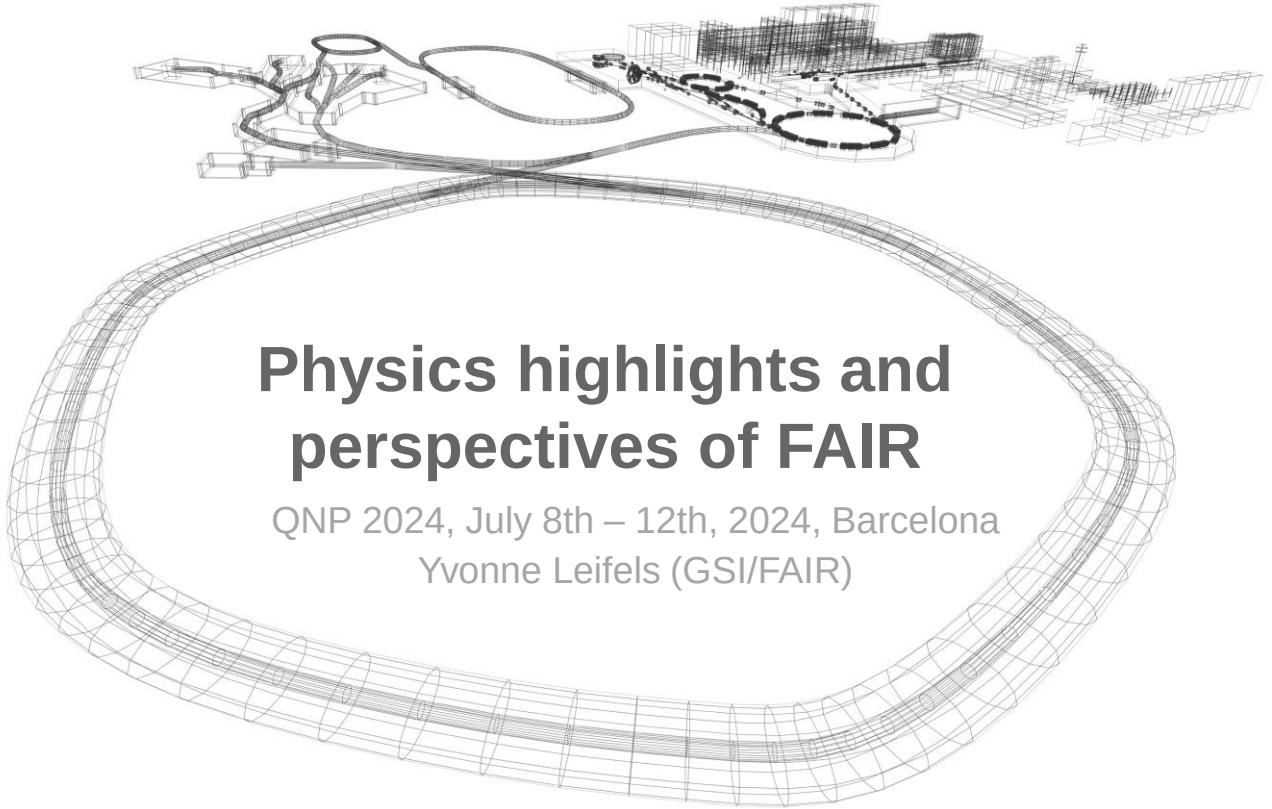


Physics highlights and perspectives of FAIR

QNP 2024, July 8th – 12th, 2024, Barcelona

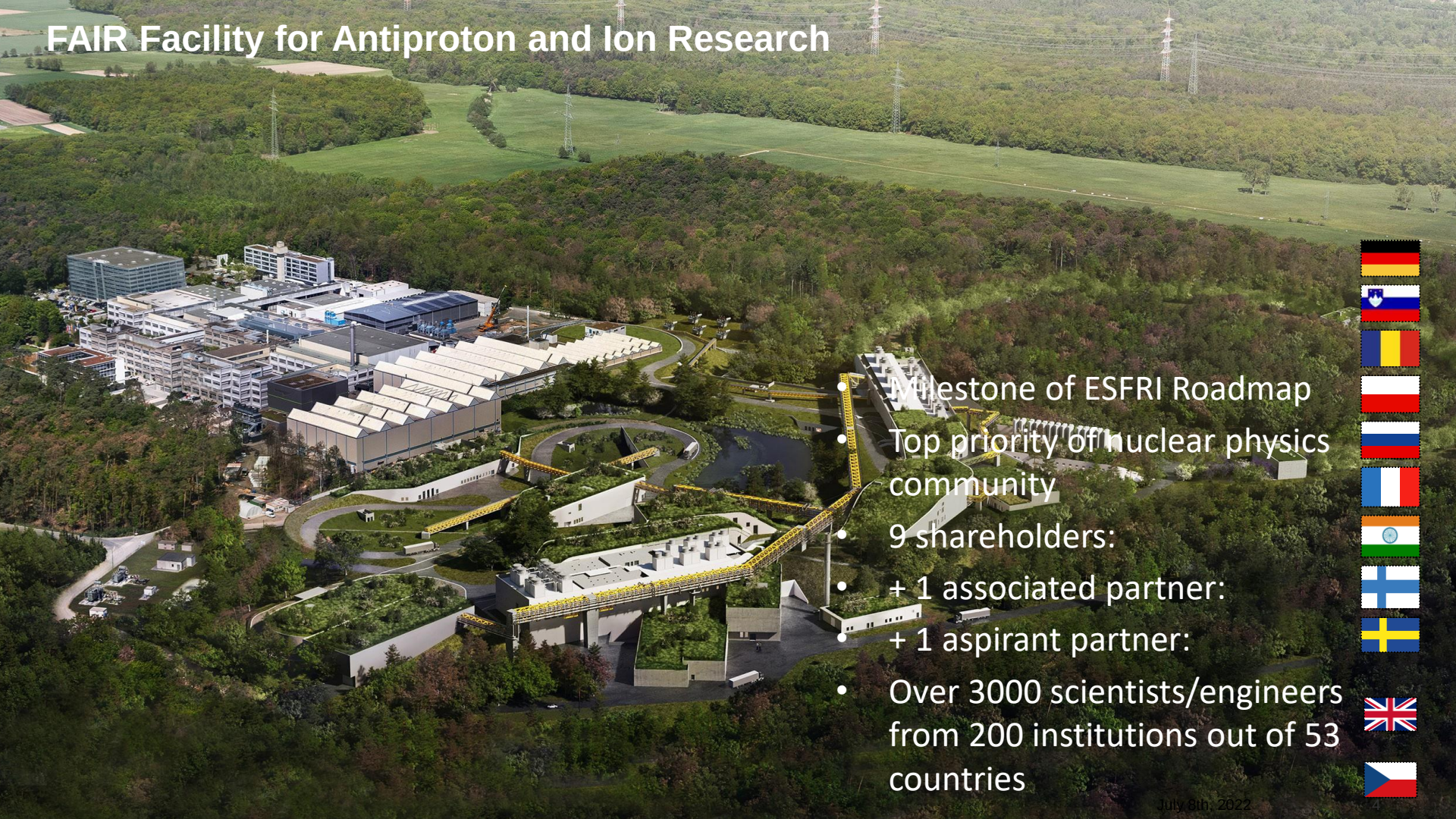
Yvonne Leifels (GSI/FAIR)

Overview

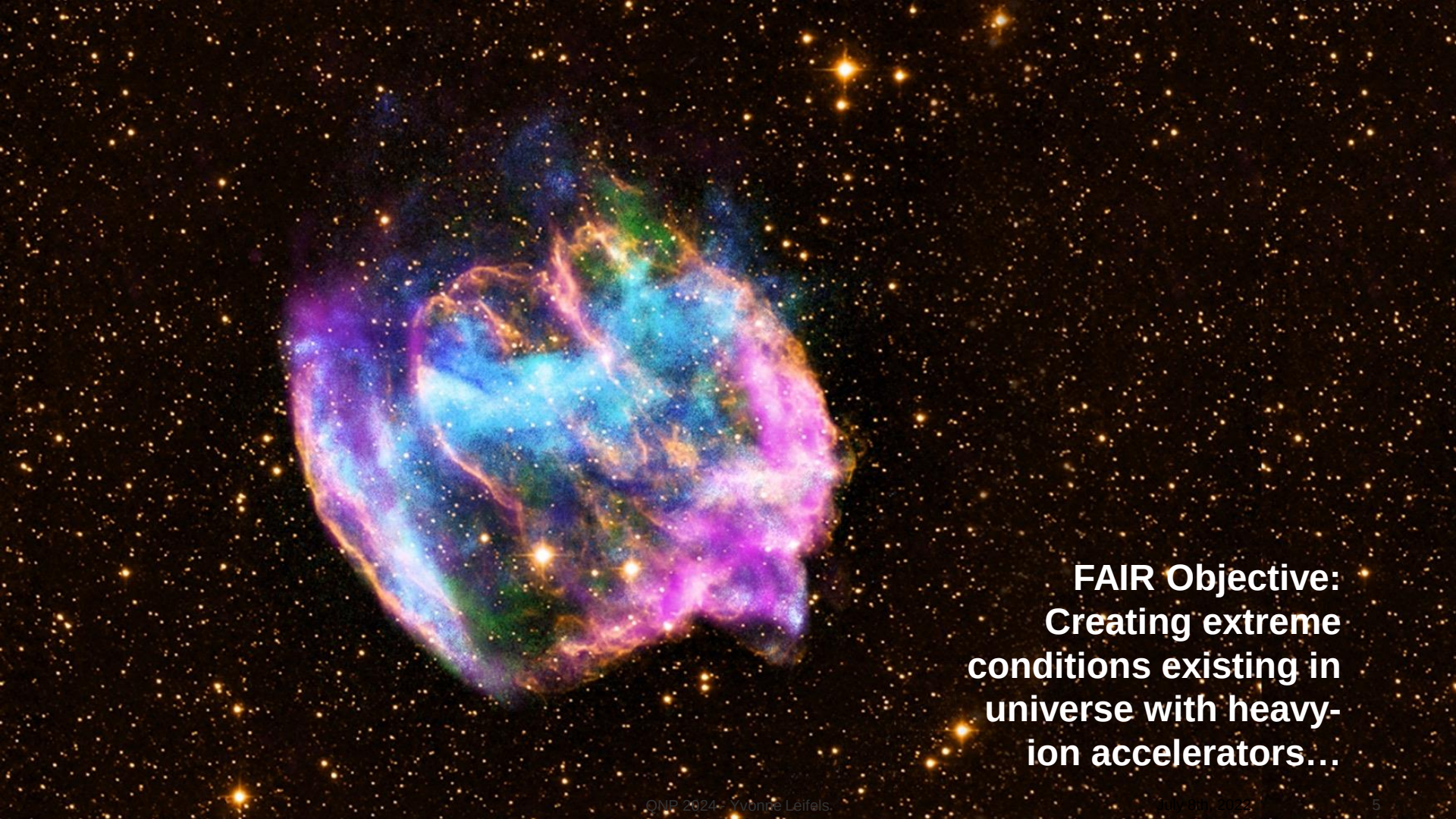
- Introduction to FAIR
- Status of FAIR construction
- Scientific perspectives
  - Primary beams
  - Exotic beams
  - Storage rings
- Summary and Outlook


