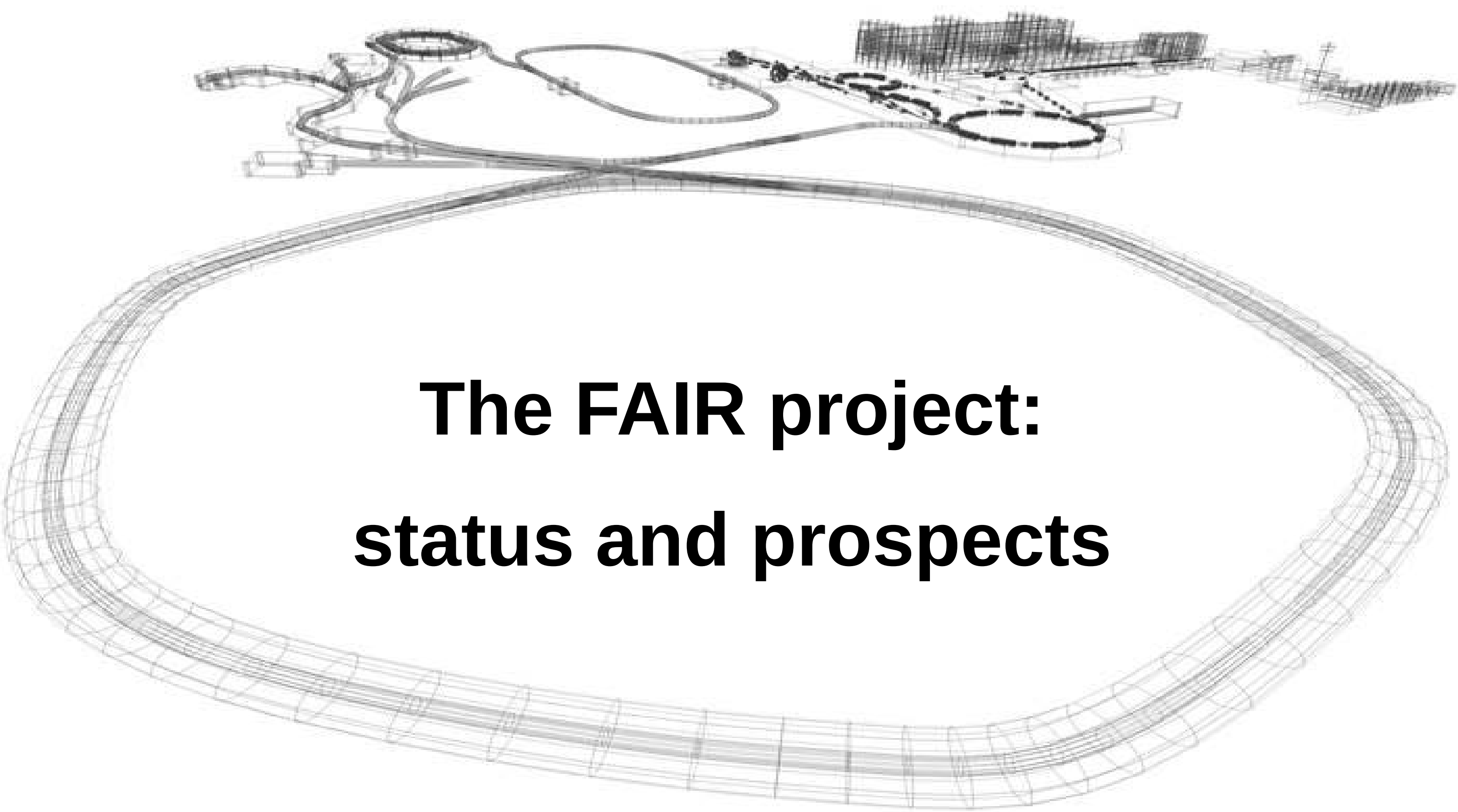
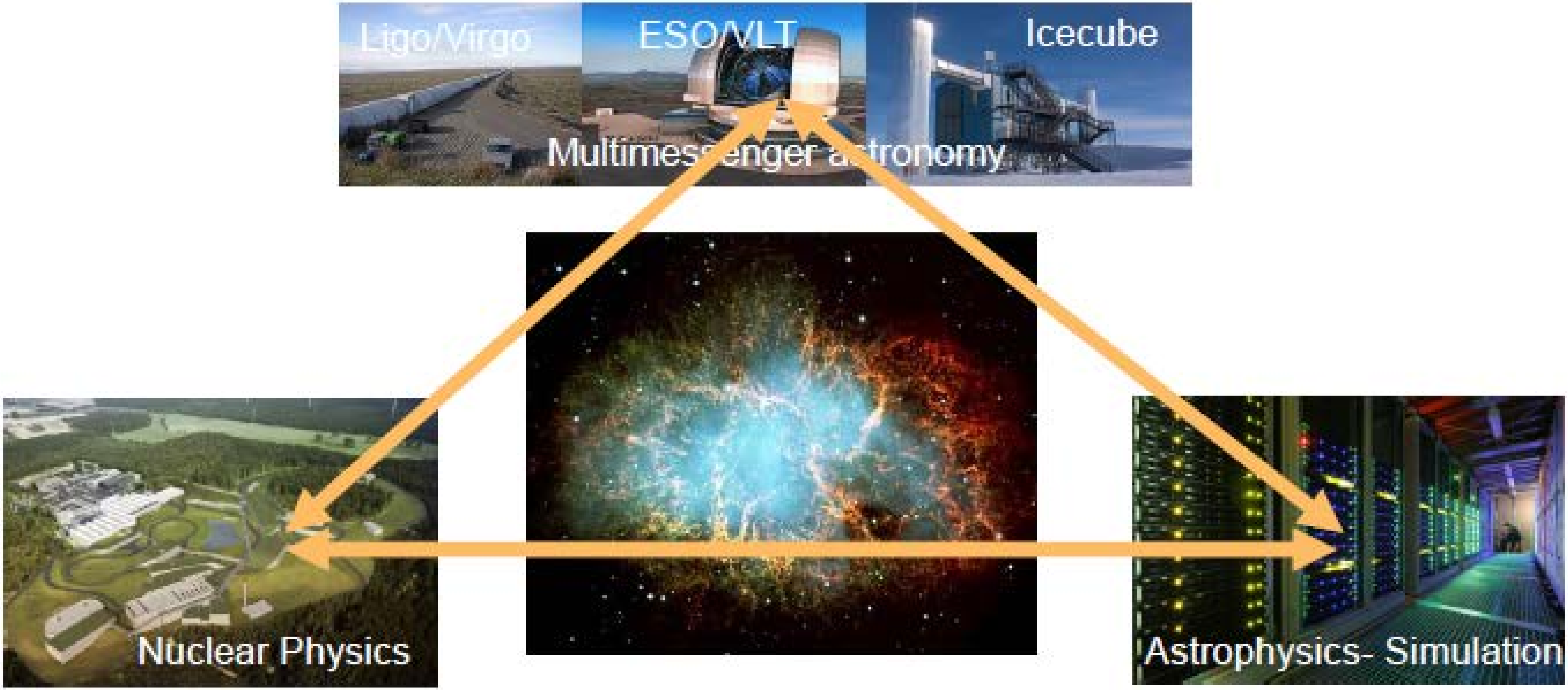


The FAIR project:
status and prospects

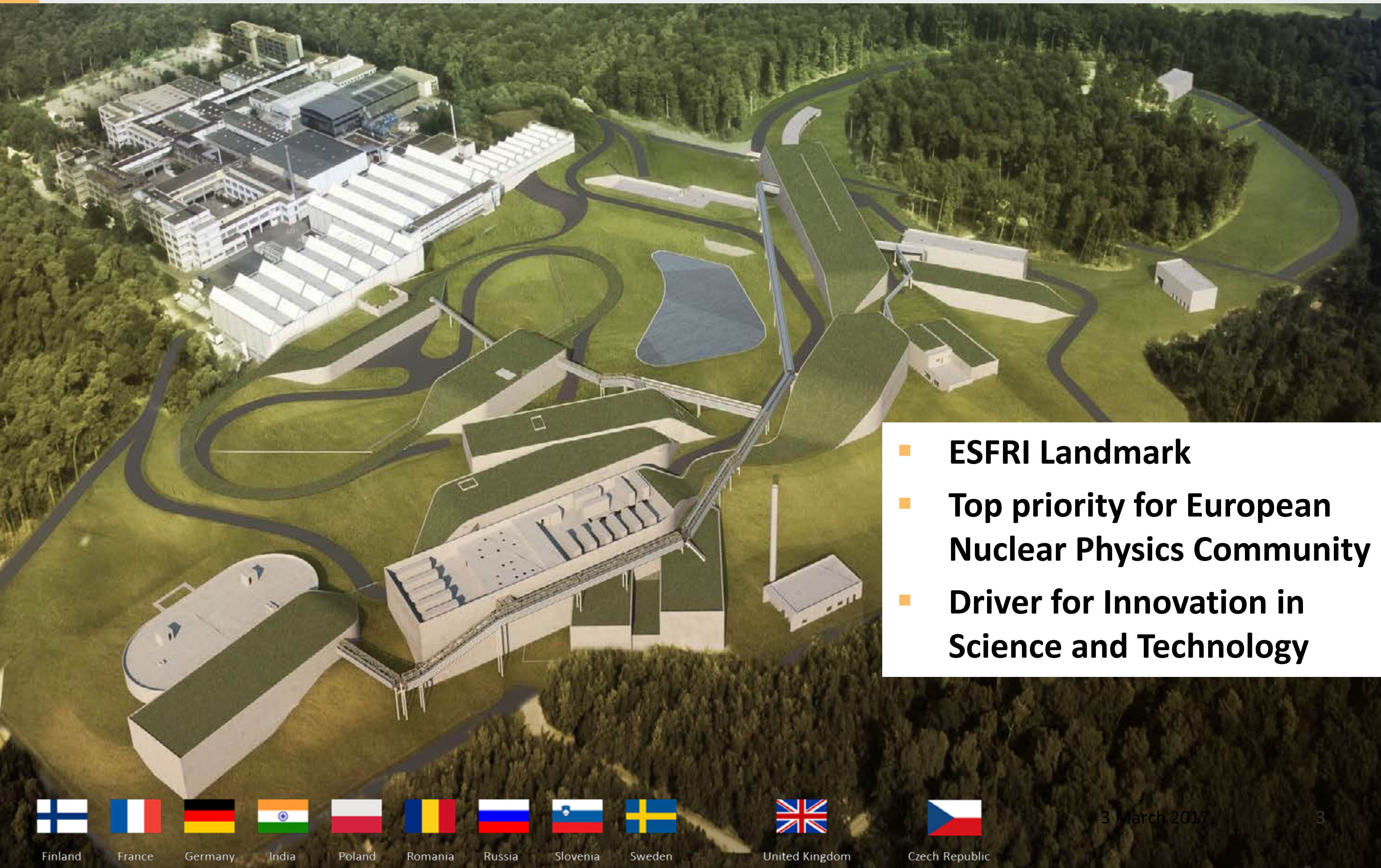
Paolo Giubellino

ATHIC2021, 5–9 Nov 2021, Inha Univ. Incheon, South Korea

On the trail of the secrets of the universe



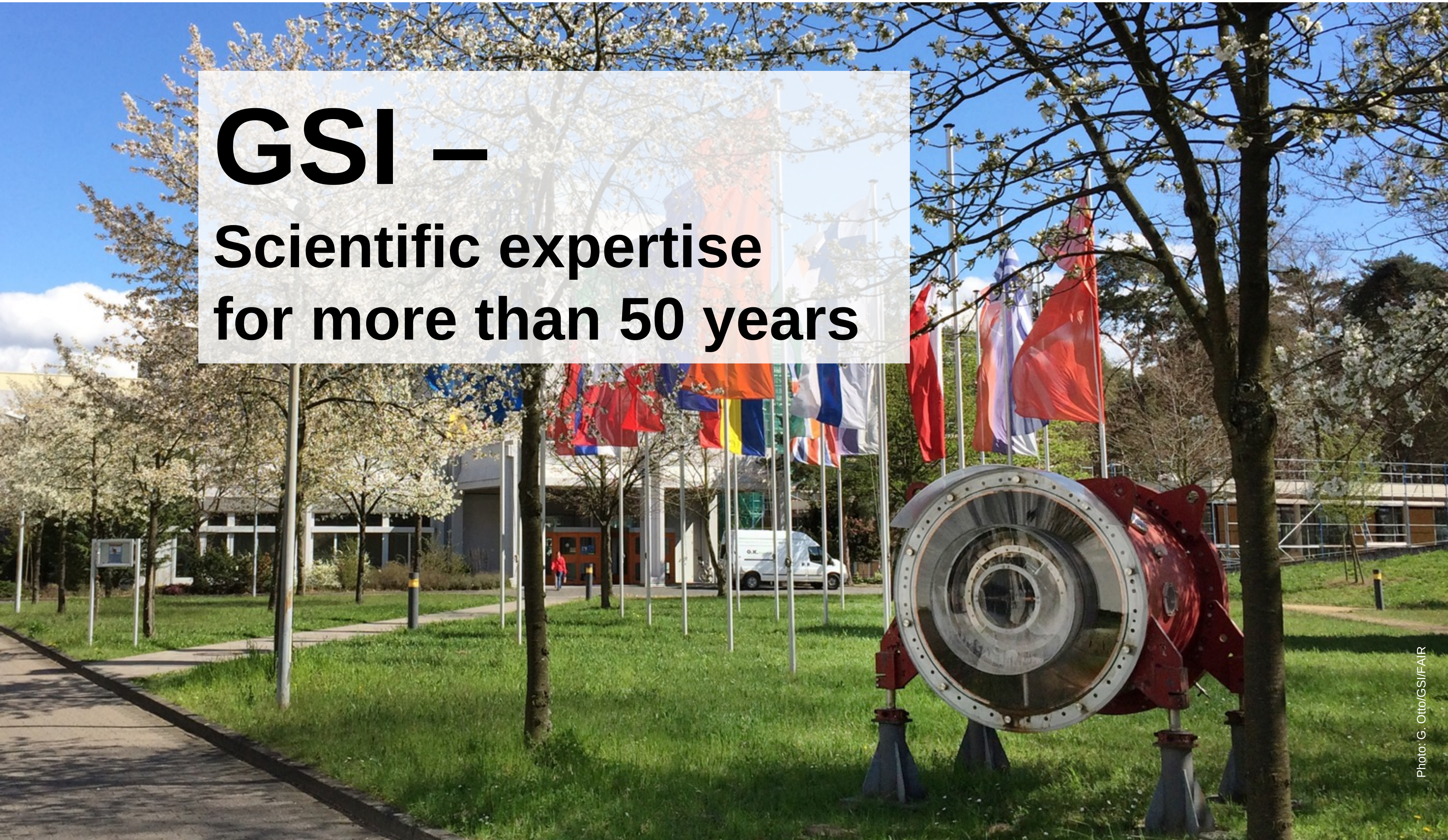
FAIR: Facility for Antiproton and Ion Research



