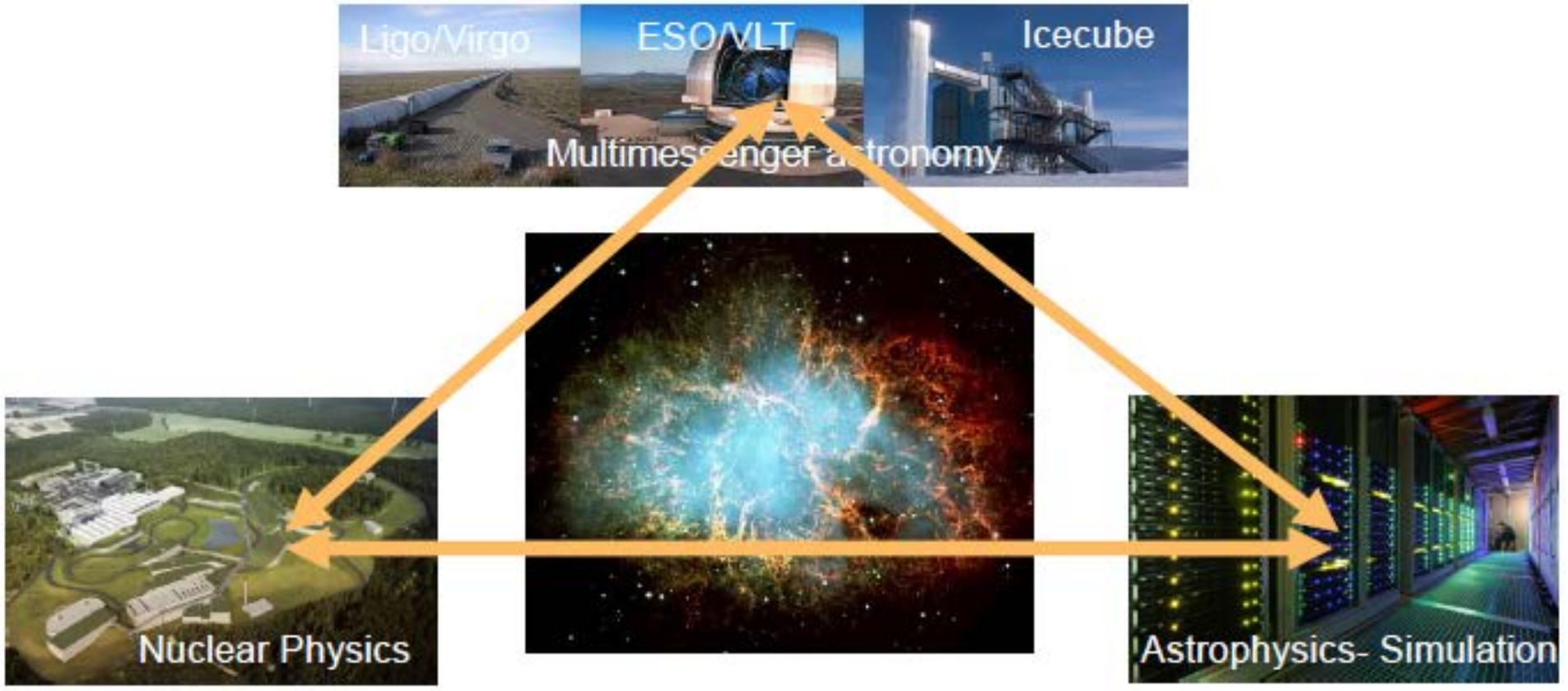
FAIR

the Universe in the Lab

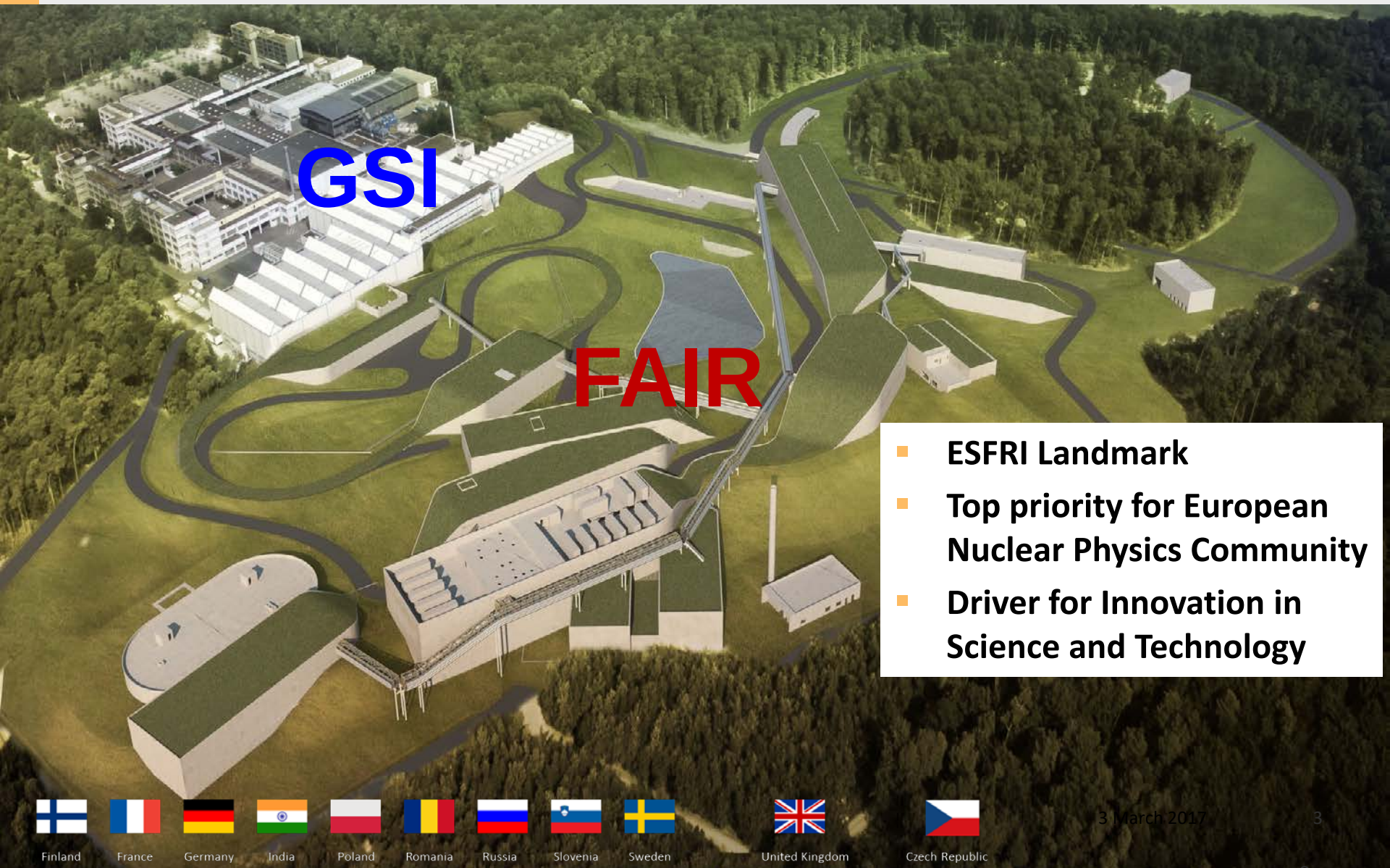
Paolo Giubellino

Erice, June 18th 2022

On the trail of the secrets of the universe



FAIR: Facility for Antiproton and Ion Research
– builds on Competence of GSI and the Community worldwide



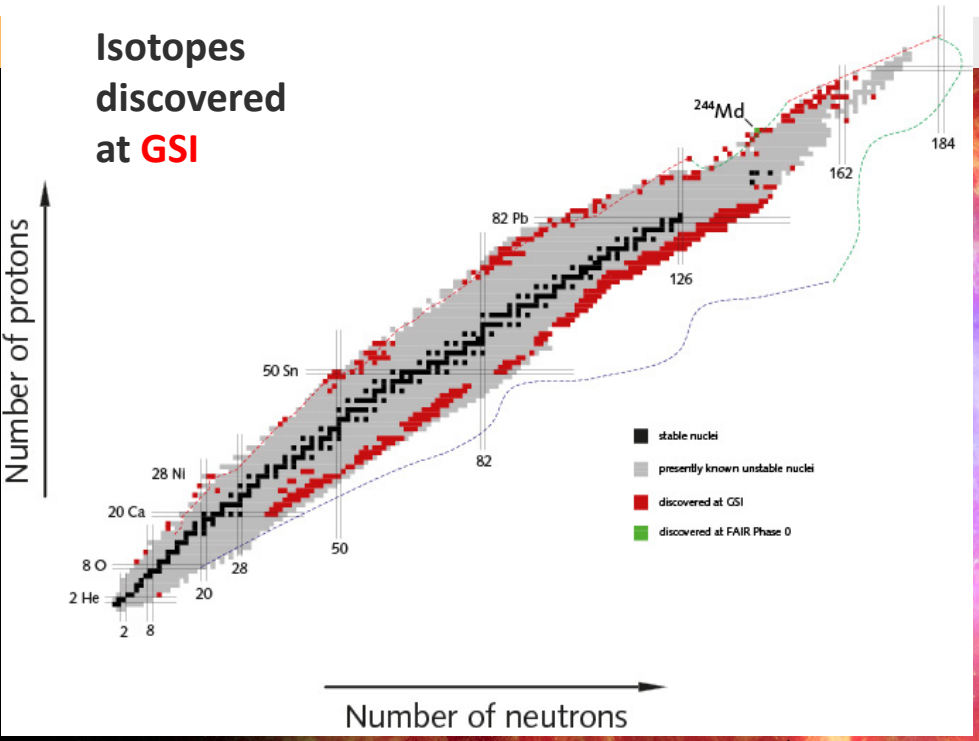
- **ESFRI Landmark**
- **Top priority for European Nuclear Physics Community**
- **Driver for Innovation in Science and Technology**

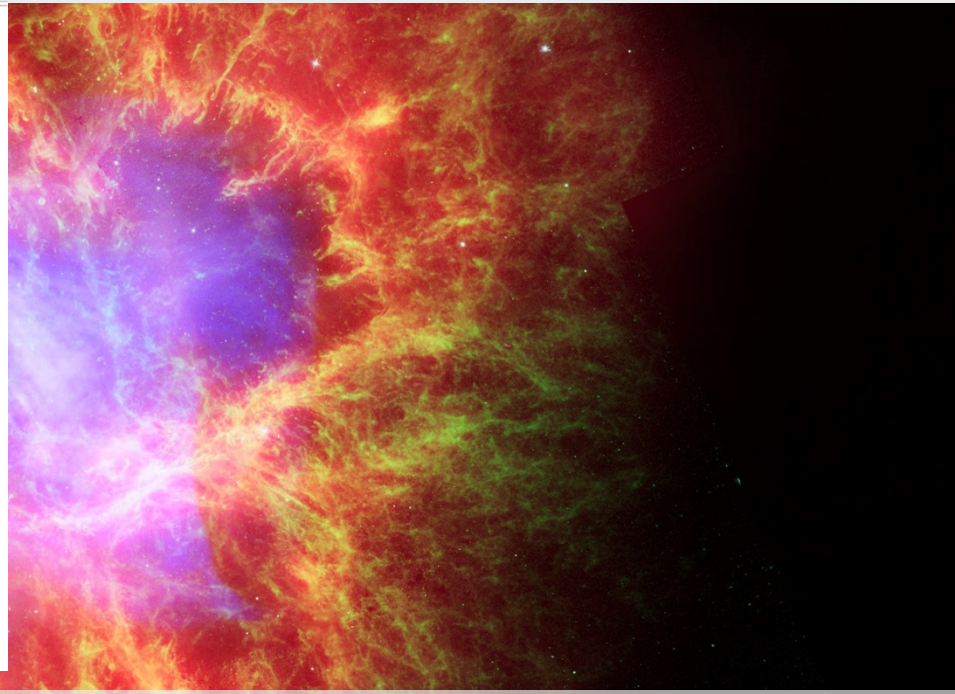
Finland France Germany India Poland Romania Russia Slovenia Sweden United Kingdom Czech Republic

