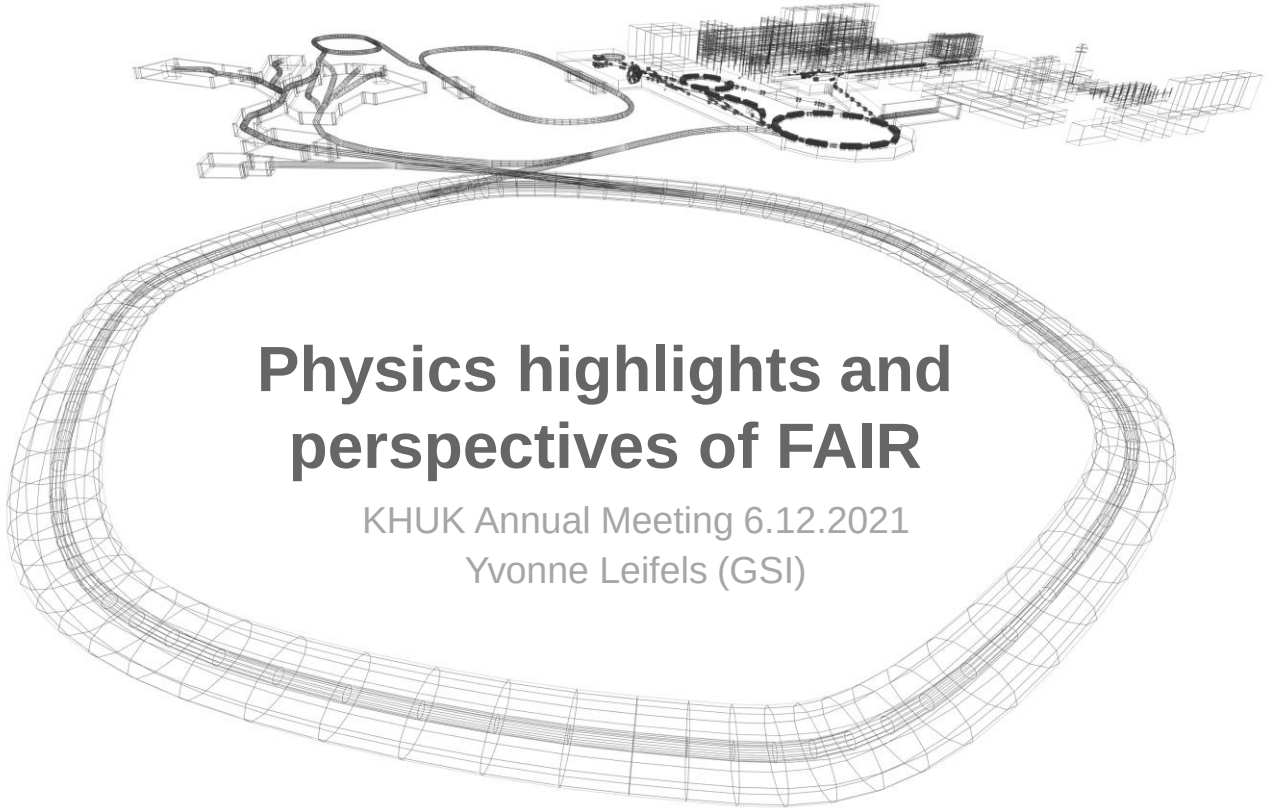


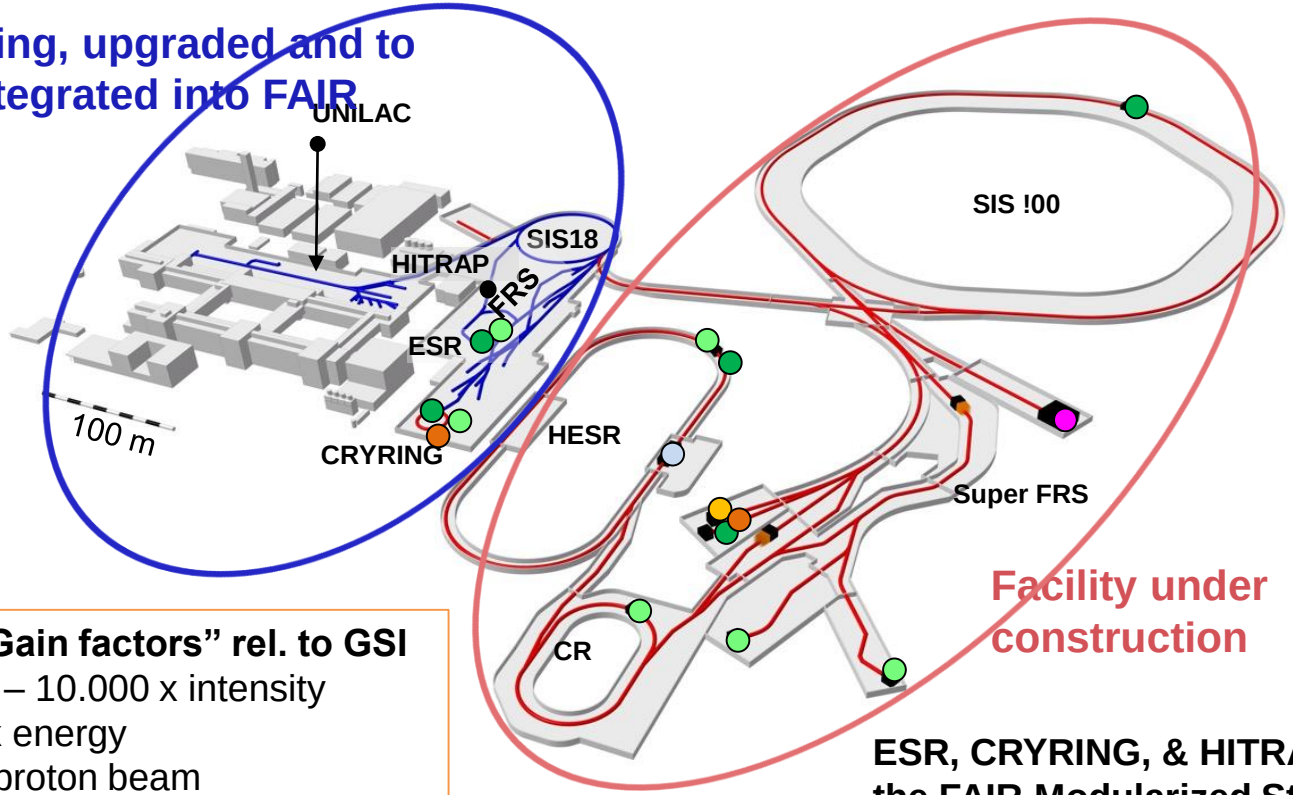
Physics highlights and perspectives of FAIR

KHUK Annual Meeting 6.12.2021

Yvonne Leifels (GSI)

FAIR Facility

Existing, upgraded and to be integrated into FAIR



Facility under construction

APPA
- BIOMAT
- HED
- SPARC
- **CBM/HADES**
- **NUSTAR**
- **PANDA**

FAIR "Gain factors" rel. to GSI
- 100 – 10.000 x intensity
- 10 x energy
- antiproton beam

ESR, CRYRING, & HITRAP are part of the FAIR Modularized Start Version

FAIR status and perspectives

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

FAIR Phase-0
since 2019

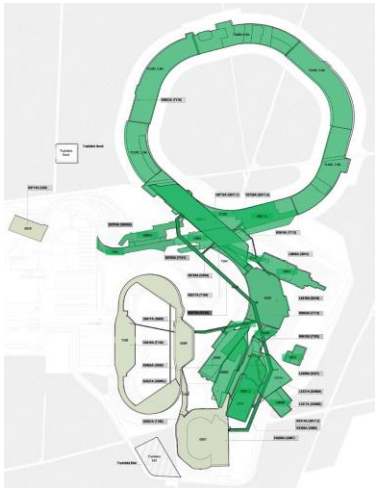
FAIR
Early Science
SIS18 beam

FAIR operation
Intermediate
objective

FAIR full
operation MSV:
p-linac, CR and
HESR
depending on
availability of
funding

Working towards completion of
FAIR Modularized Start Version MSV

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



FAIR Phase 0
Research Program

FAIR Phase-0

started in 2019 and will continue with ~ 3 months of beam time / year until start of FAIR

FAIR status and perspectives

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

FAIR Phase-0
since 2019

FAIR
Early Science
SIS18 beam

FAIR operation
Intermediate
objective

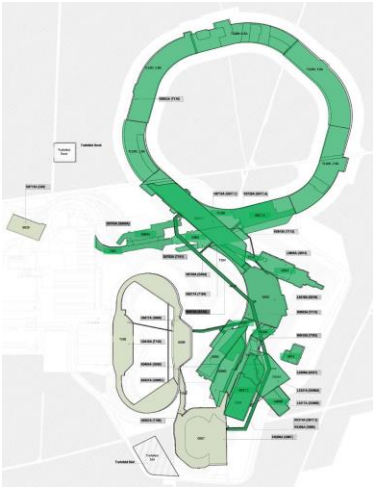
FAIR full
operation MSV:
p-linac, CR and
HESR
depending on
availability of
funding