- **ESFRI Landmark**
- **Top priority for European Nuclear Physics Community**
- **Driver for Innovation in Science and Technology**

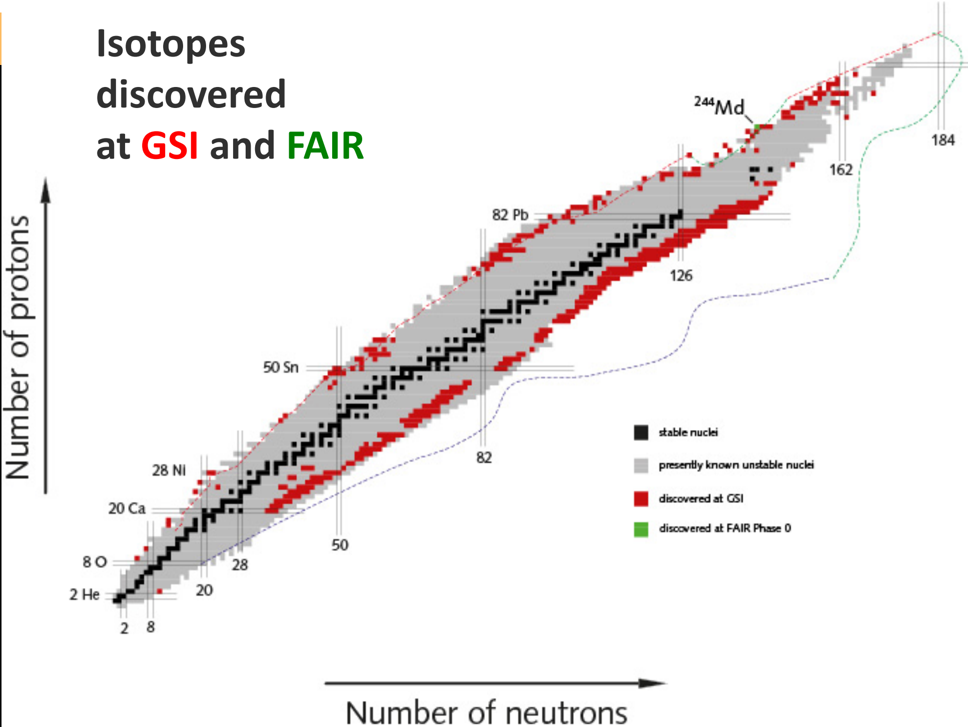
GSI –

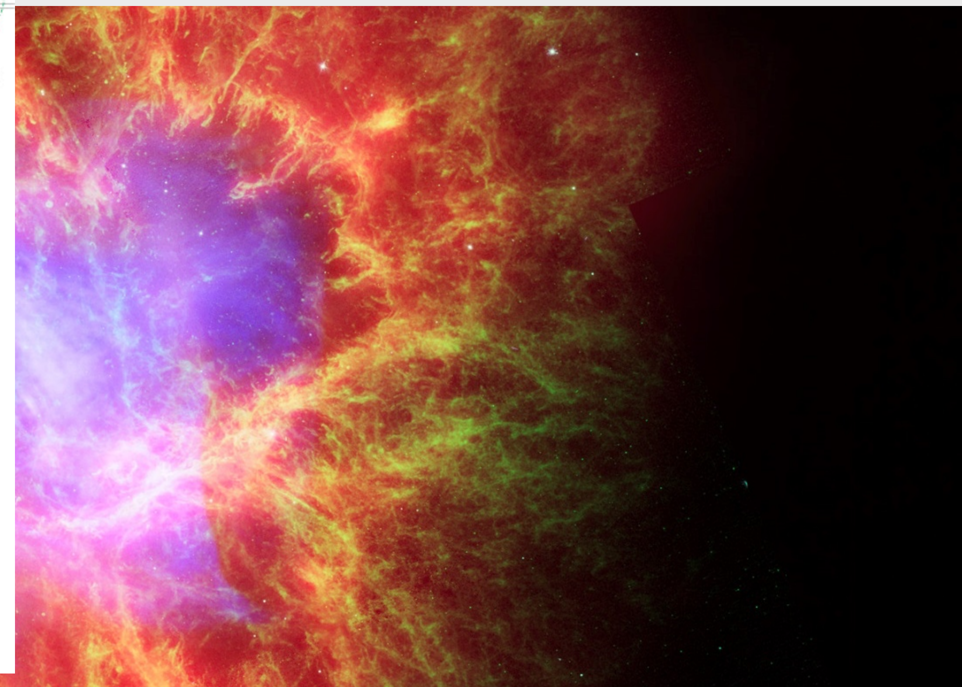
Scientific expertise for more than 50 years