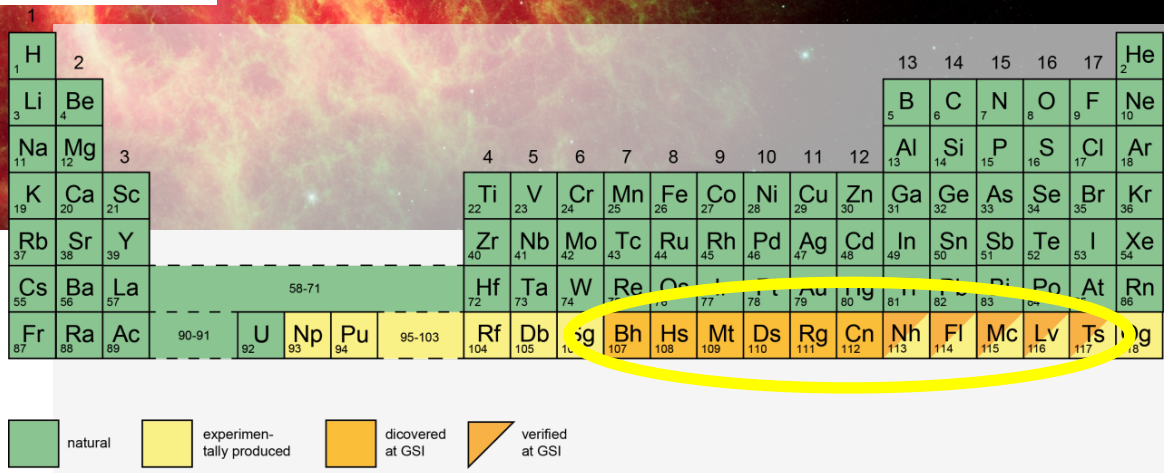

GSI –
Scientific expertise
for more than 50 years
Photo: G. Otto/GSI/FAIR

GSI Discoveries

Isotopes discovered at GSI

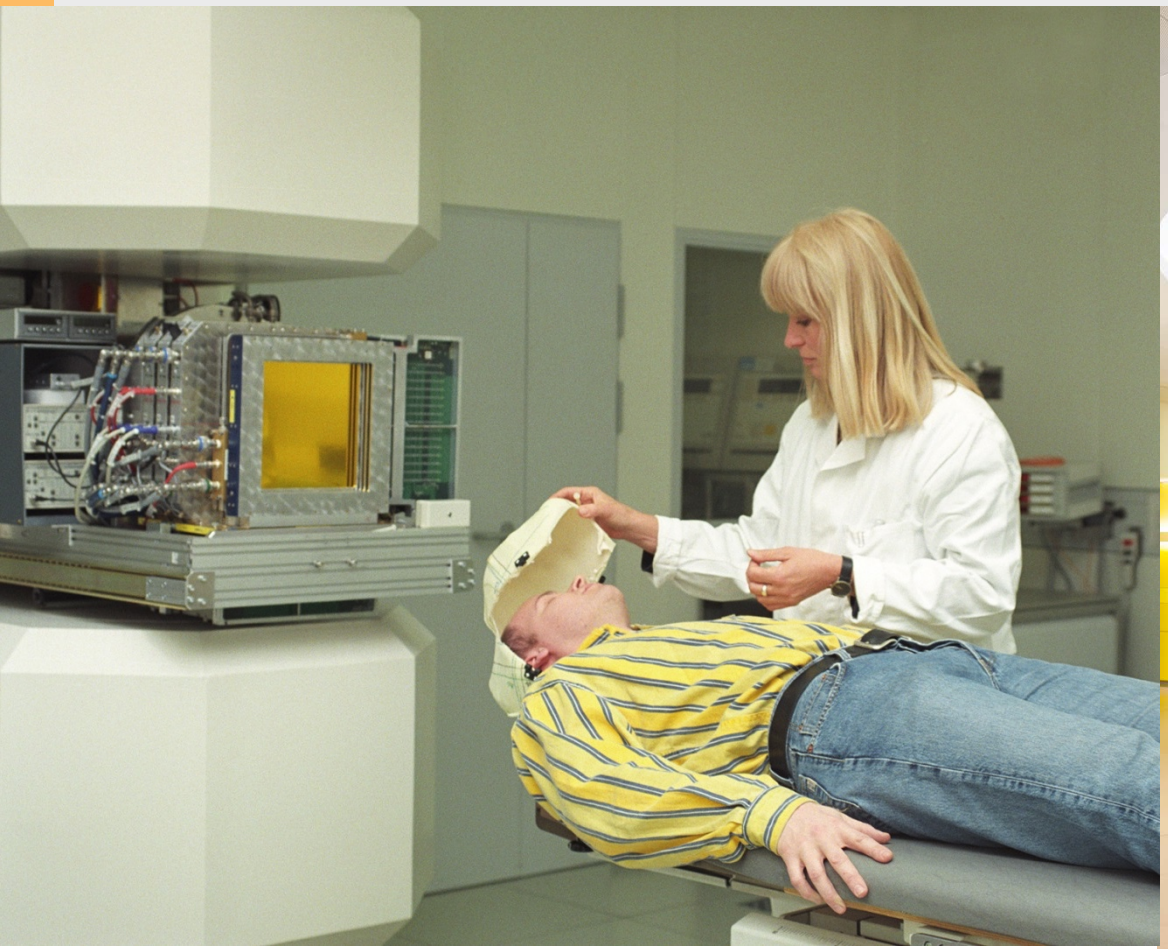






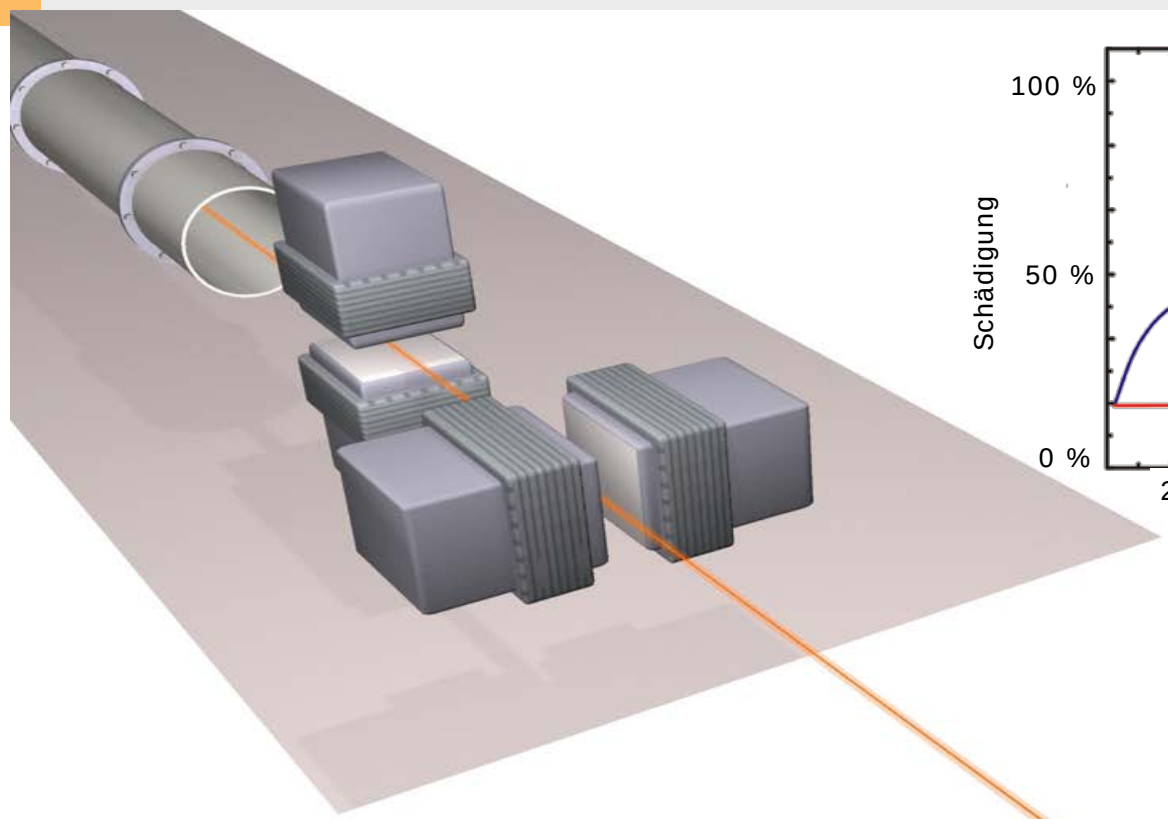
- New chemical elements
- Hundreds of new isotopes
- New decay modes

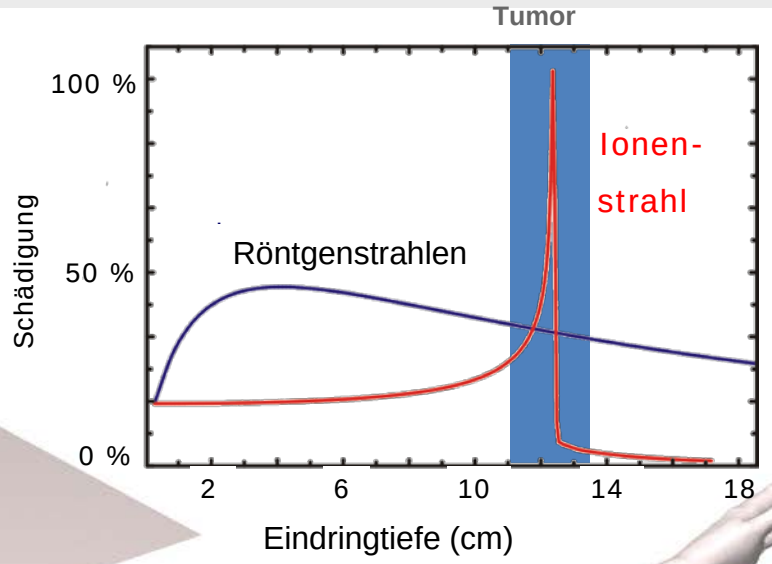
GSI Discoveries

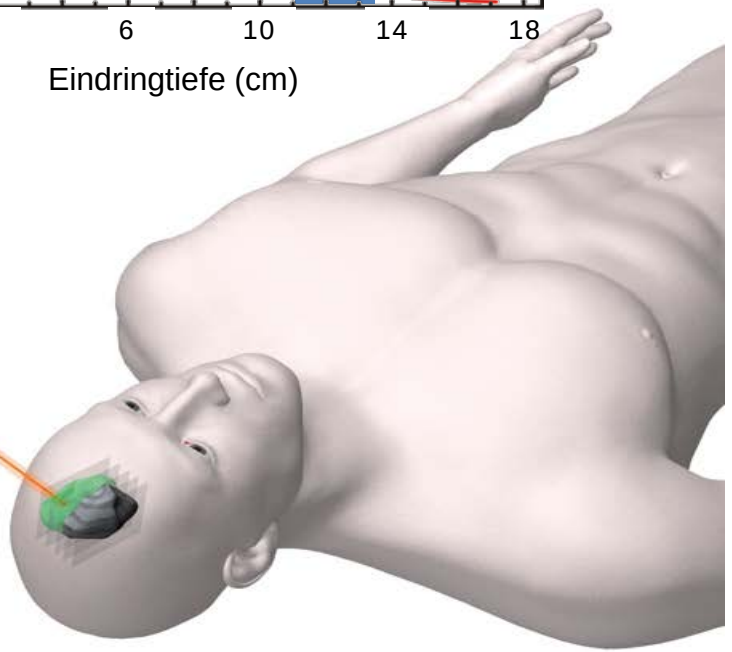


- Innovation in cancer therapy

Major Developments: Ion Beam Therapy

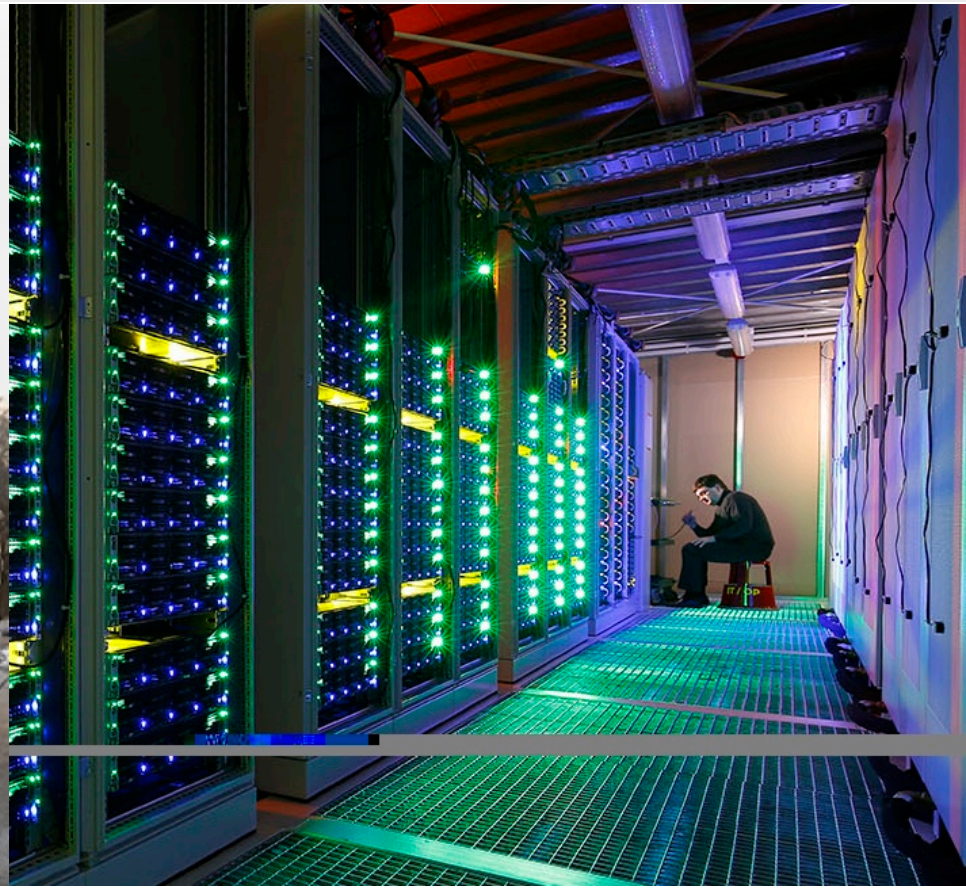






- precise like a scalpel
- extremely efficient in destroying the tumor cells
- spares the healthy tissue

