HELMHOLTZ

RESEARCH FOR
GRAND CHALLENGES

Cosmic Matter in the Laboratory

Outlook

Tetyana Galatyuk & Frank Maas

DESY. JÜLICH Forschungszentrum GSI HI JENA HELMHOLTZ Helmholtz Institute Jena 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

Cosmic Matter in the Laboratory within MU

Address fundamental and unanswered questions

- How exactly does the strong force produce confinement?
- How do the complex spectra of hadrons and nuclei arise from the strong force?
- How does nuclear matter behave under extreme conditions?
- How exactly are the heavy elements in the universe formed and where are the limits of stability?
- How can fundamental symmetries be tested? Is there physics beyond the standard model?

watch FAIR construction site 2021

COSY
at Jülich

LHC at CERN
ALICE

Where we stand and where we want to go

MU CML
MATTER AND THE UNIVERSE

FAIR Phase 0 | FAIR Early science | FAIR Day 1

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

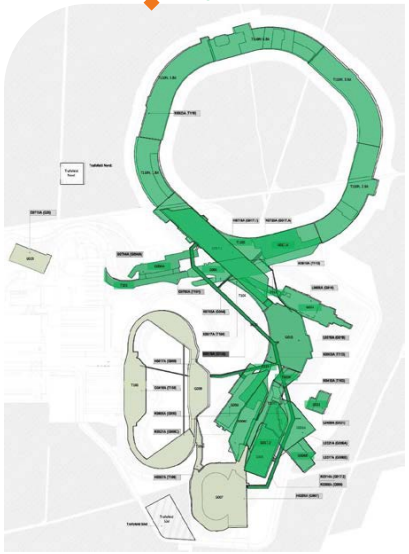
Working towards completion of
FAIR modularized start version

At the same time staged approach to FAIR science and progressive commissioning of accelerators and detectors

Early science
SIS18 beam to
Super-FRS

FAIR operation
intermediate objective

FAIR operation
full MSV (with **CR, HESR & p-LINAC**)



FAIR Phase 0
Research Program

FAIR Phase 0
Intermediate forefront research program at GSI with improved beams and FAIR detectors

Started 2018/2019 and continues with annual campaigns of ~110 days till start of FAIR

Properties of hadrons and their excitation spectrum

FAIR Phase 0 | FAIR Early science | FAIR Day 1

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

Goal: Conduct rich hadron physics program with FAIR (anti-)proton beam to advance understanding of the strong force in the non-perturbative regime

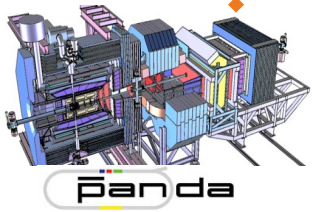
- Emergence of complex structures from QCD
- Charm sector, exotics
- Nucleon form factors

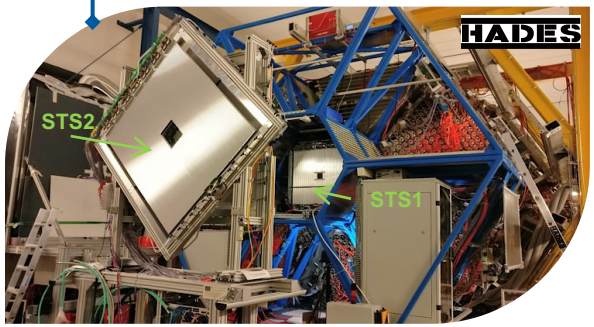
FAIR Phase 0 Research Program

Commission subdetectors and analysis algorithms of the PANDA experiment with real data

Theory: predict spectroscopy and structure

physics with antiprotons





TransFAIR, Jülich Jagiellonian Univ.