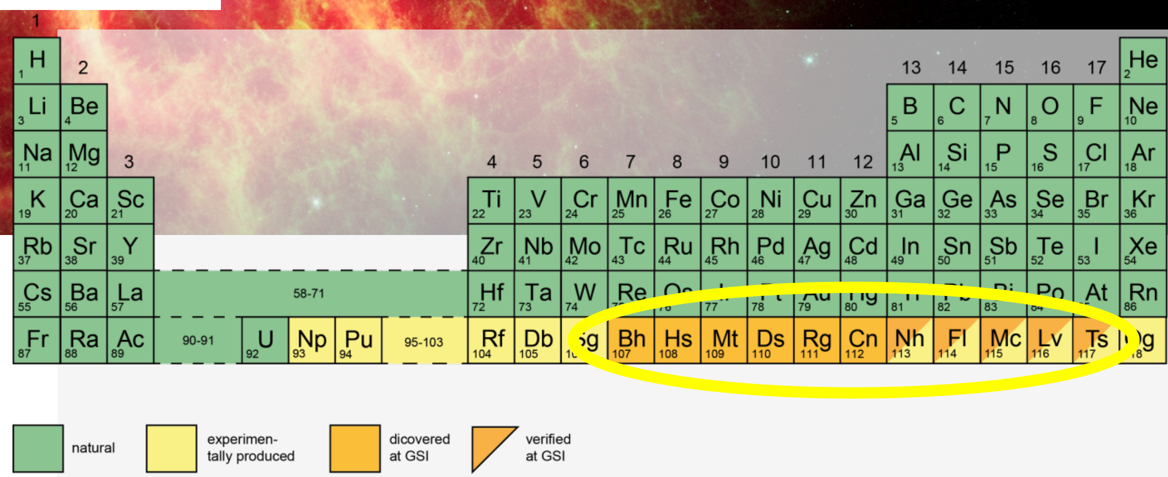


GSI Discoveries

Isotopes discovered at GSI and FAIR



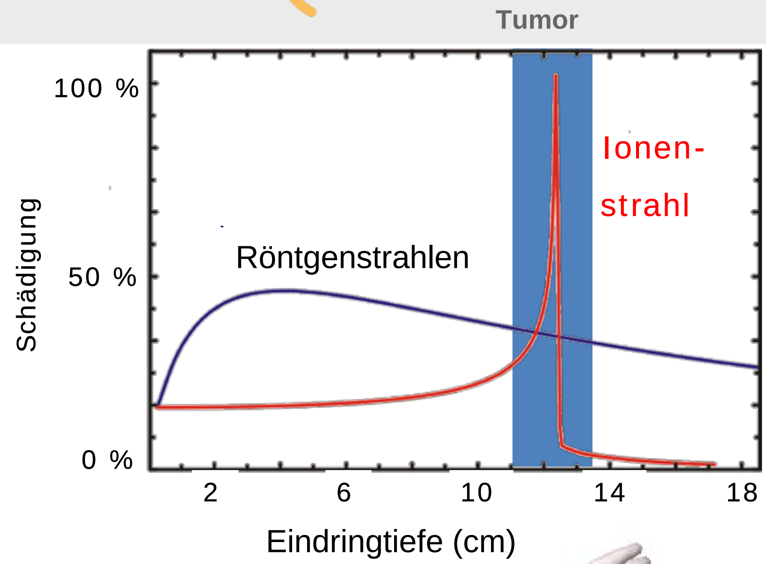


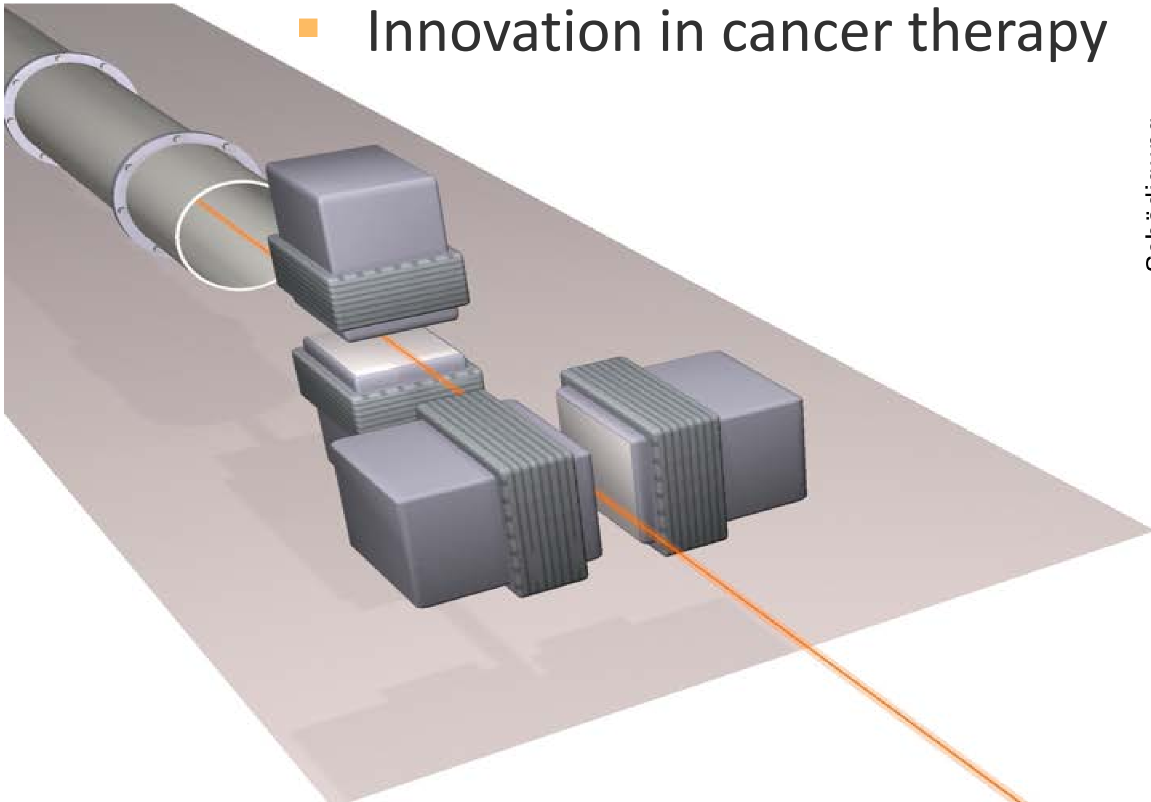


- New chemical elements
- Hundreds of new isotopes
- New decay modes

GSI Discoveries

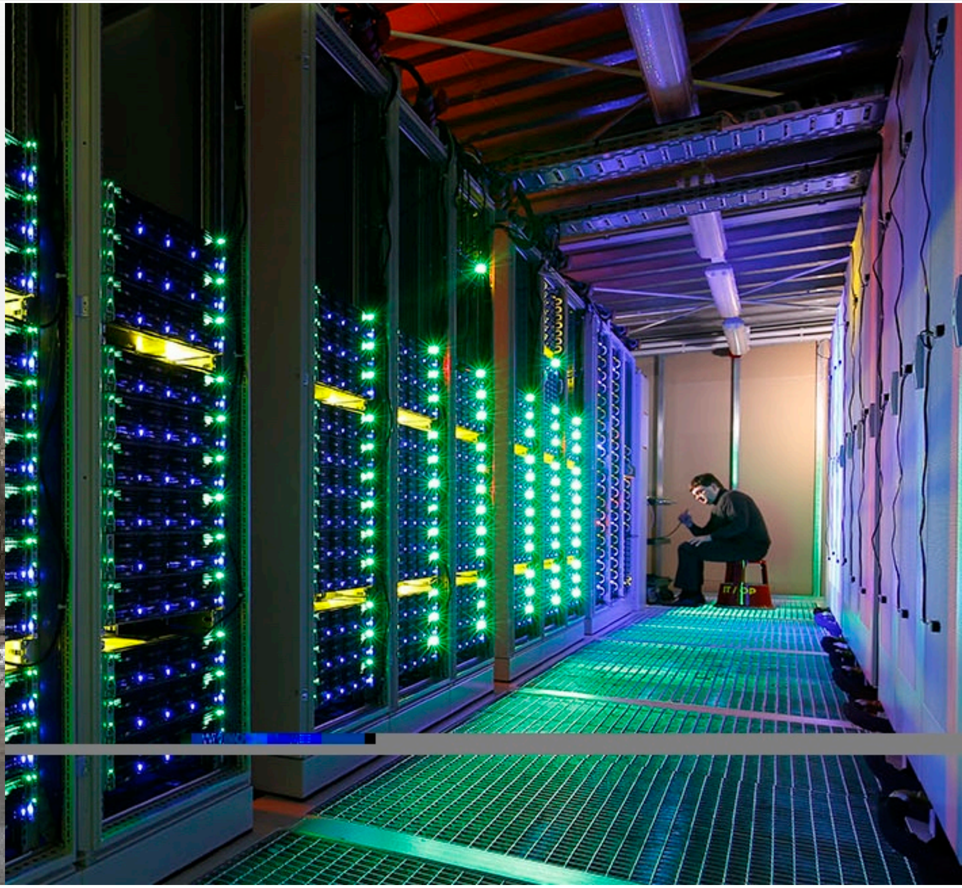
- Innovation in cancer therapy





- precise like a scalpel
- extremely efficient in destroying the tumor cells
- spares the healthy tissue

Forefront Technologies



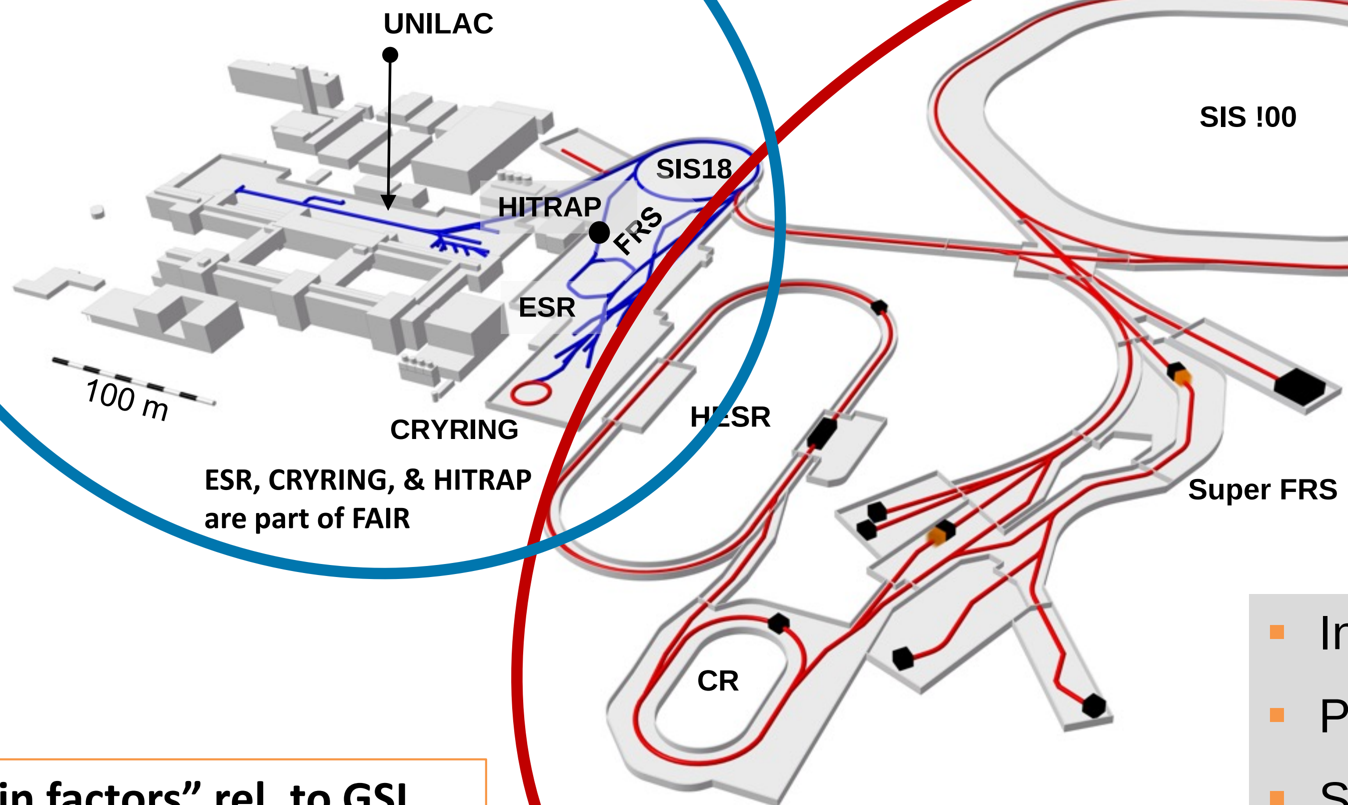
- Technological advancements in high-performance & scientific computing, Big Data, Green IT

A Talent Factory

- A unique capability to attract and create talent and know-how.
- Training and education of the next generation of scientists, engineers and computing experts from all over the world:
  - Graduate Schools with currently more than 300 doctoral students from all over the world
  - International Postdoc Programs
  - Multiple training programs for students
  - Bilateral Agreements with several countries for training and education of young scientists and engineers

GSI and FAIR – The Facility

GSI, existing (upgraded to integrate with FAIR)



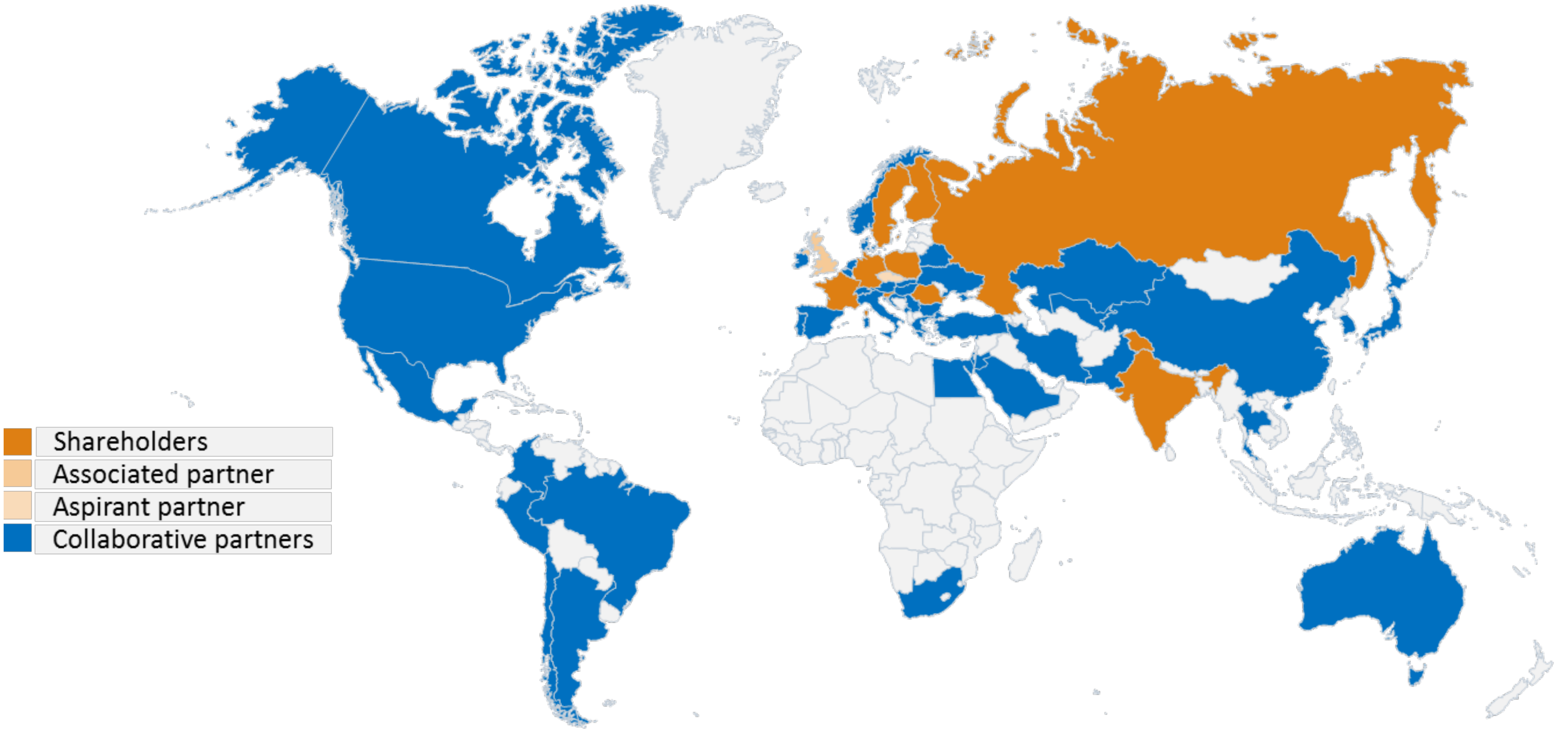
ESR, CRYRING, & HITRAP are part of FAIR

FAIR, under construction

- Intensity
- Precision
- Storage rings

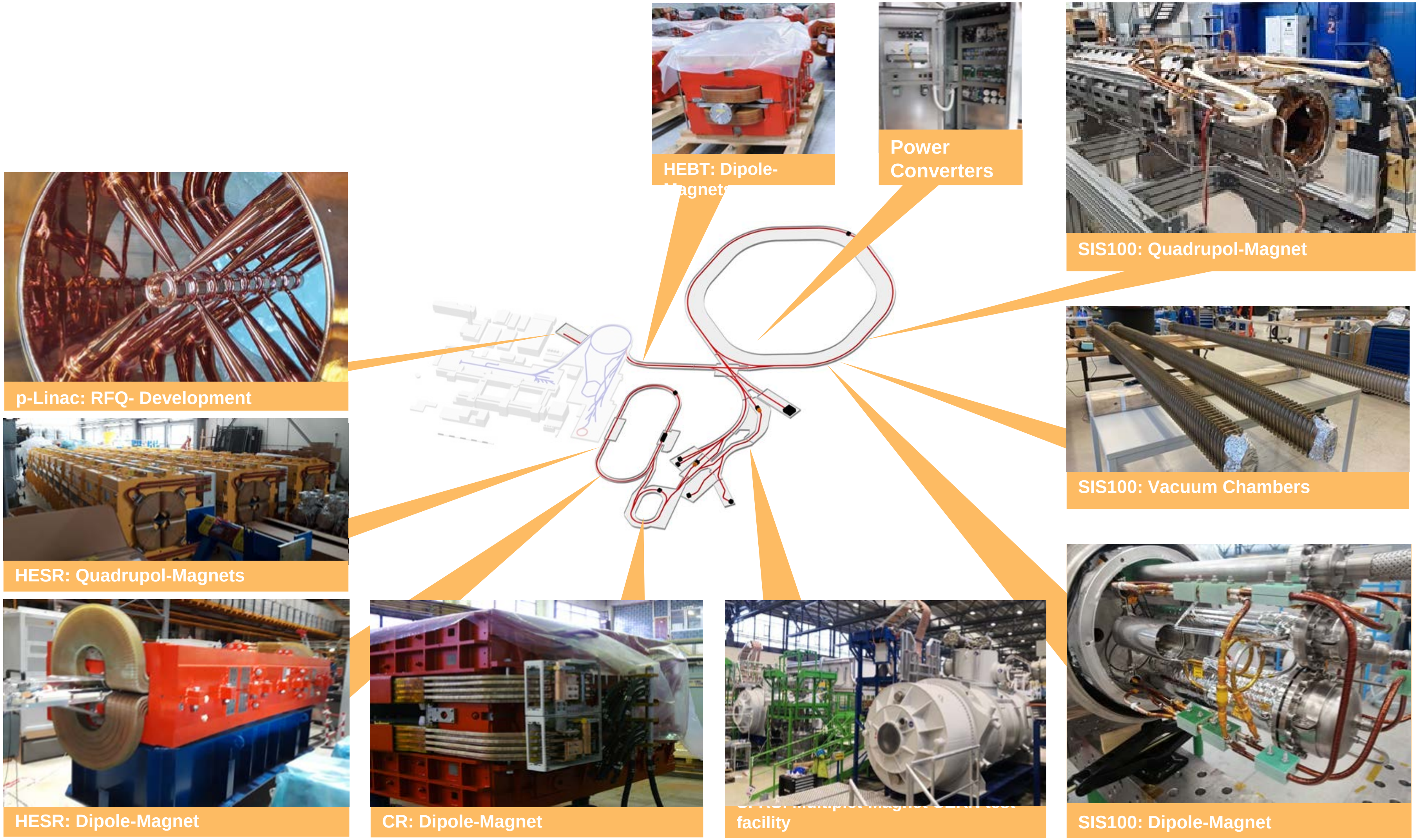
FAIR "Gain factors" rel. to GSI
- 100 – 10.000 x intensity
- 10 x energy
- antiproton beams

FAIR: International Cooperation



- **9 international FAIR Shareholders**
- 1 Associated Partner (United Kingdom)
- 1 Aspirant Partner Czech Republic (Since 2018)
- Participation of **3.000 scientists from all continents**

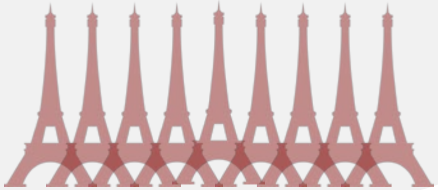
FAIR facility - worldwide production and delivery of accelerator components and



Construction Dimensions

2 Mio. m^3	600.000 m^3	65.000 t
Ground	**Concrete**	**Steel**
will be moved	will be installed	will be deployed

Status as of Oct. 2021 : more than 50 % executed

Correspond to 5,000 single-family houses	Correspond to 8-times the football stadium of Frankfurt	Correspond to 9 Eiffel Towers
		

FAIR Construction, 2021

Civil construction progressing well, concrete works of underground ringtunnel completed in May 2021.