FAIR Facility for Antiproton and Ion research
GSI Helmholtzzentrum für Schwerionenforschung Darmstadt

FAIR Facility for Antiproton and Ion Research



- Milestone of ESFRI Roadmap
- Top priority of nuclear physics community
- 9 shareholders:
- + 1 associated partner:
- + 1 aspirant partner:
- Over 3000 scientists/engineers from 200 institutions out of 53 countries



FAIR Objective: Creating extreme conditions existing in universe with heavy-ion accelerators…

The begin of a new era

Multimessenger astrophysics

Nuclear physics

Simulations

… to answer fundamental questions:

Synthesis of chemical elements in the cosmos

Building blocks of life: Production of carbon and oxygen in stars

Neutron star mergers: equation of state, strong force, neutron rich nuclei

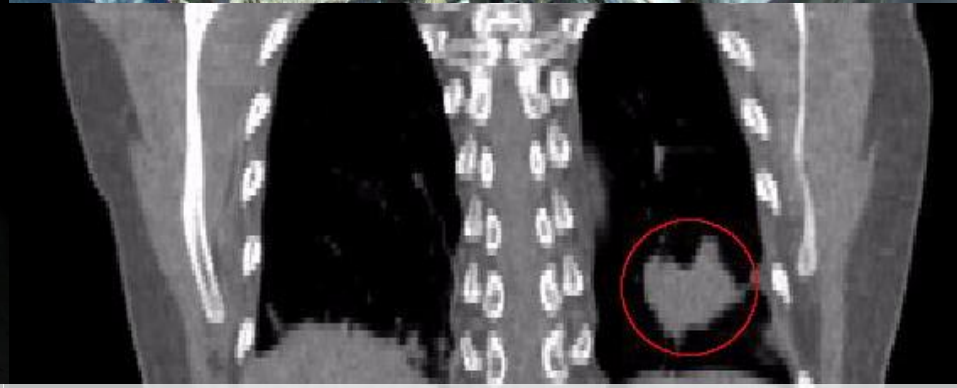
Matter in the interior of Earth and of large planets

… with direct applications

High-performance and scientific computing, big data, green IT

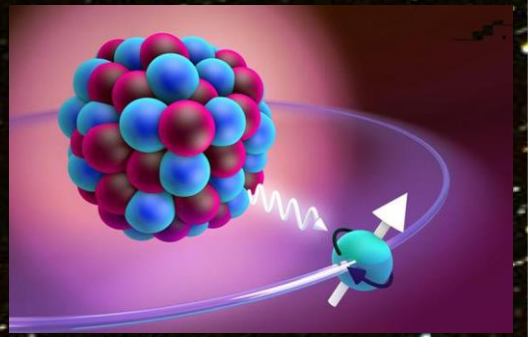
Space radiation protection investigations in collaboration with ESA

Development of nuclear clock: Promising candidate thorium-229



Novel applications for tumor and non-tumor diseases

APPA

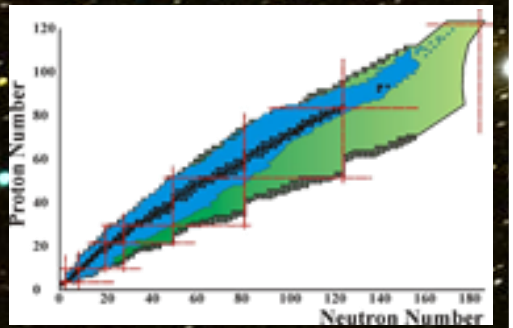


- Precision tests of QED
- Cosmic ray simulator for irradiation studies
- Materials under high pressure

CBM HADES

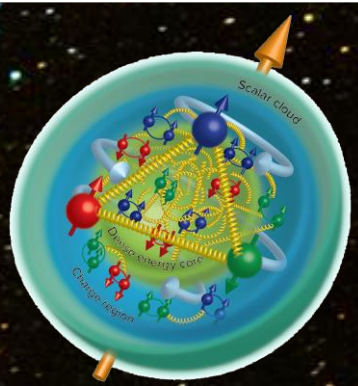
- QCD matter at high baryon densities
- Phase transition and critical point
- Particles in dense medium

NUSTAR



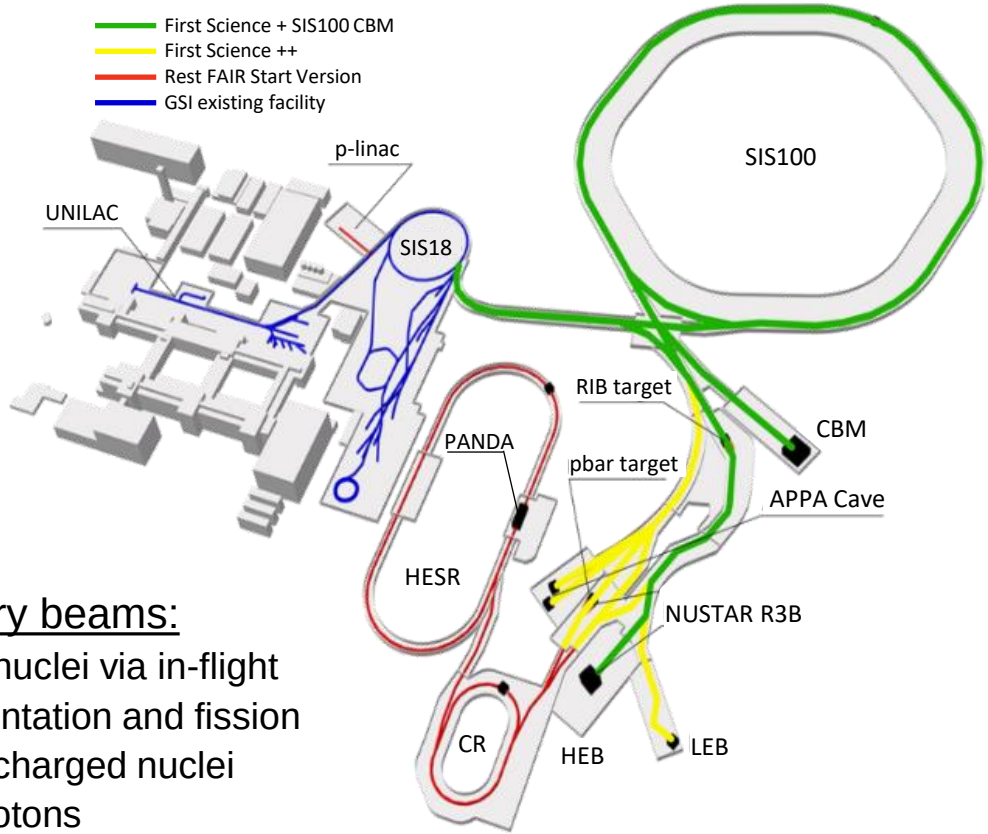
- Nucleosynthesis of heavy elements
- Structure of exotic nuclei (e.g. hyper nuclei)
- Neutron matter equaton of state

panda



- Gluonic excitations: Hybrids, glueballs
- Precision spectroscopy of charmonium states
- Time-like form factors, nucleon structure

FAIR Accelerator facilities



SIS100 primary beams:

- 10^9/s Au up 11 GeV/u
- 10^9/s C, Ca, … upto 14 GeV/u
- 10^{11}/s p up to 29 GeV/u

Secondary beams:

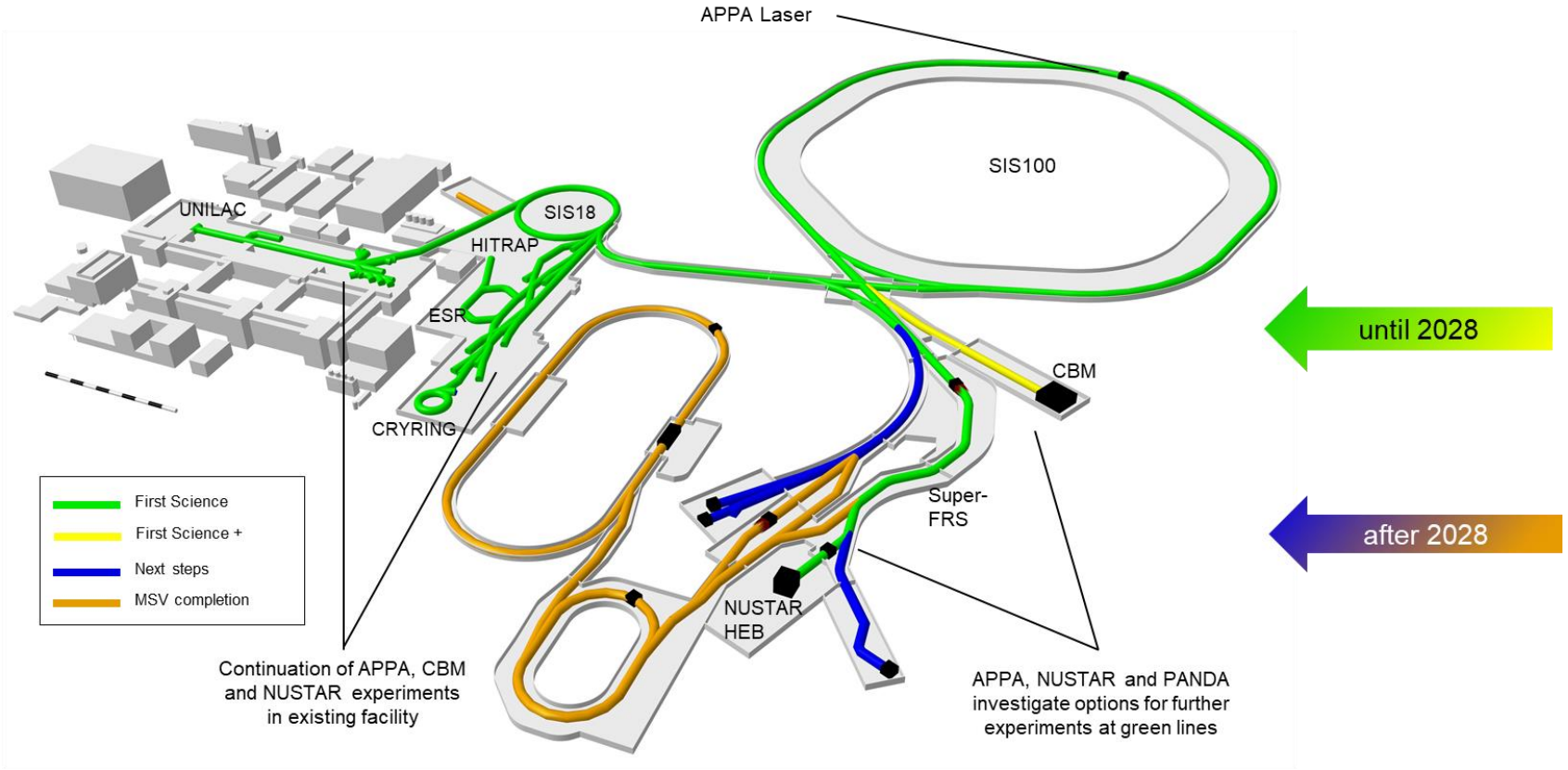
- exotic nuclei via in-flight fragmentation and fission
- highly charged nuclei
- anti-protons

