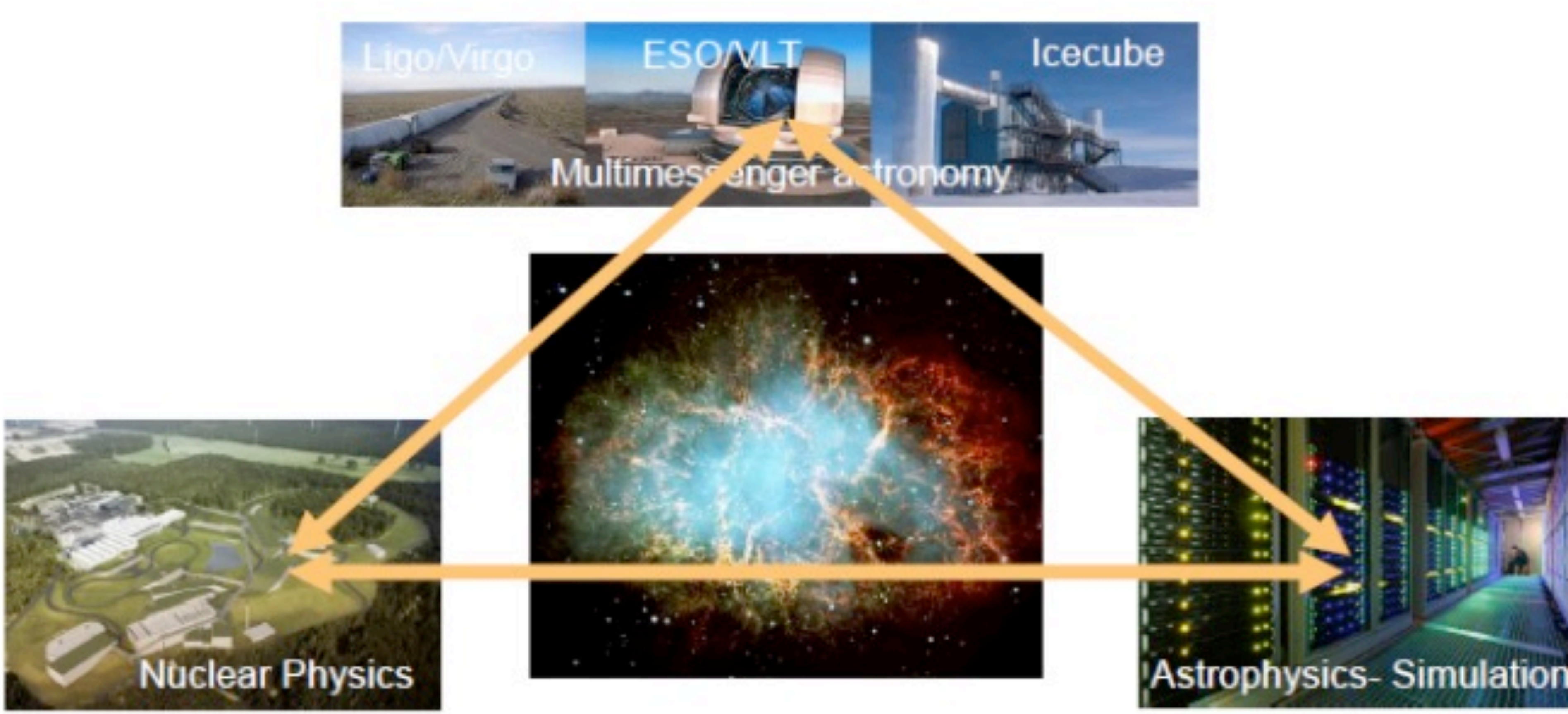
FAIR

the Universe in the Lab

Paolo Giubellino

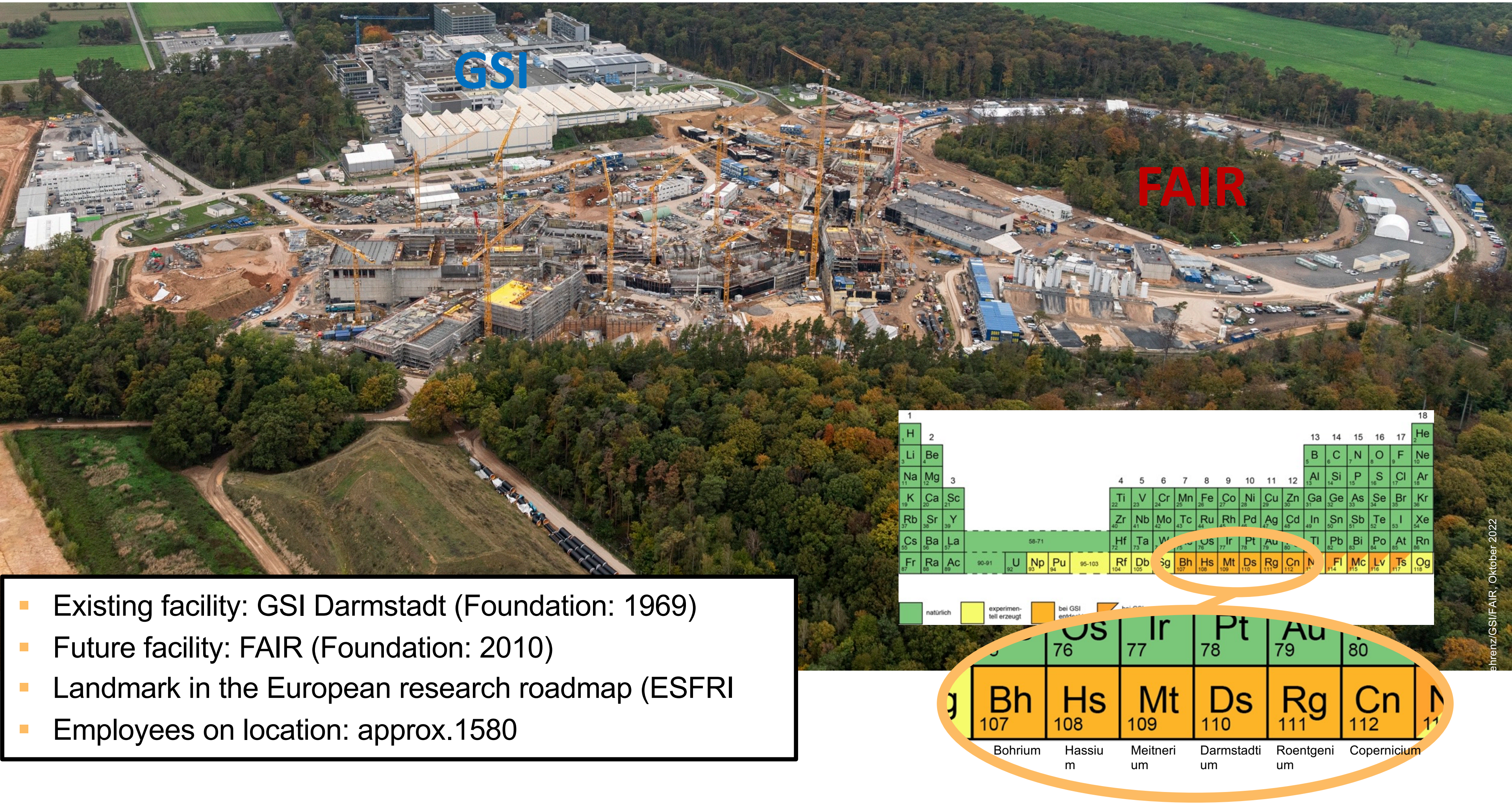
Erice, June 15th 2023

A special moment for Nuclear Physics



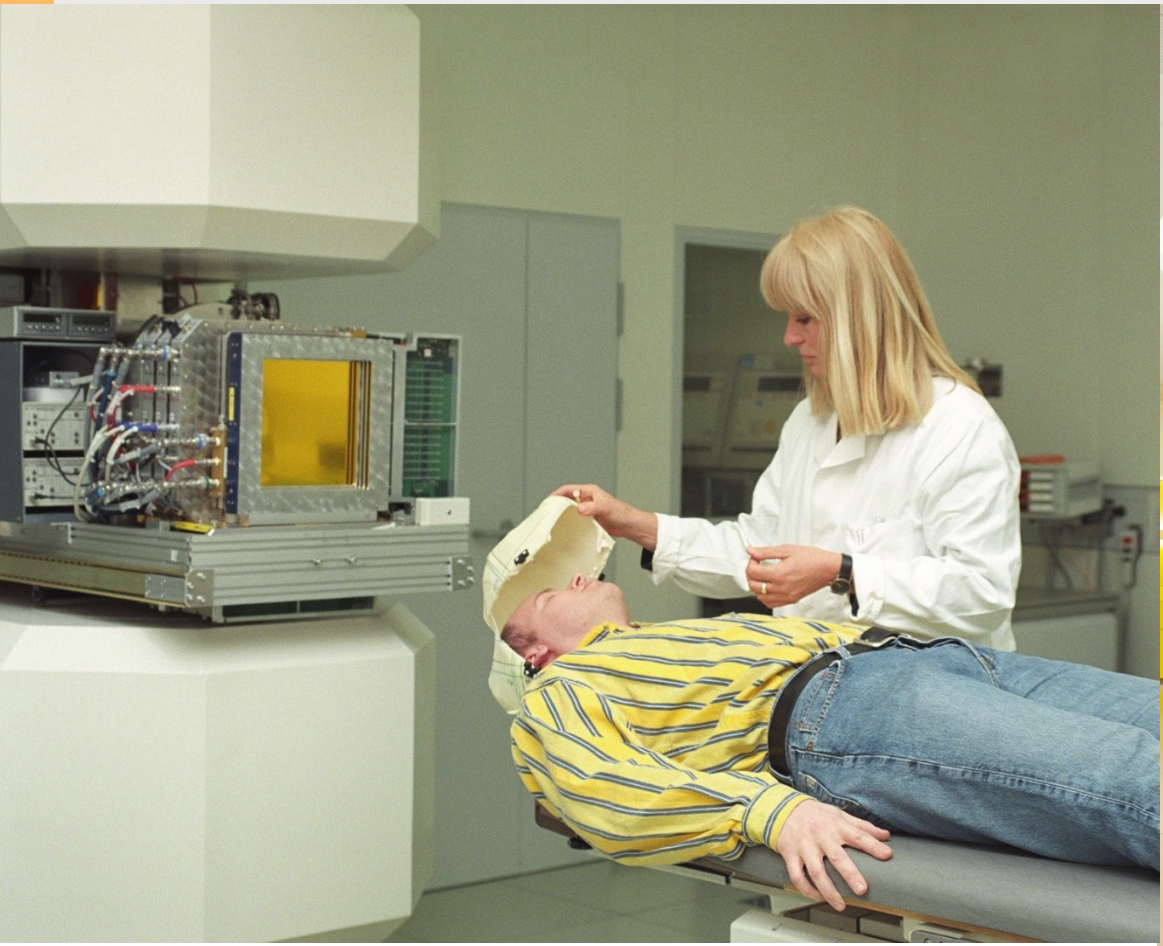
- **But also "Nuclear Physics in Everyday Life"**<u>... space, energy, medicine...</u>
- <u>https://www.nupecc.org/pub/np_life_web.pdf</u>