Manufacturing of accelerator and experiment components by all partner countries ongoing worldwide.

Many accelerator and experiment components are delivered and tested ready for installation

FAIR in construction

FAIR in construction

FAIR in construction

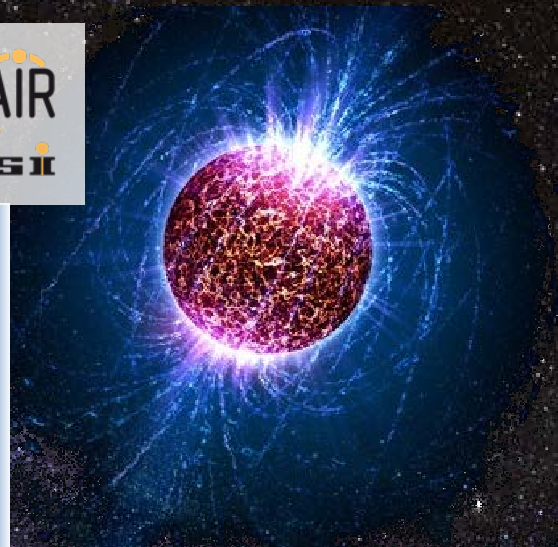
FAIR in construction

Foto: NASA, ESA, G. Dubner (IAFE, CONICET-University of Buenos Aires) et al.; A. Loll et al.; T. Temim et al.; F. Seward et al.; VLA/NRAO/AUI/NSF; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; and Hubble/STScI (oben), Penn State University (unten)

Creating extreme conditions existing in the universe with heavy ion accelerators

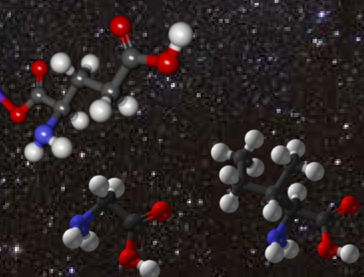
To find answers to fundamental questions about the Universe :
The Universe in the lab ...

Where are heavy elements created?



What is in the interior of a neutron star?

What happens to human cells on the way to Mars?

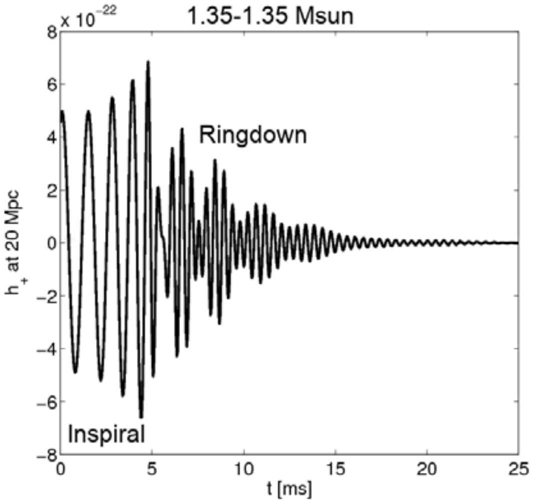


How are complex molecules created?

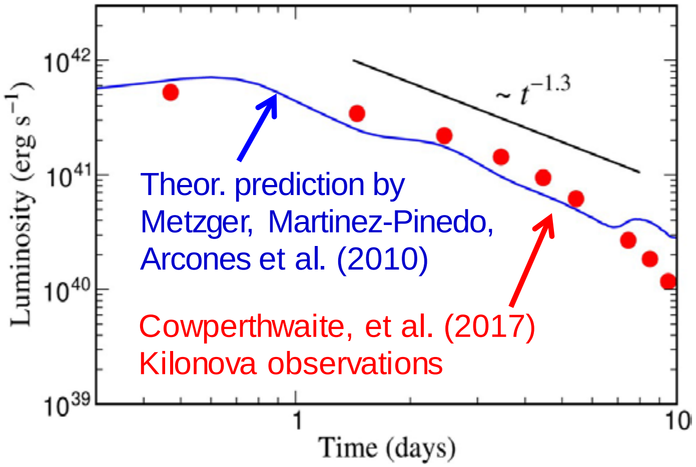
How do materials behave under high pressure?

Fotos: Uranus, Jupiter, Erde Quelle: http://de.wikipedia.org

Neutron star mergers and their role for the production of heavy elements ....



Gravitational wave signal



Elektromagnetic “Kilonova”-Signal

Electromagnetic afterglow - "Kilonova-lightcurve" - reveals that heavy elements, e.g. Au and Pt, were produced (r-process), as predicted by GSI theorists.

Neutron Stars and Mergers vs HI collisions

Neutron stars

Temperature
T < 10 MeV

Density
$\rho < 10\ \rho_0$

Lifetime
T ~ infinity

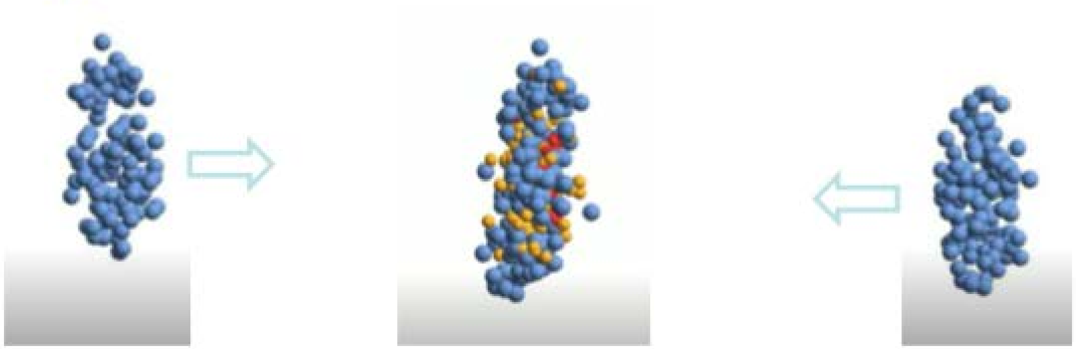
Neutron star merger

Temperature
T < 50 MeV

Density
$\rho < 2 - 6\ \rho_0$

Reaction time
(GW170817)
T ~ 10 ms

Heavy ion collisions at SIS100



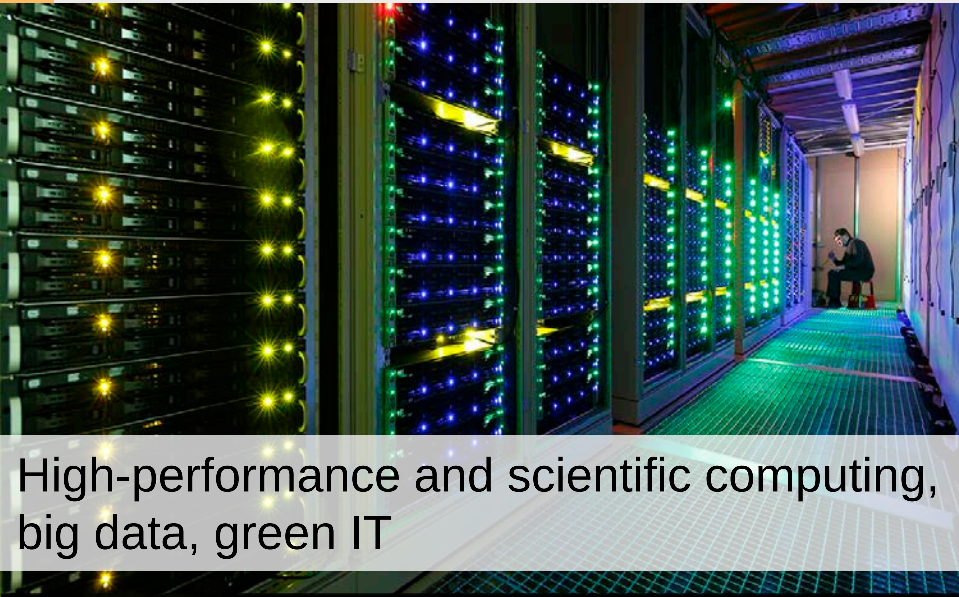
Compressed Baryonic Matter

Temperature
T < 120 MeV

Density
$\rho < 8\rho_0$

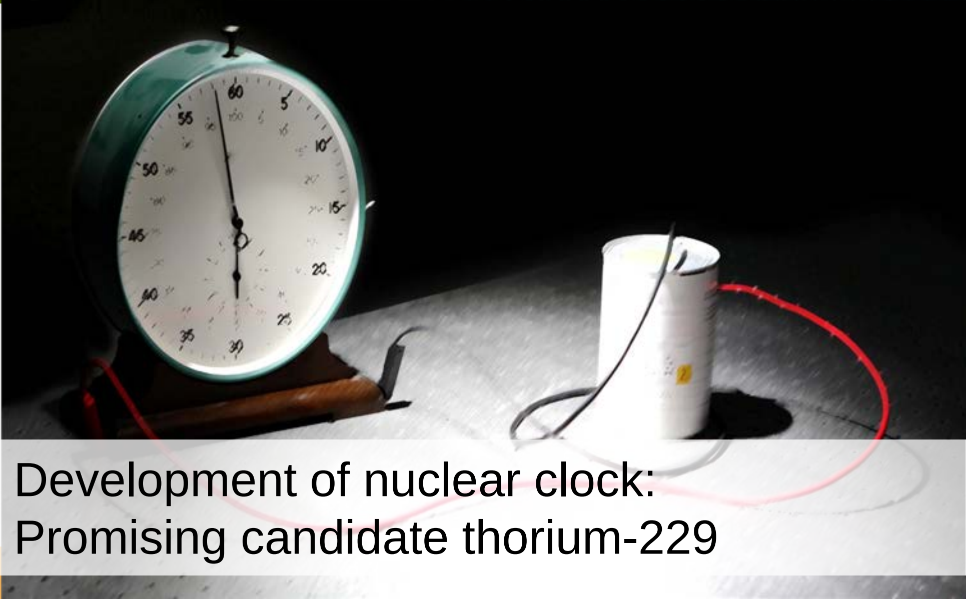
Reaction time
$t \sim 10^{-23}$ s

… with direct applications

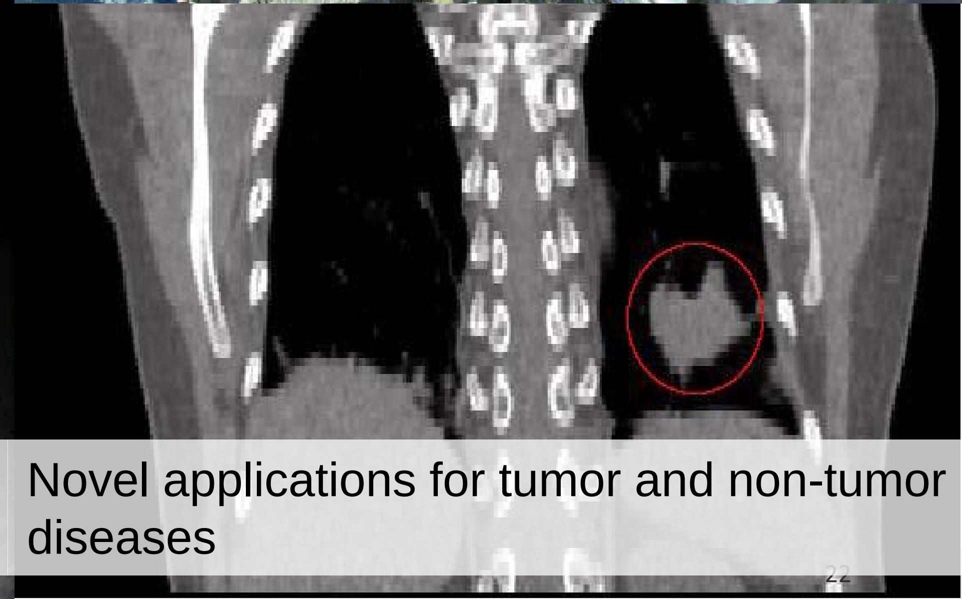


High-performance and scientific computing, big data, green IT

Space radiation protection, unique facility for simulation, collaboration with ESA