Introduction

Scientific status and perspectives

- APPA
- NUSTAR
- C.B.M.
- PANDA

Summary



FAIR Phase-0 not only at the GSI Facilities

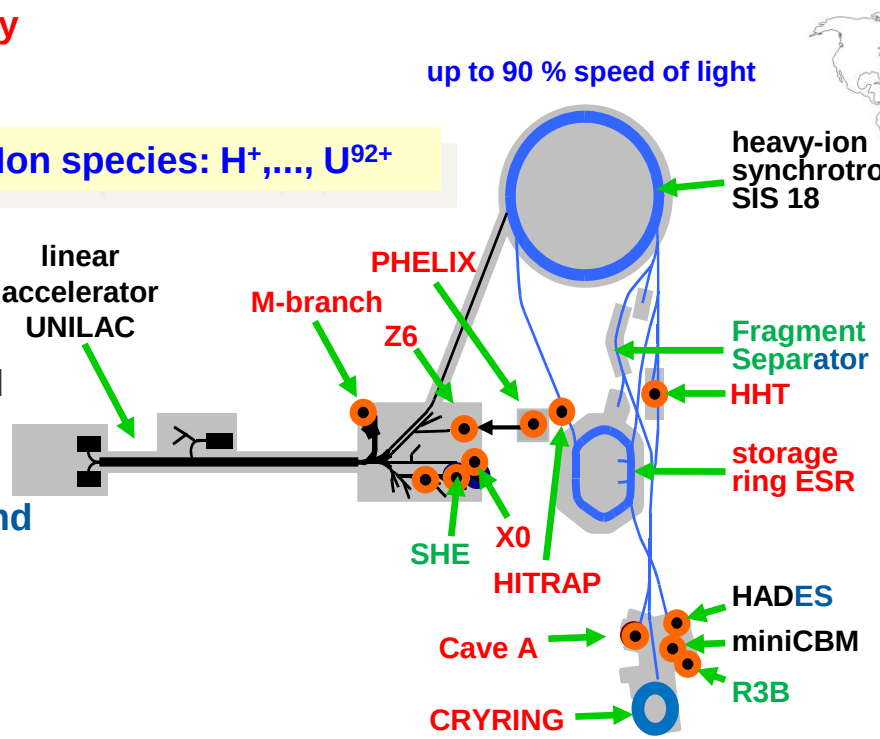
APPA: Atomic physics with highly charged ions, plasma physics,
materials science, and biophysics

NUSTAR: Nuclear structure, nuclear reactions, and super-heavy elements

C.B.M.: QCD phase structure and properties of QCD matter

PANDA: Properties of hadrons and their excitation spectrum

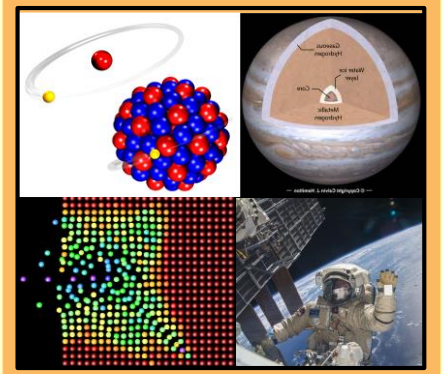
Scientific high-performance computing



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

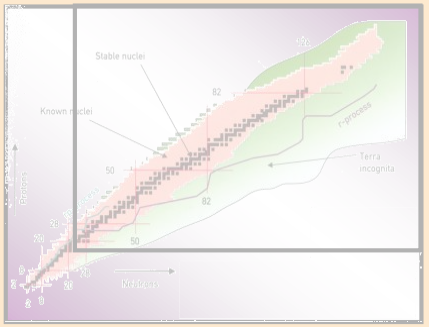
FAIR research pillars

APPA



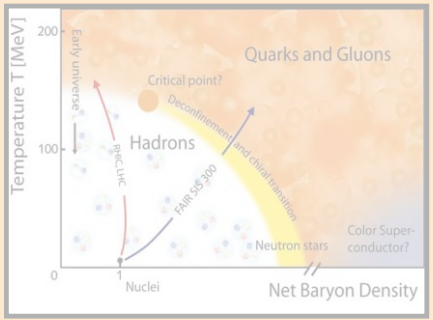
atomic physics, plasma physics, materials science, biophysics

NUSTAR



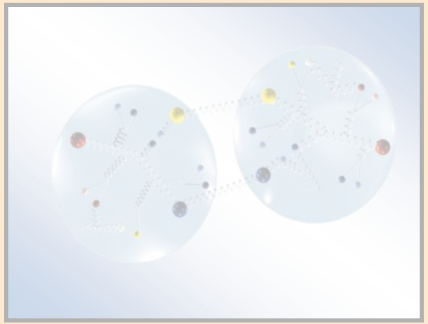
nuclear structure and nuclear astrophysics

CBM



QCD phase structure and properties of QCD matter

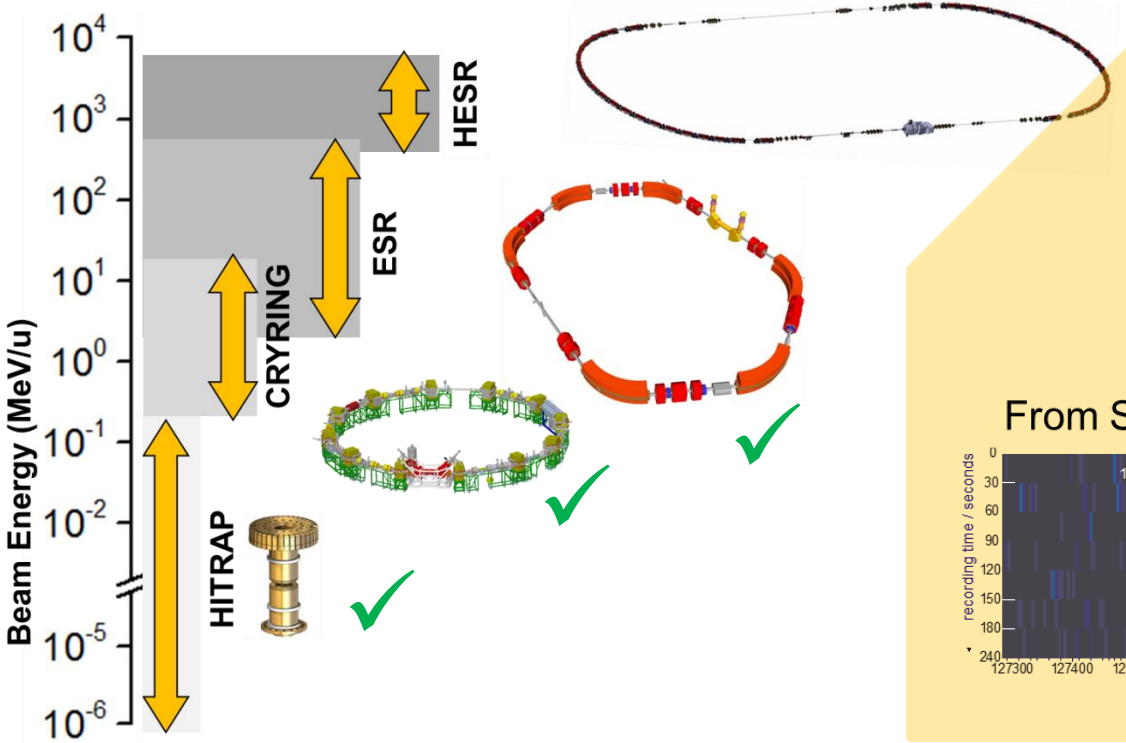
PANDA



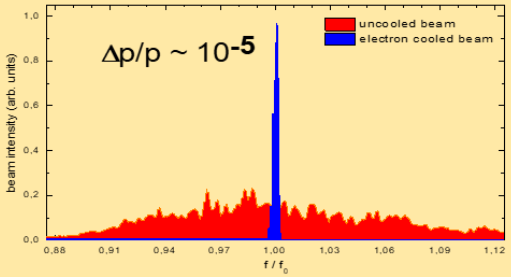
hadron structure and dynamics

APPA: Atomic Physics, Plasma physics, and Applied science

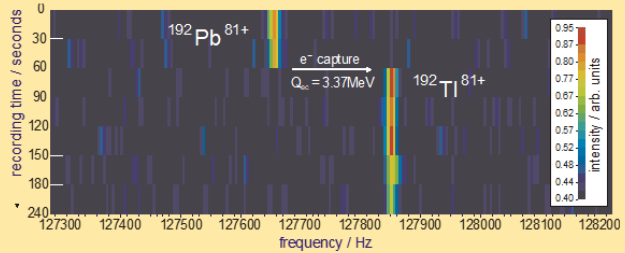
SPARC Precision physics by trapping and storage



Cooling: The Key for Precision



From Single Ions to Highest Intensities



High resolution x-ray spectroscopy at CRYRING

First Fine (sub) structure resolved measurement of groundstate transitions in He-like high Z-ions

U^{28+} 1.4 MeV/u

UNILAC – accl.