GSI GmbH – Helmholtzzentrum für Schwerionenforschung
FAIR GmbH – Facility for Antiproton and Ion Research



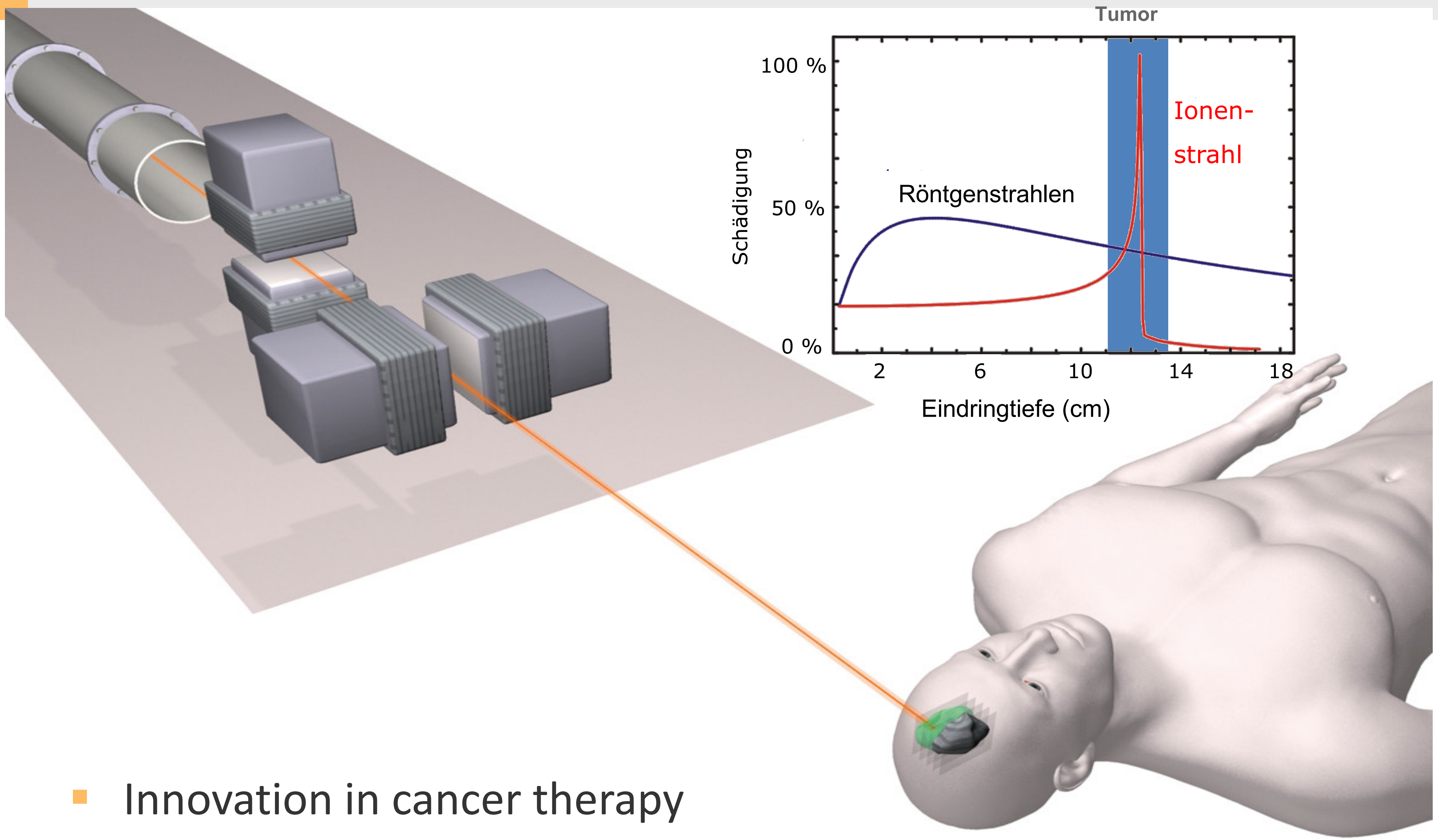
- Existing facility: GSI Darmstadt (Foundation: 1969)
- Future facility: FAIR (Foundation: 2010)
- Landmark in the European research roadmap (ESFRI
- Employees on location: approx.1580