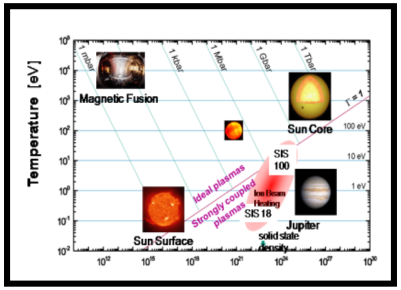


Development of nuclear clock: Promising candidate thorium-229



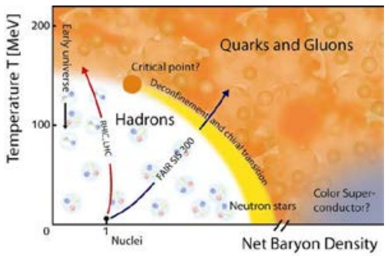
Novel applications for tumor and non-tumor diseases

The FAIR science: four pillars



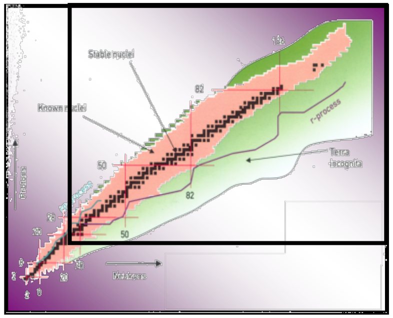
atomic physics, biophysics, plasma physics, material research

APPA



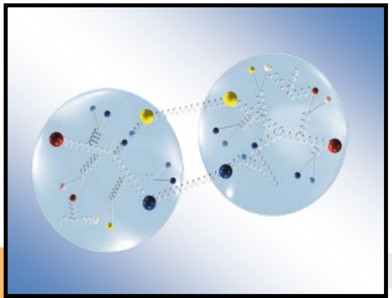
nuclear- and quark-matter

CBM



nuclear structure and nuclear astrophysics

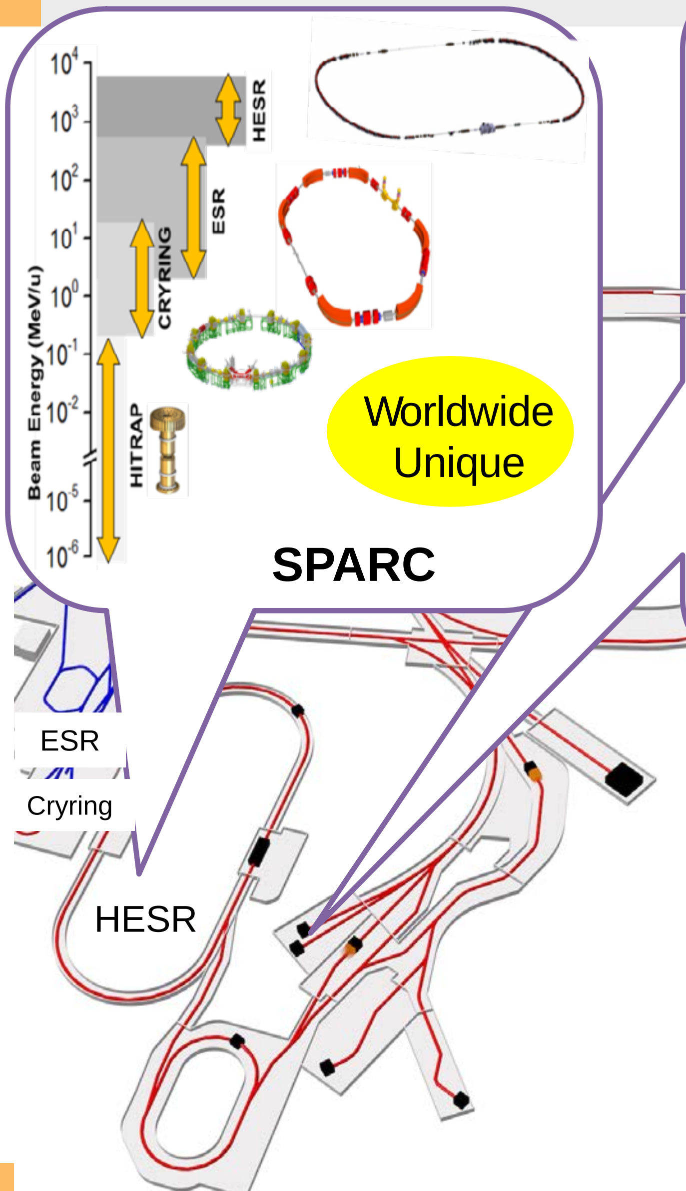
NuSTAR

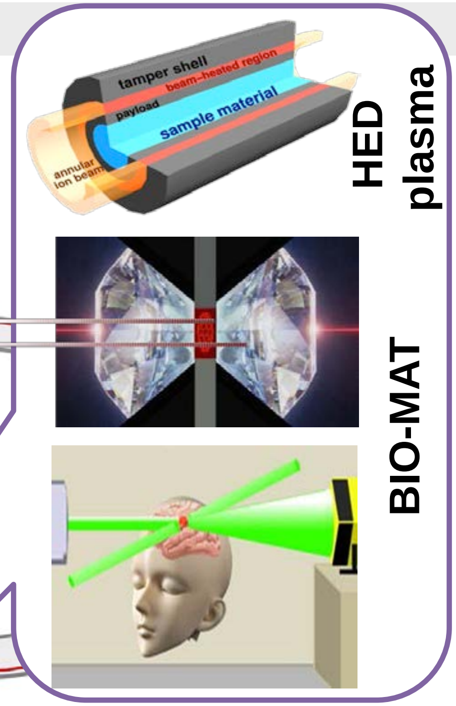


hadron structure and dynamics

PANDA

APPA





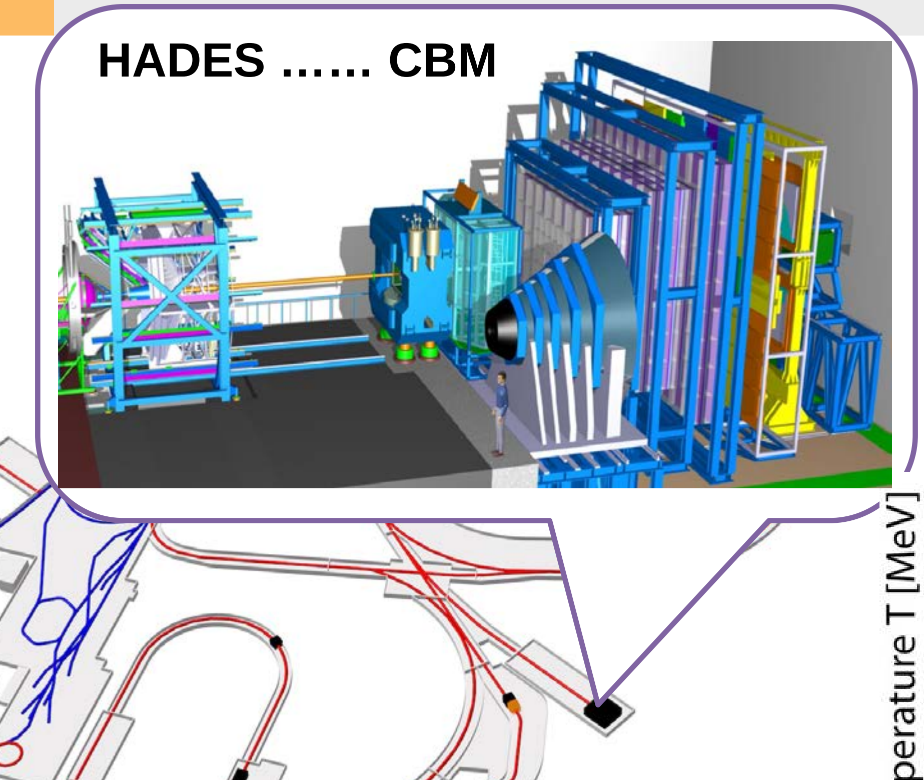
- Atomic, Plasma Physics and Applications
  - About 800 members
  - Wide field of science
    - basic research into material, biological and medical applications and space research

Atomic Physics
SPARC: ~400 members from 26 countries

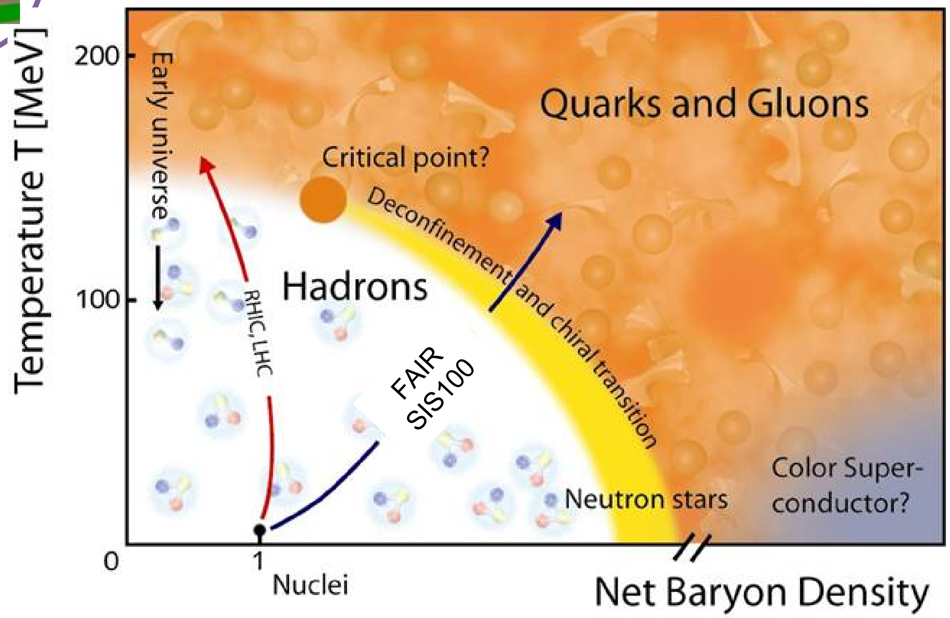
Plasma Physics
HED: ~300 members from 16 countries

Materials Research and Biophysics
BIOMAT: ~100 members from 12 countries

C.B.M.

