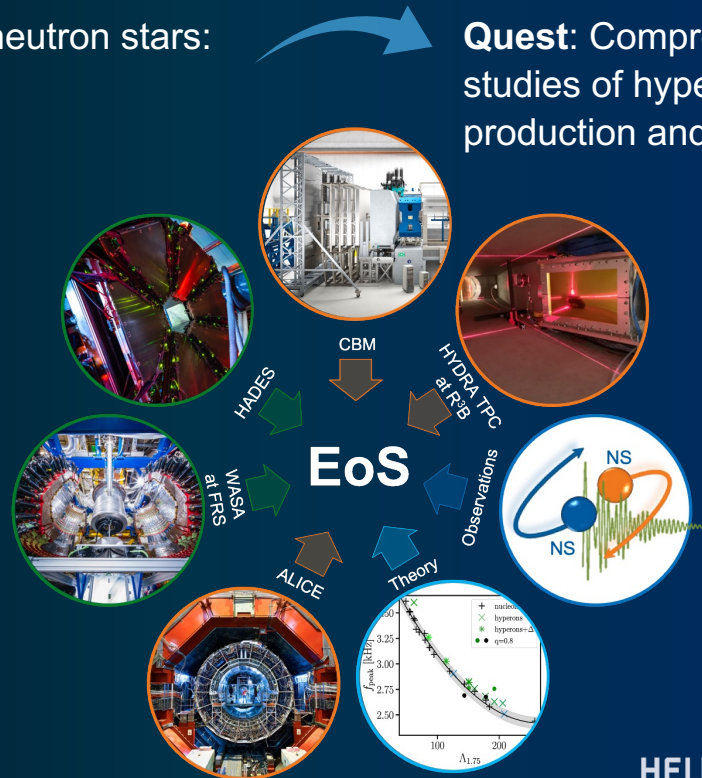
Presence of **non-nucleonic degrees of freedom** in neutron stars:

- Sizeable **softening** of the **EoS**
- Affect neutron star cooling and merger dynamics
- Potential impact on nucleosynthesis and kilonovae

Quest: Comprehensive studies of hypernuclei production and interactions



PRR 8 (2026) 013253

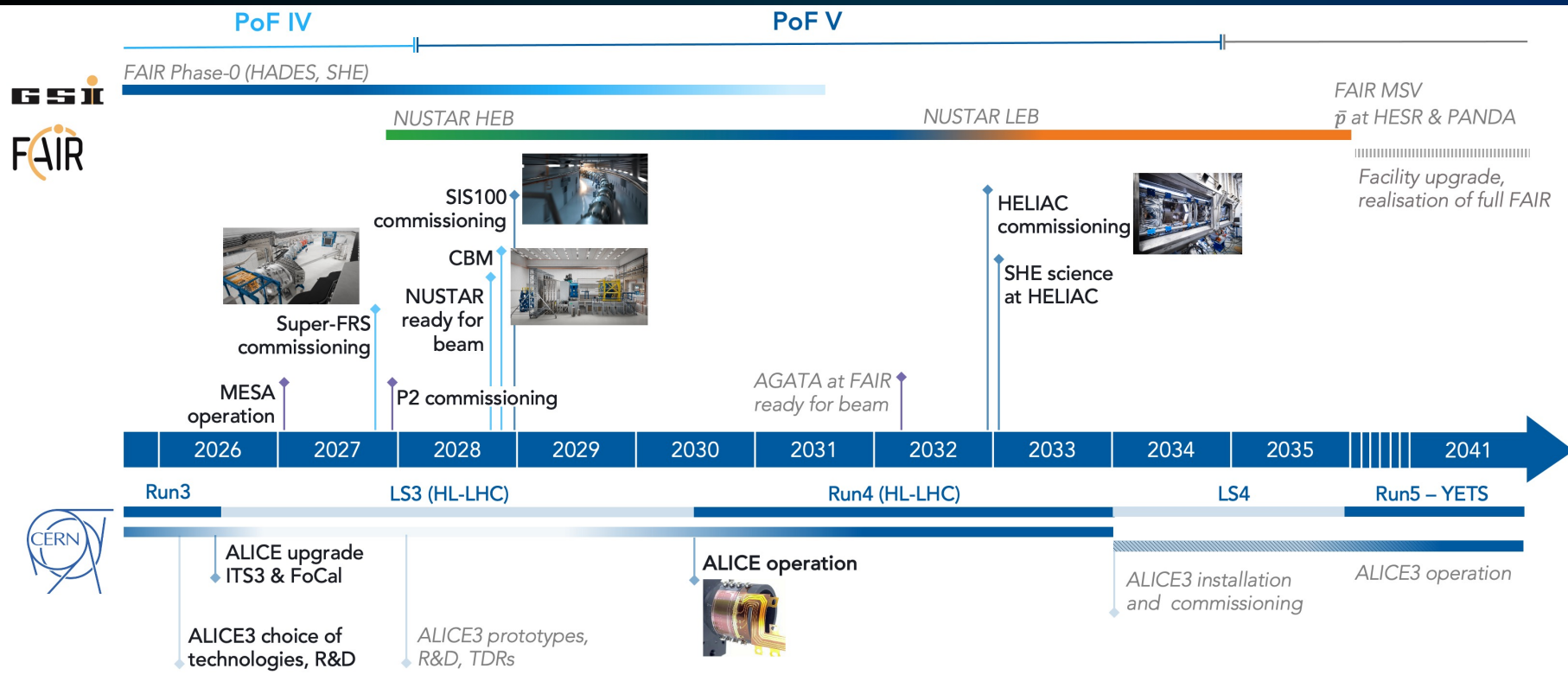


Coherence and synergies

Within Helmholtz Matter



Timeline



Our vision

Strong force at all the relevant length scales

Start of FAIR → Physics harvest during PoF V

Understand the microscopic properties of QCD matter, exploiting CBM/HADES at FAIR and ALICE at the HL-LHC



Strengthen the science output from gravitational wave and kilonova observations through theory and experiments at GSI/FAIR, HZDR Felsenkeller, and neutrino detection at JUNO

Extend the discovery range of searches for physics beyond the Standard Model at MESA, GNOME...

Comprehend nuclei far from stability and understand the origin of heavy elements