U^{73+} 11.4 MeV/u

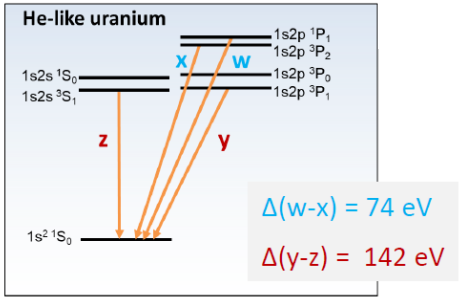
SIS18 – accl.

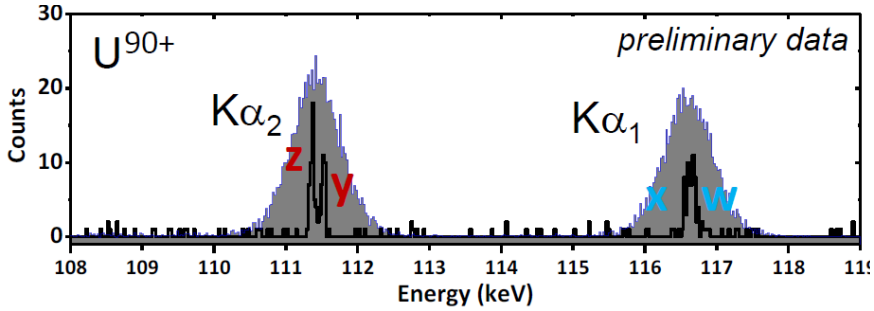
U^{90+} 400 MeV/u

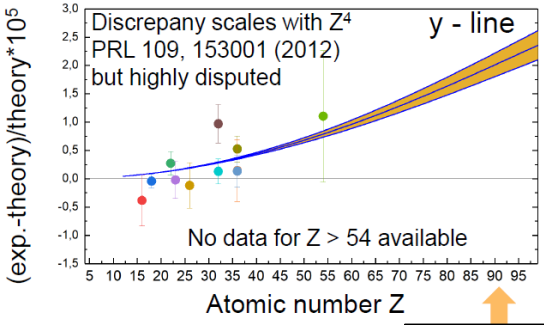
ESR– decel.

U^{90+} 10 MeV/u

CRYRING@ESR





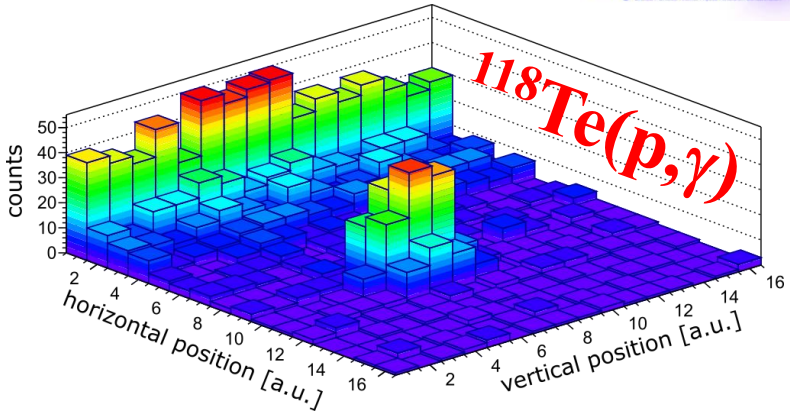


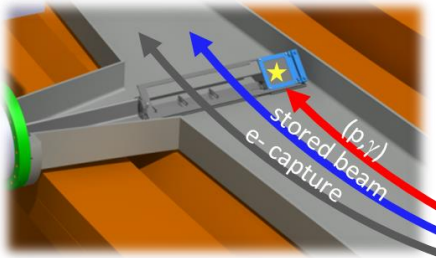
Preliminary data for 0 deg observation (black line) in comparison with scaled data from ESR (shaded area) PRL 032712 (2004)

Proton-capture rates for nuclear astrophysics:

First reaction study on stored exotic beam at **low energies**

- study of radioactive ^{118}Te (6 days half-life)
  - production, storage, accumulation and deceleration of ^{118}Te in FRS-ESR
  - proton-capture measurements realized at 7 MeV/u and 6 MeV/u
  - clear signatures with good statistics
- new background-free detection method
  - maximized sensitivity for detection of proton-capture reactions
- future prospects:
  - full access to Gamow window energies in CRYRING

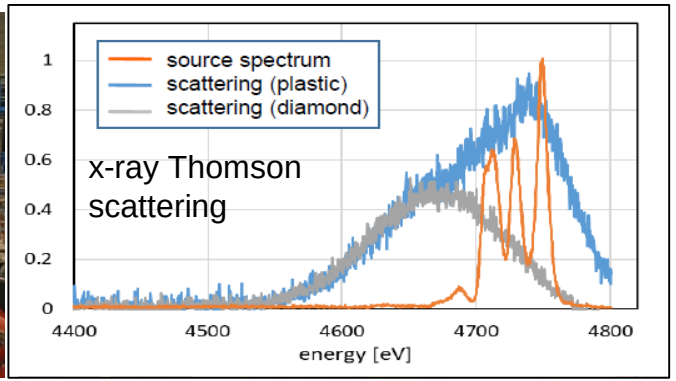


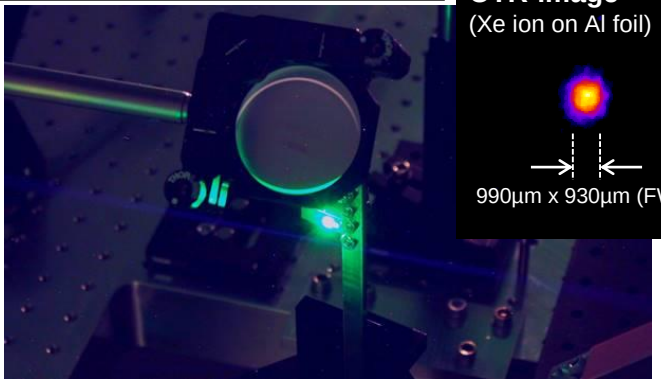


Jan Glorius et al.

High energy density science at FAIR

First PHELIX light at SIS18 beam line HHT





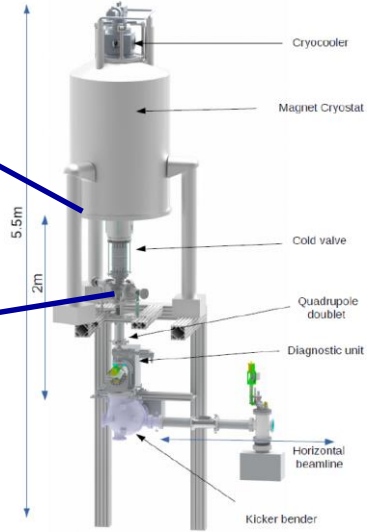
- Target chamber commissioned with up to 3E9 ions/bunch
- PHELIX-HHT laser beamline commissioned
  - ~50 µm focal spot, good stability
  - up to 100 J laser pulses in HHT target chamber
  - Timing scheme PHELIX/SIS-18 demonstrated – jitter < 10 ns (measurement precision limited
  - Demonstrated x-ray probing of dense samples
- PRIOR-II proton microscope commissioned

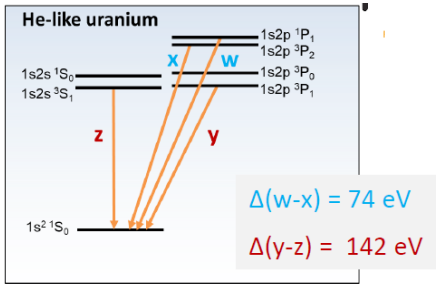
Perspectives for SPARC and HED

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

SIS18-ESR-CRYRING

1st HITRAP experiments





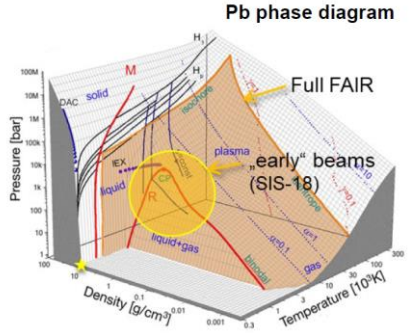
Connecting ARTEMIS to low energy beam line