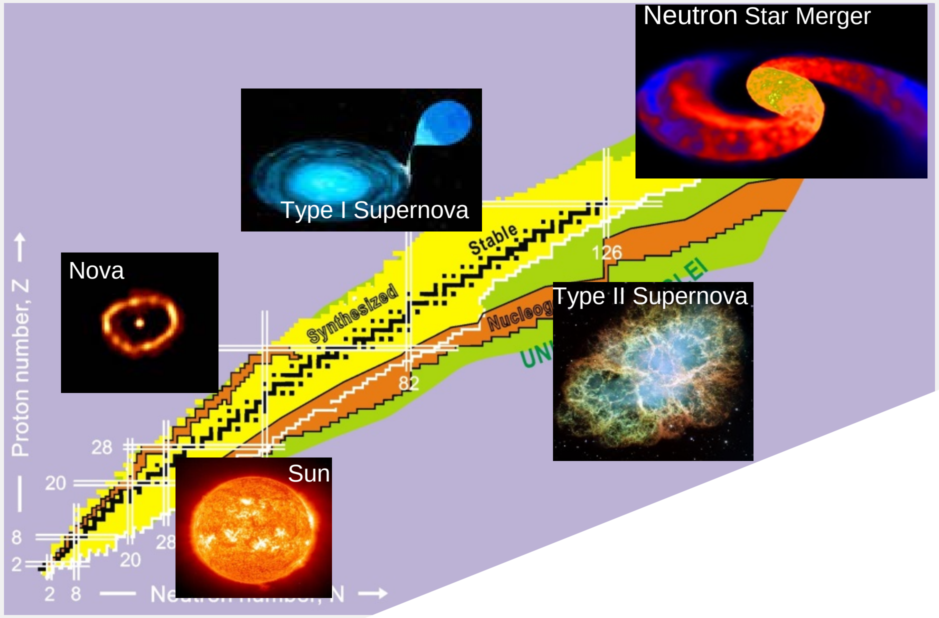


- Compressed Baryonic Matter Experiments
  - About 400 members



NUSTAR
- Origin of Elements in the Universe

„Nucleosynthesis sites“ in the universe

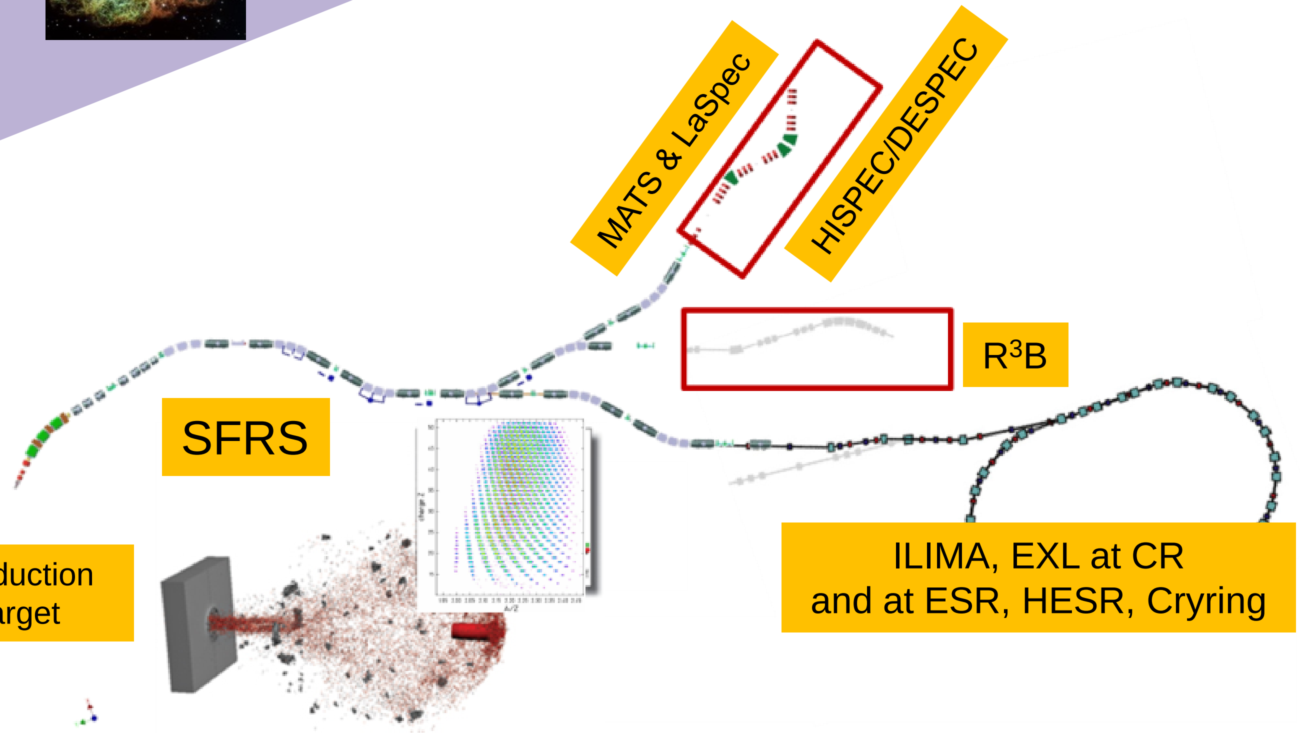


„Nucleosynthesis sites” at FAIR

Primary intensities vs. GSI: x 100

SIS 100

production target

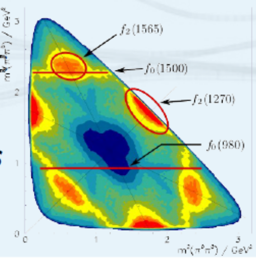


PANDA - AntiProton Annihilation at Darmstadt

Bound States of Strong Interaction

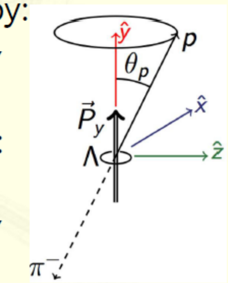
Spectroscopy

- New narrow XYZ: *Search for partner states*
- Production of exotic *QCD states: Glueballs & hybrids*



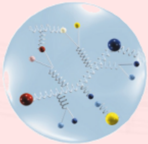
Strangeness

- Hyperon spectroscopy: *excited states largely unknown*
- Hyperon polarisation: *accessible by weak, parity violating decay*



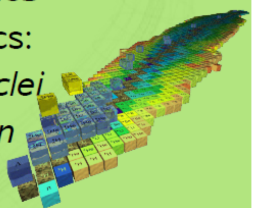
Nucleon Structure

- Generalized parton distributions: *Orbital angular momentum*
- Drell Yan: *Transverse structure, valence anti-quarks*
- Time-like form factors: *Low and high E, e and μ pairs*



Nuclear Hadron Physics

- Hypernuclear physics:
  - Double Λ hypernuclei
  - Hyperon interaction
- Hadrons in nuclei: *Charm and strangeness in the medium*



NUPECC Long Range Plan

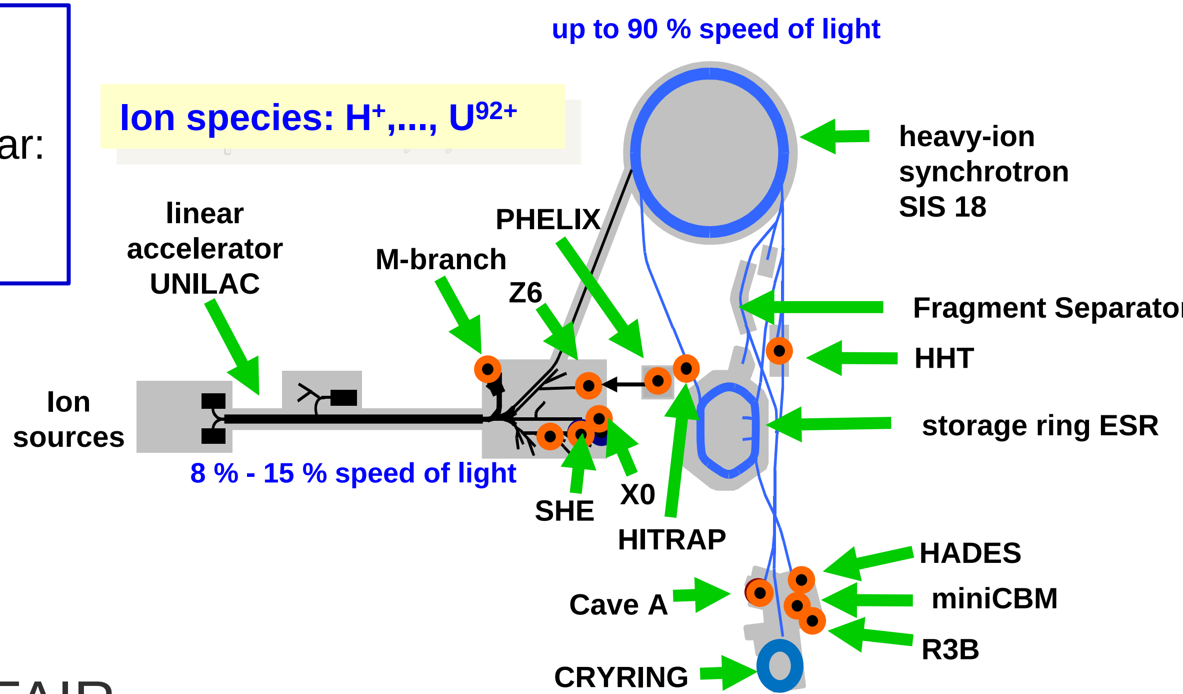
The combination of PANDA's discovery potential for new states, coupled with the ability to perform high-precision systematic measurements is not realised at any other facility or experiment in the world.

Schedule for FAIR Science

- While working towards start of FAIR, ***staged approach to FAIR science and progressive commissioning of accelerators and detectors***:
  - FAIR phase 0 : started in 2019, to continue with annual runs till start of FAIR
  - Until 2024 a block of 3 months beamtime per year. The scheme for 2025/2026 will be developed depending on commissioning progress, to ensure that the activities will be compatible
  - Installation of infrastructure items of the experiments in the new experimental halls, DURING the installation of technical infrastructure, 1 or 2 years before final delivery of the completed buildings
  - FAIR day 1 configurations/ phase 1 experiments with FAIR accelerators progressively approaching design parameters
  - Full FAIR operation

Early science program FAIR Phase-0

- Since 2019, annual runs of < ~110 days until FAIR operation
- Supported by FAIR partners, so far: Finland, France, Germany, Romania, Sweden and the UK



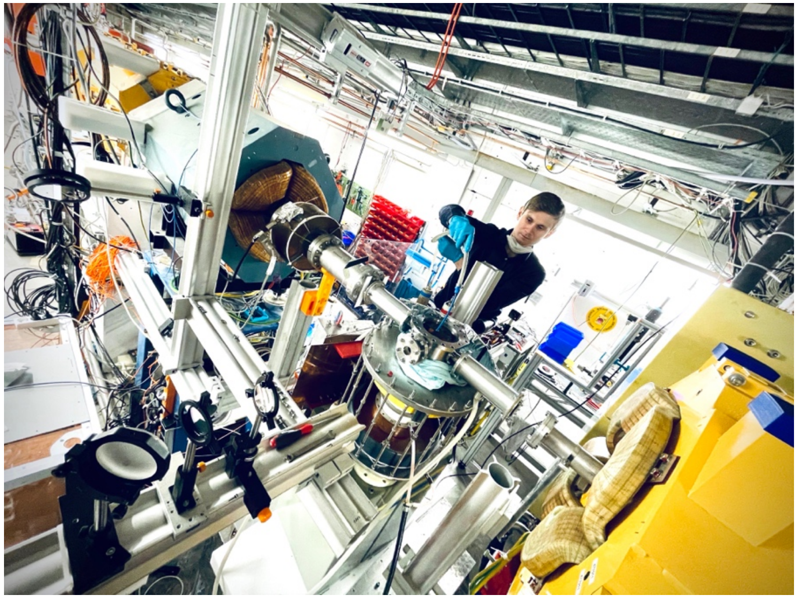
Science while realizing FAIR

- strong response by scientific community, over 1 thousand scientists involved, demand largely exceeding the available beamtime, confirming the attractiveness of the experimental opportunities
- 1/3 of the 2020 experiments could not be performed, mostly because of Covid-19, and are being performed in 2021/22
- the 2021 beamtime has been performed as planned

Example: PRIOR II, Proton Microscope

- Proton radiography
- Upgrade with new PRIOR magnets complete
- Commissioning in February 2021
- Achieved resolutions
  - spatial 20 µm
  - in time 10 ns

PRIOR-I (2014) PRIOR-II (2021)

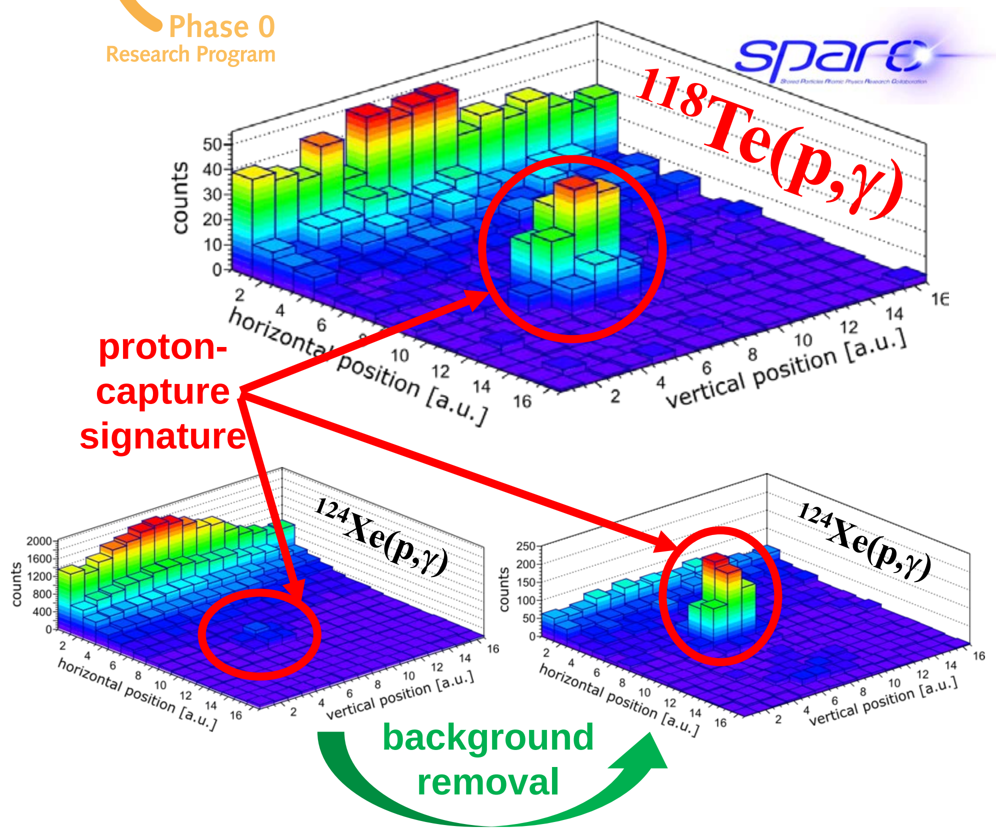


FAIR Phase 0 Research Program

Ground-breaking experiment opening way for nuclear astrophysics experiments at FAIR with ESR

Phase 0
Research Program

- E127: Proton-capture rates for nuclear astrophysics:
  First reaction study on stored radio-beam at low energies
- Study of radioactive ^{118}Te (6 days half-life)
  - production, storage, accumulation and deceleration in FRS-ESR
  - proton-capture measurements realized at 7 MeV/u and 6 MeV/u
- New background-free detection method demonstrated



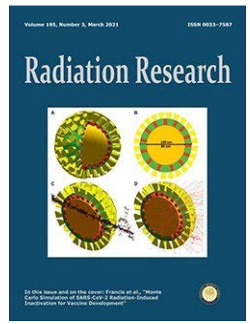
Jan Glorius et al.