GSI Discoveries



- Innovation in cancer therapy

GSI: Ion Beam Therapy



- Innovation in cancer therapy

Forefront Technologies

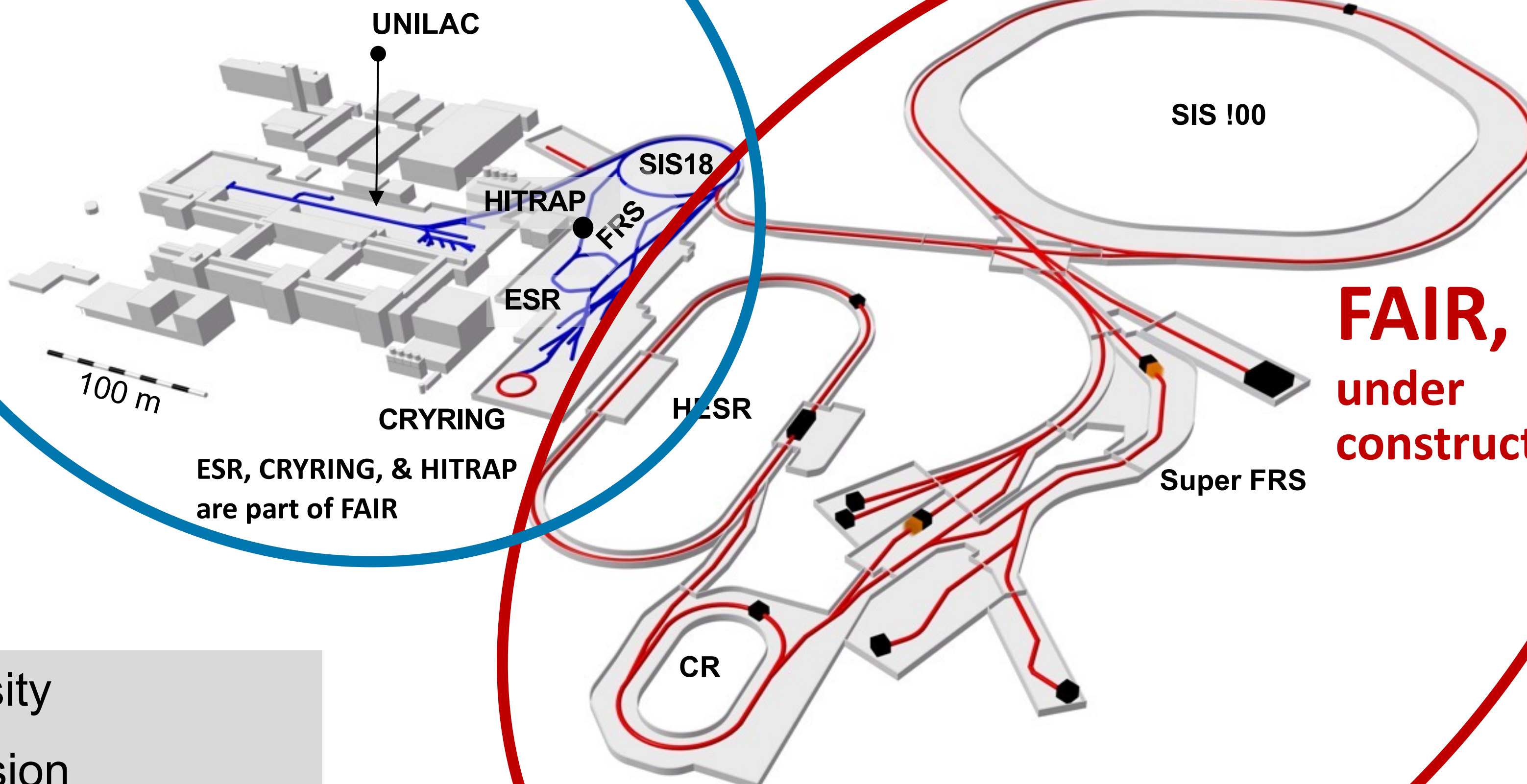
- Technological advancements in high-performance & scientific computing, Big Data, Green IT

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)



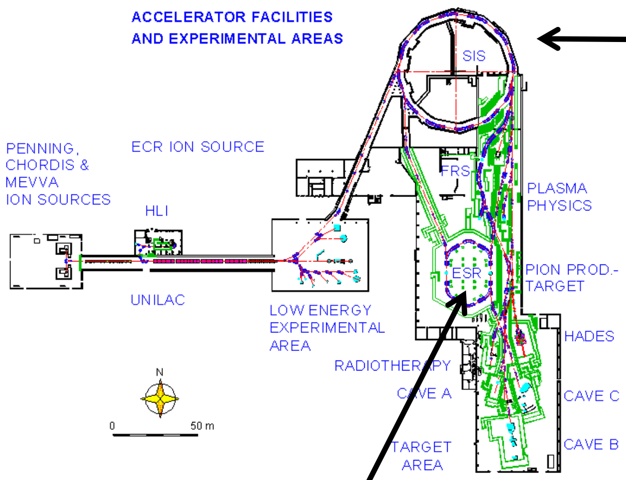
ESR, CRYRING, & HITRAP are part of FAIR

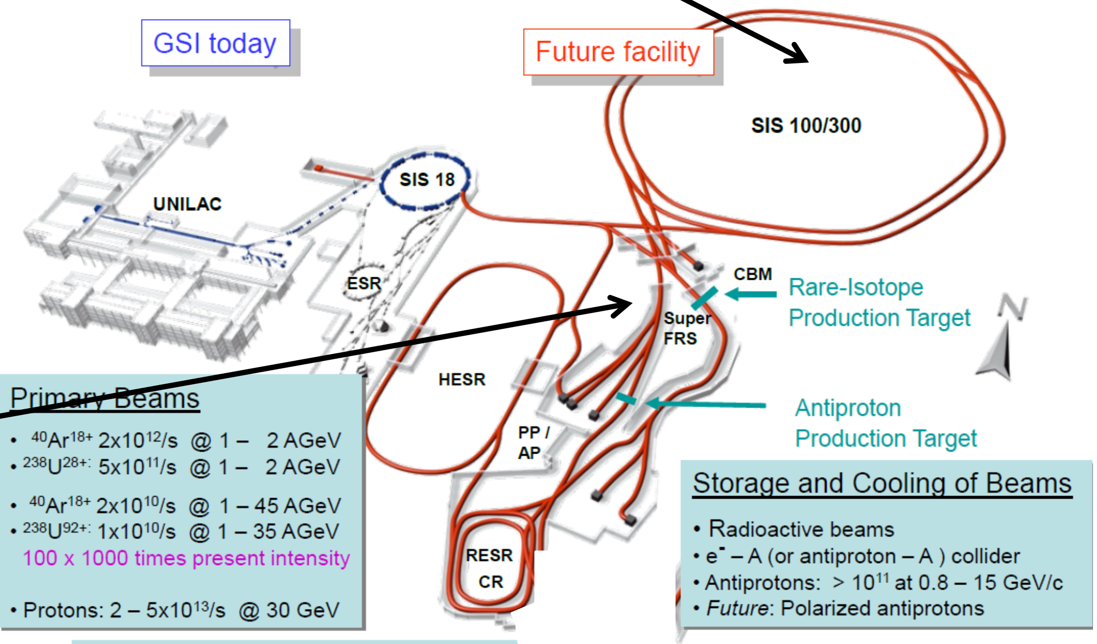
FAIR, under construction

- Intensity
- Precision
- Storage rings
- Antiproton beams

Primary Beams - Secondary Beams

Primary Beams





Secondary Beams

Primary Beams

- $^{40}Ar^{18+}$ $2x10^{12}$/s @ 1 – 2 AGeV
- $^{238}U^{28+}$: $5x10^{11}$/s @ 1 – 2 AGeV
- $^{40}Ar^{18+}$ $2x10^{10}$/s @ 1 – 45 AGeV
- $^{238}U^{92+}$: $1x10^{10}$/s @ 1 – 35 AGeV