Timeline

2018 start of FAIR Phase-0 at upgraded GSI facilties
2023 concrete construction completed
2024 start of accelerator installation
2027 first experiments with SIS18 beam
2028 start of operation with SIS100

GSI facilities continue operation

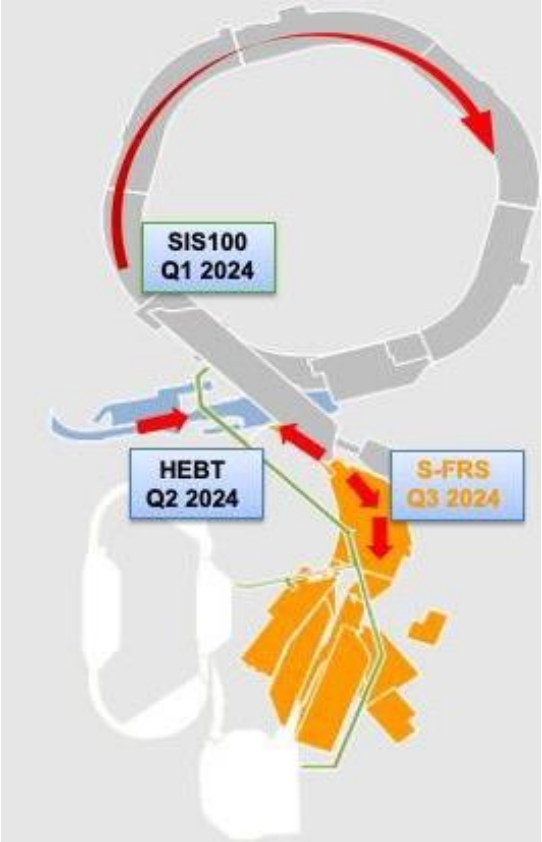
Current prospects



Concrete works finished Q4 2023

Drone video https://www.youtube.com/watch?v=wTCkZdeqI8I

FAIR Start of installations

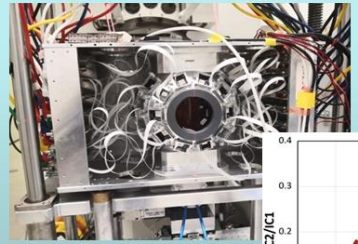


Ongoing installation work

Future

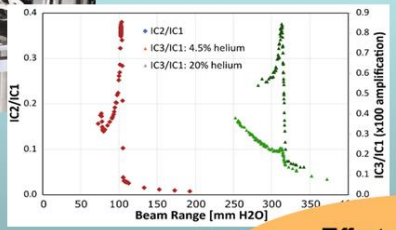
FAIR Detector R&D and construction

APPA



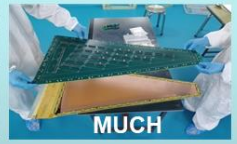
BARB PET

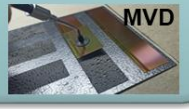
Medical applications: Two ion species within one bunch



CBM

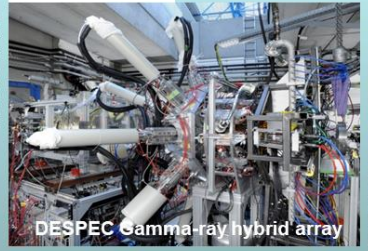
CBM detectors (pre-)production



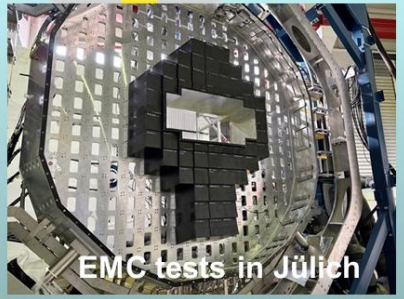


Effort to best use the part of FAIR which will be available by 2028

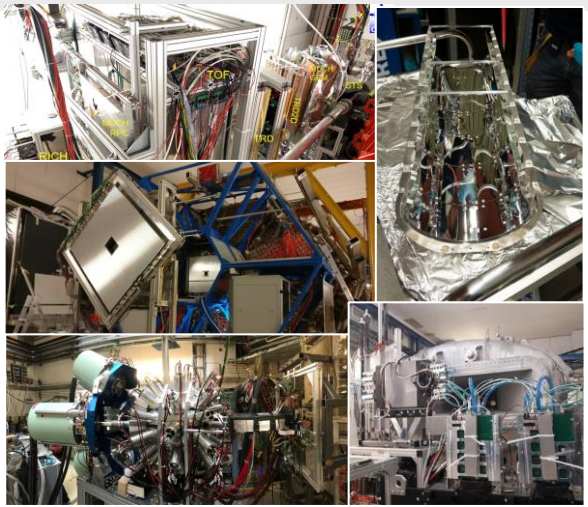
NUSTAR

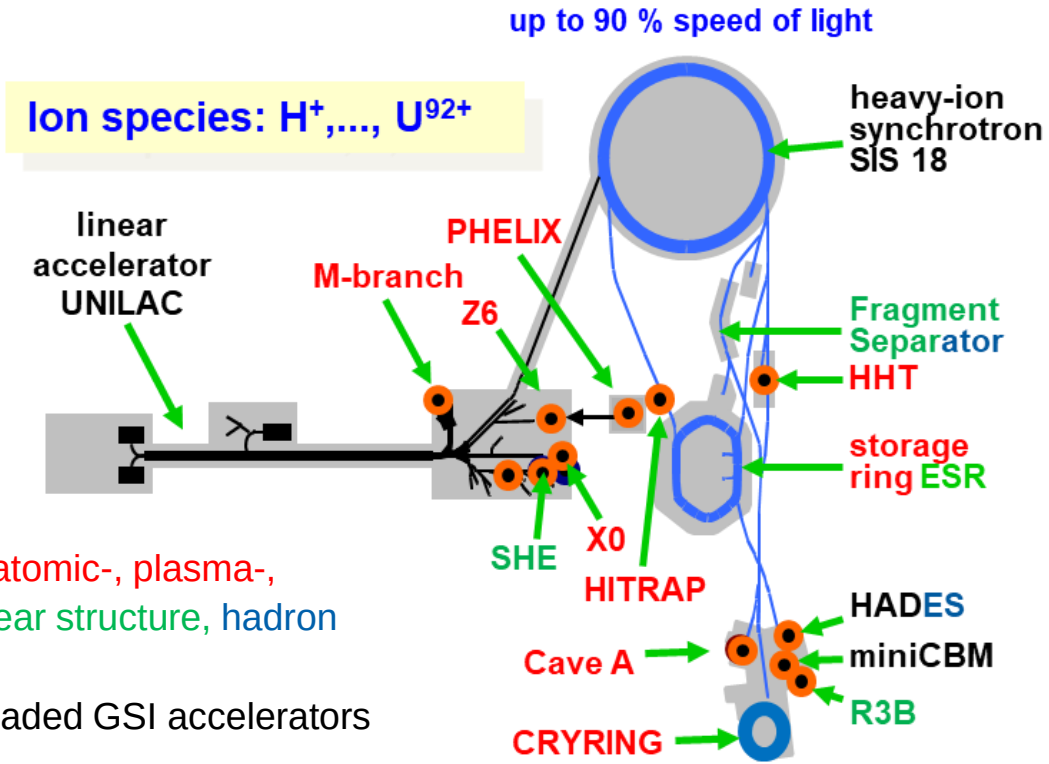


PANDA



FAIR Phase-0
Research program at upgraded GSI accelerators using FAIR detectors





FAIR Phase-0 started in 2019

- Stepwise approach to FAIR science: atomic-, plasma-, biophysics, materials reasearch, nuclear structure, hadron physics, dense matter physics
- Commissioning and operation of upgraded GSI accelerators and newly built FAIR detectors
- Education and training of early career researchers

Primary beams
Biophysics: Cosmic ray simulator

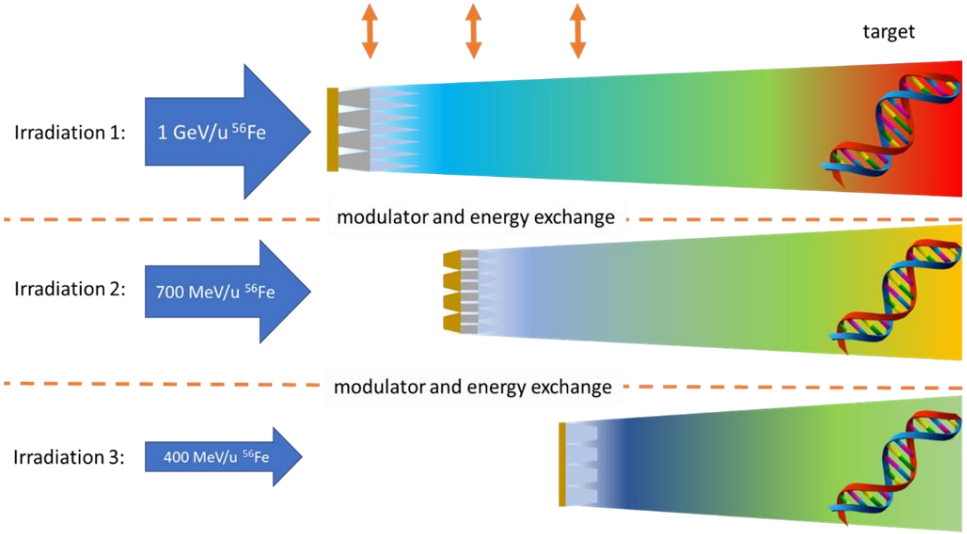
- At FAIR nearly the full space spectrum will be reproduced and used for experiments with biological tissues, shielding, and microelectronics
- A hybrid active-passive method to produce a mixed radiation spectrum similar to the cosmic ray spectrum in deep space will be used

3D ripple filter tested at HIT (Heidelberg) for producing mixed fields in a water phantom