SIS18 beam in APPA Cave

SPARC at HESR

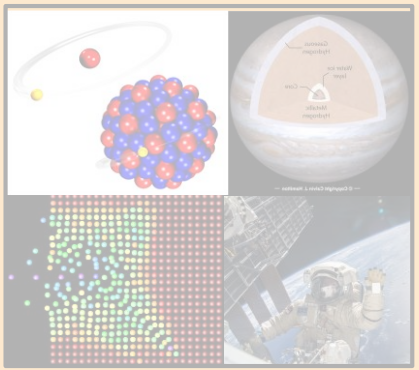
Equation of state of metals near the critical point

- laser gas phase transition and coexistence regime
- advanced theoretical models differ by up to 100 %



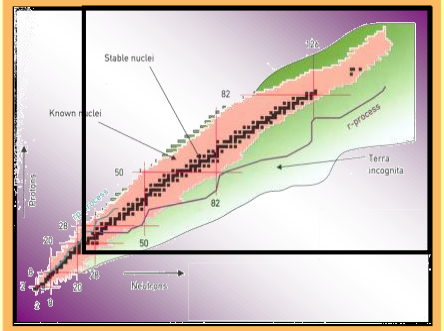
FAIR research pillars

APPA



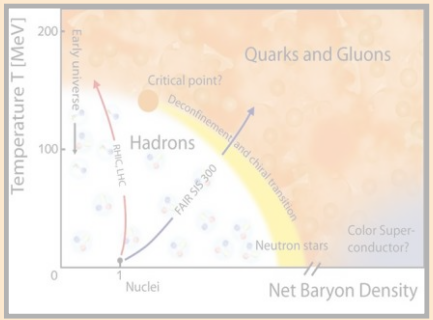
atomic physics, plasma physics, materials science, biophysics

NUSTAR



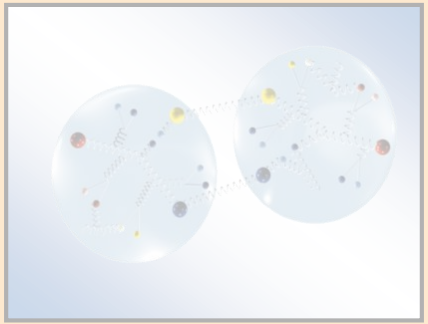
nuclear structure and nuclear astrophysics

CBM



QCD phase structure and properties of QCD matter

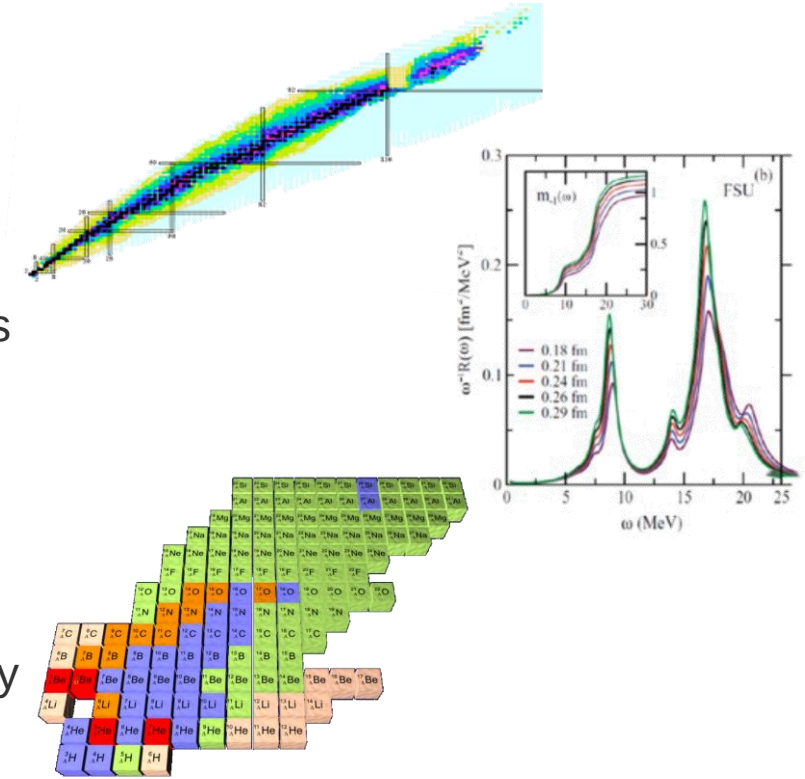
PANDA



hadron structure and dynamics

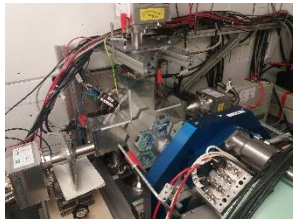
NUSTAR experimental program

- Understanding nucleosynthesis by means of comprehensive measurements of lifetime, masses, dipole strengths, and the level structure
- Astrophysical relevant reaction cross sections
- Constraining the equation of state of asymmetric matter
- Hyper nuclei with large N/Z asymmetry and nucleonic excitations in the nuclear medium
- Characteristics and production of super-heavy elements

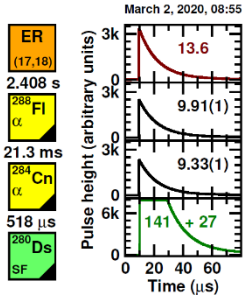


NUSTAR – Superheavy Elements

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

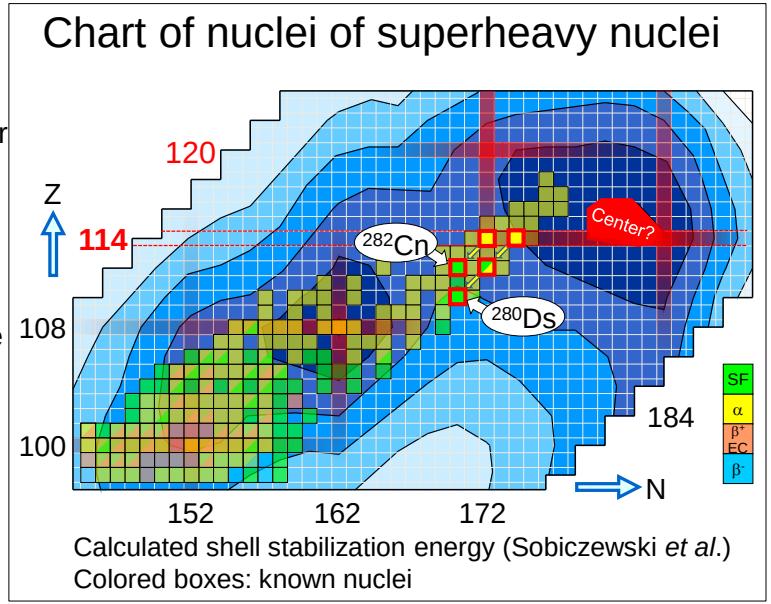


TASISpec+



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?**



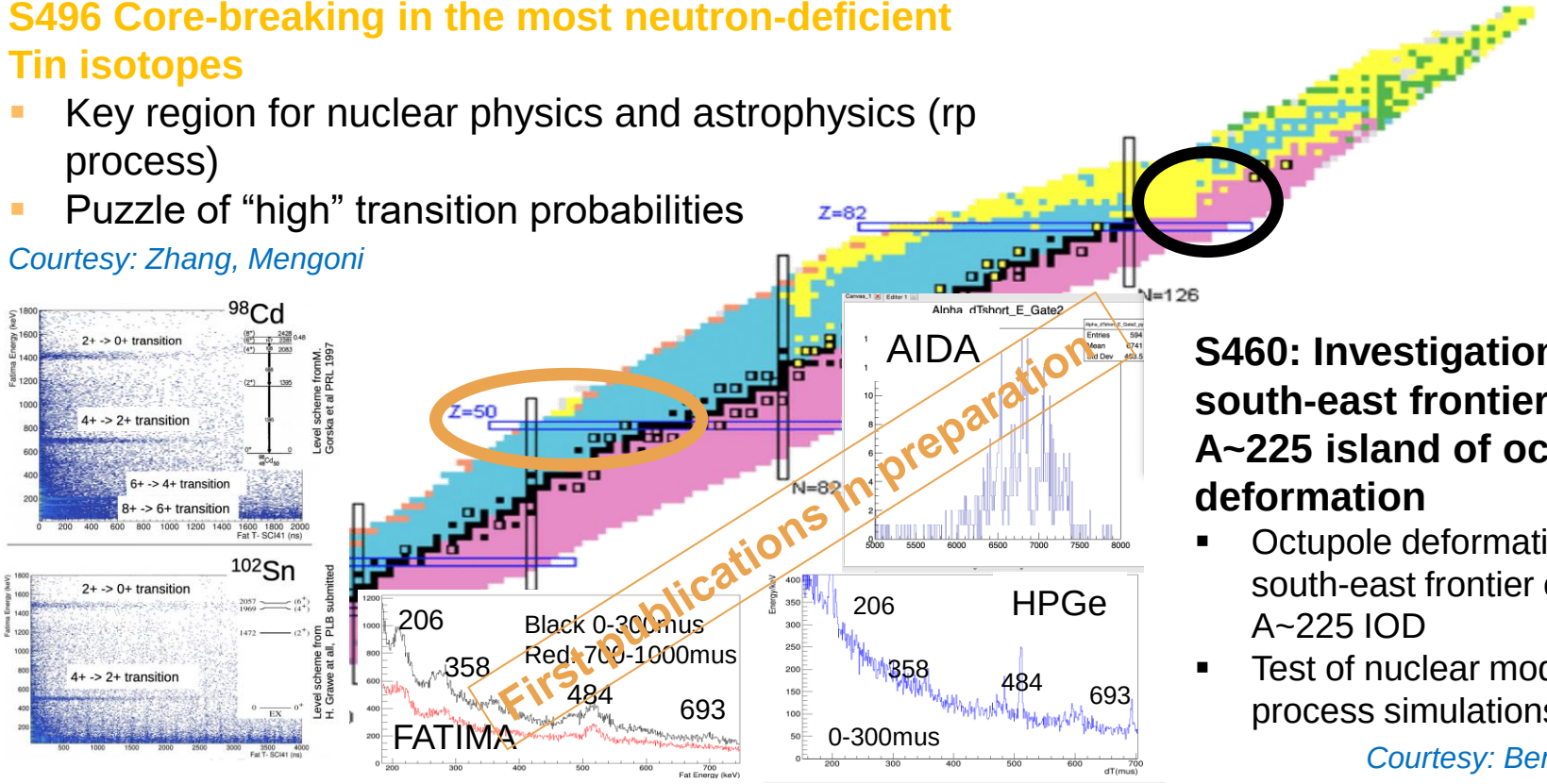
A. Såmark-Roth *et al*., Phys. Rev. Lett. 126 (2021) 032503
J.L. Egido & A. Jungclaus, Phys. Rev. Lett. 125 (2020) 192504; *ibid*., 126 (2021) 192501
Spokesperson: D. Rudolph, Lund. Univ.