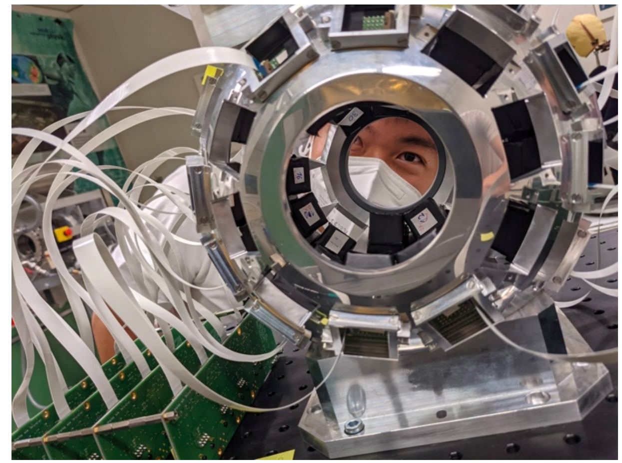
SPONSORED BY THE
Federal Ministry of Education and Research

Biophysics FAIR Phase-results examples

FLASH – new method for ultrafast, high dose treatment of cancer with carbon ion beams

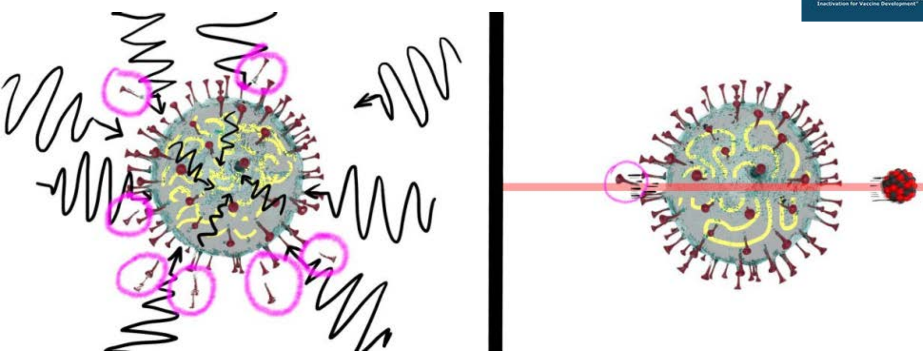
FAIR Phase 0 Research Program





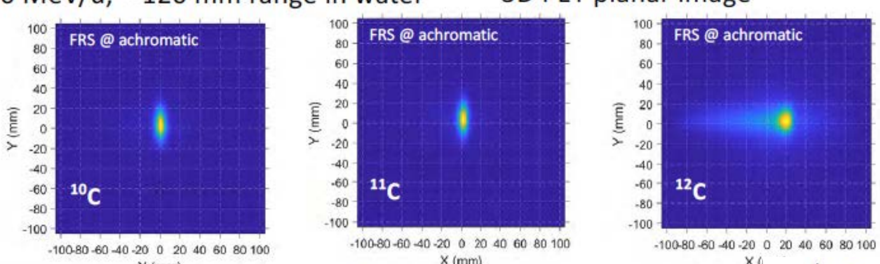
Hybrid γ-PET detectors for RIB

BARB (ERC Grant) – Cancer Therapy with radioactive isotopes for simultaneous treatment and PET



Research on COVID-19 vaccines production with heavy ion beams in cooperation with HZI-Braunschweig

~270 MeV/u, ~120 mm range in water   3D PET planar image



www.gsi.de/BARB

Latest news: Combination of heavy ion beam therapy with mRNA-Vaccine in cancer therapy (Cooperation with TRON)

FAIR Phase-0 results on Material Science, example

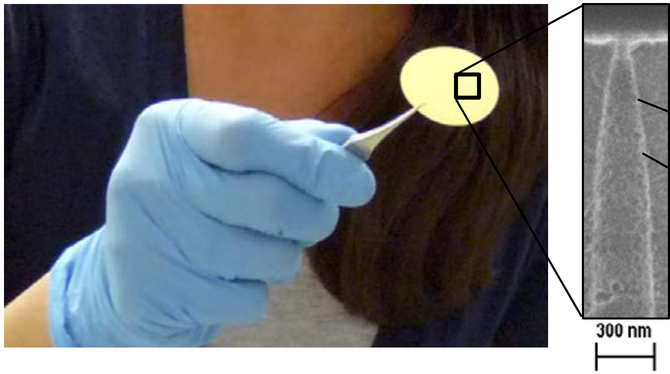
- New sensor for SARS-CoV-2 and other viruses based on GSI/FAIR nanotechnology
  - better and faster virus detection with single nanopore membranes
  - detection of SARS-CoV-2 in saliva, serum or wastewater without sample pretreatment
  - same sensitivity as a qPCR test, result in 2 hours
  - sensor distinguishes infectious from non-infectious corona viruses

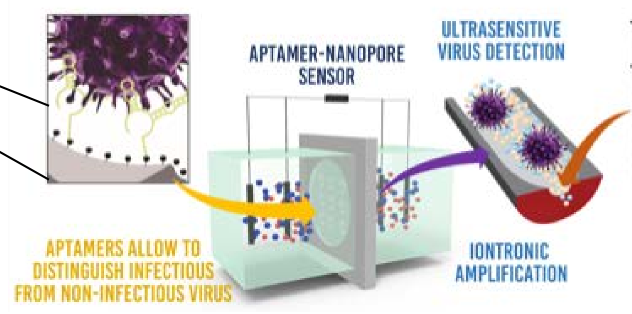
FAIR Phase 0 Research Program

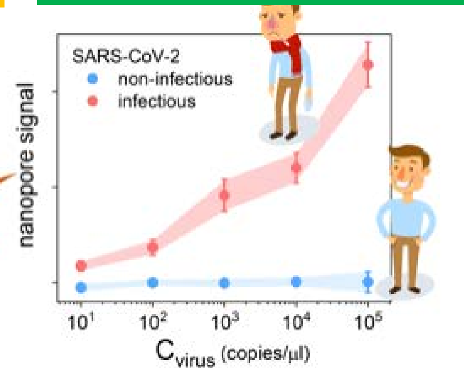
Highly sensitive nanopore by Ion-track nanotechnology

High selectivity by coating nanopore with selective aptamers that bind specific virus (tested with SARS-CoV-2 and adenovirus)

Transport measurements through coated nanopore indicate infectious state of tested virus

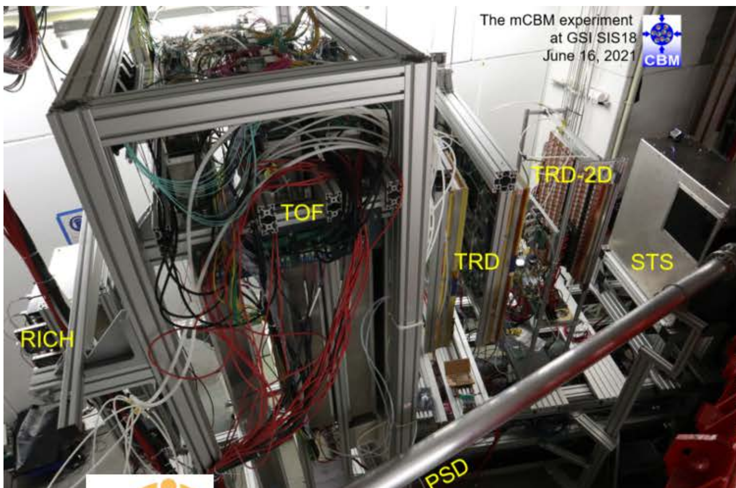






CBM in Phase-0: mCBM

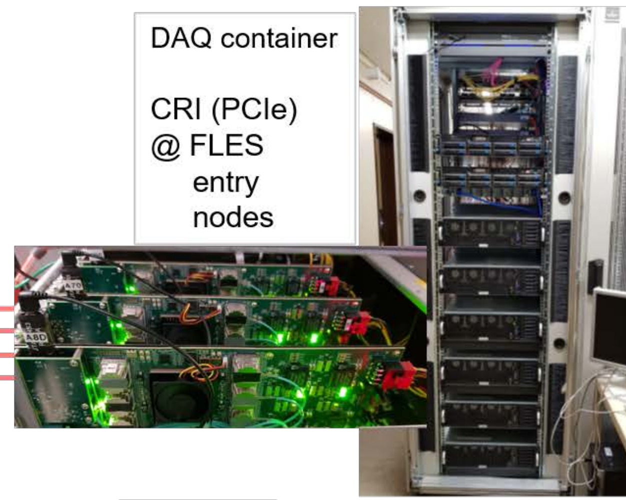
- During the last campaign, mCBM was successfully tested with the highest collision rates available in FAIR Phase-0
- Customised chain of electronics to process and transfer the data of all subsystems to the final data processing proven its capability



optical
fibers
50m

DAQ container

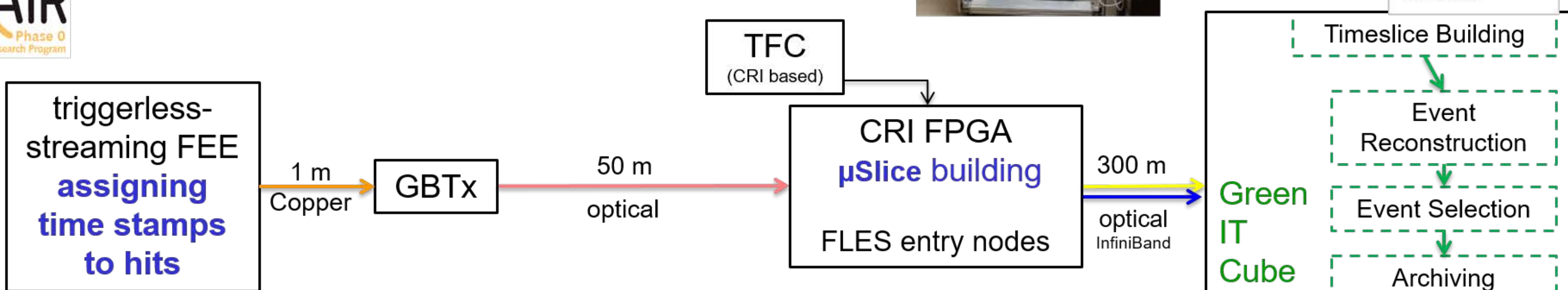
CRI (PCIe)
@ FLES
entry
nodes



optical
fibers

300 m

FLES
processing
nodes



FAIR: Unique Opportunities . . . & Challenges

We look forward to an exciting science program for the coming years!

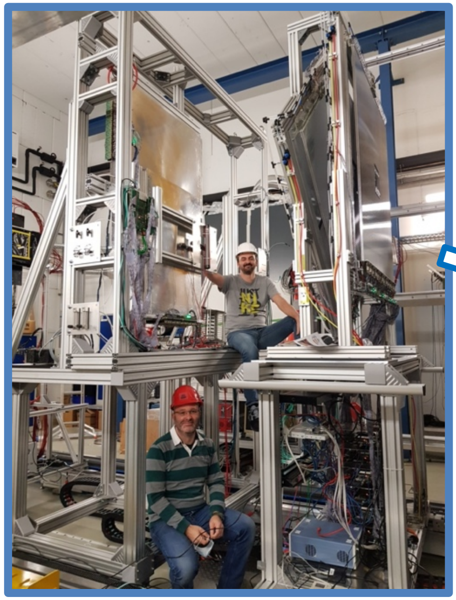
Backup

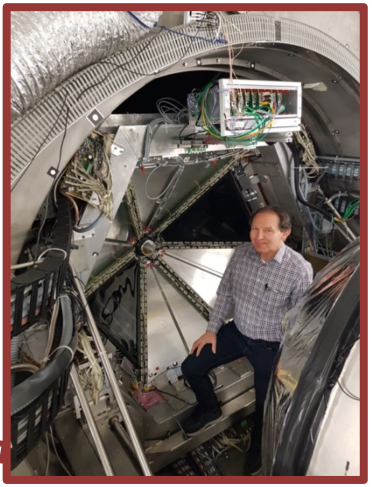
HADES

Upgrades for the FAIR Phase-0 beam time in 2022

FAIR GSI

- 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.





Forward RPC

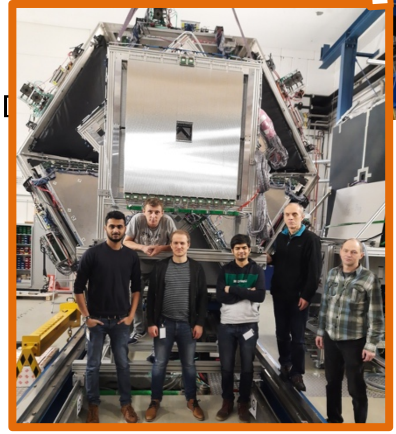
LIP Coimbra

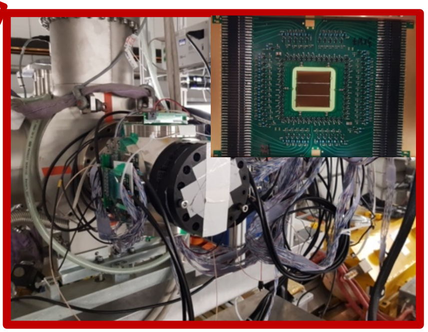
- Based on R&D for neuLAND
- TRB3 read-out

iTOF

TransFAIR, Jülich

- APD read-out
- Enhances trigger pu





STS2

Jagiellonian Univ.