STS1 + STS2
straw technology
PASTTREC FEE chip

Hyperon physics with pp (complementary to $\bar{p}p$)

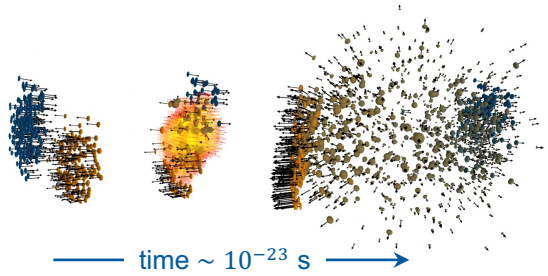
- Excited hyperon radiative decays – **establish** branching ratios, missing resonances
- Electromagnetic transition form factor of hyperon decay ($Y \to \Lambda e^+ e^-$ **never measured!**)
- Explore double strange $\Xi^-(1321)$ production
- $\Lambda\Lambda$ correlation function (input to studies of high density equation of state)

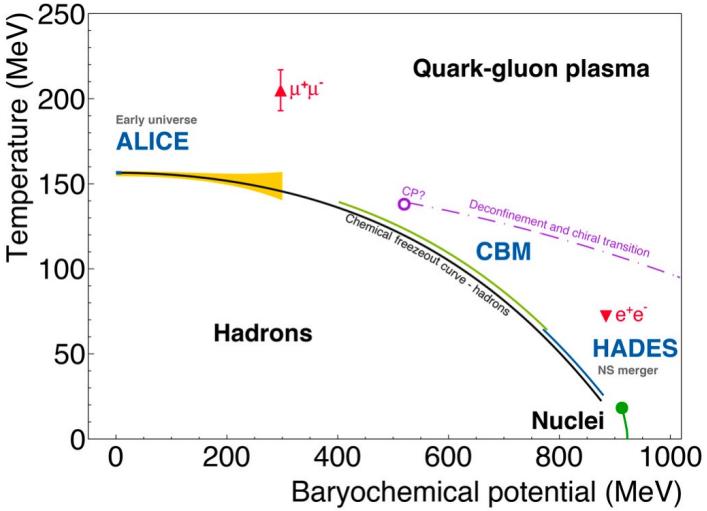
QCD phase structure and properties of QCD matter

MU CML
MATTER AND THE UNIVERSE

Goal: Produce and investigate transient states of QCD matter under extreme conditions of temperature and density

- Explore the QCD phase structure
- Extract transport properties of QCD matter
- Understand hadronization process equation of state





Experiments

Beam energy: from GeV to TeV per pair of nucleons

High rate detectors: stand 50 kHz to 10 MHz interaction rate

ALICE CBM HADES

Theory

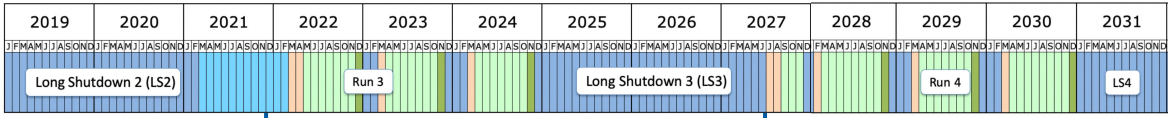
No critical point indicated by lattice QCD at $\mu_B^{CEP}/T_c \leq 3$

Quantitative predictions for observables in non-perturbative QCD

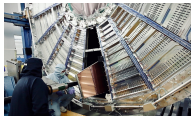
LHC schedule and ALICE plans

A Large Ion Collider Experiment

MATTER AND THE UNIVERSE

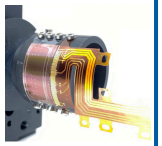


GEM TPC readout



Online/Offline system (O2)
Silicon tracker (ITS2)
Fast Interaction Trigger (FIT)

Silicon tracker (ITS3) - cylindrical, wafer-size sensors with ultra-low material budget

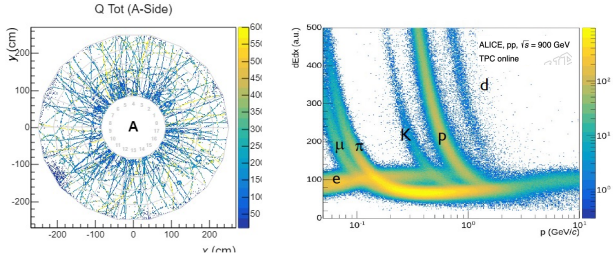


Forward Calorimeter (FoCAL)

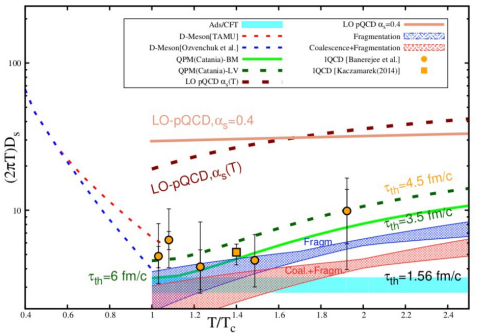
ALICE Run 3&4 ~100 times more statistics
13 nb^{-1} (0.5T, 0.2T) Pb-Pb collisions