NUSTAR – Characteristics of exotic nuclei

S496 Core-breaking in the most neutron-deficient Tin isotopes

- Key region for nuclear physics and astrophysics (rp process)
- Puzzle of “high” transition probabilities

Courtesy: Zhang, Mengoni



S460: Investigation the south-east frontier of the A~225 island of octupole deformation

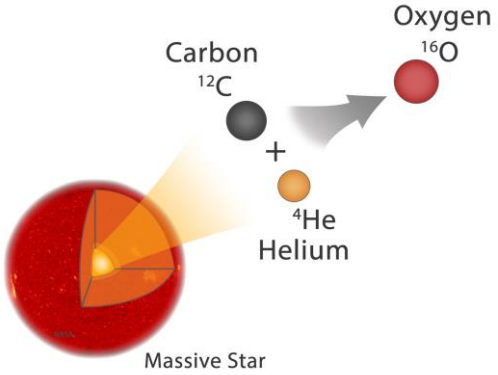
- Octupole deformation in the south-east frontier of the A~225 IOD
- Test of nuclear models for r-process simulations

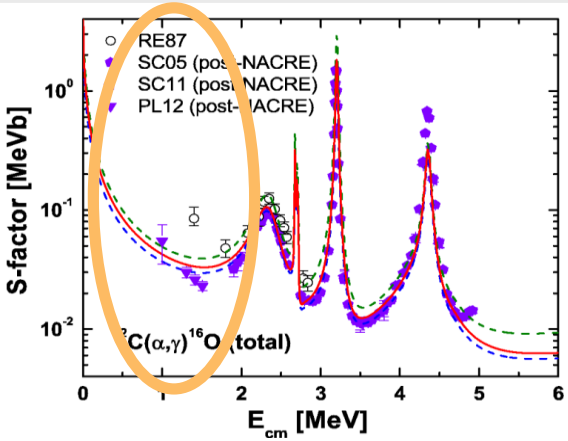
Courtesy: Benzoni, Dobon

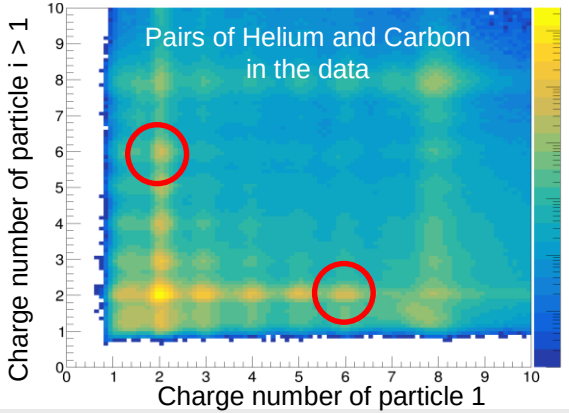
NUSTAR – Astrophysical important reactions

Coulomb dissociation of ^{16}O into ^{12}C and ^{4}He

- $^{12}C(\alpha,\gamma)^{16}O$ 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 ions/s







Perspectives for NUSTAR

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

Integration of WASA (COSY) in the FRS at GSI

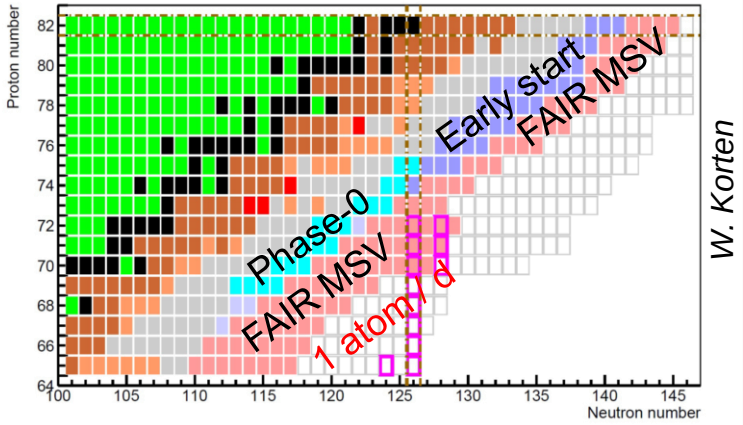
- hypernuclei production
- nucleonic resonances
- other exotics

SIS18 beam to S-FRS

SIS100 beam to S-FRS

Key experiment:

- towards the r-process waiting points at the **N=126 shell closure**

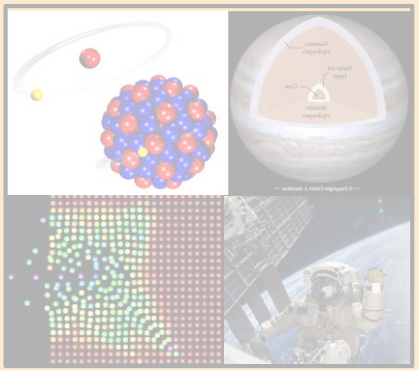


S-FRS will provide

- higher yields by higher transmission (and thicker targets)
- higher count rate by better suppression (two stage suppression)
- access to shorter (µs) lifetime

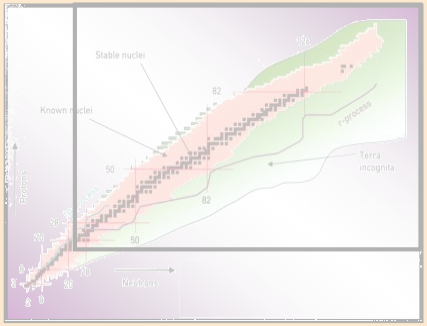
FAIR research pillars

APPA



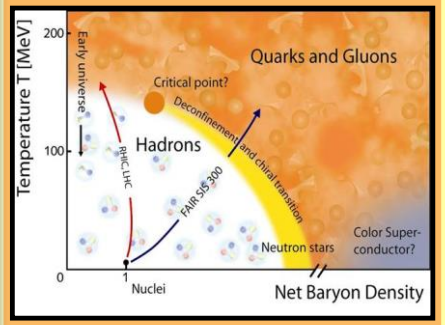
atomic physics, plasma physics, materials science, biophysics

NUSTAR



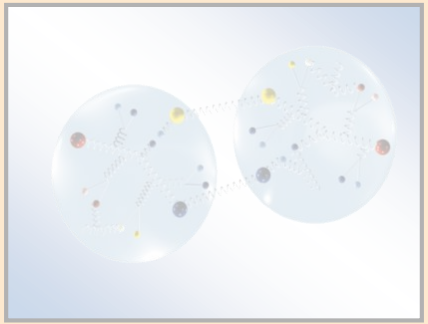
nuclear structure and nuclear astrophysics

C.B.M.