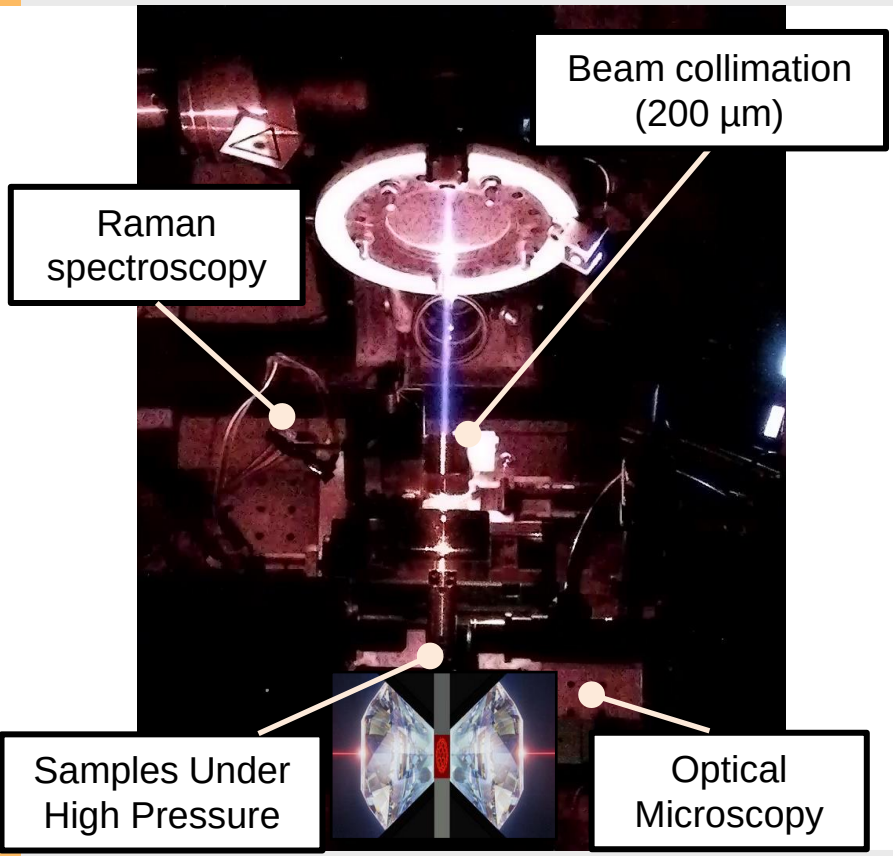
Schuy *et al.*, *Front. Phys.* 2020

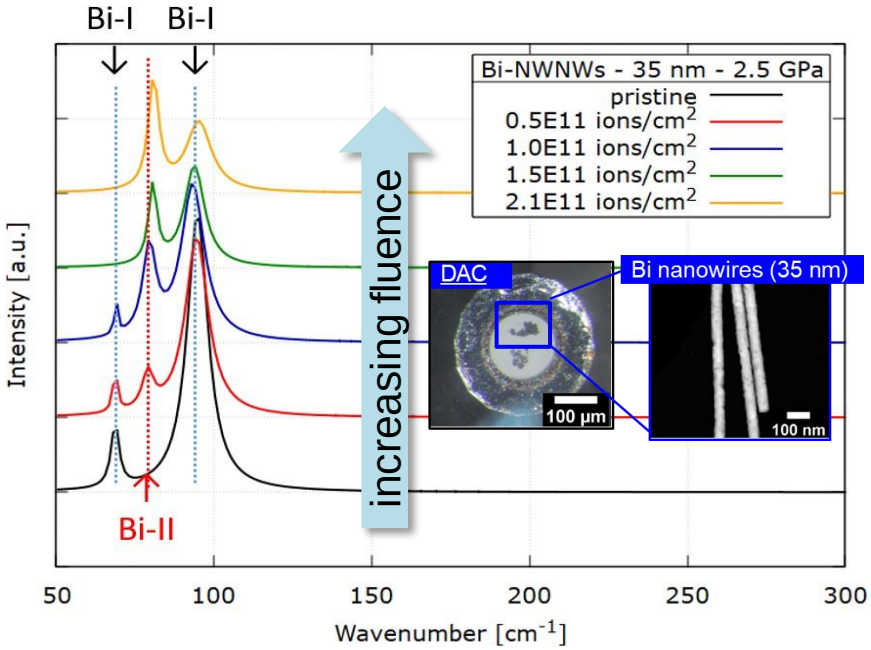
Funded by esa

superposition of radiation fields



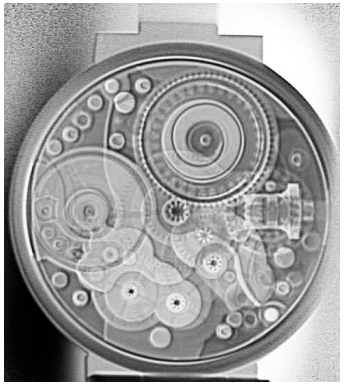
Materials Research
Irradiation under high pressure





Plasma physics
High energy density studies

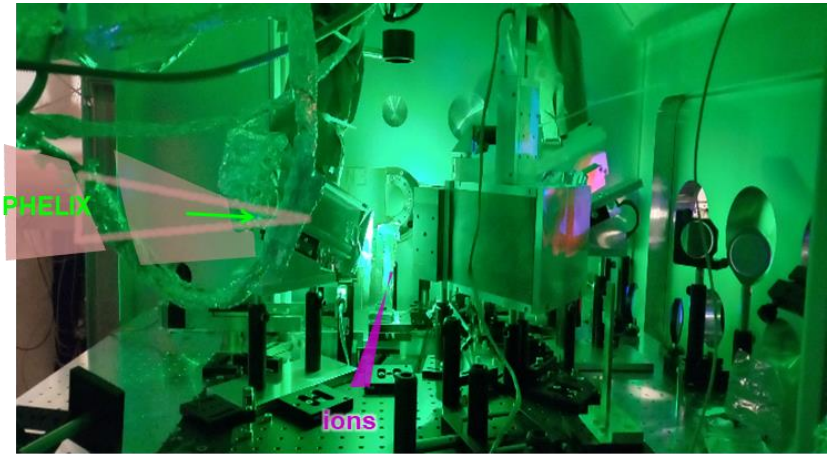
PRIOR – heavy ion radiography



▲ Small wrist watch (left) imaged with 975 MeV/u Carbon beam (right). (2mm mono CsI, PCO Edge 5.5 CLHS).

- Spatial resolution performance of heavy-ions worse than protons but sufficient for physics experiments
- Improved density contrast for 975 MeV/u Carbon for certain target areal densities
- Contrast advantage depends on beam energy

Plasma diagnostics with lasers



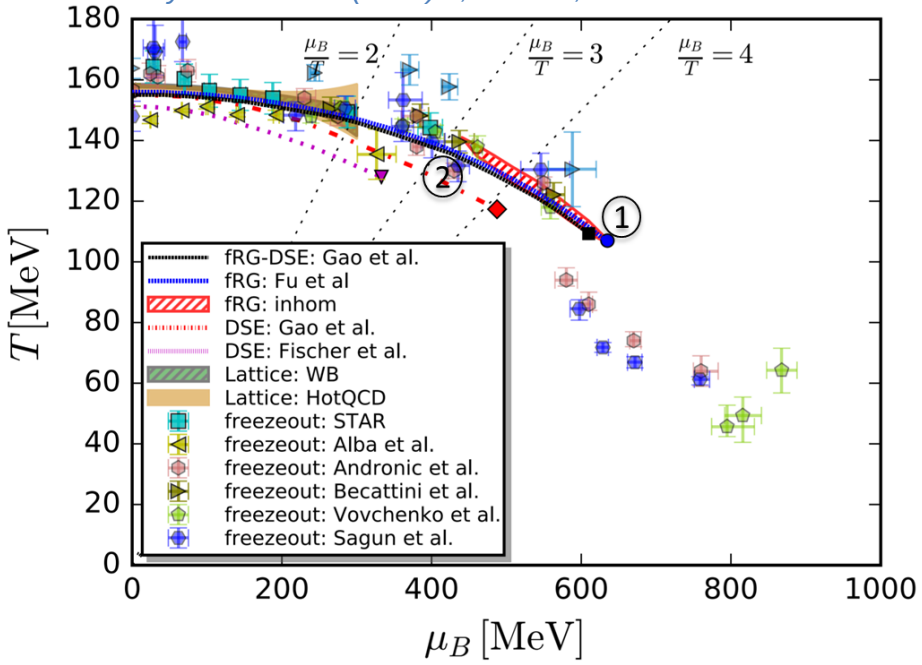
Combination of PHELIX laser with heavy-ion beams

- Volumetric heating by heavy-ion pulses
- Diagnostics with laser-driven x-ray sources
- Broadband x-ray spectrum, based on the enhancement of continuum emission by radiative recombination

CBM/HADES – Scientific goals at FAIR

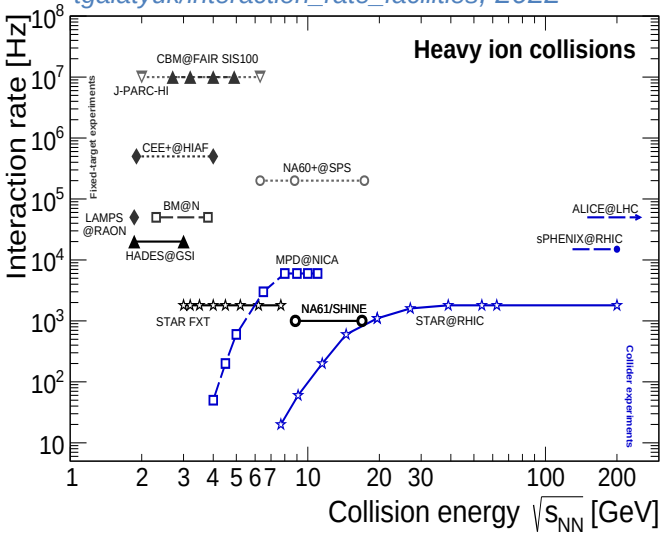
Location of chiral cross over

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



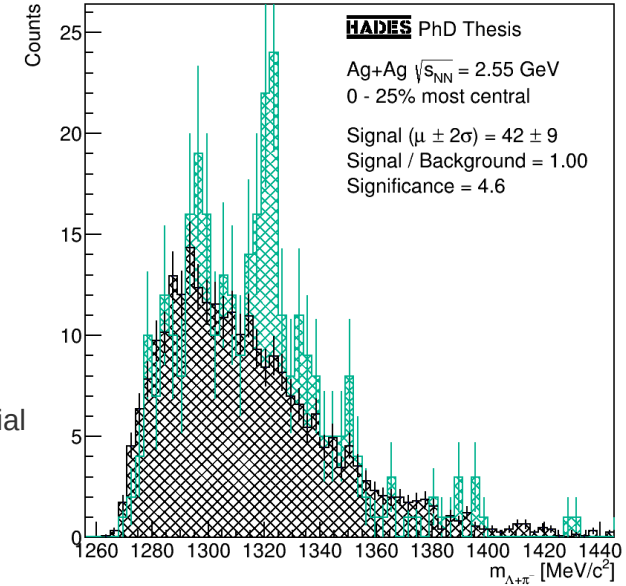
Mission:
Systematically explore QCD matter
at large baryon densities
with high accuracy and rare probes.