100 x 1000 times present intensity

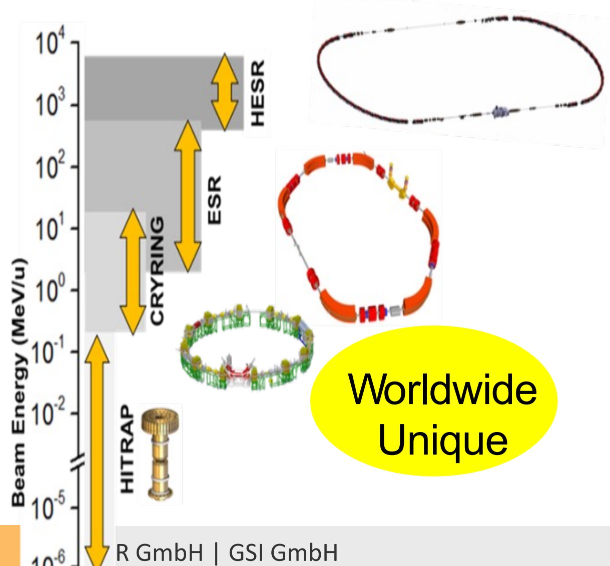
- Protons: 2 – $5x10^{13}$/s @ 30 GeV

Storage and Cooling of Beams

- Radioactive beams
- e^- – A (or antiproton – A) collider
- Antiprotons: > 10^{11} at 0.8 – 15 GeV/c
- *Future*: Polarized antiprotons

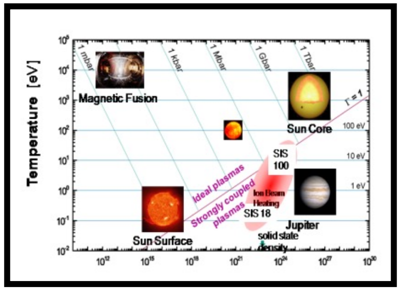
Secondary Beams

- Broad range of radioactive beams up to 1 – 2 AGeV
- RI- Intensities up to 10 000 over present
- Antiprotons



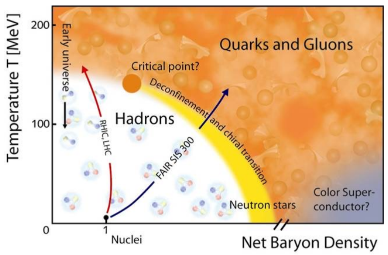
GSI and FAIR consist of primary and secondary beam facilities.

The FAIR science: four pillars



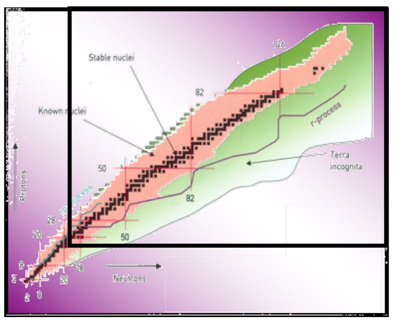
atomic physics, biophysics, plasma physics, material research

APPA



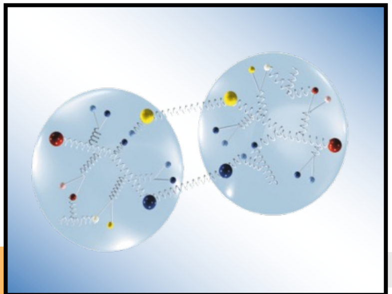
nuclear- and quark-matter

CBM



nuclear structure and nuclear astrophysics

NuSTAR



hadron structure and dynamics

PANDA

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 m³

of earth

to be moved

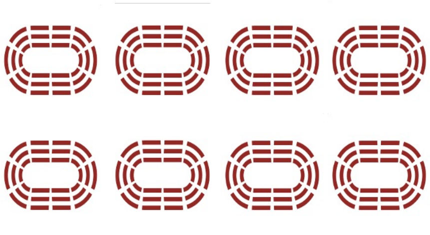
As much as for 5,000 single-family homes