QCD phase structure and properties of QCD matter

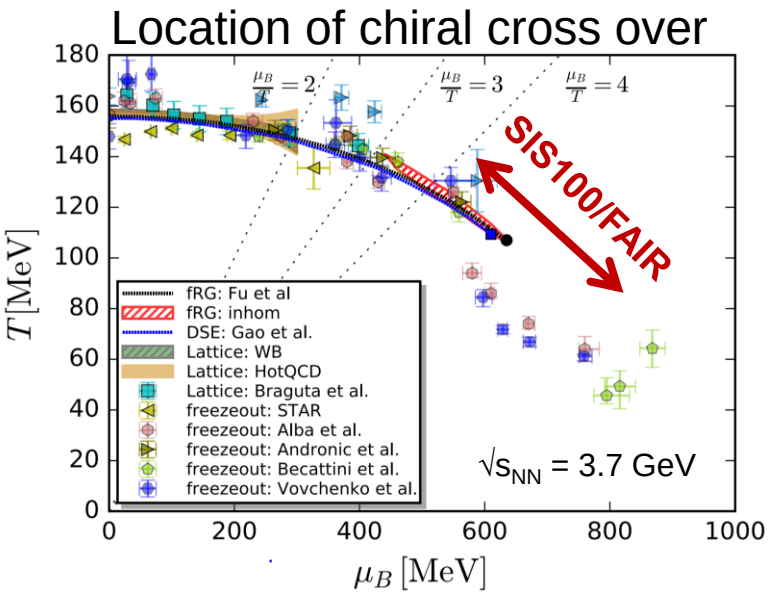
PANDA



hadron structure and dynamics

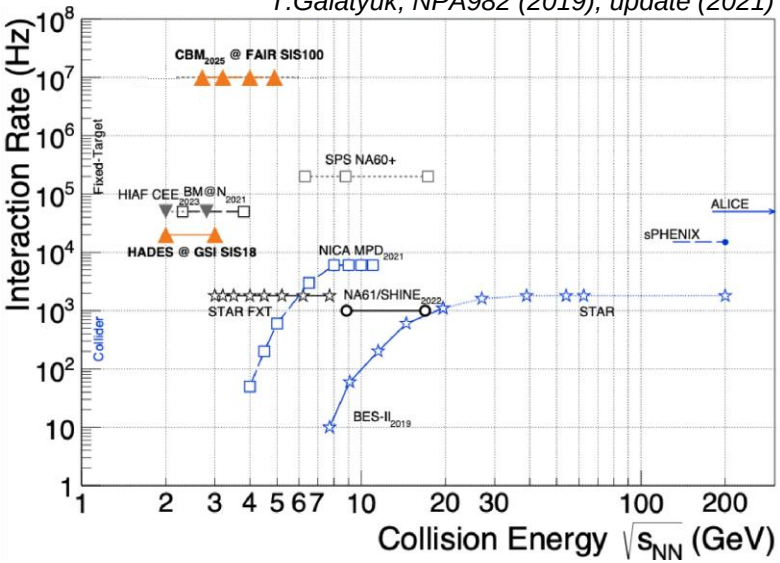
Compressed Baryonic Matter

QCD Phase Structure and Properties of QCD Matter



W. Fu, J. Pawlowski, F. Rennecke,
Phys.Rev.D 101 (2020) 5, 054032, arXiv:1909.02991

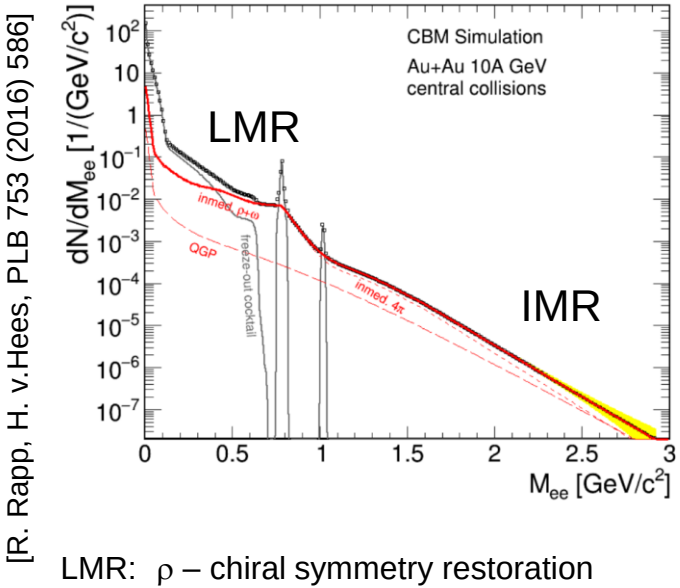
CBM Collaboration, EPJA 53 3 (2017) 60
T.Galatyuk, NPA982 (2019), update (2021)



CBM/HADES - Mission:
Systematically explore QCD matter at large baryon densities with high accuracy and rare probes.

Compressed baryonic matter

Dileptons as probes for dense matter



LMR: ρ – chiral symmetry restoration
fireball space – time extension

IMR: access to fireball temperature
ρ-a$_1$ chiral mixing

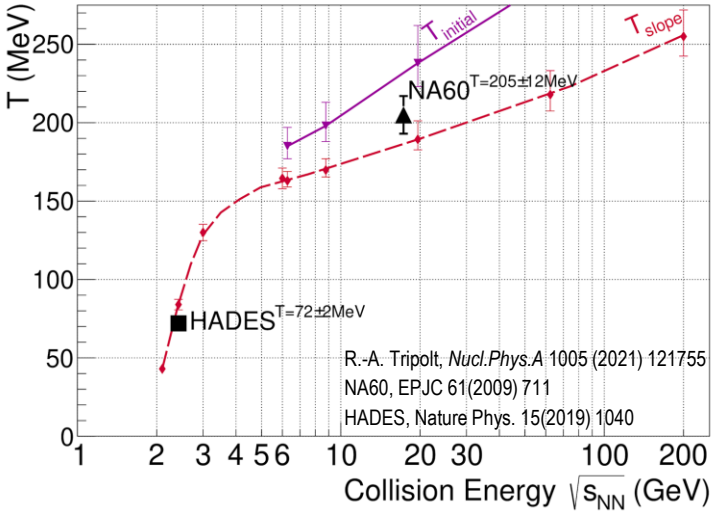


Figure:
T. Galatyuk

Measurement program:

- excitation function of LMR – excess
- excitation function of IMR – slope (caloric curve)

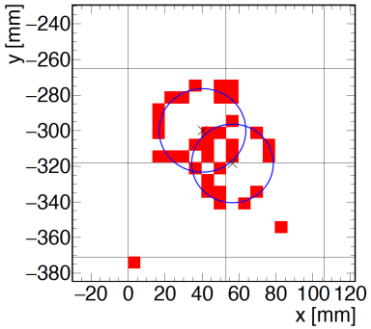
Sensitivity to phase transition:

non – monotonic behavior of T$_{slope}$

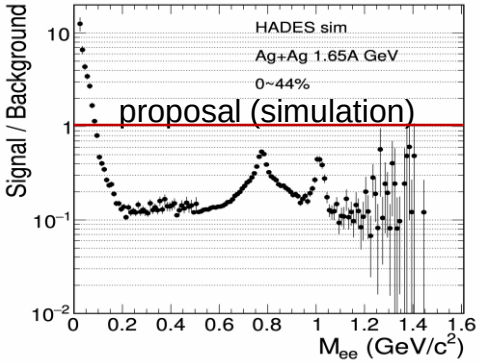
Compressed baryonic matter

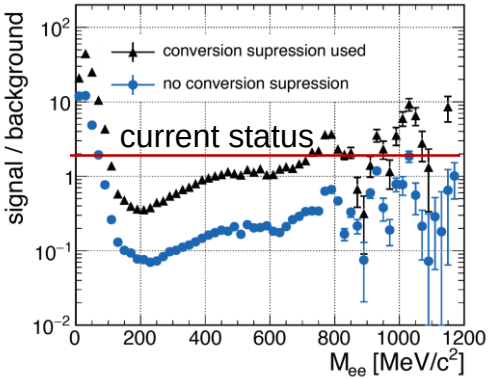
Improved Dilepton Identification using CBM Technology

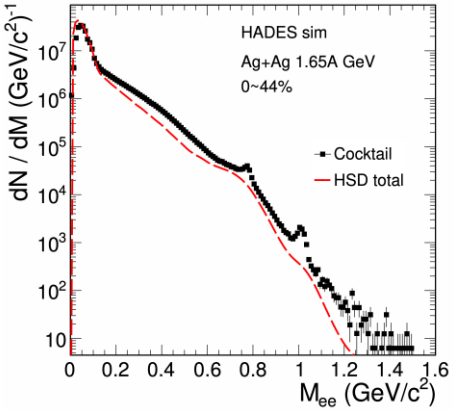
Factor of 3 better electron identification efficiency

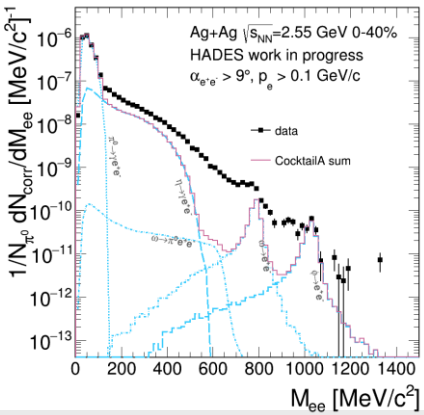


Excellent double ring detection: Factor of 8 better S/B (even above expectation)