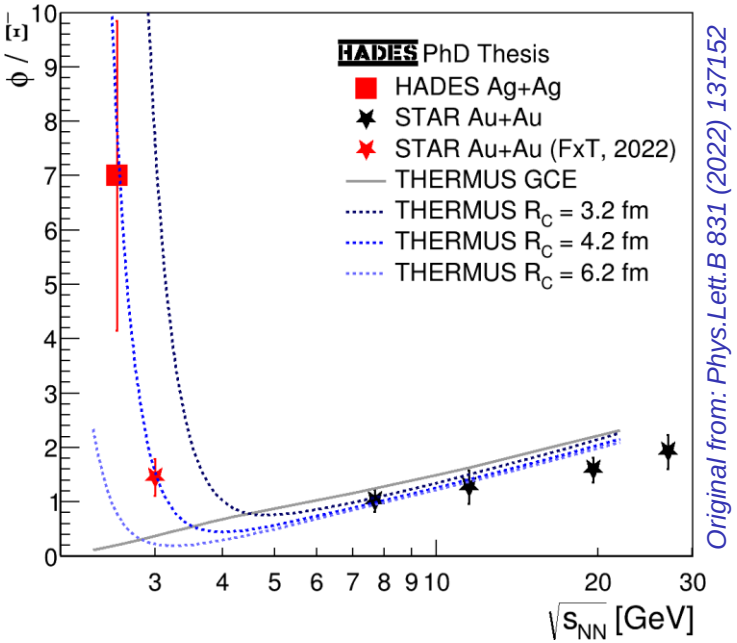
T. Galatyuk, https://github.com/
tgalatyuk/interaction_rate_facilities, 2022



HADES@FAIR Phase-0
Ξ^- production in Ag+Ag @ $\sqrt{s}$ = 2.55 GeV

- Over four weeks, HADES collected 14 billion central Ag+Ag events @ $\sqrt{s}$ = 2.55 GeV
- Ξ^- hyperons detected via the decay chain: $\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\,\pi^-\,\pi^-$
  - excellent background suppression by using artificial neural networks
- Significance slightly below 5σ, yet clear signal above background
- Canonically extended SHM model predicts strong dependence of canonical radius R_C and Φ/Ξ^- ratio



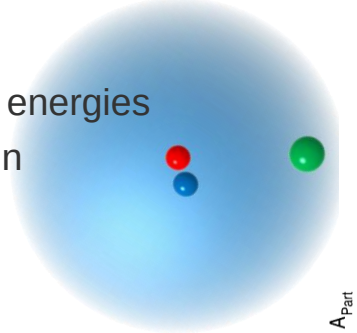


Original from: Phys.Lett.B 831 (2022) 137152

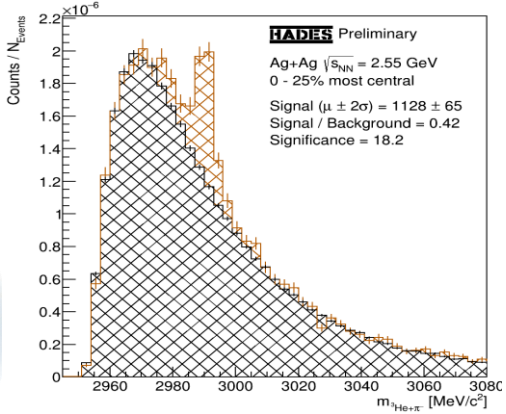
reaction	$\sqrt{s}$ (GeV)	T_{lab} (GeV)
$pp \rightarrow K^+K^+\Xi^-p$	3.247	3.7

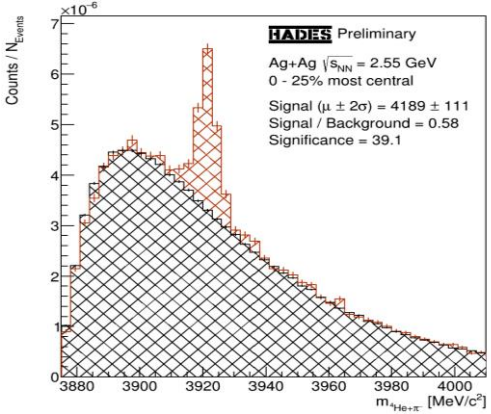
Hypernuclei at HADES: Ag+Ag@√s = 2.55 GeV

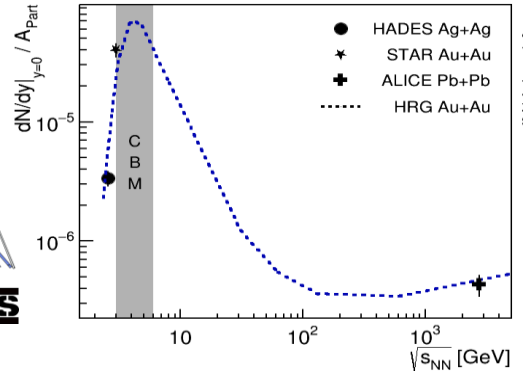
- **Information on Λ(Λ)N(N) interactions important for understanding of neutron stars**
- **Characteristics**
  - lifetime and binding energies
  - size and deformation
  - excitations
  - super-halos

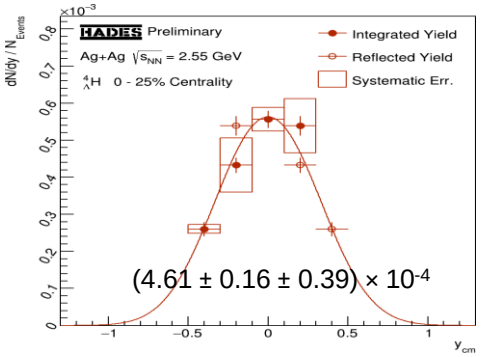


- **production mechanisms**
  - understanding clustering phenomena









Hypernuclei at FAIR

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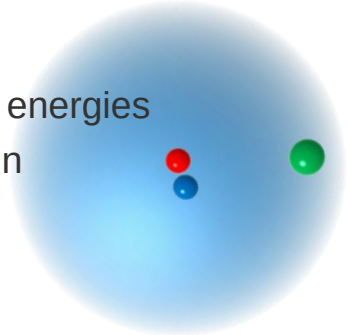
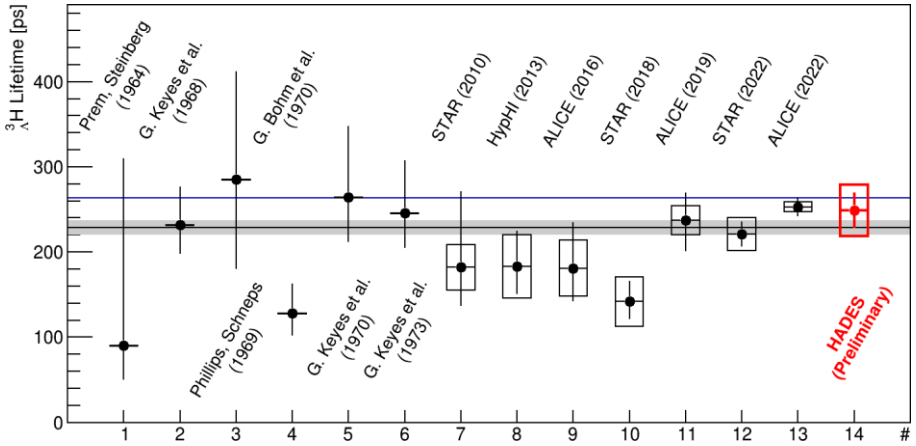


- **Further experiments**
  - WASA@Super-FRS (binding energies, spectroscopy)
  - HYDRA@R3B (binding energies, radius)

HADES Ag+Ag@√s = 2.55 GeV:

- Lifetime of (249 ± 21 ± 30) ps compatible with free Λ lifetime measured



Charm production in pp/pA collisions at SIS100 with CBM

J/ψ production

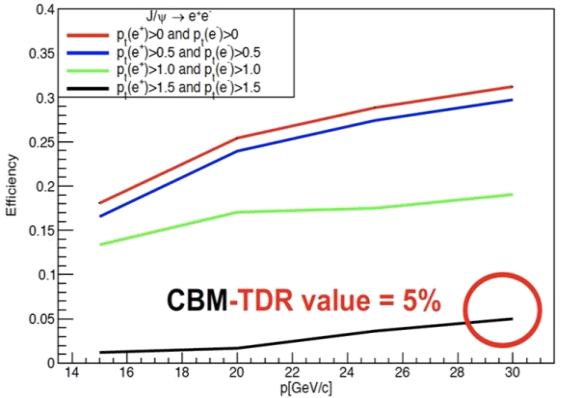
- Cross section ≈ 1 nb at 30 GeV/c ($\sqrt{s}$=7.5 GeV)
- Large and uniform reco eff. 5-30%
- Strong background suppression (Kinematic-fit)

Scientific questions

- Influence of internal charm of proton on cross section close to threshold?
- J/ψ-N interaction with multiple gluon exchange with proton
  - Forward (t=0) J/ψ dσ/dt related to J/ψ–N scattering amplitude, and nucleon mass via trace anomaly
  - J/ψ-N interaction related to pentaquark searches
  - J/ψ in-medium characteristics
- comparing pp to pA/AA-reactions

Signal	Cross Section [μb]
$pp \rightarrow ppJ/\psi(\rightarrow ee)$	10^{-3} (×0.06 BR)

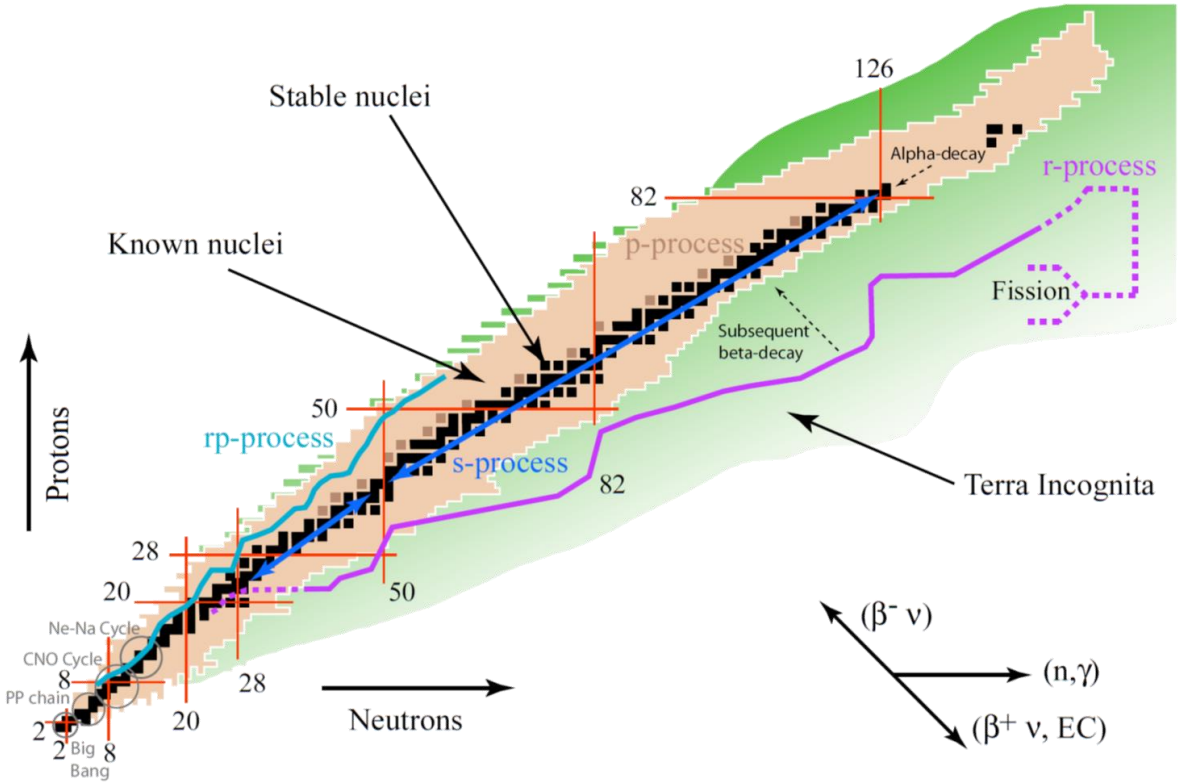
Reco Efficiency pCBM: $pp \rightarrow ppJ/\psi$