- PANDA straw technology
- PANDA PASTTREC FEE chip

STS1

TransFAIR, Jülich

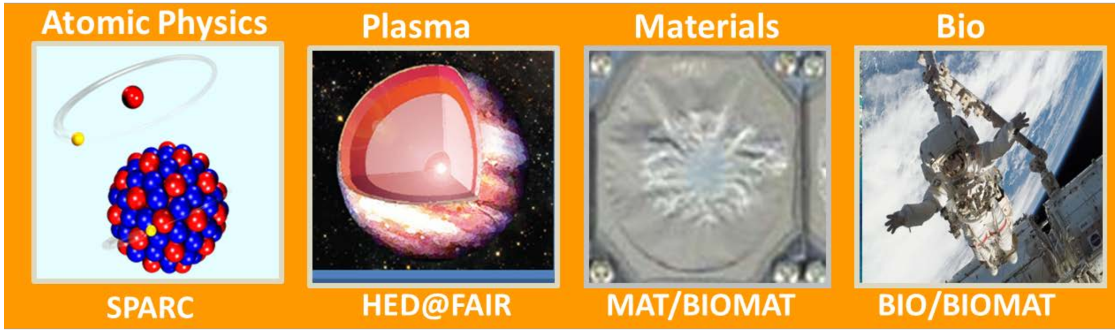
- PANDA straw technology
- PANDA PASTTREC FEE chip

T0

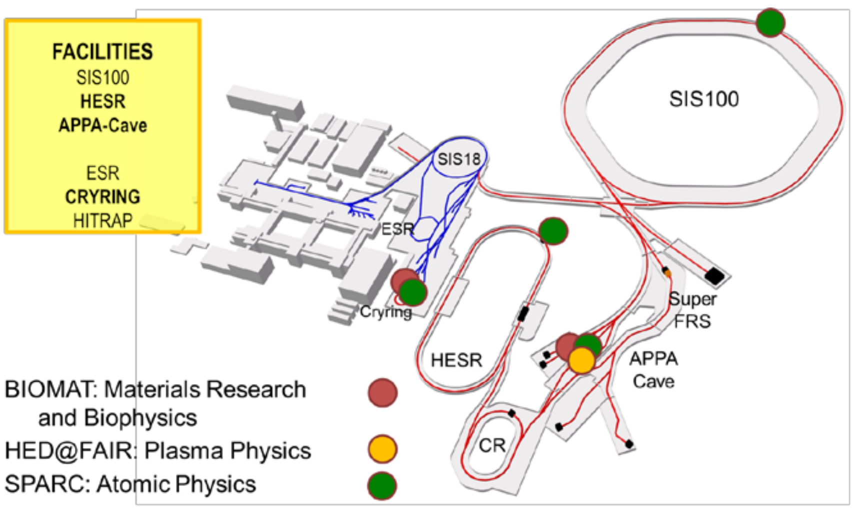
GSI, TU Darmstadt

- LGAD technology
- In-beam detector

APPA - Atomic Physics, Plasma Physics, and Applied Sciences



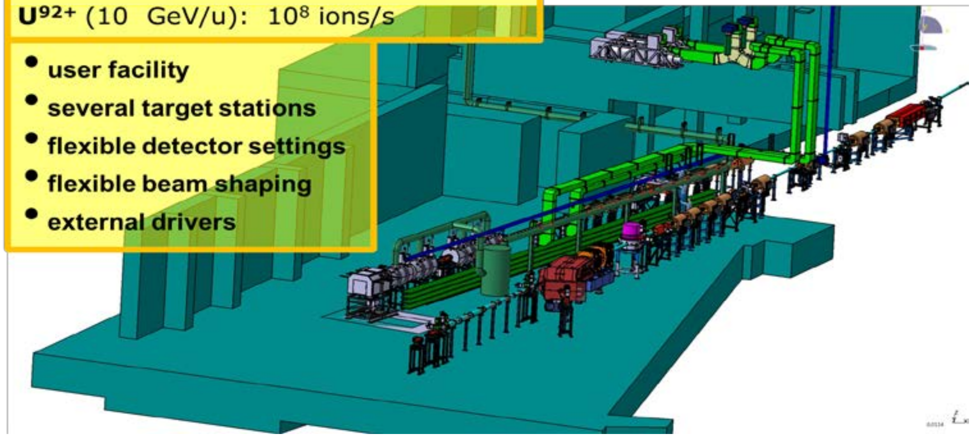
strong field research ... probing of fundamental laws of physics	**warm dense matter** ... states of matter common in astrophysical objects	**radiation hardness** ... mechanical and electrical degradation of materials	**space travel** ... cosmic radiation risk and shielding



APPA Cave

protons (10 GeV): 2 × 10^{13} p/bunch
U^{28+} (2 GeV/u): 5 × 10^{11} ions/bunch
U^{92+} (10 GeV/u): 10^{8} ions/s

- user facility
- several target stations
- flexible detector settings
- flexible beam shaping
- external drivers



FAIR - The Universe in the Laboratory

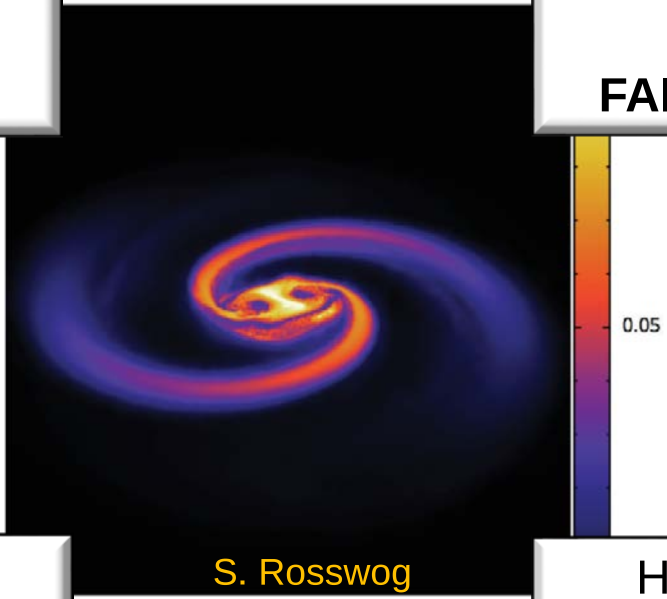
From Neutron Star Mergers to Platinum and Gold

How Matter behaves at extreme electromagnetic Field Strengths

FAIR/ APPA

How Matter behaves at extreme Densities and Temperatures

FAIR/ CBM-HADES



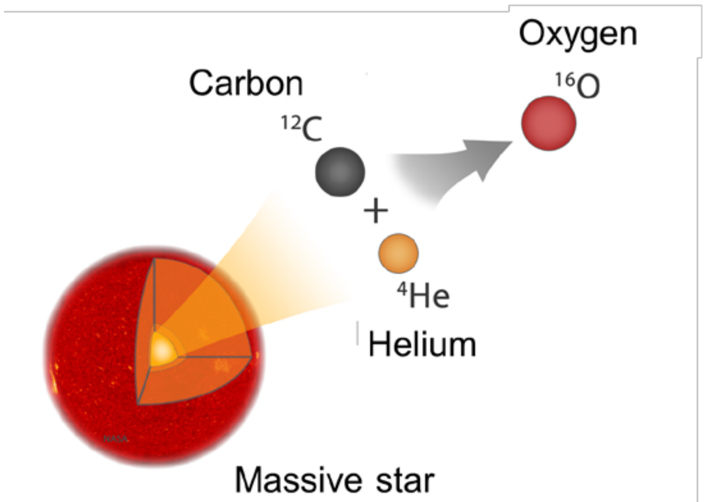
How the chemical elements evolve from Neutron-Star Matter

FAIR/ NUSTAR

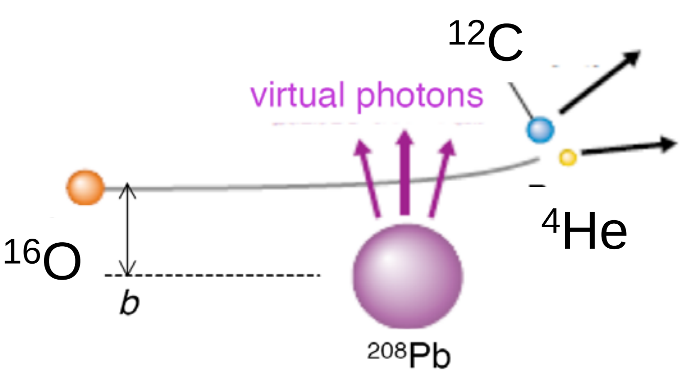
How the Protons and Neutrons are formed

FAIR/ PANDA

How Nature makes the building blocks of life



rate insufficiently known at astrophysically energies



Alpha fusion on 12C is the stellar reaction of paramount importance,

W.A. Fowler, Nobel lecture 1983

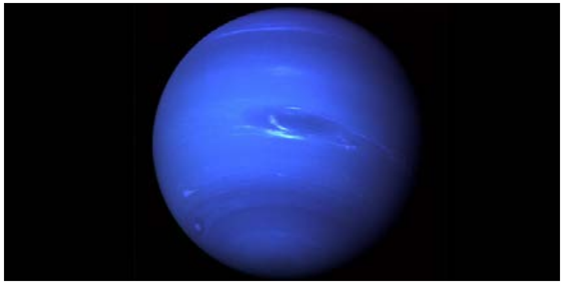
Experiment in inverse kinematics (Coulomb dissociation) requires high energies -> GSI/FAIR

Questions about the Universe

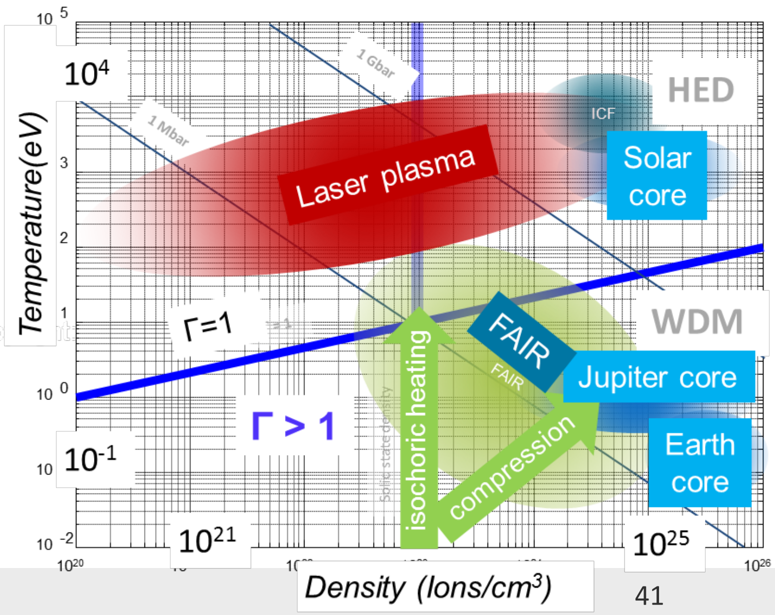
Matter in the interior of the Earth and of large planets

- The interior of our Earth is most likely composed of liquid iron. What is exactly the melting curve for iron?

- Does hydrogen form a metallic state under the extreme conditions of pressure and temperature on and in Jupiter? How does hydrogene separate from He?



- Are there diamond layers in Uranus and Neptune? What role does the high-density metallic state of water play for the magnetic field in Uranus and Neptune?

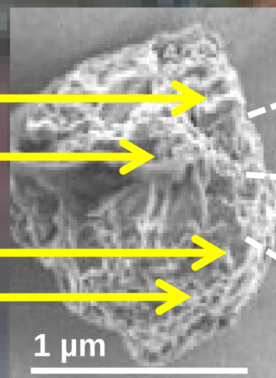


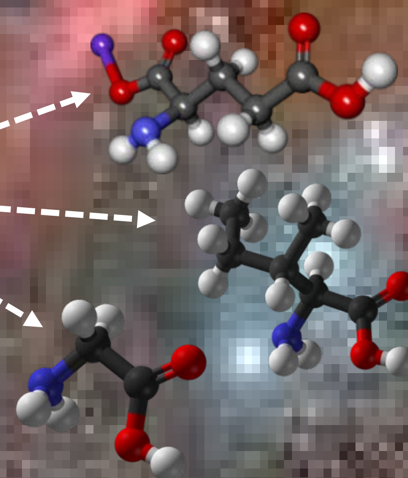
Studying cosmic radiation induced processes

FAIR GSI

astrophysical ice grains (H_2O, CH_4, CO_2, NH_3, SO_2...)

200 MeV Ca ions





C_nH_m polyaromatic hydrocarbons

$C_6H_{13}NO_2$ amino acids

C_{60}, C_{70} fullerenes


irradiation chamber and spectrometer

spectrum of large desorbed molecules