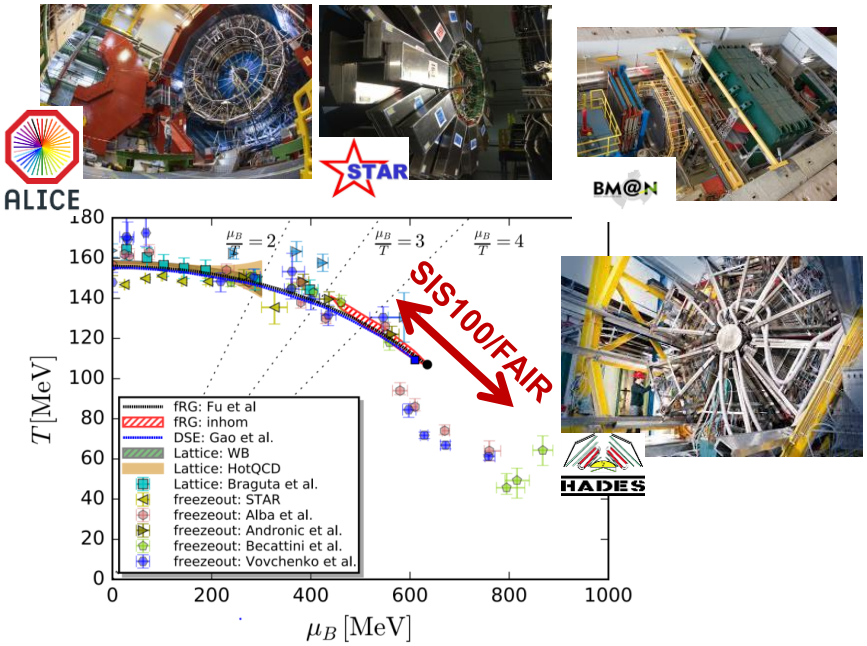
Ag+Ag 1.58A GeV ($\sqrt{s} = 2.55\ A\ \mathrm{GeV}$)

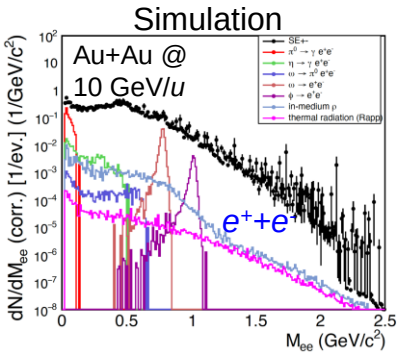
- 180.000 signal pairs above π^0 Dalitz region
- First measurement of dilepton yield beyond vector meson mass region
- Vector-meson peaks (ω, φ) clearly visible
- Short run (3 days) Ag+Ag 1.23A GeV with 18.000 signal pairs above π^0 Dalitz

Perspectives for CBM / HADES

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

Study of strongly interacting matter

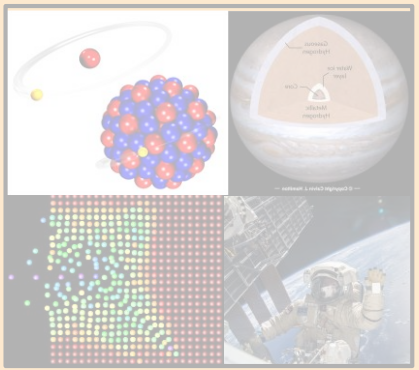




- Access to thermal signal is feasible with good background description
- Statistical accuracy for T_{slope} of 10% requires ~10^{11} events, ~ 20 days of beamtime
- **CBM will be the first experiment to use di-leptons for systematic measurements**

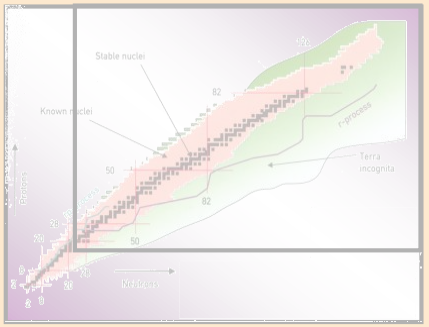
FAIR research pillars

APPA



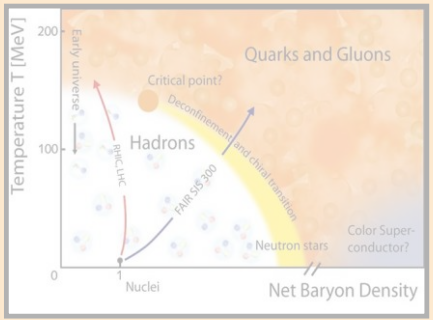
atomic physics, plasma physics, materials science, biophysics

NUSTAR



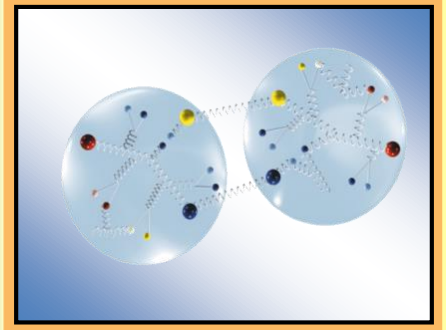
nuclear structure and nuclear astrophysics

CBM



QCD phase structure and properties of QCD matter

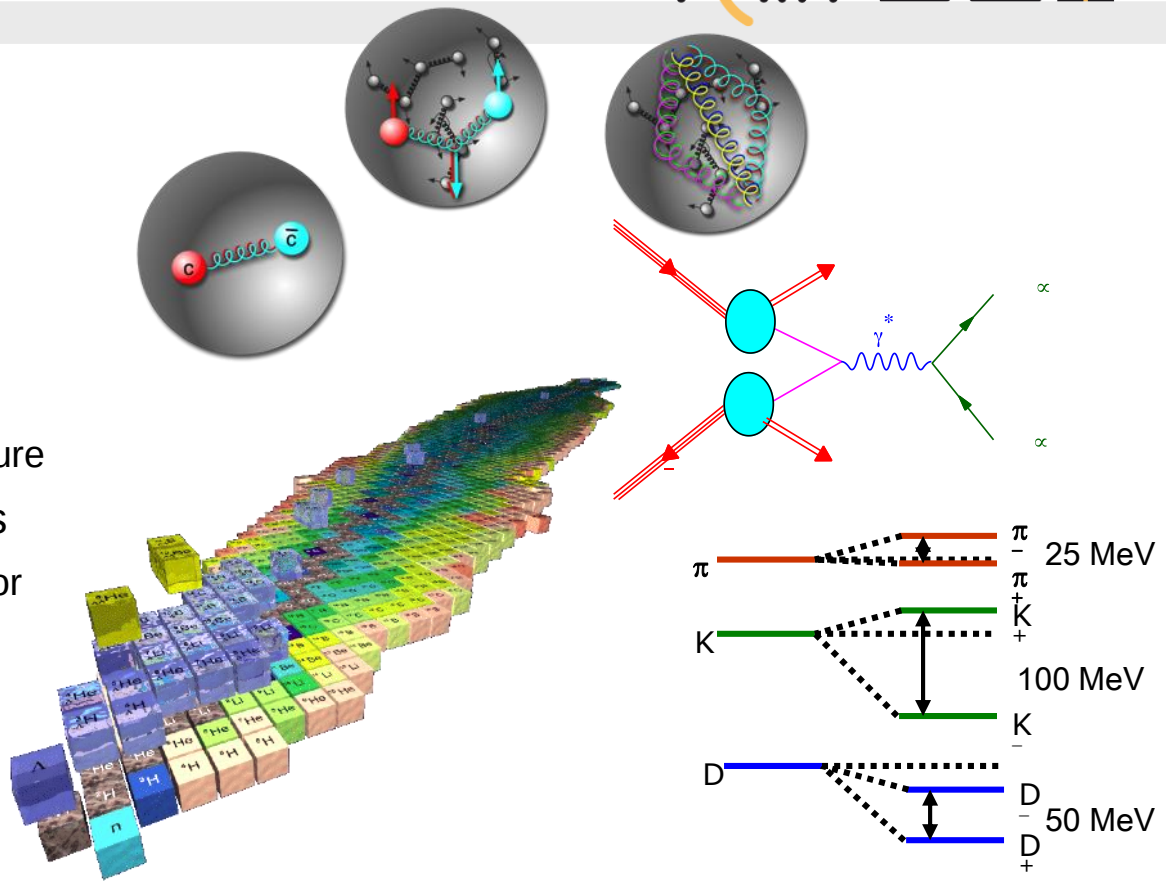
PANDA



hadron structure and dynamics

PANDA physics case

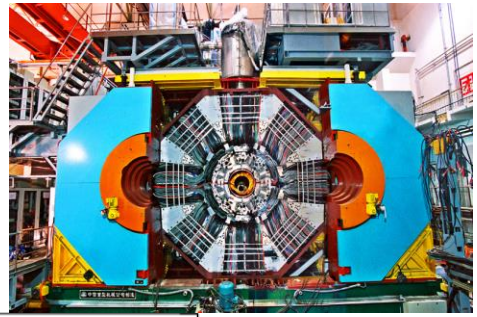
- Gluonic excitations
  - Hybrids, glueballs
- Charmonium states
  - Precision spectroscopy
- Time-like
  - Form factors, nucleon structure
- In medium mass modifications
  - Extension to the charm sector
- Extension of nuclear chart
  - Double hypernuclei
- And much more...