J. Ritman et al. FFN (GSI)

Expected reconstructed exclusive events / Day @ 30 GeV/*c*, σ = 10^{-3} μb	
1 MHz	$1.6 \cdot 10^3$
10 MHz	$1.6 \cdot 10^4$

Exotic beams
NUSTAR: Investigating properties of exotic nuclei



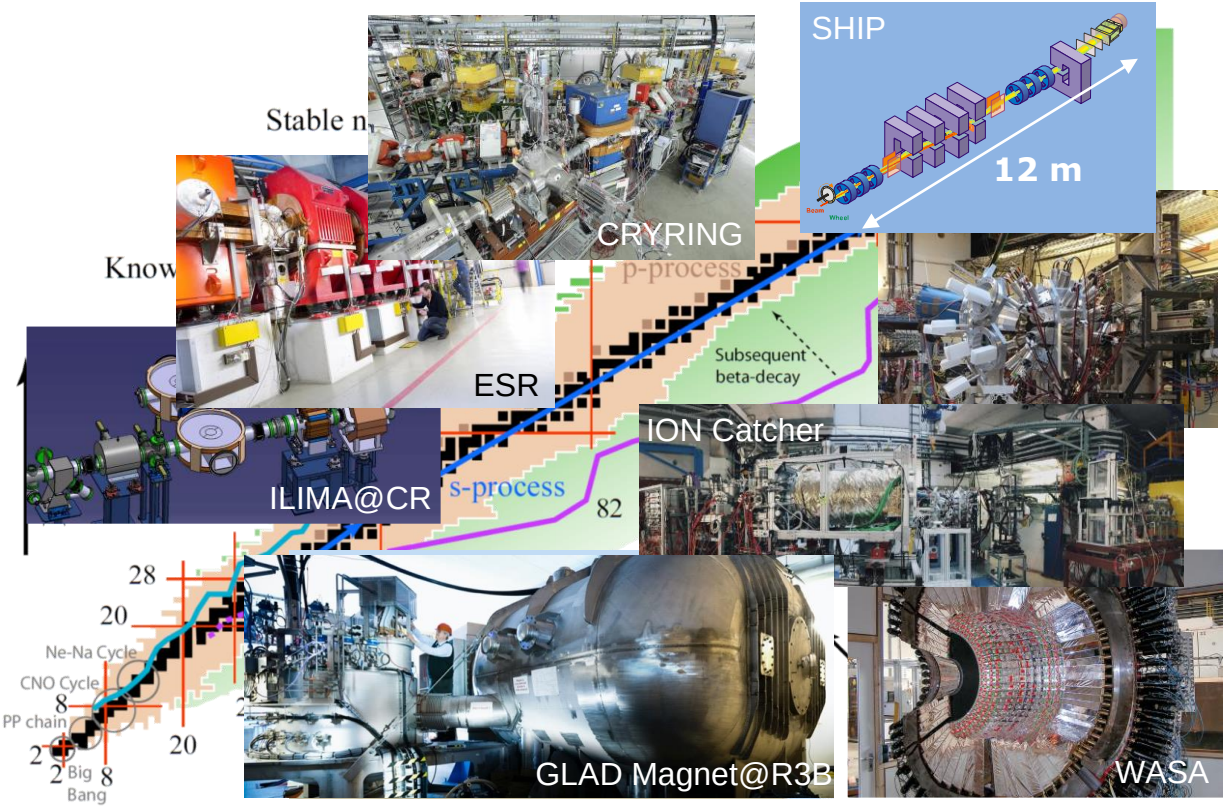
Production, identification and separation

- Super-FRS
  - in-flight fragmentation/fission

Properties being measured

- masses
- half lifes
- mass/charge radii
- single particle structure
- collective behavior
- equation of state of asymmetric nuclear matter
- exotic systems (hyper nuclei)

Exotic beams
NUSTAR: Investigating properties of exotic nuclei



Production, identification and separation

- Super-FRS
  - in-flight fragmentation/fission

Properties being measured

- masses
- half lifes
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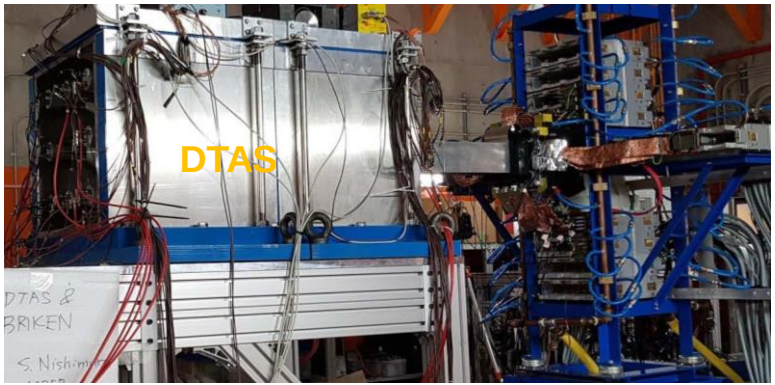
- collective behavior
- equation of state of asymmetric nuclear matter
- exotic systems

DESPEC set-ups prepared for Phase-0 and ready for Early/First Science

DESPEC High-resolution set-up with novel DEGAS Ge detectors



DESPEC High-efficiency set-up with DTAS Total Absorption Spectrometer

Phase-0

^{203}Ir, ^{202}Os, ^{203}Pt, ^{202}Ir

Full β-γ spectros.

^{203,204}Pt, ^{204}Au, ^{206}Au, ^{207}Hg

TAS & B(GT) measurement

Early Science

Pt, Ir, Os chain up to N=**127**

^{207}Au$_{128}$
^{205}Pt$_{127}$

$T_{1/2}$ & β-delayed n emission

Full β-γ spectros.

First Science

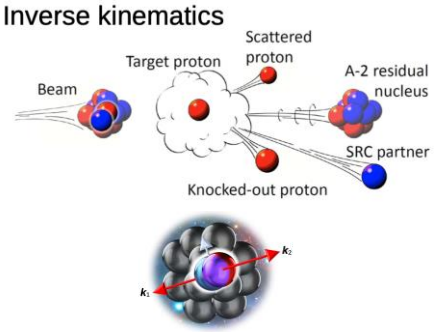
Os, Re to N=**129**
^{201}W$_{127}$

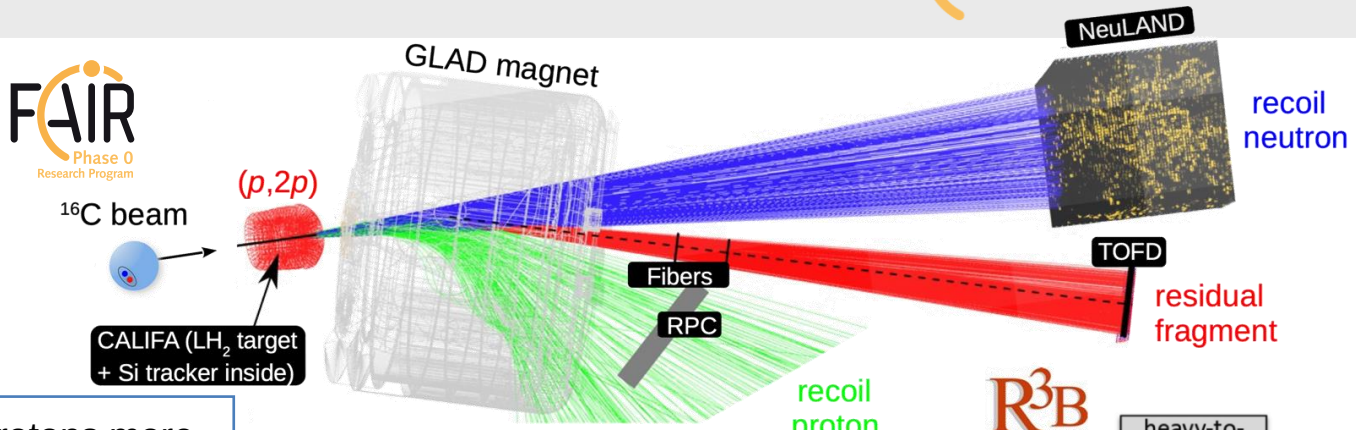
$T_{1/2}$ & β-delayed n emission

^{205}Ir$_{128}$
^{203}Os$_{127}$

Full β-γ spectros.

NUSTAR / R3B set-up for kinematically complete measurements of nuclear reactions





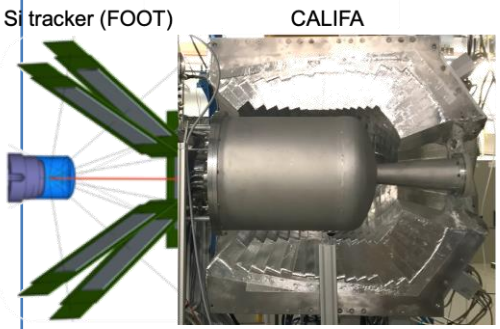
JLAB (e+A) conclusion: Protons more correlated in neutron-rich, stable nuclei

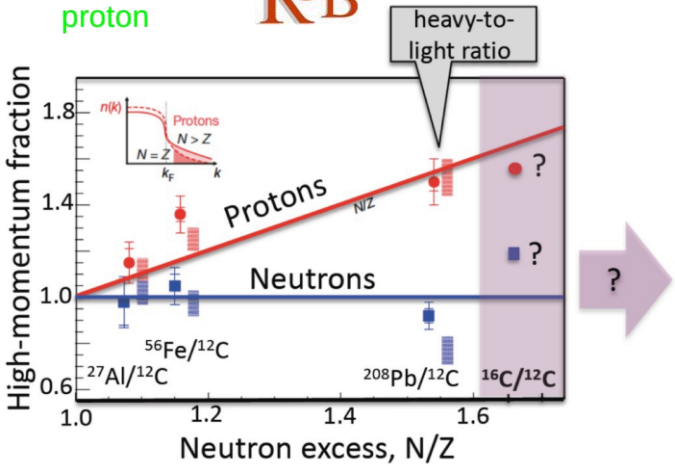
Open questions

- effect of mass ratio or asymmetry?
- development towards large N/Z

FAIR Phase-0 experiment at R3B

- changing N/Z at similar mass
- kinematically complete measurement using ^{12}C, ^{16}C beams
- A. Corsi et al. R3B