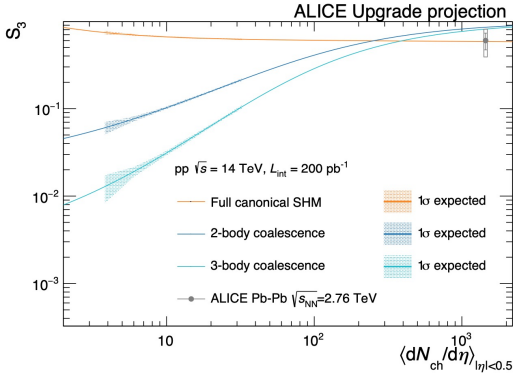
- Extract transport properties of quark-gluon plasma with charm- and beauty quarks (R_{AA} and v_2)
- Unified picture of production mechanism of (hyper-)(anti-)nuclei from small (pp) to larger (p–A and A–A) systems

Successful pilot beam test (18 – 31 Oct.) pp 900 GeV **continuous readout**, online reconstruction and data reduction → **50 kHz interaction rate of Pb-Pb**



Diffusion coefficient





Compressed Baryonic Matter

MU CML MATTER AND THE UNIVERSE

FAIR Phase 0 | FAIR Early science | FAIR Day 1

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

FAIR Phase 0 Research Program

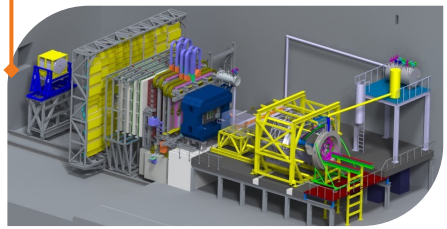
Commission subdetectors and analysis algorithms of the CBM experiment with real data

CBM cave ready (heavy infra.)

CBM magnet supports services

CBM detectors

physics with CBM

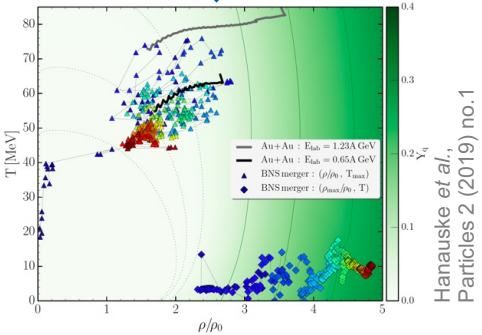


mCBM online Λ reco. at 10MHz demonstrated

HADES Au+Au 0.2 – 0.8 GeV/u

HADES mCBM BM@N

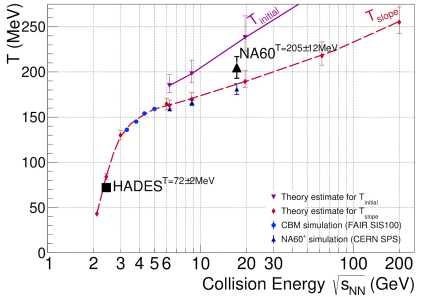
STAR ALICE



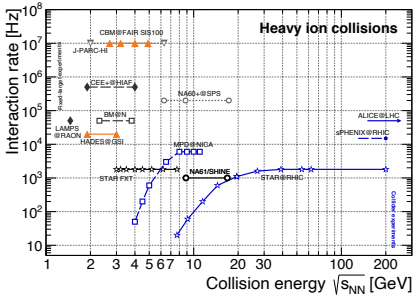
Hanauske *et al.*, Particles 2 (2019) no.1

- Search for deconfinement & chiral phase transition and CEP
- Study microscopic properties of high baryon density matter with **rare probes** (thermal e^+e^- spectrum, charm) with **utmost precision**

CBM projection thermal dileptons



https://github.com/tgalatyuk/QCD_caloric_curve



https://github.com/tgalatyuk/interaction_rate_facilities

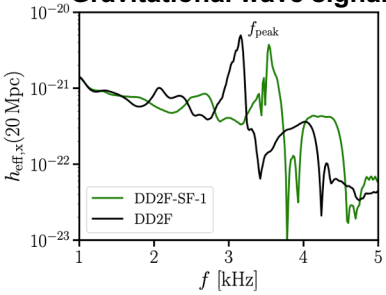
Binary neutron star merger vs heavy-ion collision: 18 orders of magnitude in scales, still similar T < 70 MeV, ρ < $3\rho_0$ for both