Forefront Technologies

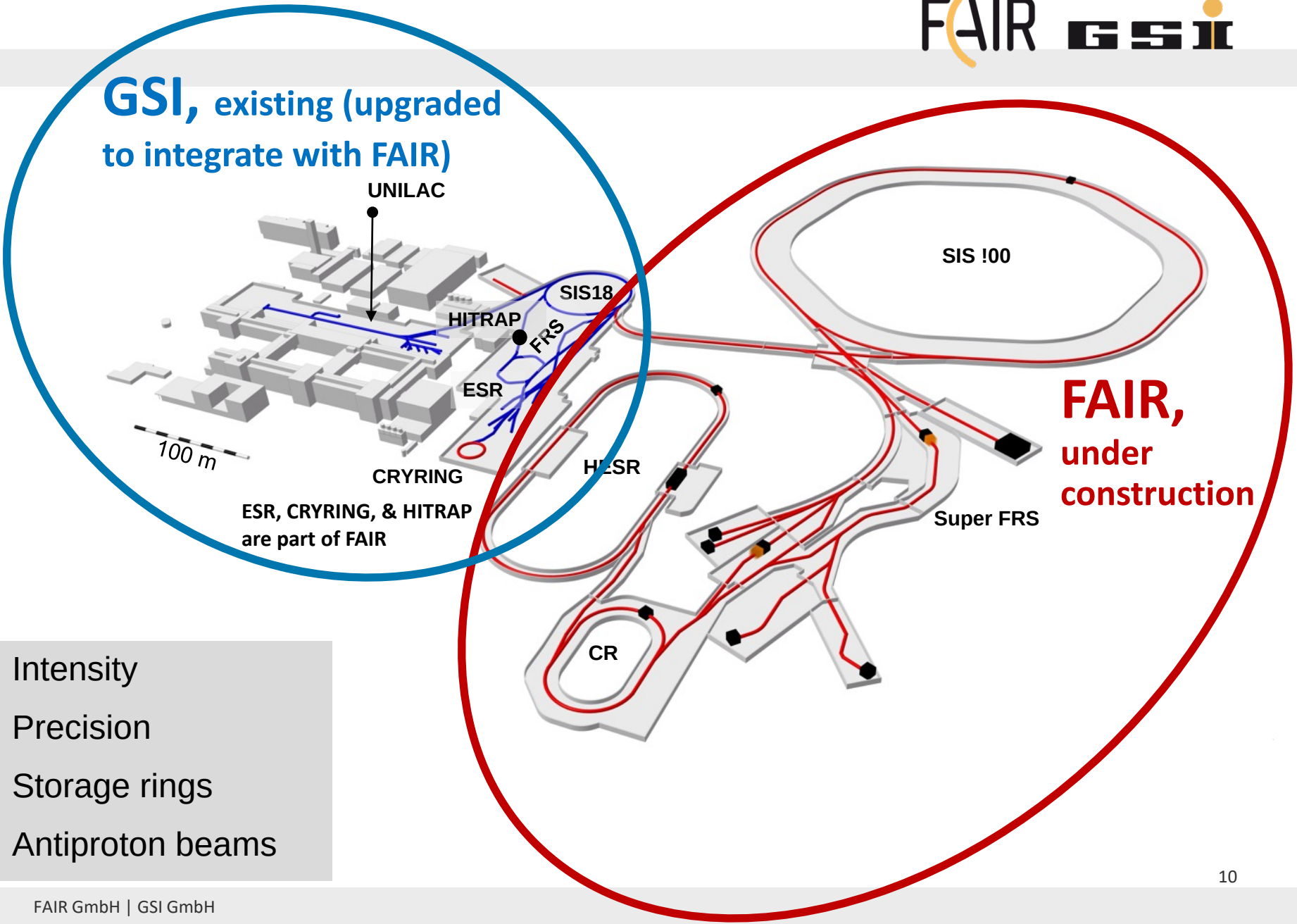


- Technological advancements in high-performance & scientific computing, Big Data, Green IT

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



- Intensity
- Precision
- Storage rings
- Antiproton beams

Poland @ FAIR

- FAIR governed by international convention
  - 9 shareholders:
  - + 1 associated partner:
  - + 1 aspirant partner:
  - Over 3000 Scientists and Engineers from all over the world
- Scientists from More than 200 institutions from 53 countries (orange + blue)

Construction volumes

2 million m^3

of earth

to be moved

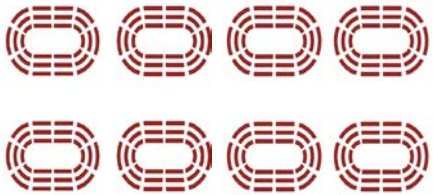
As much as for 5,000 single-family homes

600,000 m^3

of concrete

to be used

As much as eight Frankfurt soccer stadiums

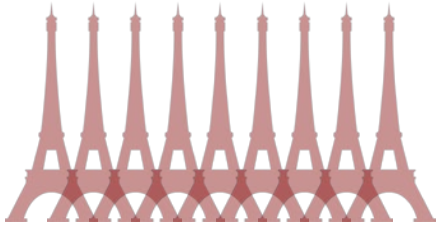


65,000 tons

of steel

to be utilized

As much as nine Eiffel Towers



Building FAIR

FAIR (May 2022)

Building FAIR

Nord

Sud

April 2022: inside the SIS100 tunnel

Accelerators:
delivery of components continue steadily

Storage Area Weiterstadt

Completed and delivered high-tech components for accelerator and experiments

- Storage area: approx. 9.900 m²
- 4.195 objects (Components, assemblies, boxes, etc.)
- 08/2021 - Commissioning of a warehouse frame with approx. 1000 pallet spaces
- 50% of SIS100 components stored

Creating extreme conditions existing in the universe with heavy ion accelerators

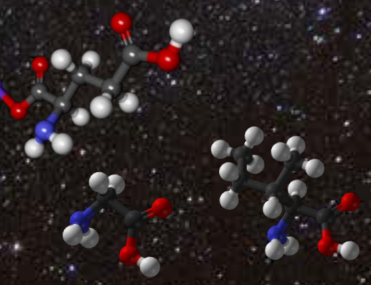
Foto: NASA, ESA, G. Dubner (IAFE, CONICET-University of Buenos Aires) et al.; A. Loll et al.; T. Temim et al.; F. Seward et al.; VLA/NRAO/AUI/NSF; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; and Hubble/STScI (oben), Penn State University (unten)

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

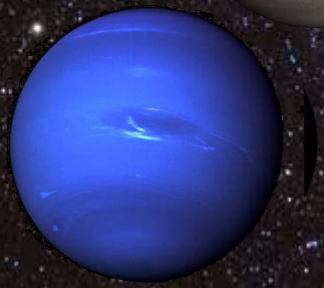
Where are heavy elements created?

What is in the interior of a neutron star?

What happens to human cells on the way to Mars?



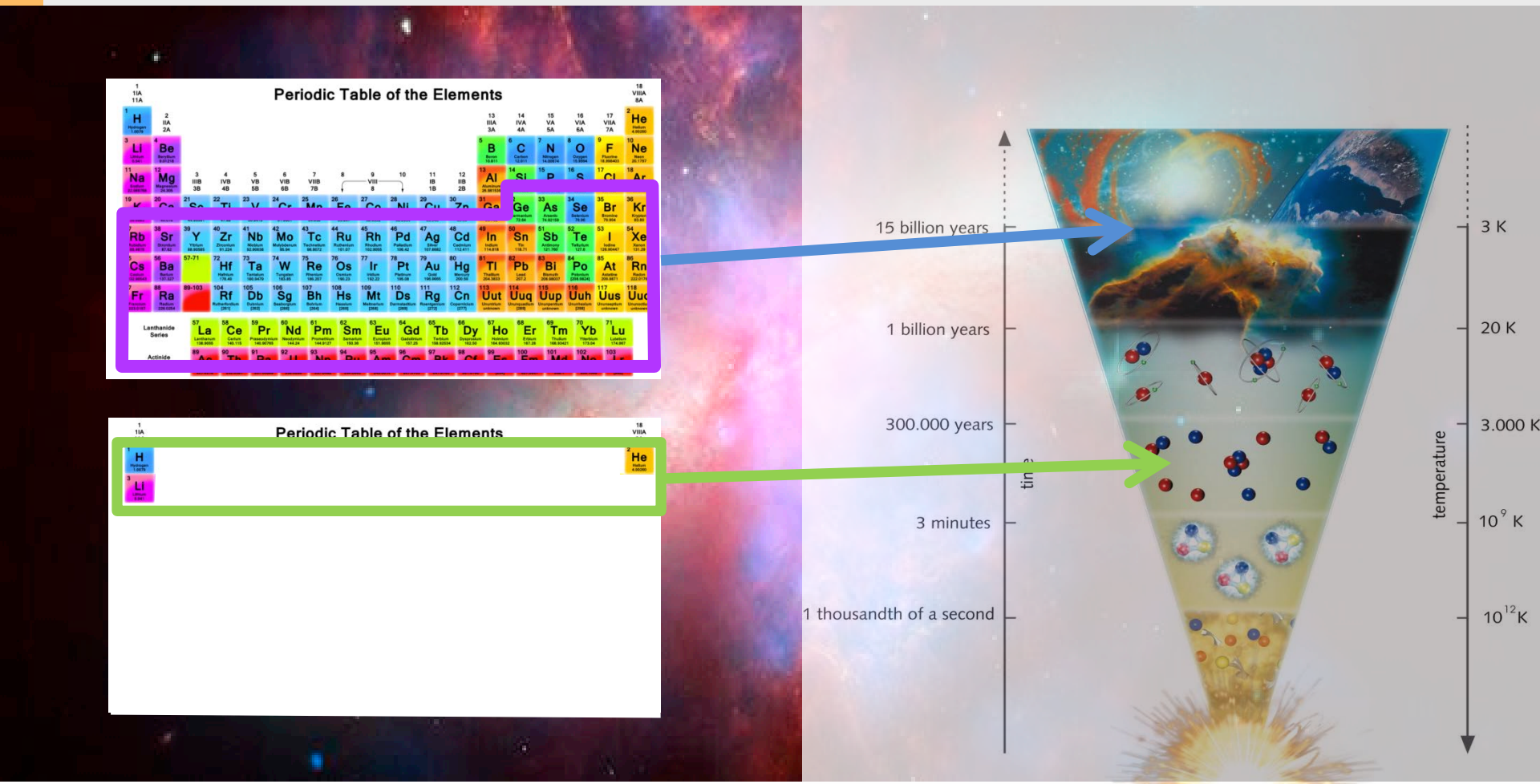
How are complex molecules created?



How do materials behave under high pressure?