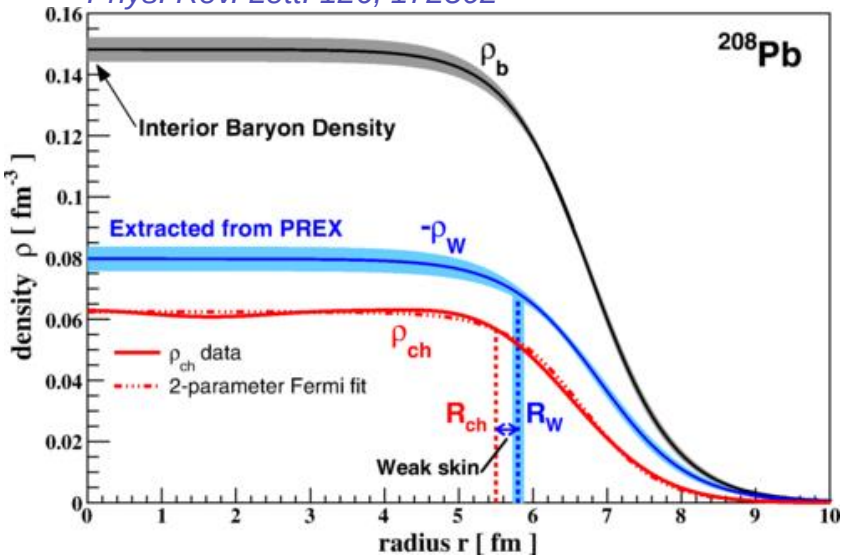


NUSTAR
First R3B experiment

Neutron skin measurements constrain symmetry energy at ρ_0

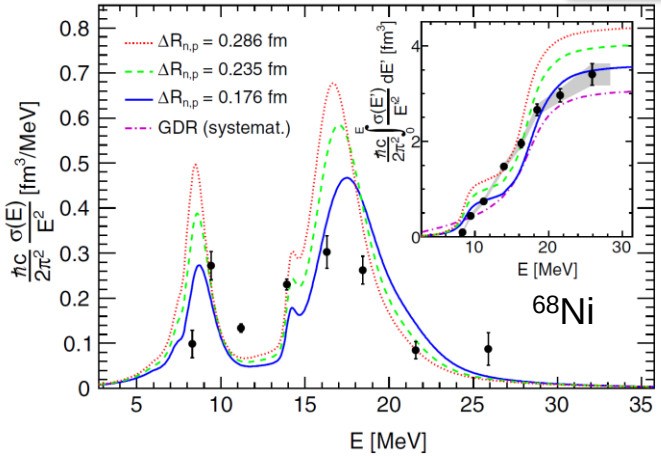
- parity violating electron scattering

PREX@JLAB Collaboration
Phys. Rev. Lett. 126, 172502



Precise constraints on the neutron pressure around saturation density from measurements of **neutron skins** in Sn isotopes

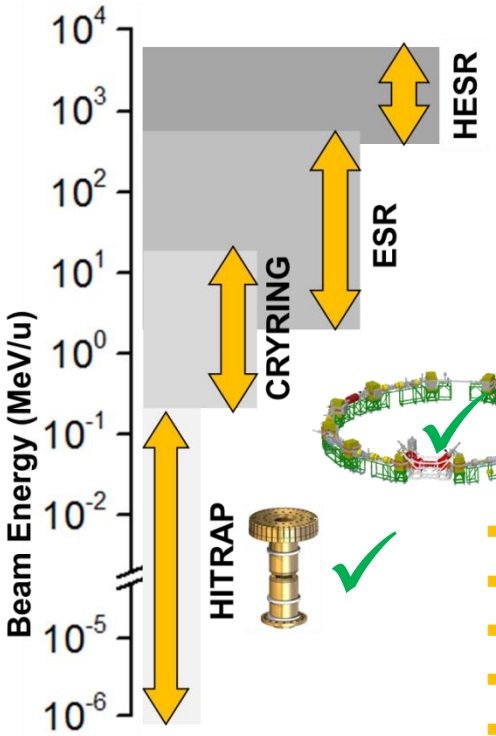
- dipole polarizability
- neutron removal

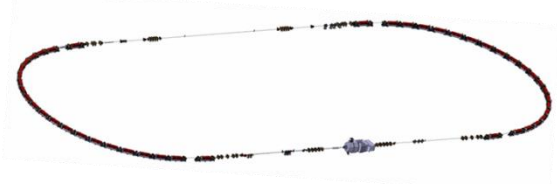


D. M. Rossi et al.
Phys. Rev. Lett. 111, 242503

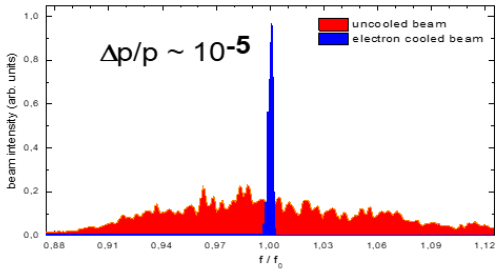
Storage rings
Atomic Physics

SPARC Precision physics by trapping and storage of higly charged ions



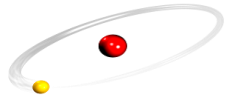


Cooling a key to precision



- Radiative corrections in the non-perturbative regime
- Correlated multi-body dynamics for atoms and ions
- Precision determination of fundamental constants
- Influence of atomic structure on nuclear decay properties
- Astrophysics with stored highly charged ions

hydrogen

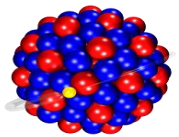


Z=1

E_b = 13.6 eV

$Z \cdot \alpha \ll 1$

uranium ion



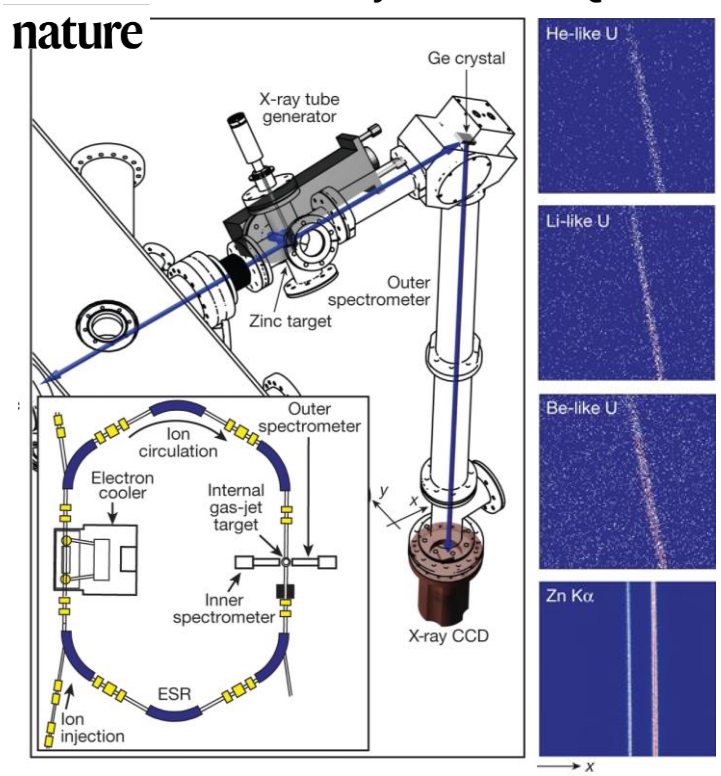
Z=92

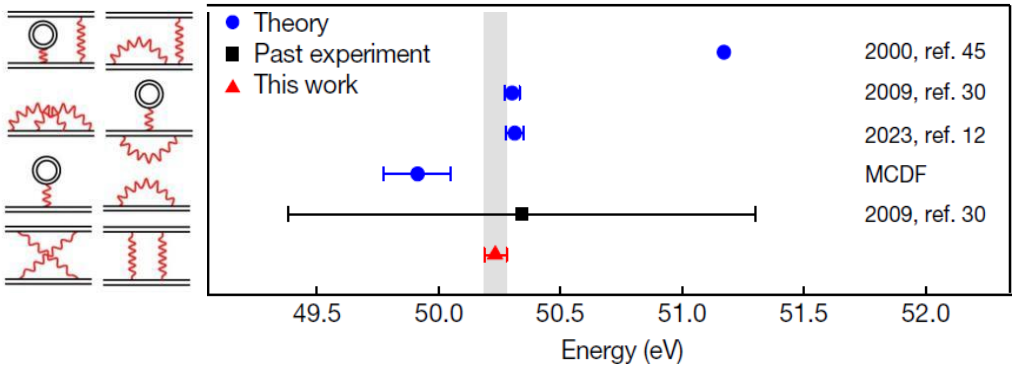
E_b = 132 keV

$Z \cdot \alpha \approx 1$

Precision measurement of intrashell transitions in He-like uranium in ESR

Validity check of **QED in extremely strong electromagnetic fields**



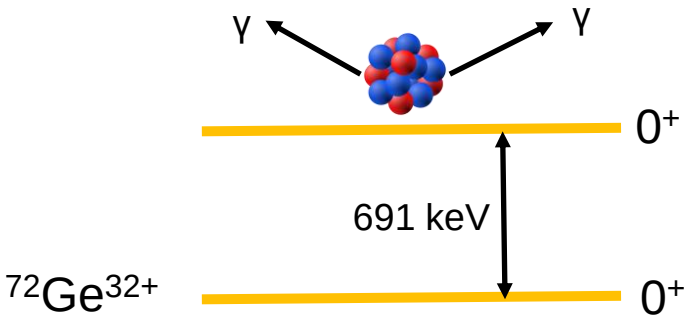


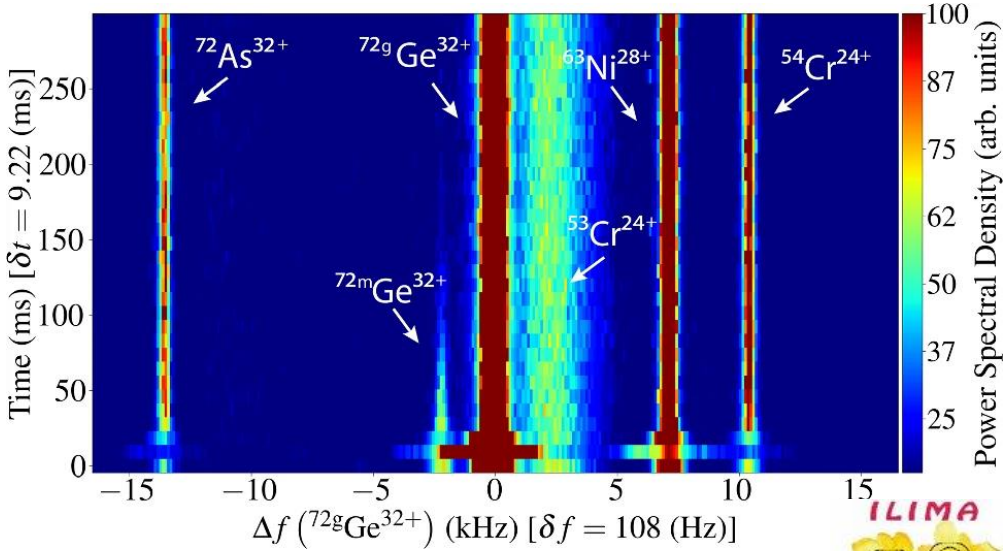
- experimental and theoretical values for the intrashell transitions (*absolute energy* and energy differences between He- and Li-like ions of $1s_{1/2}2p_{3/2}\,J=2 \rightarrow 1s_{1/2}2s_{1/2}\,J=1$).
- result is factor of 6 more precise compared to former study and probes 2nd order radiative corrections.