600,000 m³

of concrete

to be used

As much as eight Frankfurt soccer stadiums

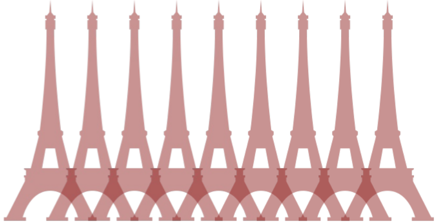


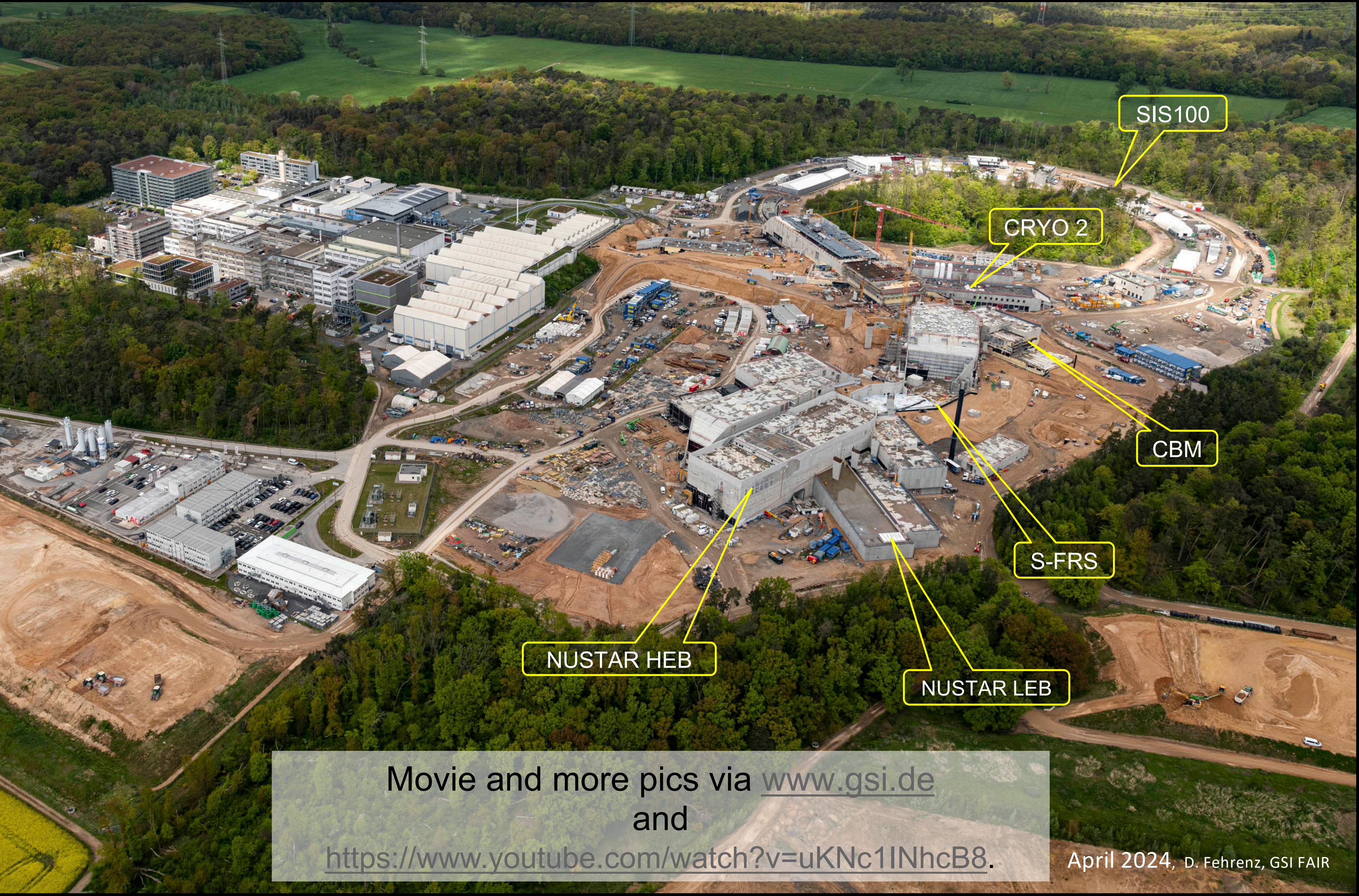
65,000 tons

of steel

to be utilized

As much as nine Eiffel Towers





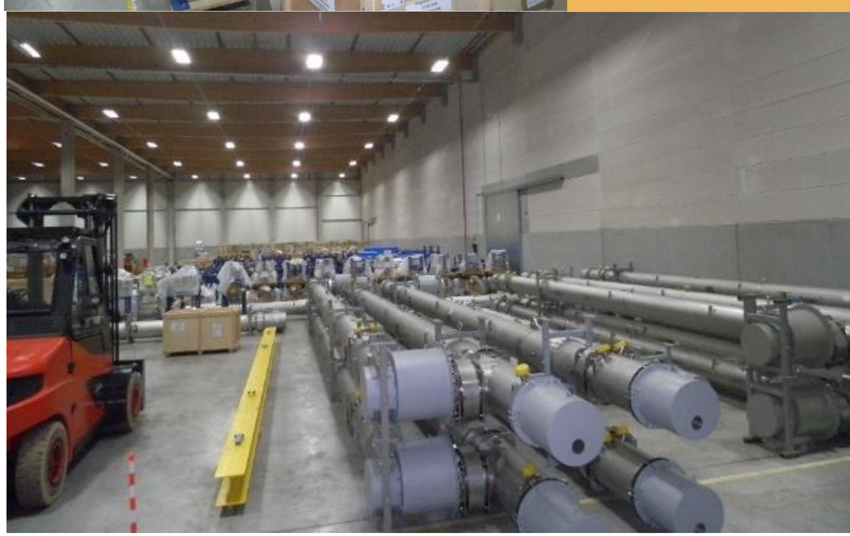
Movie and more pics via www.gsi.de
and
https://www.youtube.com/watch?v=uKNc1INhcB8.

April 2024, D. Fehrenz, GSI FAIR

FAIR Area South just a few months ago

Accelerators: delivery of components continues steadily

- Storage area: approx. 9.900 m²
- 4.195 objects (Components, assemblies, boxes, etc.)
- 50% of SIS100 components stored
- 90% of HESR components stored

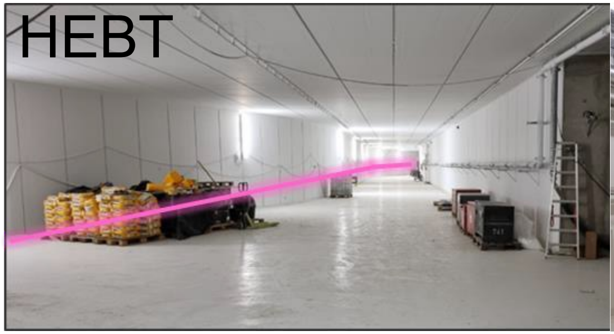


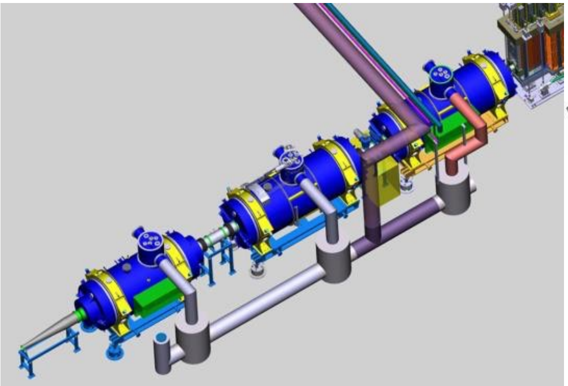
FAIR-COnstruction: Cryoplants

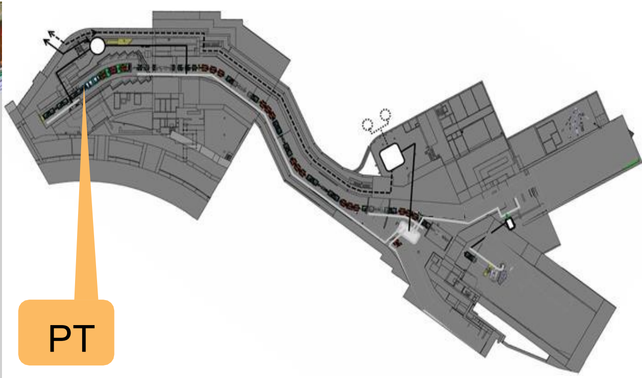
FAIR Insallation, infrastructure:
Cryo distribution and Power supplies

Installation of FAIR Accelerators

Installation procedes at four locations





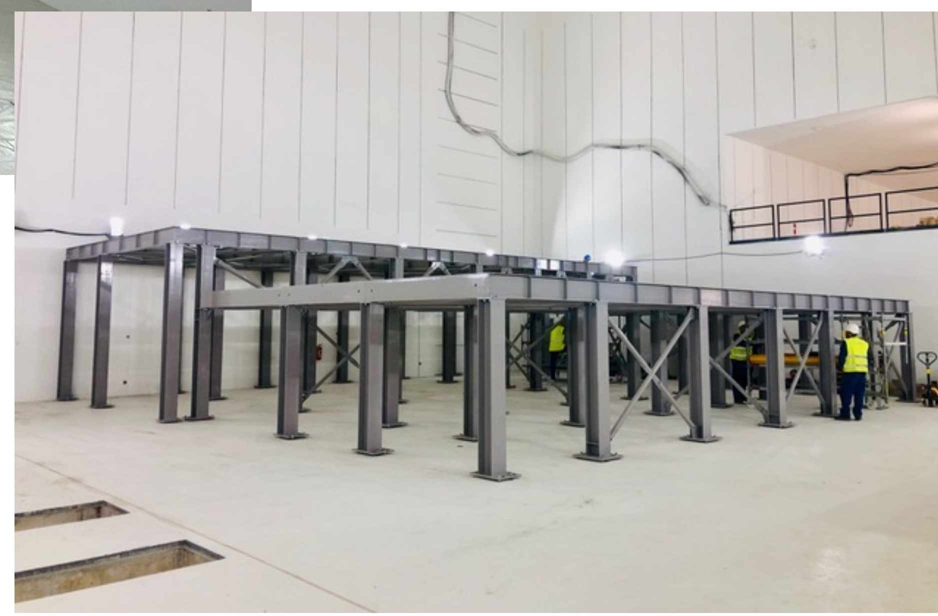


FAIR Installation

- March 2024: Insertion of the first quadrupoles for section T1S2

FAIR installation:
one 6th of the SIS 100 dipoles are in the tunnel being connected