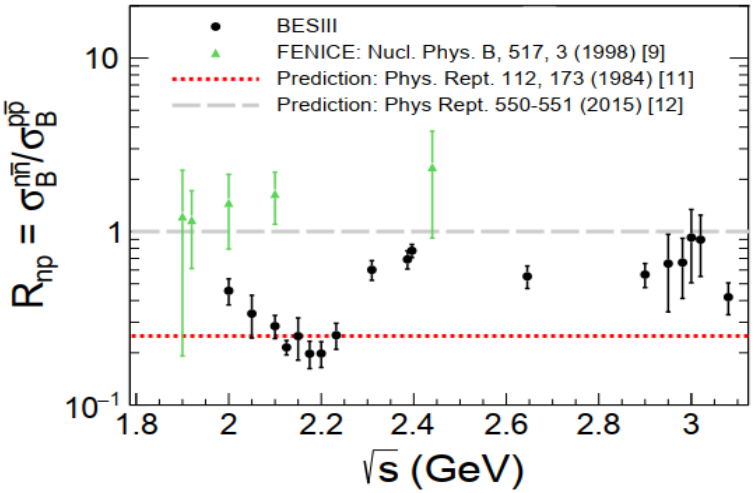


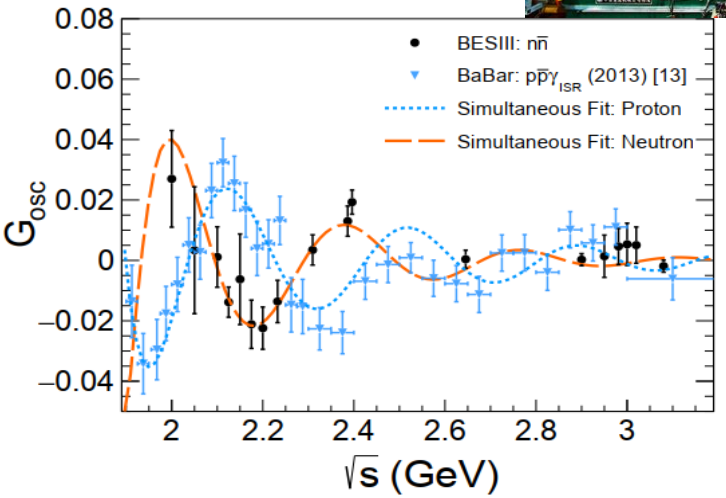
PANDA in FAIR Phase-0

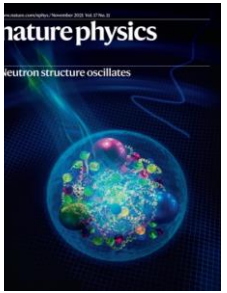
Precise Electromagnetic Structure of the Neutron from BESIII

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









HIM
Helmholtz-Institut Mainz

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

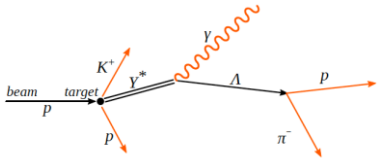
PANDA in FAIR Phase-0

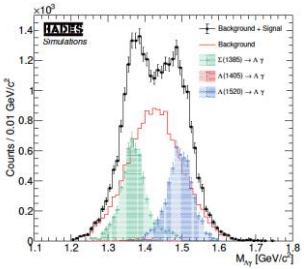
Production and Electromagnetic Decay of Strange Hyperons

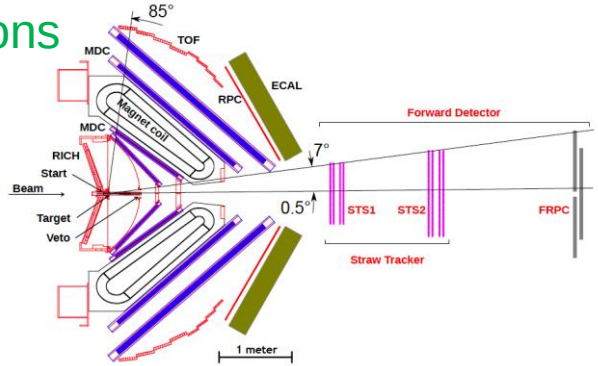
HADES measurement p+p (4.5 GeV) beam in Feb. 2022

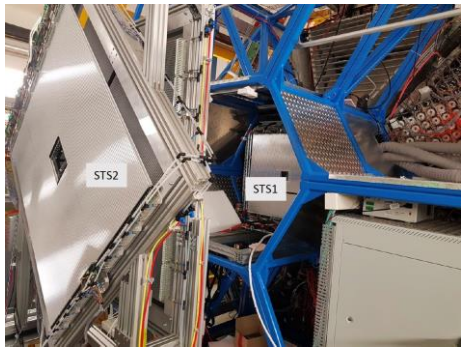
Physics goals published in *Eur.Phys.J.A* 57 (2021) 4, 138

Simulation of electromagnetic final states of excited hyperons Σ (1385) and Λ(1520)

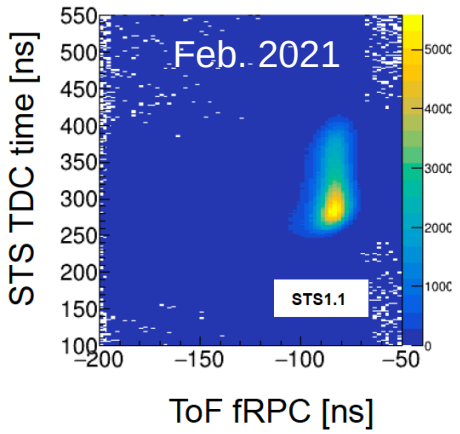








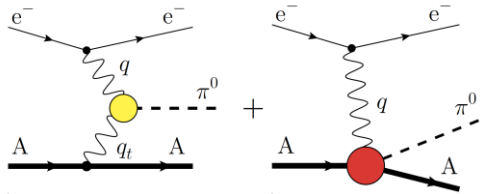
STS1 / ST2	IKP Jülich, Cracow, Orsay	tracking
Part of iTof	IKP Jülich	trigger hodoscope
Part of fRPC	Coimbra	time-of-flight

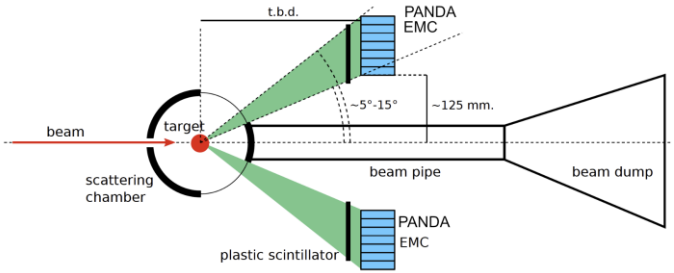


Perspective for PANDA

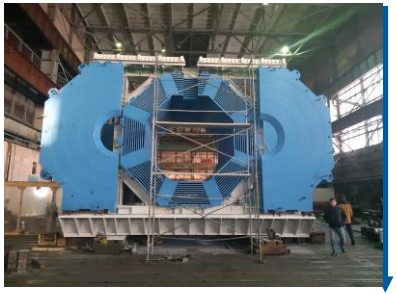
2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028

At MAMI Mainz:
Measurement of the electromagnetic transition form factor of the π^0 in the space-like region via Primakoff electroproduction

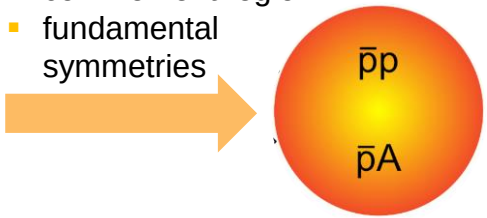




The setup of the PANDA backward EMC within the A1 experiment at MAMI



Essential questions
- QCD in the confinement region
- fundamental symmetries



PANDA Physics
- nucleon structure
- strangeness and charm
- hadrons in nuclei
- exotics

Summary and Conclusion

FAIR Phase-0 at GSI

- Staged approach to FAIR science and by smooth transition from GSI to FAIR operation
  - education of young scientists and engineers
  - maintaining expertise and skills
- Fostering a close collaboration between experiment and theory

Start of FAIR

- Stepwise process
  - allows early science already end of 2025