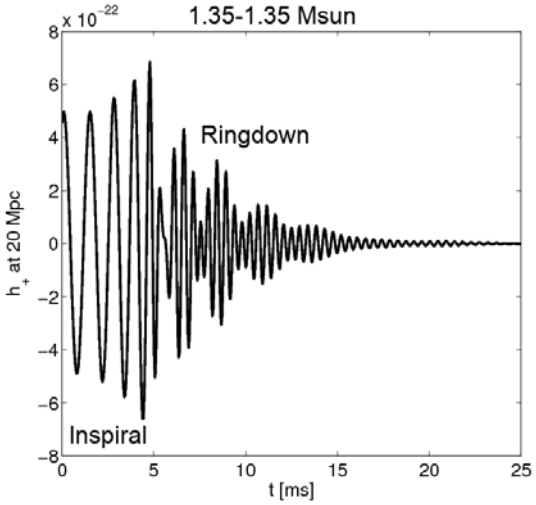
Fotos: Uranus, Jupiter, Erde Quelle: http://de.wikipedia.org

Why FAIR? (... just SOME of the questions)

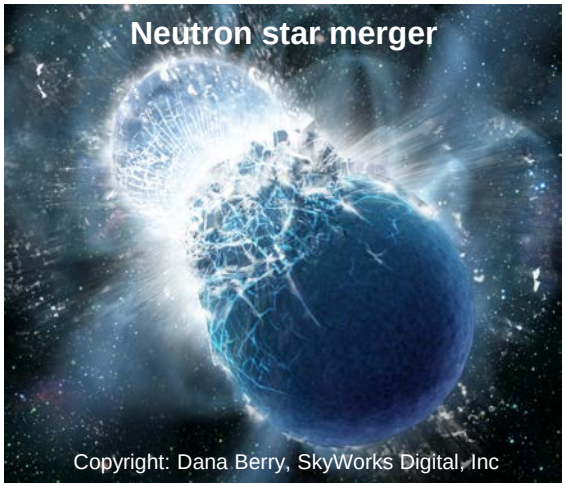


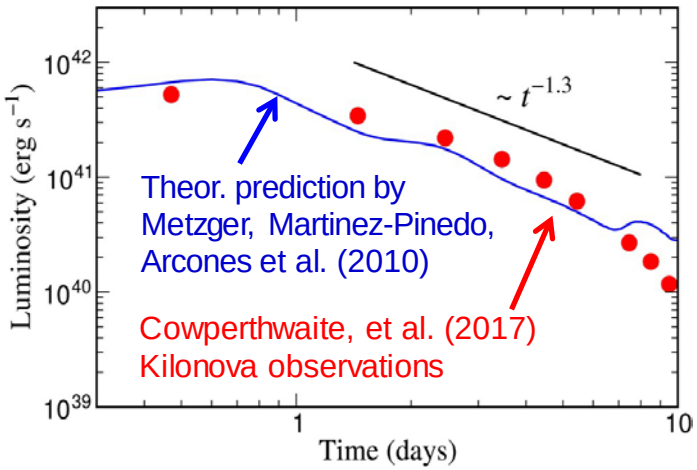
- Where and how were the heavy elements made in the universe? ← ***One of the top unanswered questions in Physics***

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

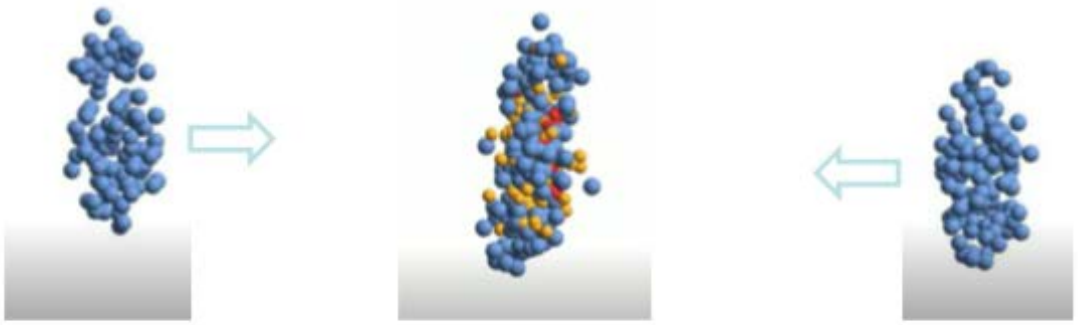
Neutron star merger

Temperature
T < 50 MeV

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

Reaction time
(GW170817)
T ~ 10 ms

Heavy ion collisions at SIS100



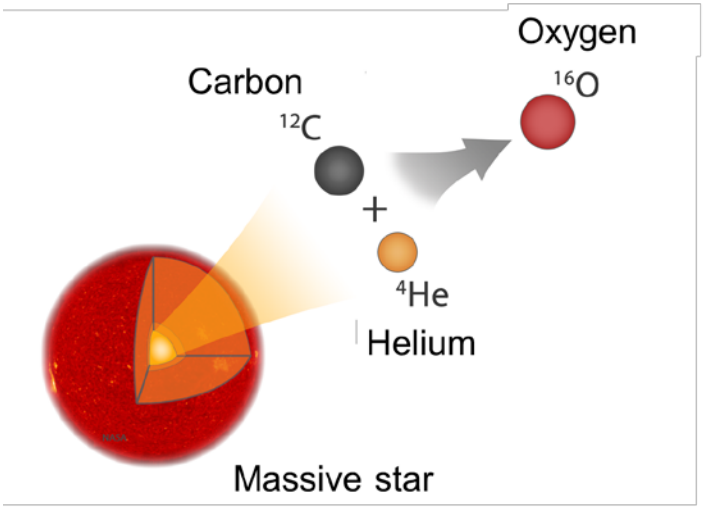
Compressed Baryonic Matter

Temperature
T < 120 MeV

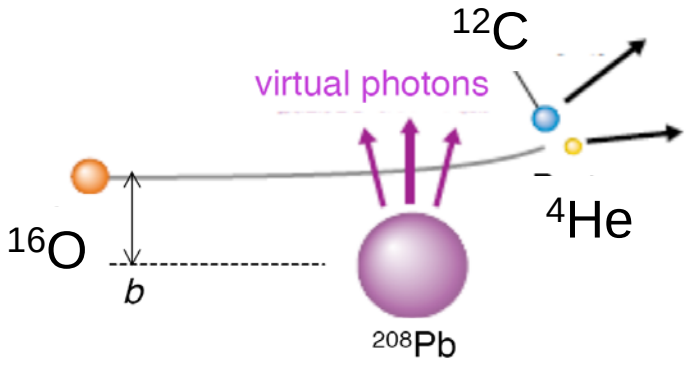
Density
$\rho < 8\rho_0$

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

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

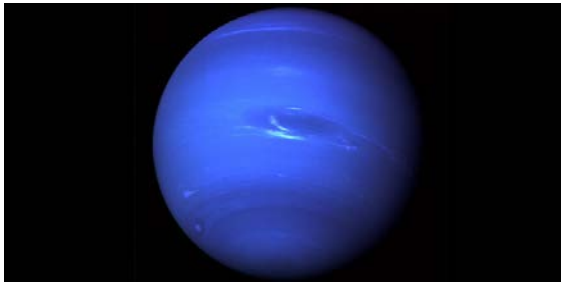
Experiment in inverse kinematics (Coulomb dissociation) requires high energies -> GSI/FAIR

Questions about the Universe

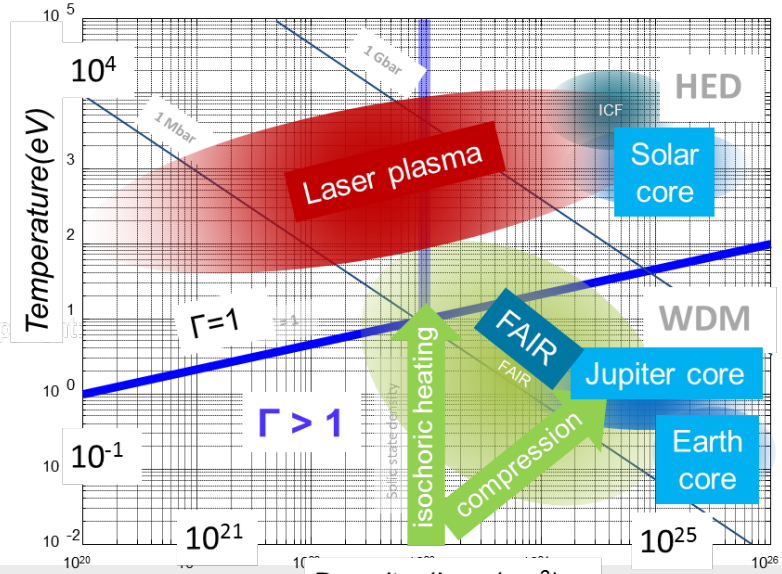
Matter in the interior of the Earth and of large planets

- 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?



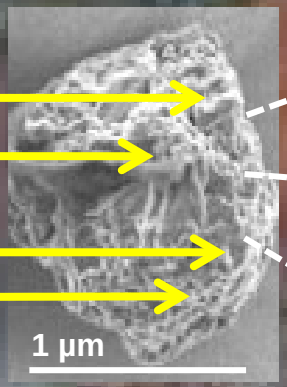
- Are there diamond layers in Uranus and Neptune? What role does the high-density metallic state of water play for the magnetic field in Uranus and Neptune?