FAIR-Installation

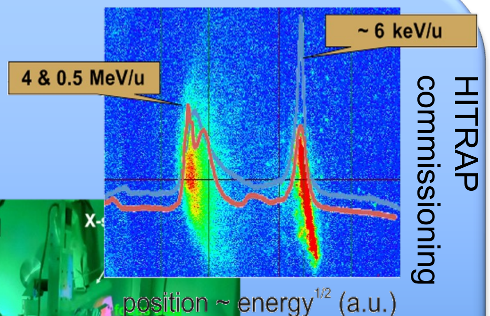


Experimental areas:

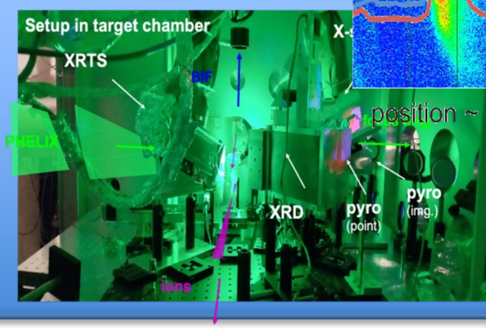
FAIR CBM Cave

Experiment Construction

APPA

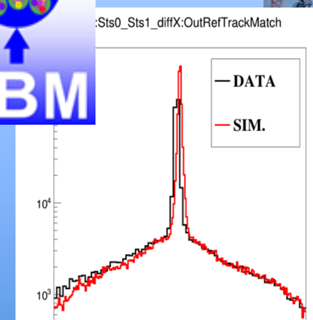


HITRAP commissioning



HED@FAIR diagnostics

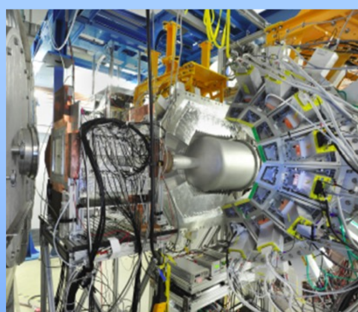
CBM



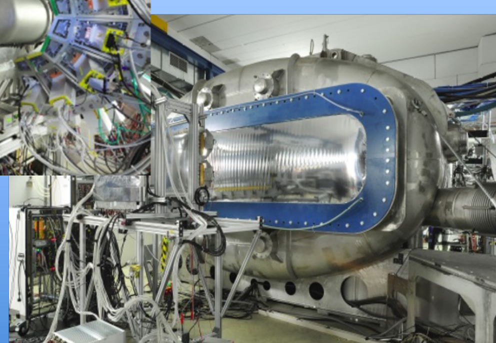
mCBM performance

Available detectors are used in Phase-0

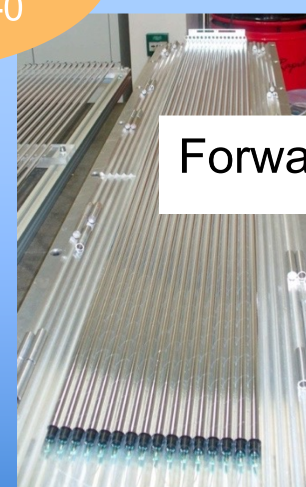
NUSTAR



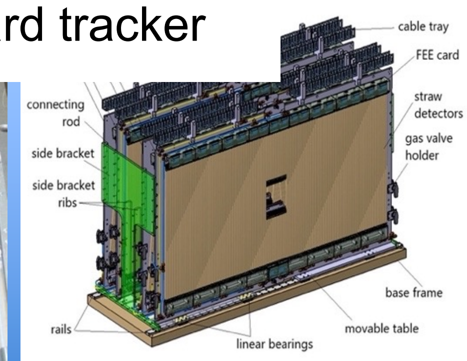
R3B: LH2 target, CALIFA, GLAD



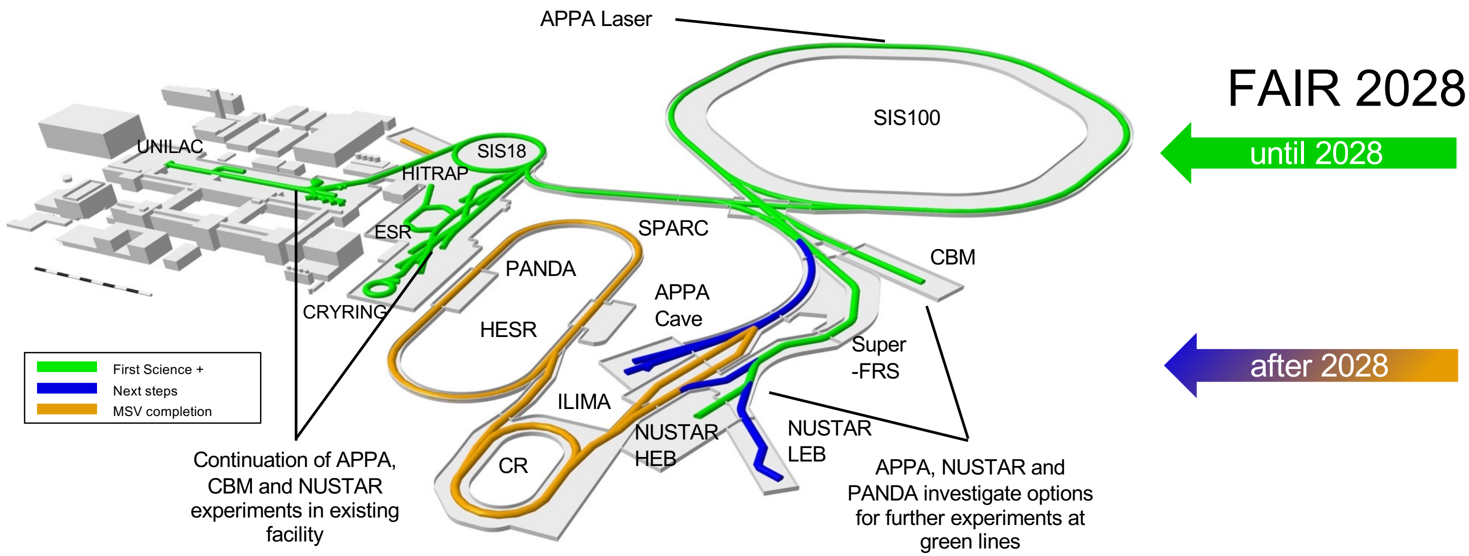
PANDA



Forward tracker



Current prospects and overall timeline