Theory: future opportunities and challenges

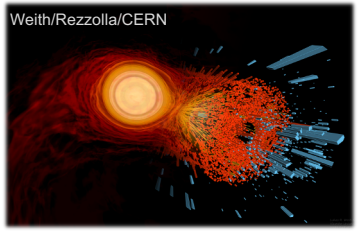
MATTER AND THE UNIVERSE

High density equation of state

Gravitational wave signal

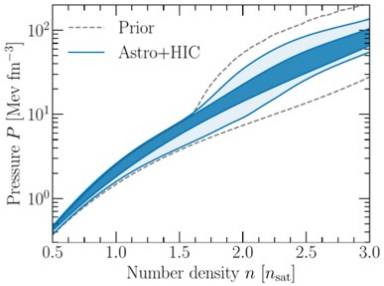


Bauswein *et al.*,
PRL 112 (2019) 061102

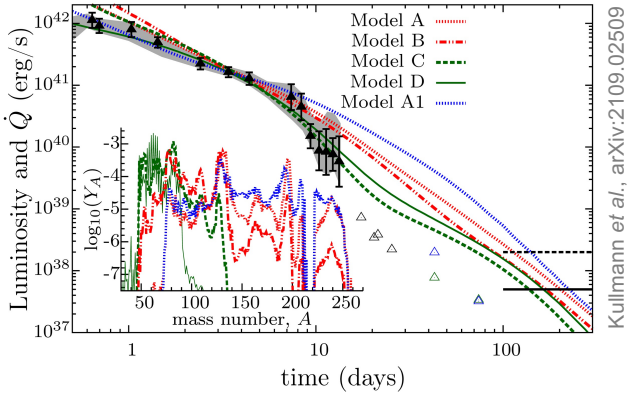


Huth *et al.*,
arXiv:2107.06229

Heavy ion collisions



Modelling r-process electromagnetic transients



Kullmann *et al.*, arXiv:2109.02509

Constrain EoS from both HIC and BNS merger

Study impact of **quark deconfinement** on observables:

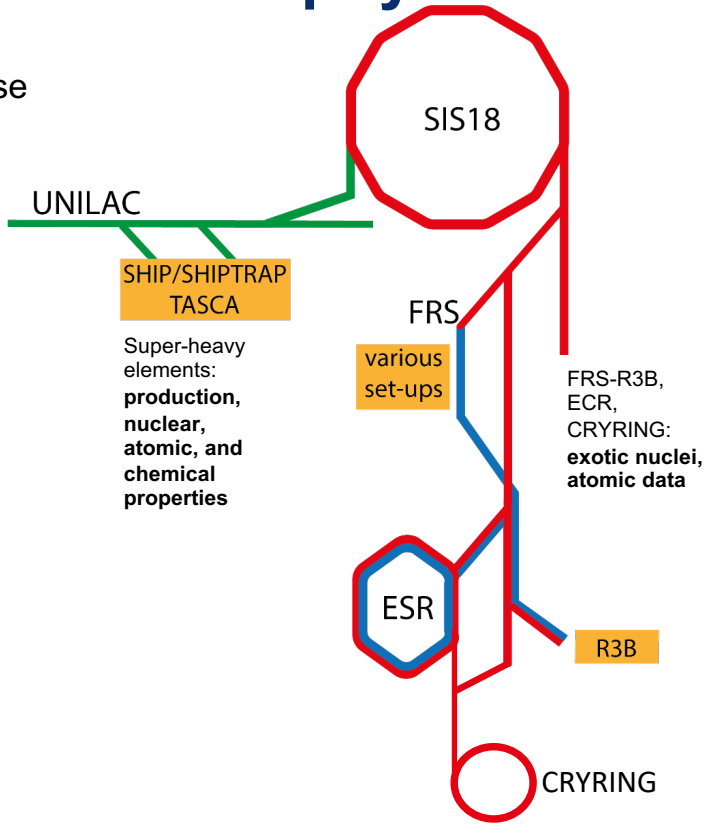
- Qualitative signatures for HI experiments
- Characteristic imprint of quark matter on postmerger GW emission
- Influence on nucleosynthesis and kilonova lightcurves