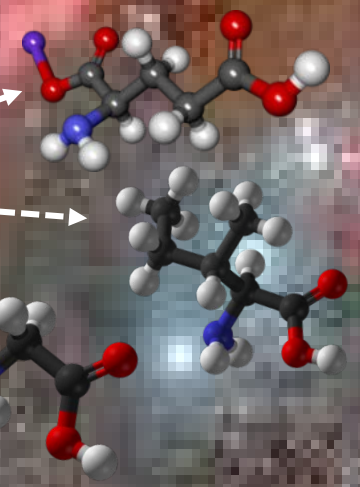


Studying cosmic radiation induced processes

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

200 MeV Ca ions

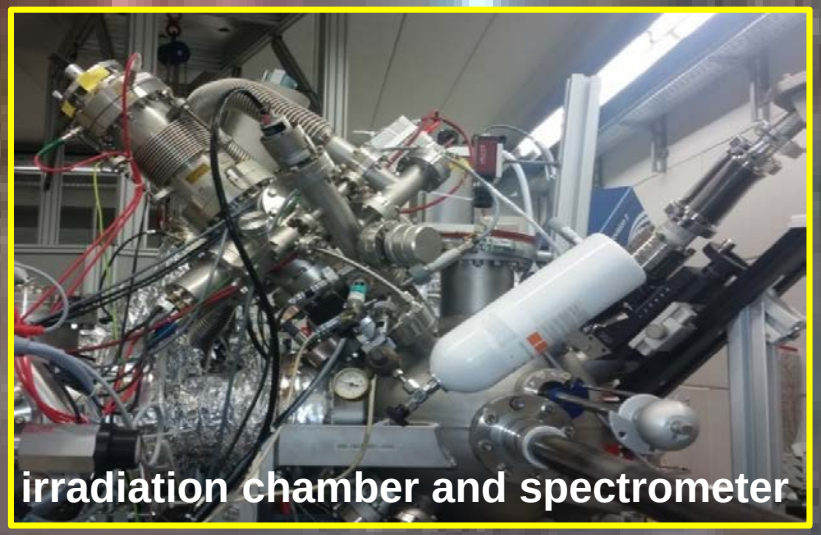




C_nH_m polyaromatic hydrocarbons

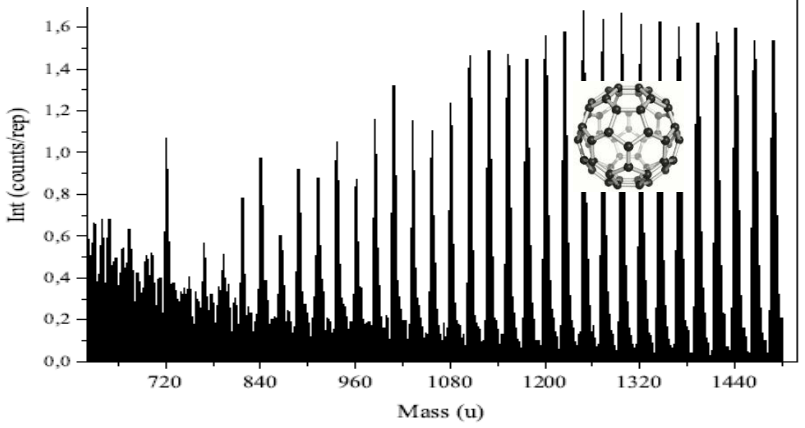
$C_6H_{13}NO_2$ amino acids

C_{60}, C_{70} fullerenes



irradiation chamber and spectrometer

spectrum of large desorbed molecules

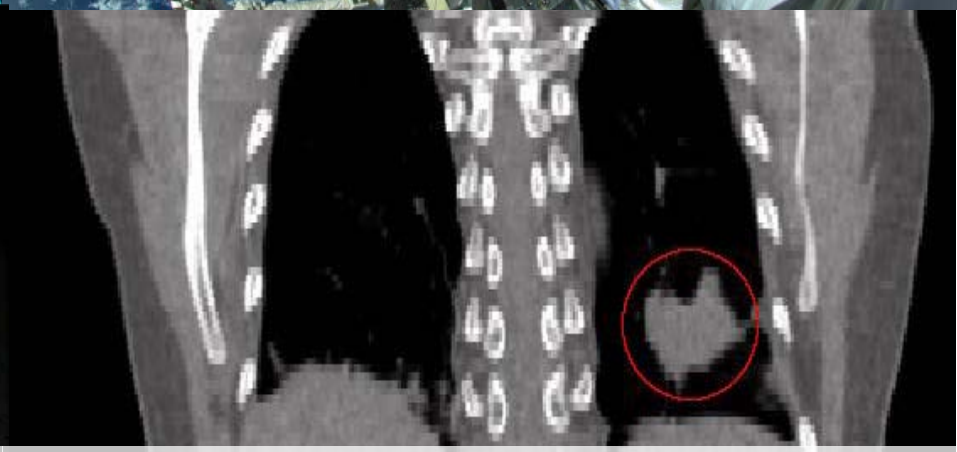


… with direct applications

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

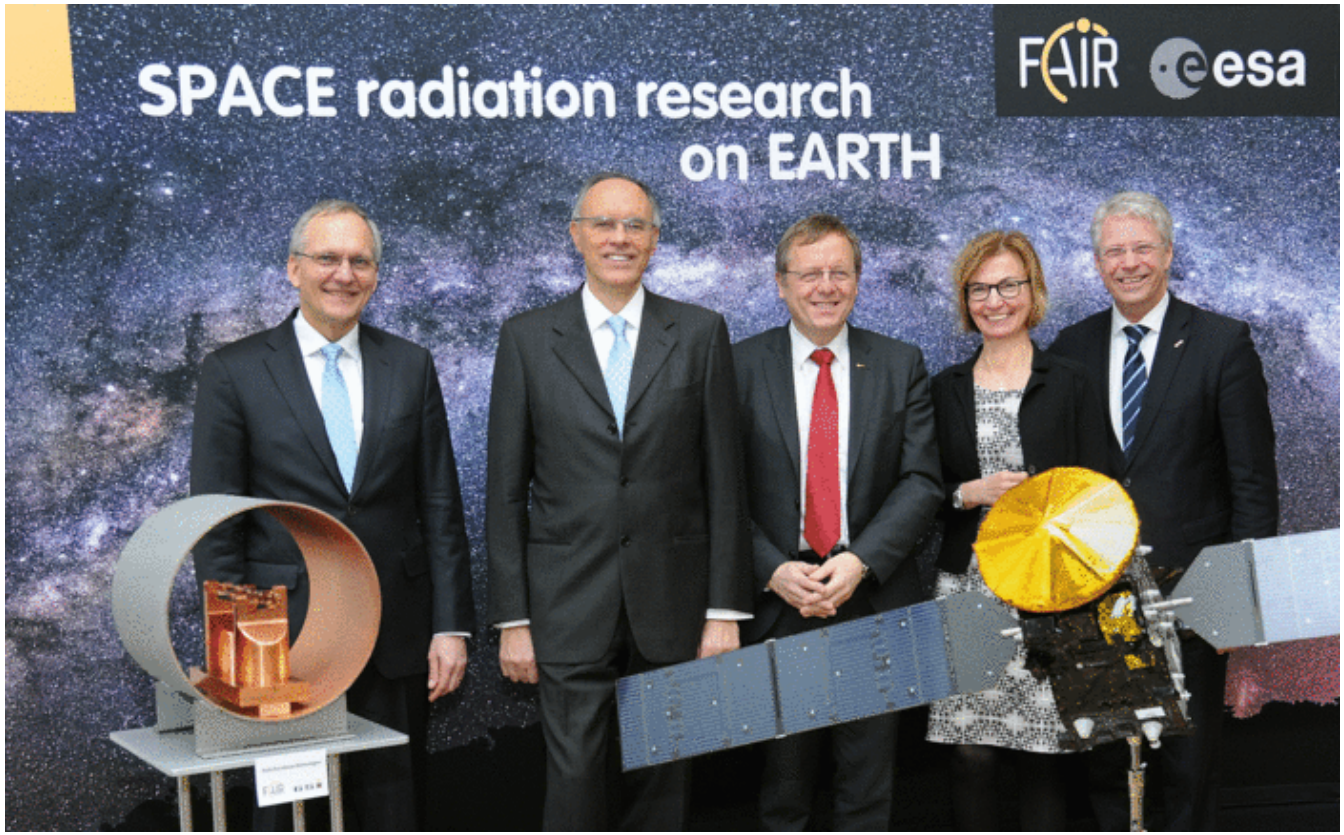
Space radiation protection, unique facility for simulation, collaboration with ESA

Development of nuclear clock: Promising candidate thorium-229



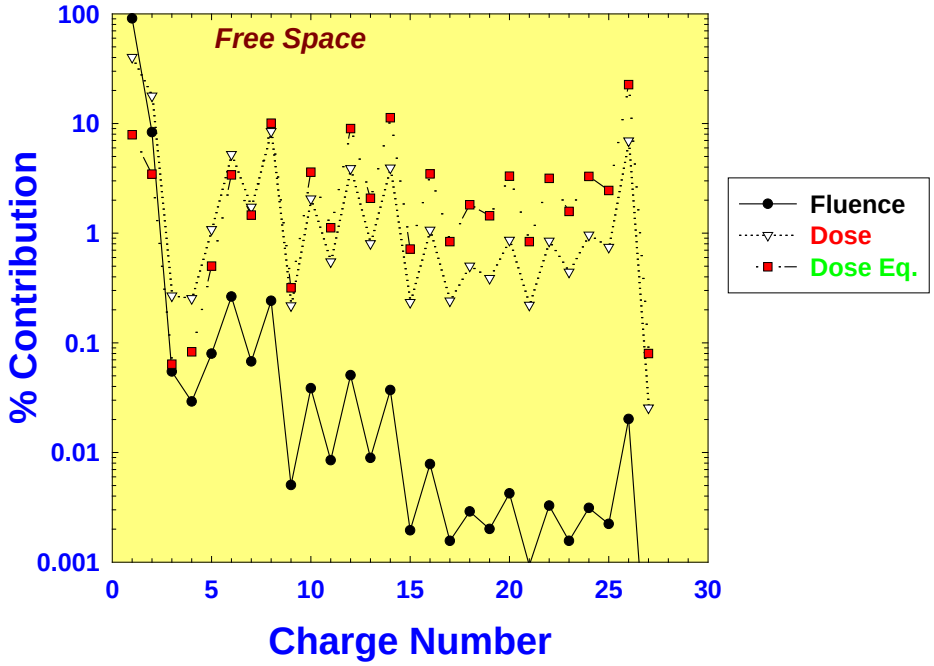
Novel applications for tumor and non-tumor diseases

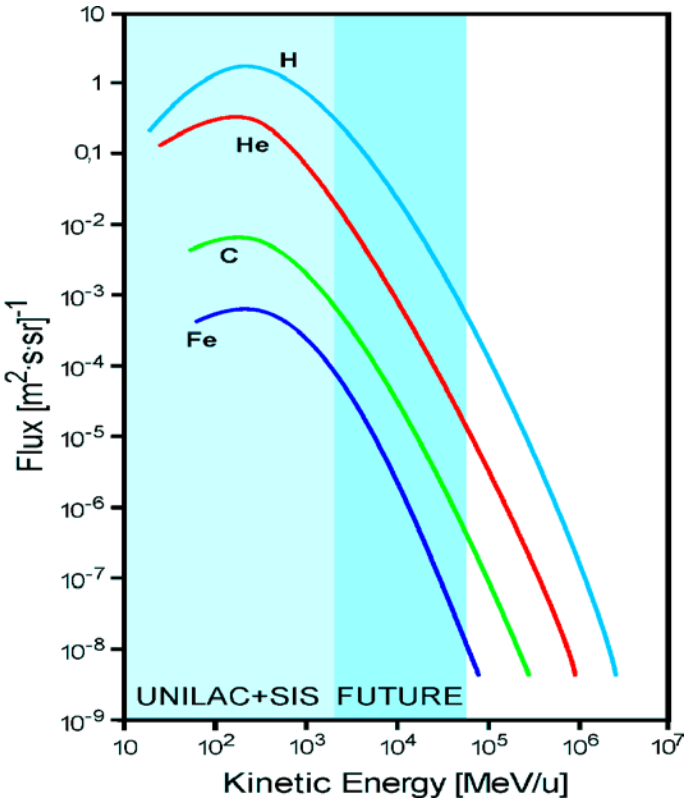
MoU FAIR-GSI, 2018



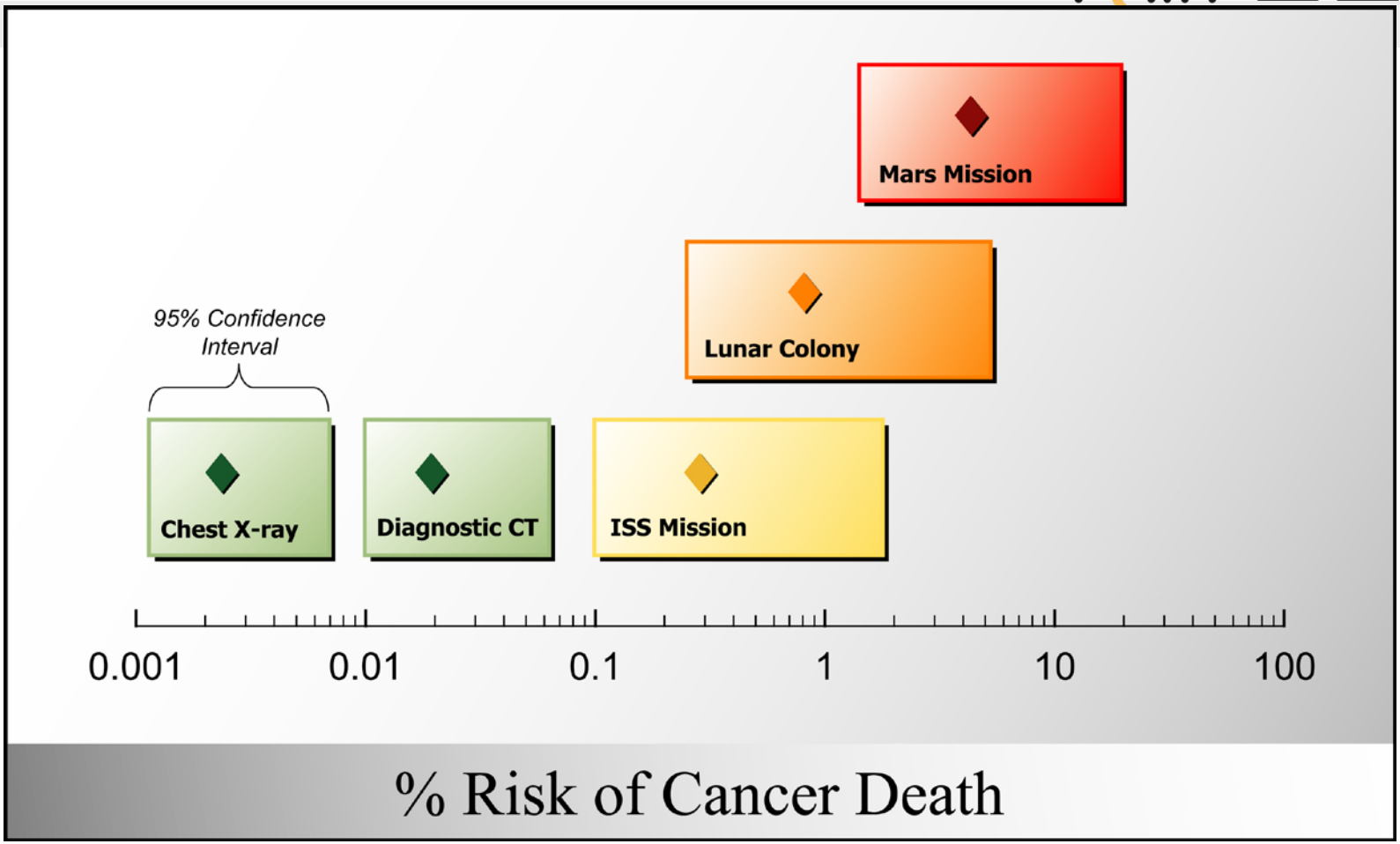
Galactic Cosmic Radiation

GCR Charge Contributions





Durante and Cucinotta, *Rev. Mod. Phys*. 2011



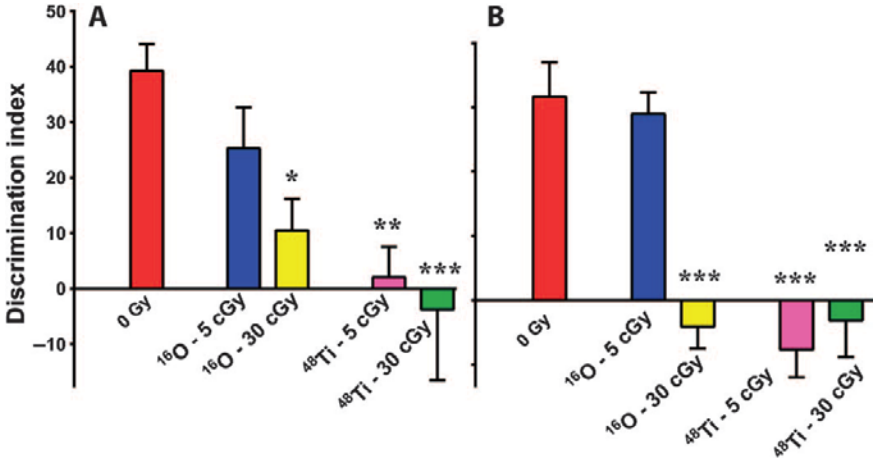
Durante & Cucinotta, *Nature Rev. Cancer* (2008)