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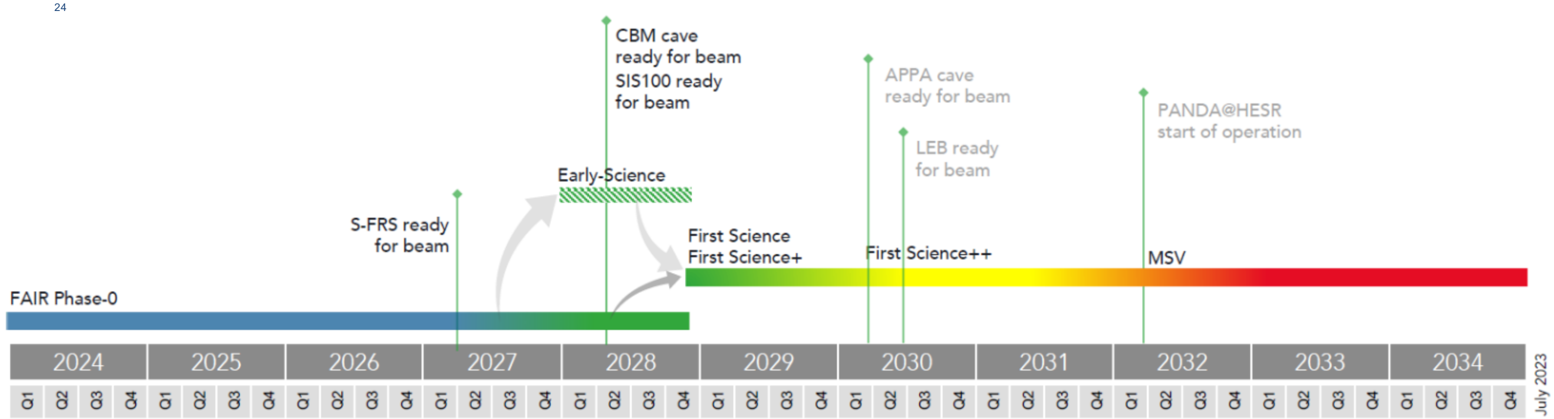
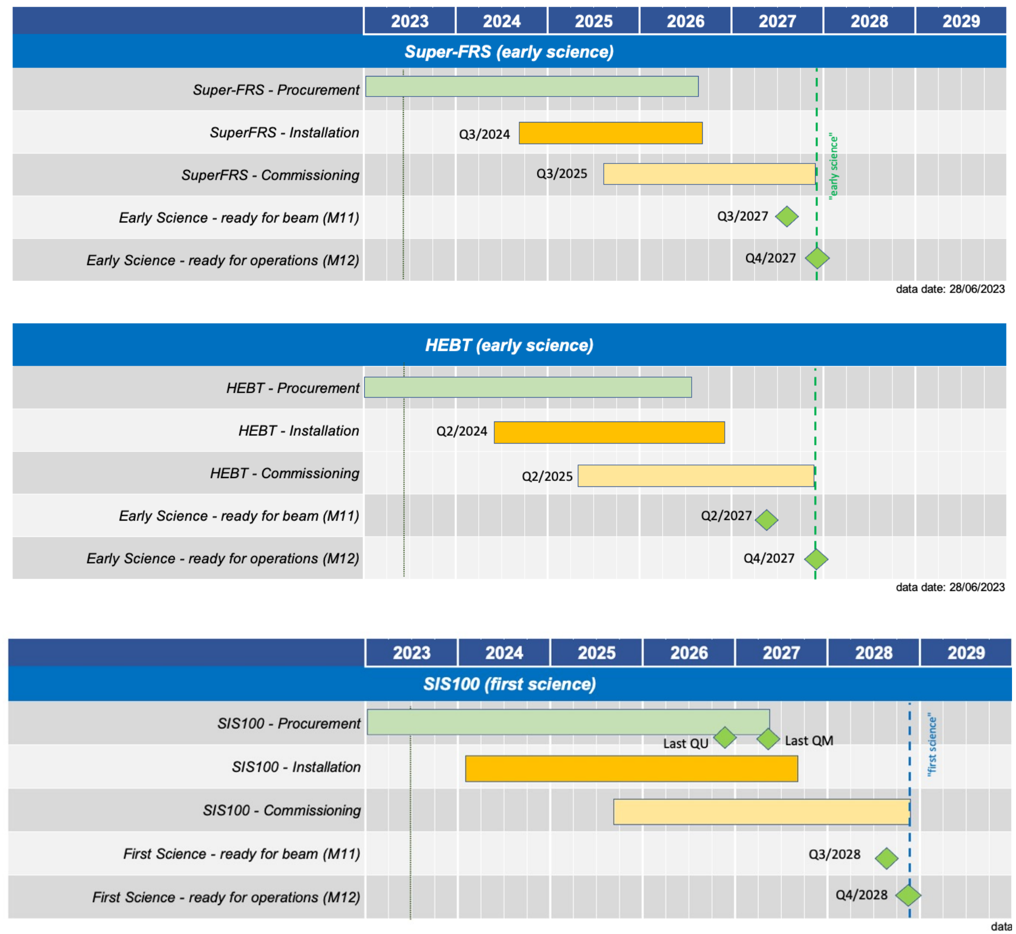


Project Timeline – On Track for Start in 2027/28

- Timeline on track to meet the project milestones
  - Start of Early Science operation by the end of 2027
  - Start of First Science operation by the end of 2028
  - First Science + can be achieved at the same time provided the shareholders approve it.
  - Next steps depend on funding



Creating extreme conditions existing in the universe with heavy ion accelerators

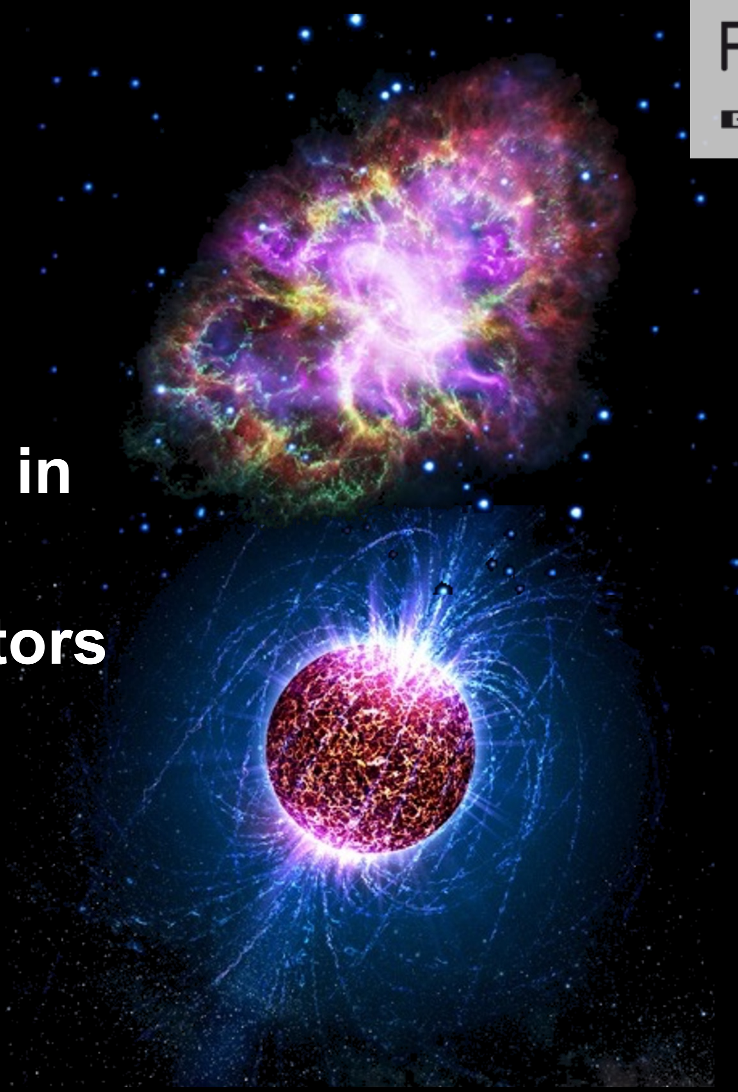
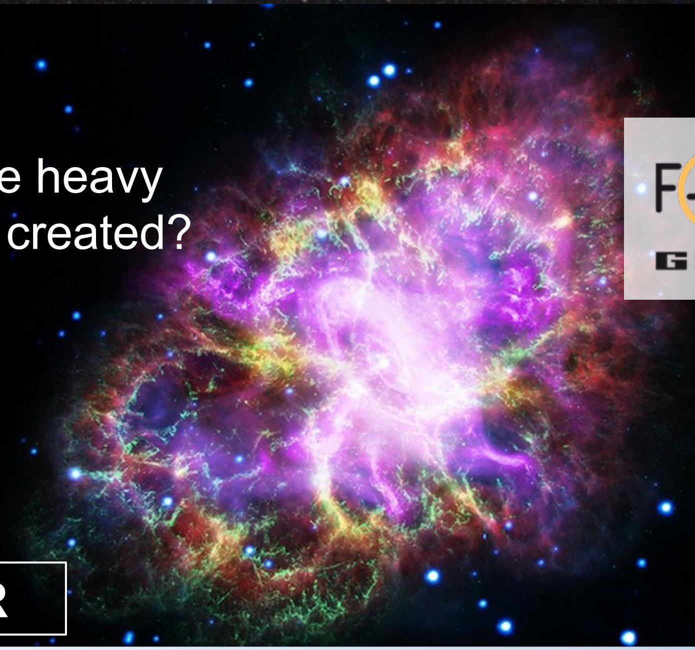