- Determine role of neutrinos on light curve
- Develop a complete database of atomic opacities
- Identify key nuclei affecting light curves
- Guide experiments at GSI/FAIR

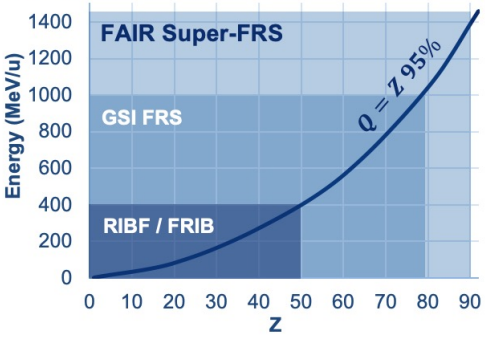
Nuclear structure, nuclear reactions, and super-heavy elements and their relevance for nuclear astrophysics

Goal Advance understanding of the origin of the elements in our universe

- Obtain unified picture and understanding of atomic nuclei
- Shell structure at large neutron excess
- Isospin dependence of equation of state
- Limits of nuclear existence



Reach for fully stripped exotic nuclear beams



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

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

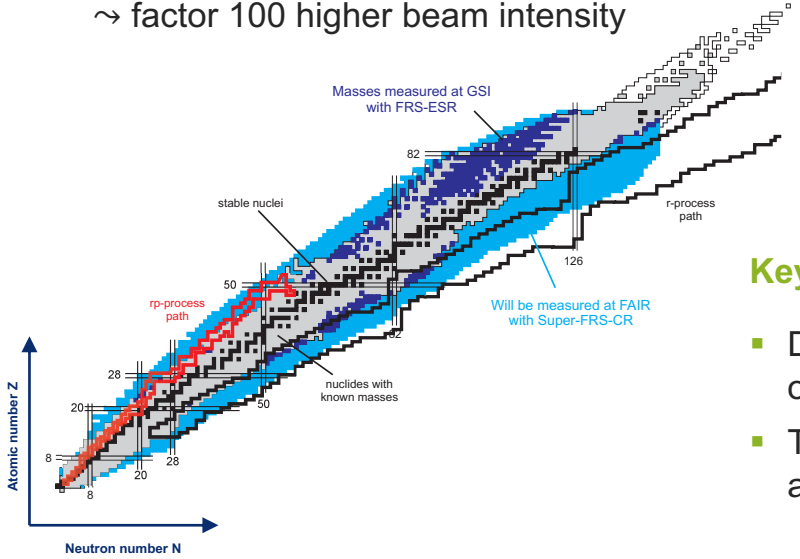
NUSTAR: Early science SIS18 beam to Super-FRS

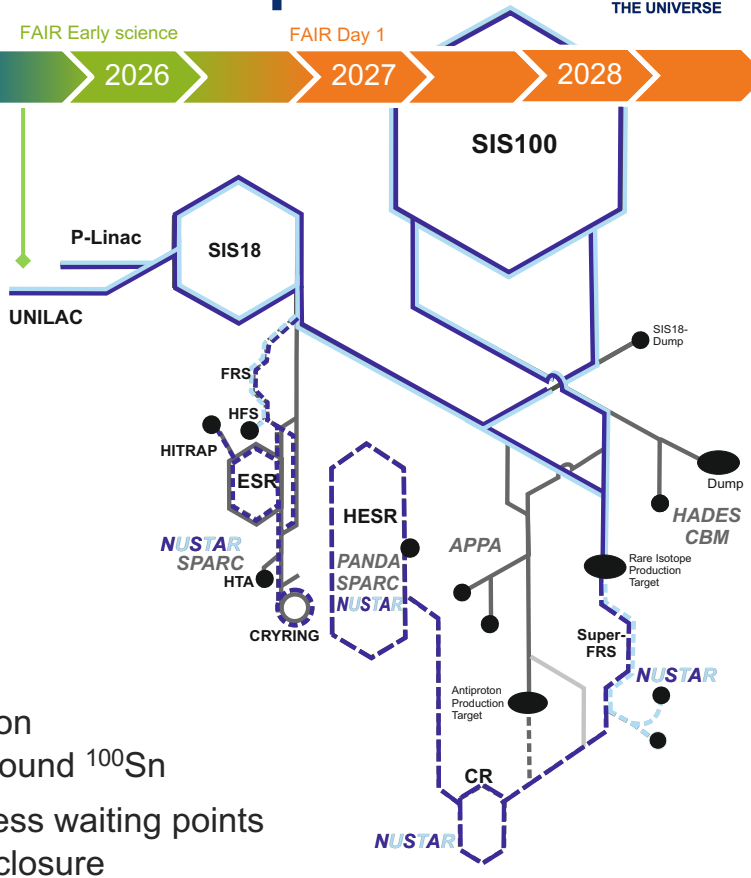
FAIR Phase 0 | FAIR Early science | FAIR Day 1