R. Loetzsch et al. Nature 625, 2024, 673, doi: s41586-023-06910-y

Mass measurements in storage rings

- investigation of isomeric states
- 102 individual injections into ESR
- decay of $^{72m}Ge^{32+}$ is clearly observed

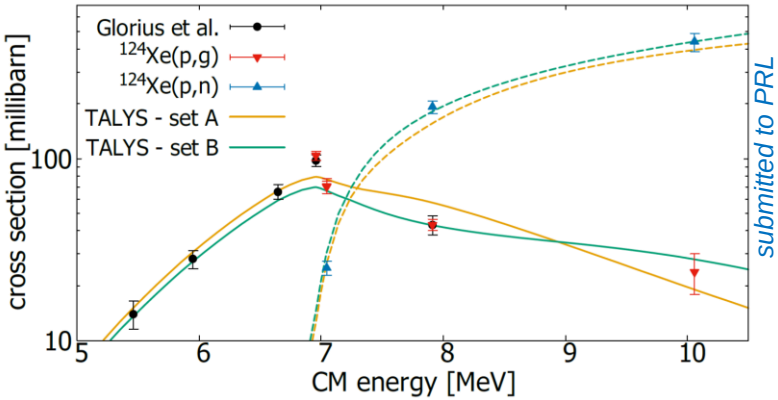


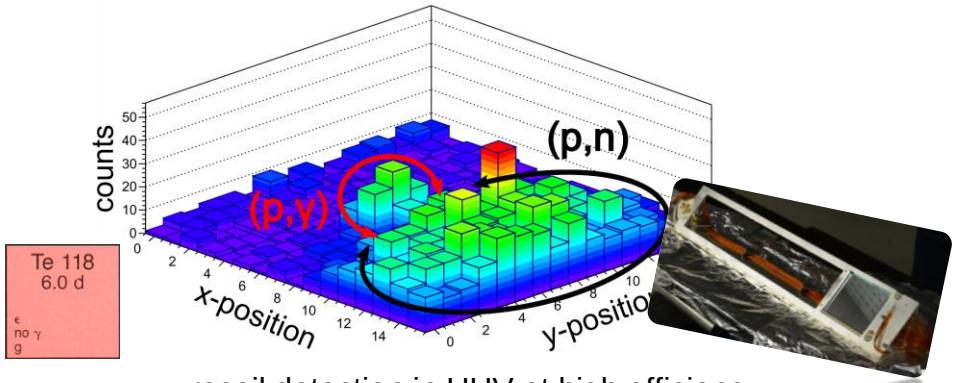


D. Freire-Fernández, W. Korten, R.J. Chen, et al. arXiv:2312.11313

Reaction studies in storage rings

- How did supernovae contribute to the element composition of the solar system?
  - challenging nuclear cross section measurements are needed on radioactive nuclei
  - a new experimental scheme for (p,γ) reactions established in the ESR storage ring
- 1st measurement of ^{124}Xe(p,n)
  - new background-free detection method & maximized sensitivity
  - (p,n) reaction now generally accessible for experiment
  - stronger constraints for underlying nuclear physics models
- 1st radioactive beam measurement
  - reliable data for ^{118}Te(p,γ) and ^{118}Te(p,n)
    - ➢ analysis on-going





recoil detection in UHV at high efficiency

Summary and outlook

Primary and secondary beam capabilities at FAIR opens up a wealth of different physics opportunities

- strong interaction studies in pp and pA reactions
- QCD phase diagram at high densities
- equation of state of neutron-rich matter
- characteristics of exotic nuclei
- astrophysical relevant reactions
- high-precision tests of QED
- materials under extreme conditions

International FAIR community looks forward to continued explotation of the FAIR facilities on the GSI campus and…

Summary and outlook

Primary and secondary beam capabilities at FAIR opens up a wealth of different physics opportunities

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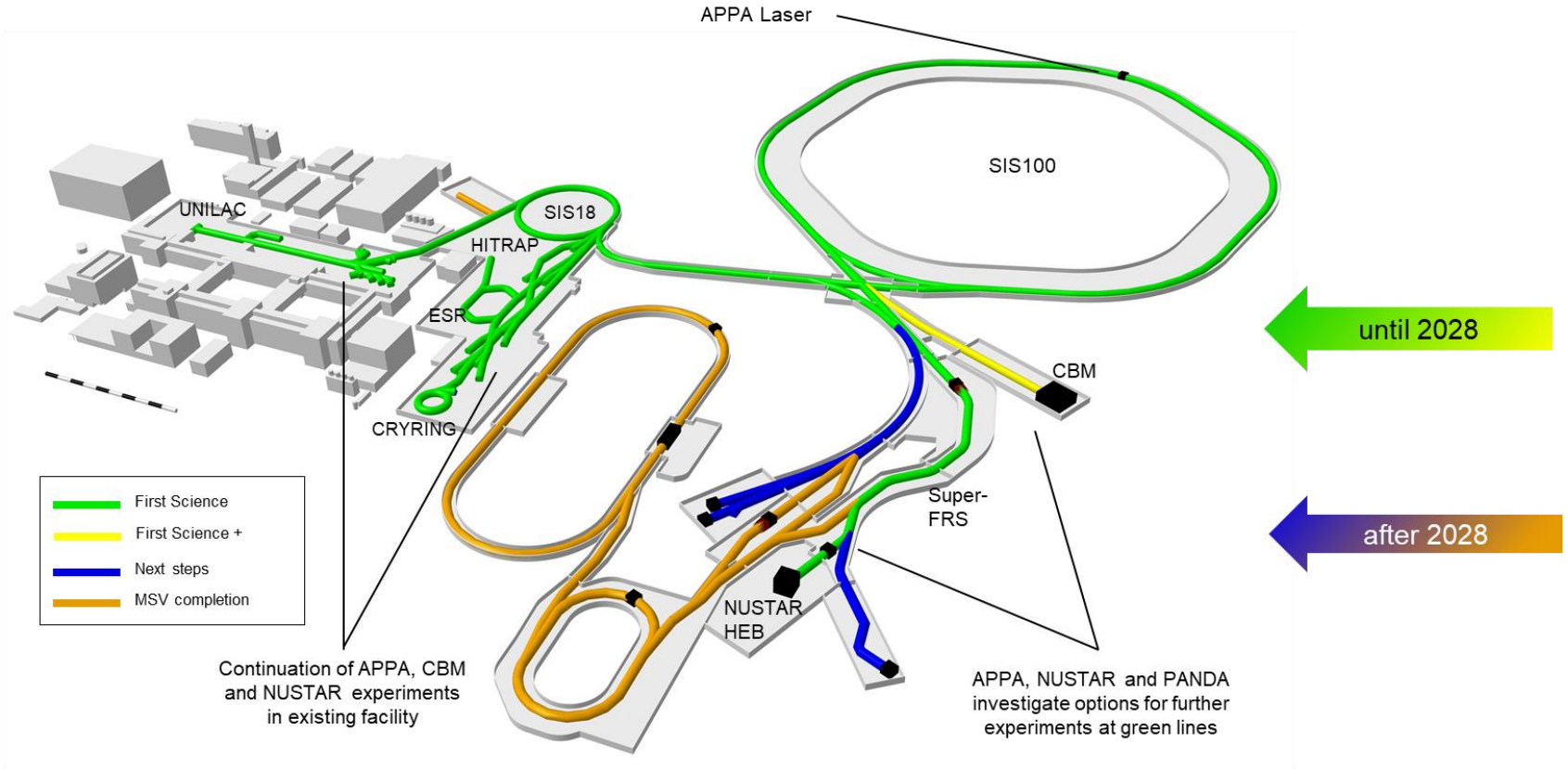
…. looks forward to

2027 Start of experiments at Super-FRS with SIS18 beams

2028 Start of experiments with SIS100

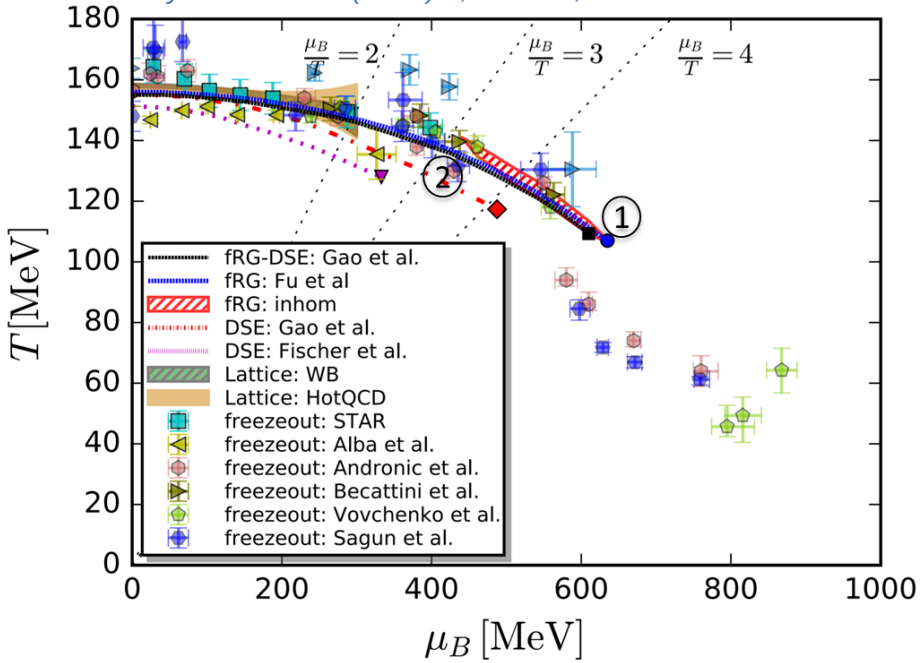
Current prospects



CBM – Scientific goal

Location of chiral cross over

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



Strange and charmed particle production thresholds in pp - collisions

reaction	$\sqrt{s}$ (GeV)	T_{lab} (GeV)
$pp \to K^+\Lambda p$	2.548	1.6
$pp \to K^+K^-pp$	2.864	2.5
$pp \to K^+K^+\Xi^-p$	3.247	3.7
$pp \to K^+K^+K^+\Omega^-n$	4.092	7.0
$pp \to \Lambda\bar{\Lambda}pp$	4.108	7.1
$pp \to \Xi^-\bar{\Xi}^+pp$	4.520	9.0
$pp \to \Omega^-\bar{\Omega}^+pp$	5.222	12.7
$pp \to J/\Psi\, pp$	4.973	12.2