RESEARCH ARTICLE Parihar *et al.* Sci. Adv. 2015;1:e1400256 1 May 2015

COGNITIVE NEUROSCIENCE

What happens to your brain on the way to Mars

Vipan K. Parihar,[1] Barrett Allen,[1] Katherine K. Tran,[1] Trisha G. Macaraeg,[1] Esther M. Chu,[1] Stephanie F. Kwok,[1] Nicole N. Chmielewski,[1] Brianna M. Craver,[1] Janet E. Baulch,[1] Munjal M. Acharya,[1] Francis A. Cucinotta,[2] Charles L. Limoli[1]*

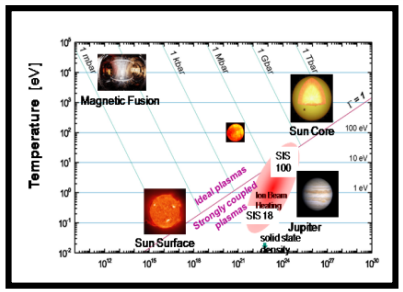


ROSSINI experiment

Schuy *et al.*, *Radiat. Res*. 2019

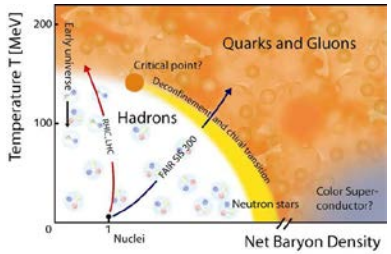
Giraudo *et al.*, *Radiat. Res*. 2018

The FAIR science: four pillars



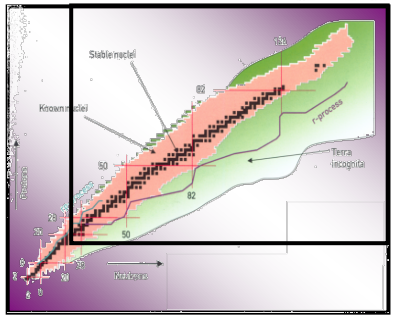
atomic physics, biophysics,
plasma physics, material research

APPA



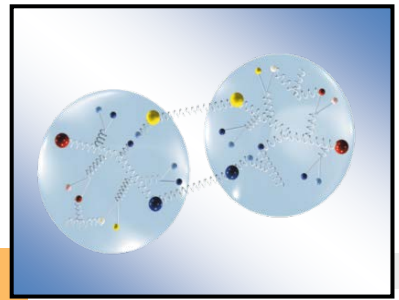
nuclear- and quark-matter

CBM



nuclear structure and
nuclear astrophysics

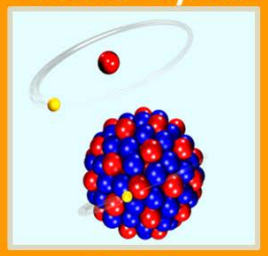
NuSTAR

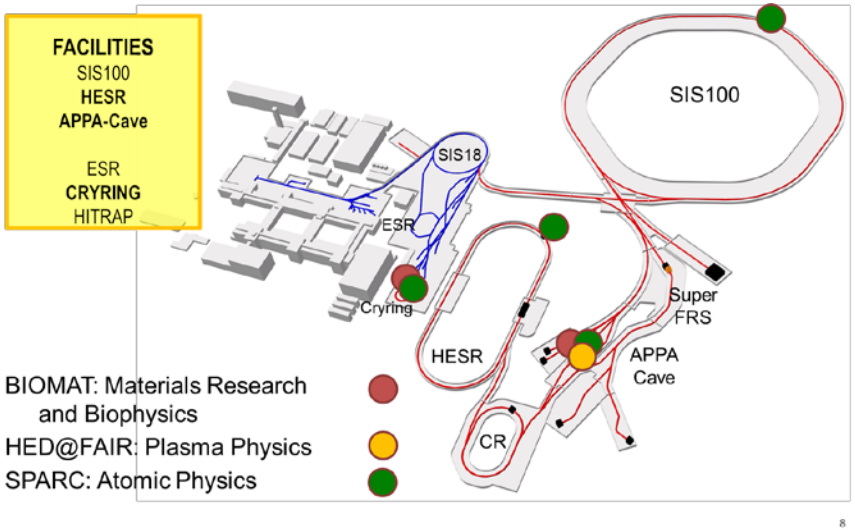


hadron structure and dynamics

PANDA

APPA - Atomic Physics, Plasma Physics, and Applied Sciences

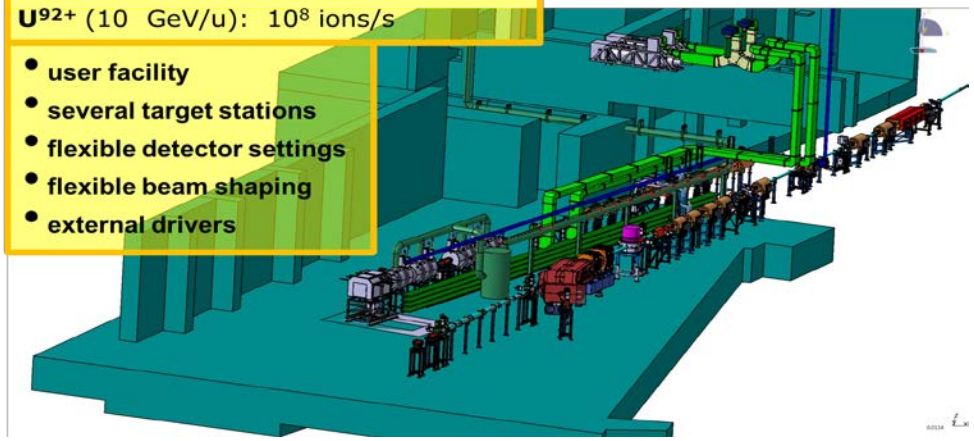
Atomic Physics	Plasma	Materials	Bio
			
SPARC	HED@FAIR	MAT/BIOMAT	BIO/BIOMAT
strong field research ... probing of fundamental laws of physics	**warm dense matter** ... states of matter common in astrophysical objects	**radiation hardness** ... mechanical and electrical degradation of materials	**space travel** ... cosmic radiation risk and shielding



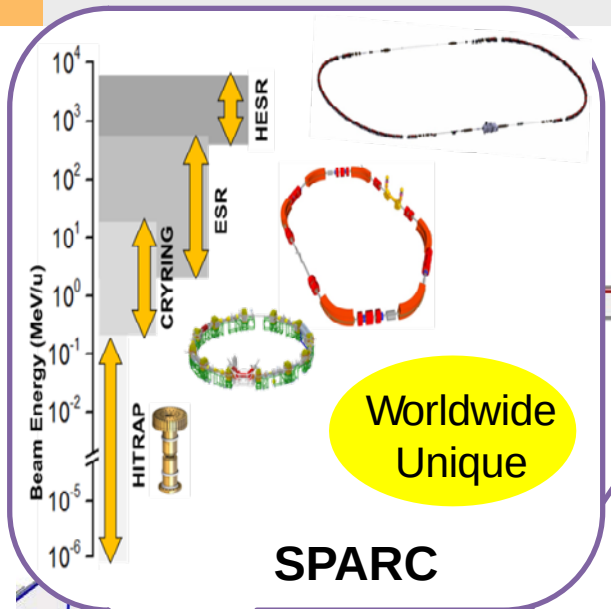
protons (10 GeV): 2 x 10^{13} p/bunch
U^{28+} (2 GeV/u): 5 x 10^{11} ions/bunch
U^{92+} (10 GeV/u): 10^{8} ions/s

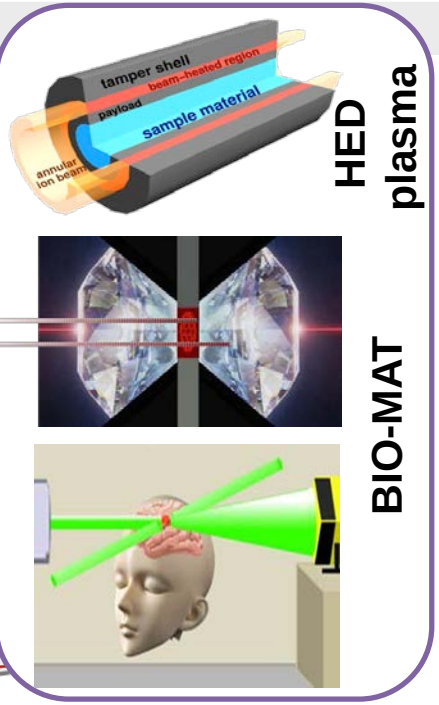
- user facility
- several target stations
- flexible detector settings
- flexible beam shaping
- external drivers

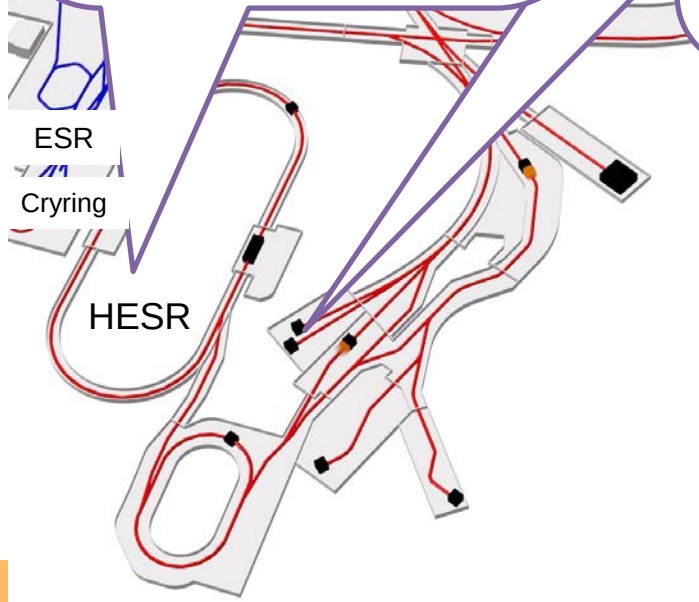
APPA Cave



APPA







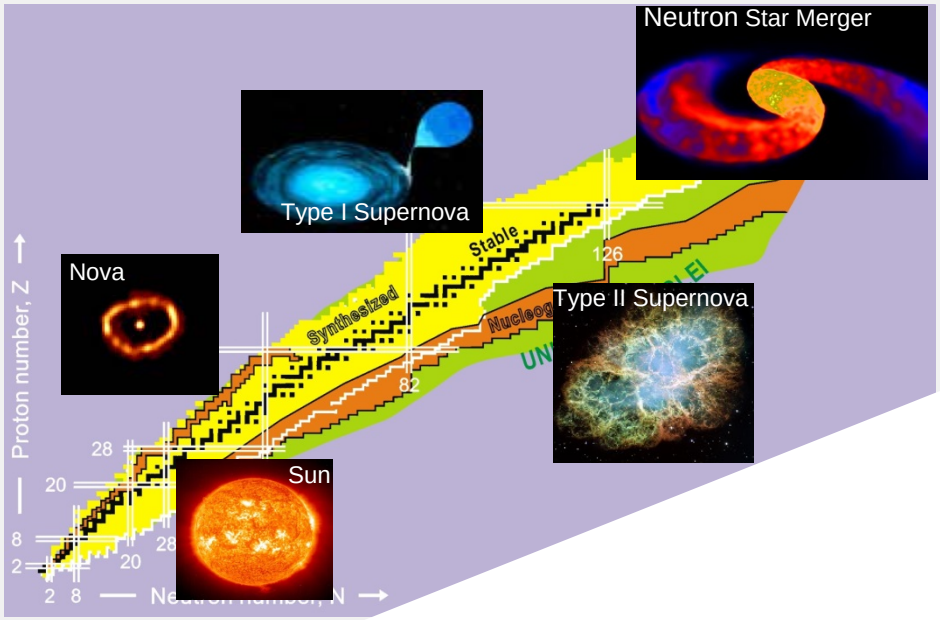
- Atomic, Plasma Physics and Applications
  - About 800 members
  - Wide field of science
    - basic research into material, biological and medical applications and space research