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

Q4 2025

- Slow beam extraction (1 s) from SIS18 to Super-FRS (design intensities)
- Xe^{48+}/U^{73+} $\sim 2\times10^{9}$ ions/s at 1 GeV/u
  $\rightsquigarrow$ factor 100 higher beam intensity





Key experiments:

- Detailed investigation of shell structure around ^{100}Sn
- Towards the *r*-process waiting points at the N=126 shell closure

Prospects: fundamental physics studies

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

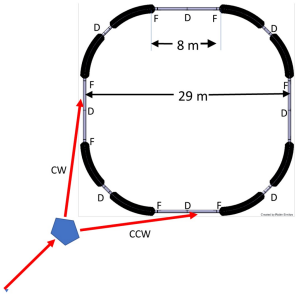
2021 — 2022 — 2023 — 2024 — 2025 — 2026 — 2027 ≈ Run 2034+

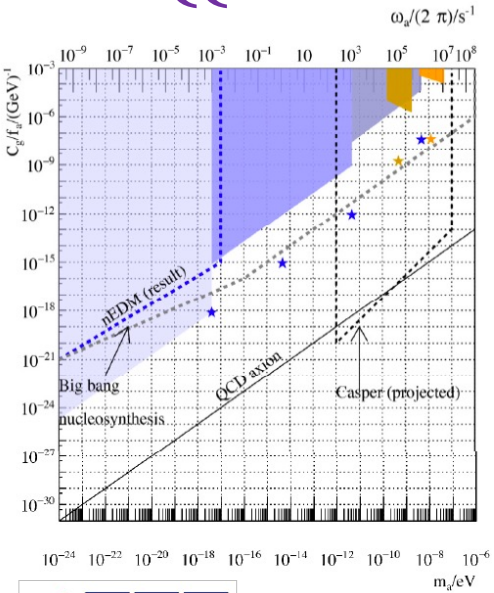
Indirect axion search via oscillating EDM

Completion of precursor experiment on deuteron EDM

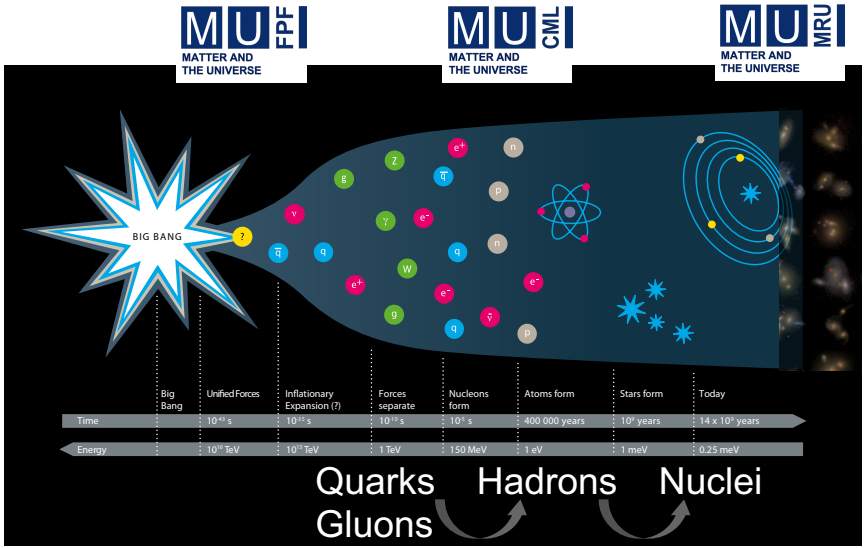
Deuteron EDM:
proof of capability with COSY, accelerator development

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





Summary: the future is bright!



Enable studies of the strong force at the relevant length scales from the quark-gluon plasma to hadrons to atomic nuclei
(in close cooperation with theory)