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

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

SFRS

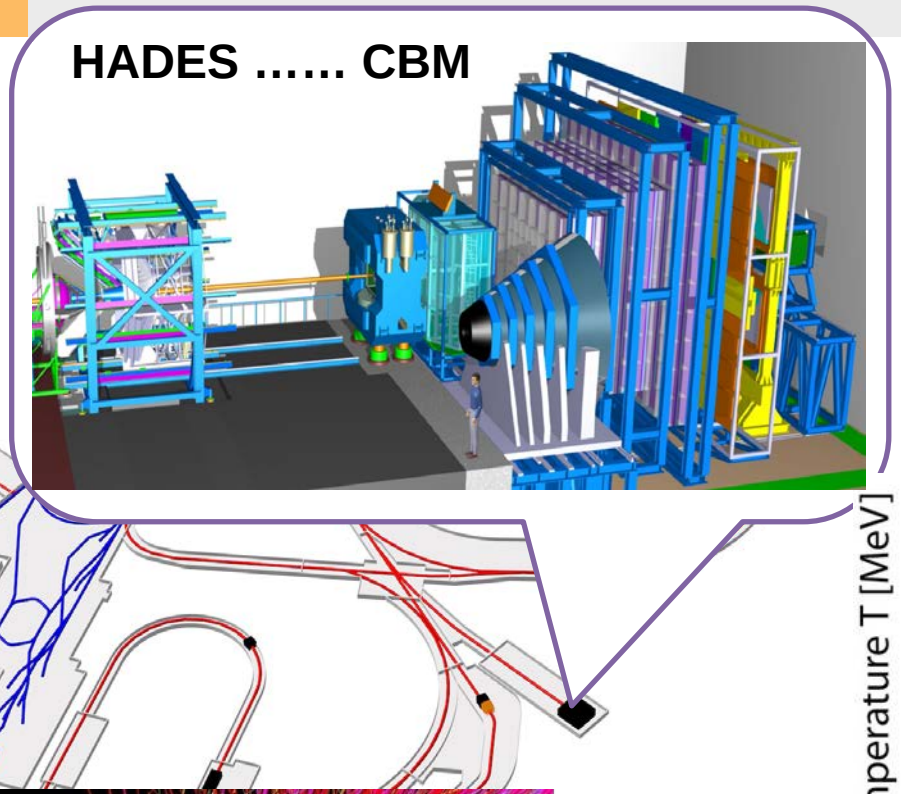
MATS & LaSpec

HISPEC/DESPEC

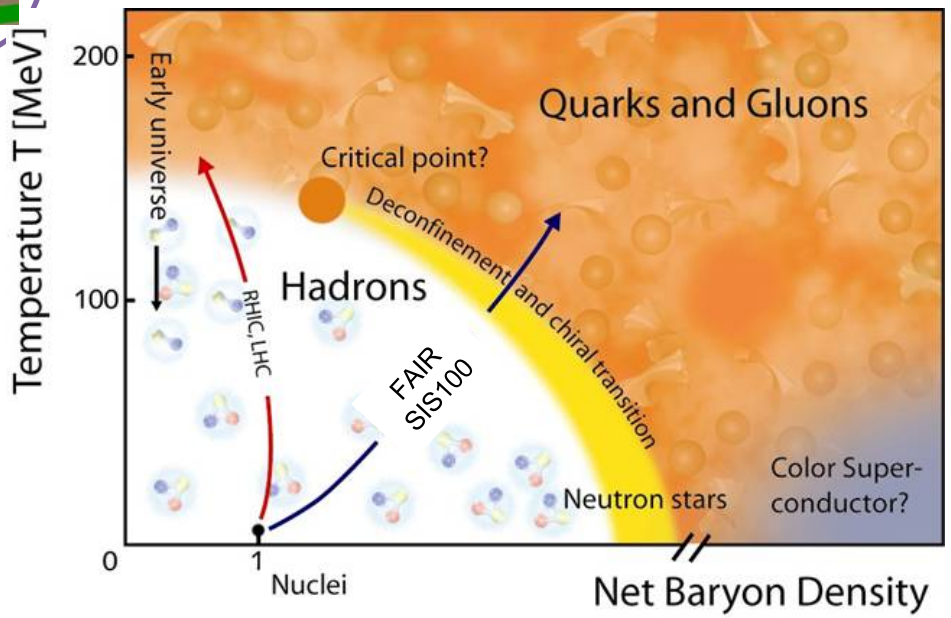
R³B

ILIMA, EXL at CR and at ESR, HESR, Cryring

C.B.M.



- Compressed Baryonic Matter Experiments
  - About 400 members

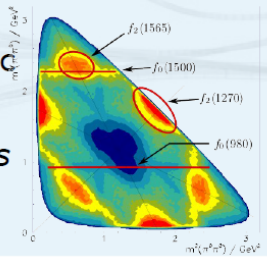


PANDA - AntiProton Annihilation at Darmstadt

Bound States of Strong Interaction

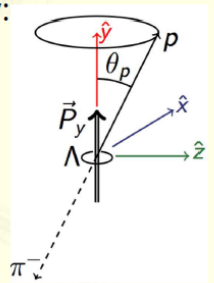
Spectroscopy

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



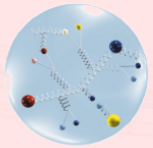
Strangeness

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



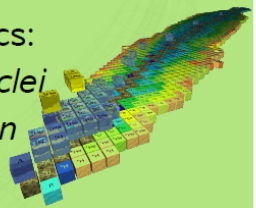
Nucleon Structure

- 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

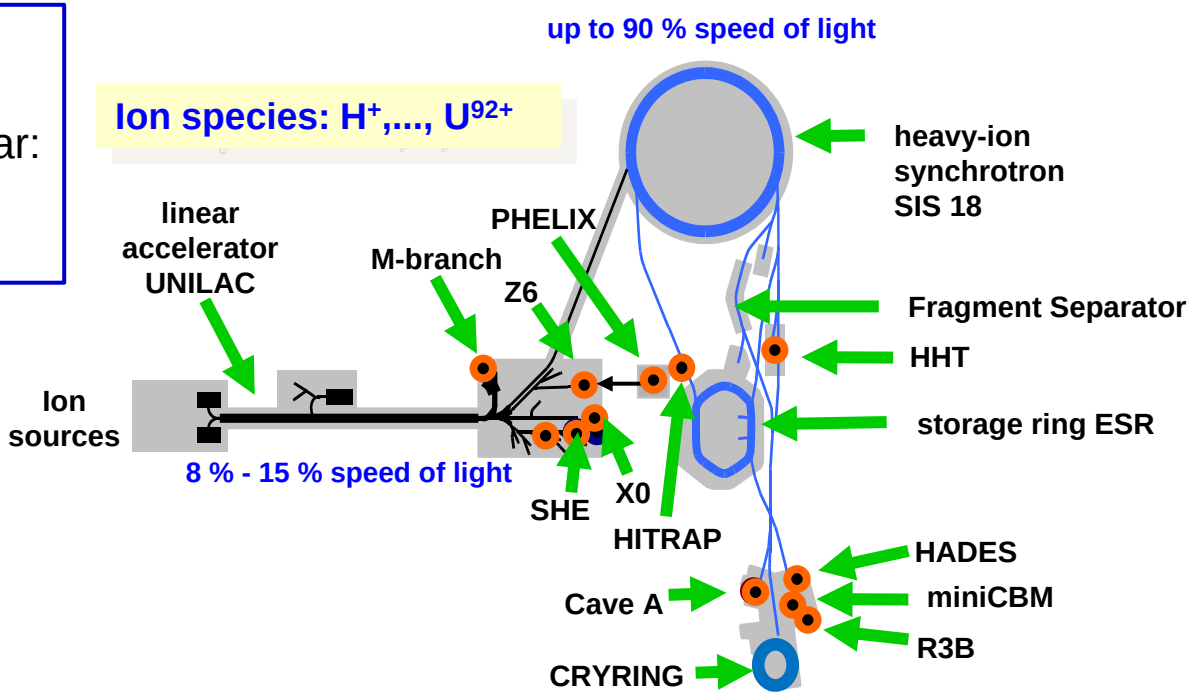
The combination of PANDA's discovery potential for new states, coupled with the ability to perform high-precision systematic measurements is not realised at any other facility or experiment in the world.

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

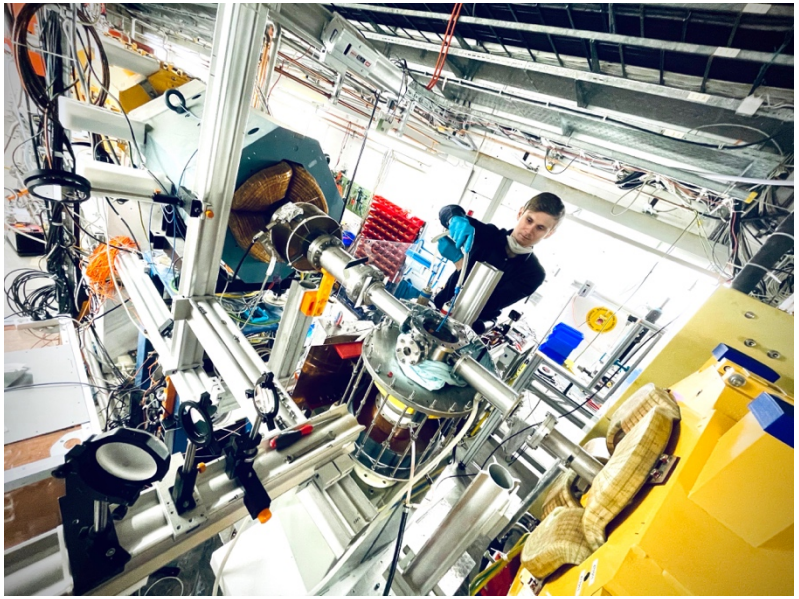


- Science while realizing FAIR
  - strong response by scientific community, over 1 thousand scientists involved, demand largely exceeding the available beamtime, confirming the attractiveness of the experimental opportunities

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

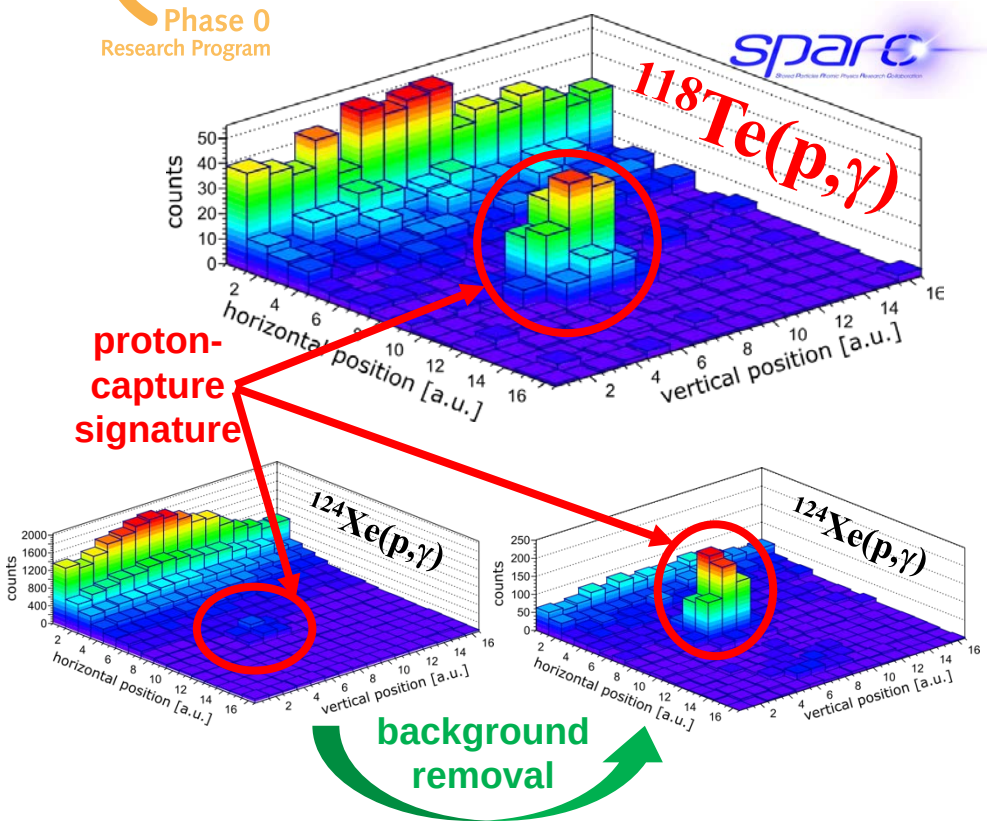
PRIOR-I (2014) PRIOR-II (2021)



Phase 0
Research Program

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

- 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



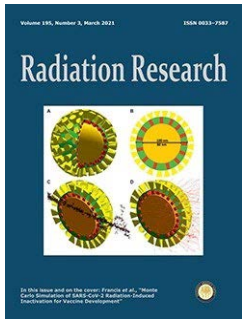
Jan Glorius et al.

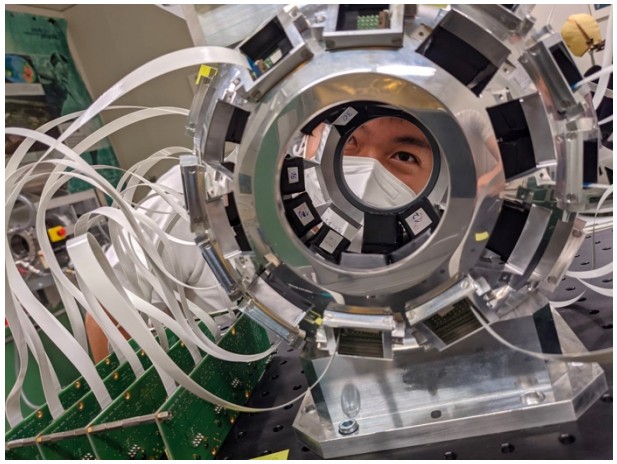
SPONSORED BY THE Federal Ministry of Education and Research

Biophysics FAIR Phase-results examples

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

FAIR Phase 0 Research Program



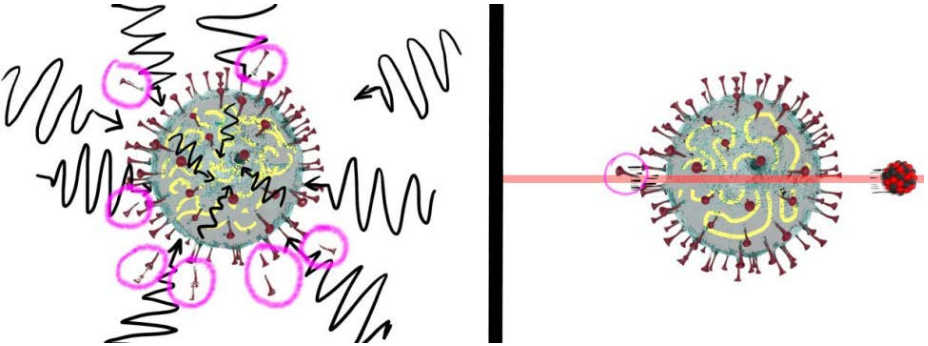


Hybrid γ-PET detectors for RIB

APPA

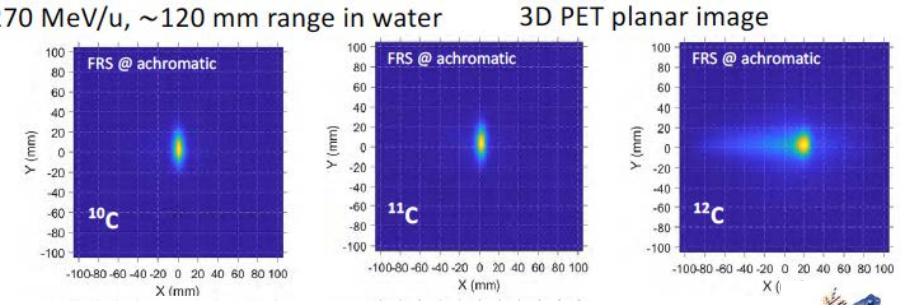
NUSTAR

LMU



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

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



www.gsi.de/BARB

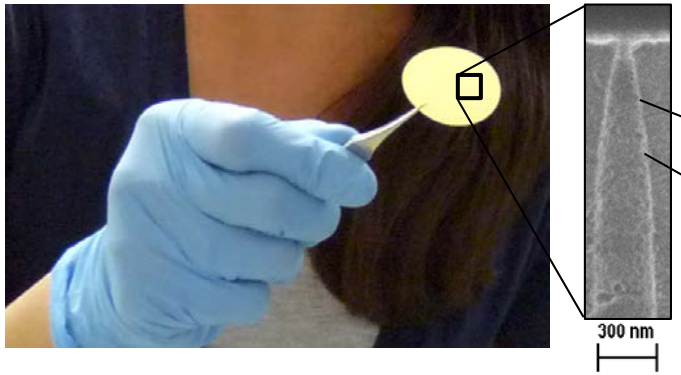
umcg

FAIR Phase-0 results on Material Science, example

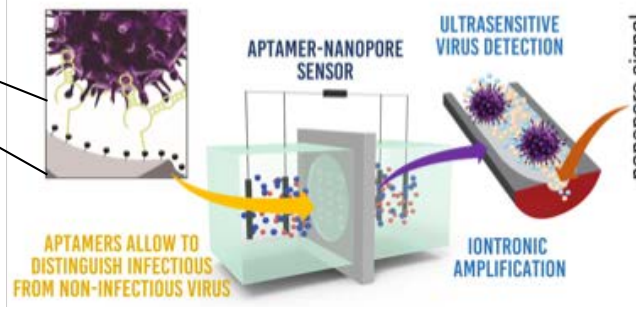
- New sensor for SARS-CoV-2 and other viruses based on GSI/FAIR nanotechnology
  - better and faster virus detection with single nanopore membranes
  - detection of SARS-CoV-2 in saliva, serum or wastewater without sample pretreatment
  - same sensitivity as a qPCR test, result in 2 hours
  - sensor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

FAIR Phase 0 Research Program

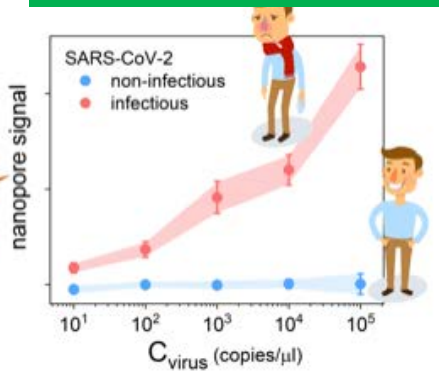
Highly sensitive nanopore by Ion-track nanotechnology



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

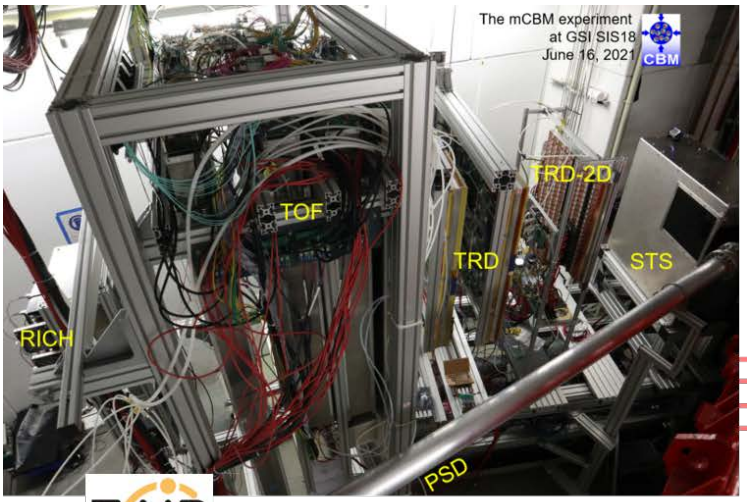


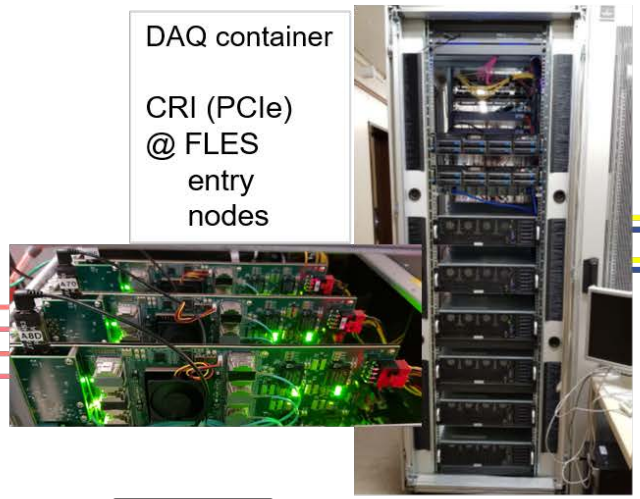
Transport measurements through coated nanopore indicate infectious state of tested virus



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

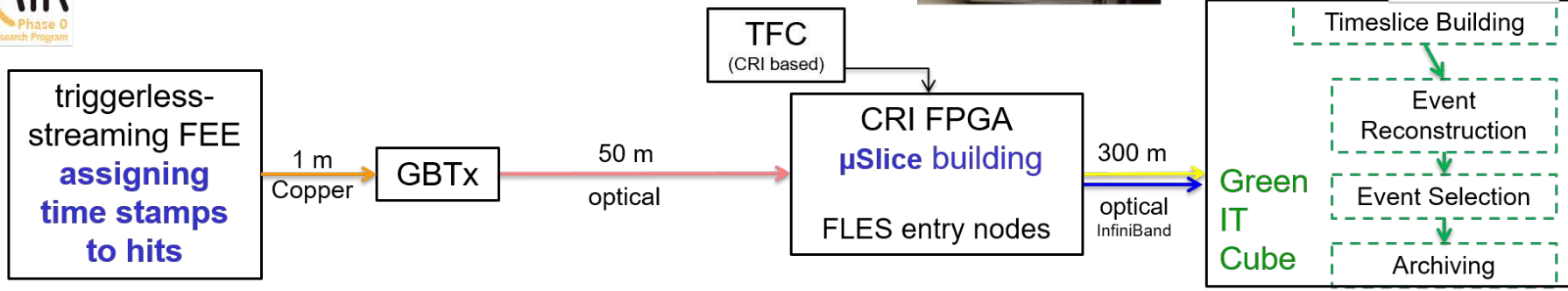




optical fibers 50m

optical fibers 300 m

FLES processing nodes



FAIR: Unique Opportunities . . . & Challenges

Backup

FAIR - The Universe in the Laboratory

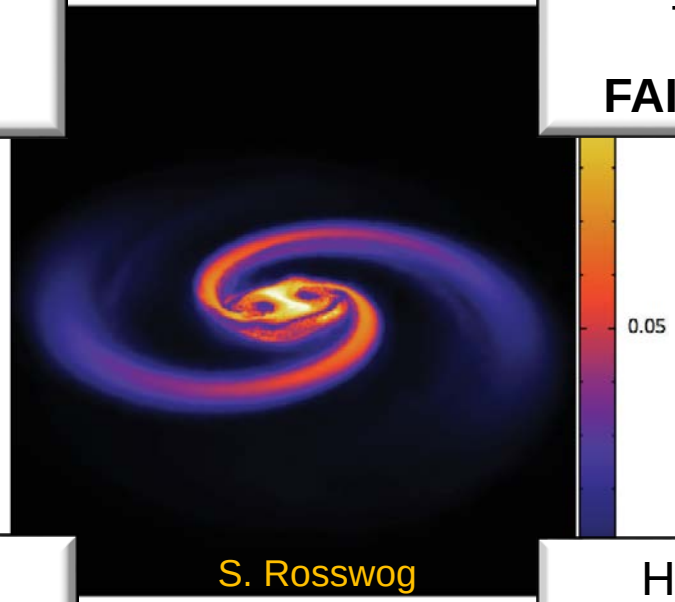
From Neutron Star Mergers to Platinum and Gold

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