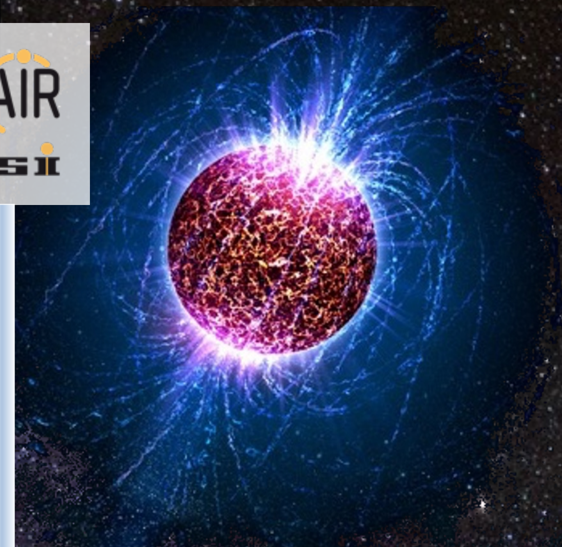
Foto: NASA, ESA, G. Dubner (IAFE, CONICET-University of Buenos Aires) et al.; A. Loll et al.; T. Temim et al.; F. Seward et al.; VLA/NRAO/AUI/NSF; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; and Hubble/STScI (oben), Penn State University (unten)

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



Where are heavy elements created?

NUSTAR



What is in the interior of a neutron star?

CBM

PANDA

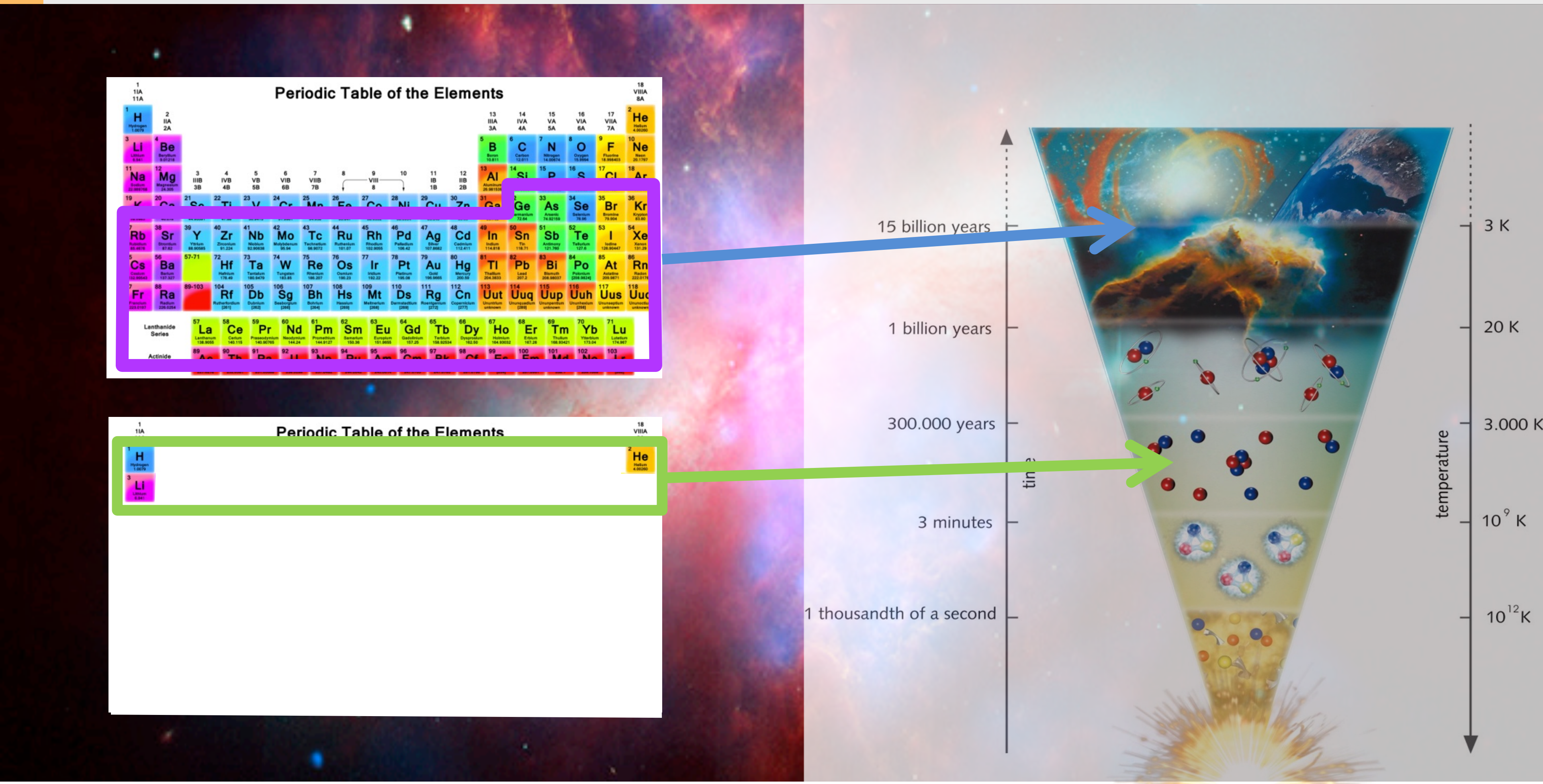
Glueballs:
What are protons and neutrons made of?
What is the structure of hadrons?

APPA

How do materials behave under high pressure?

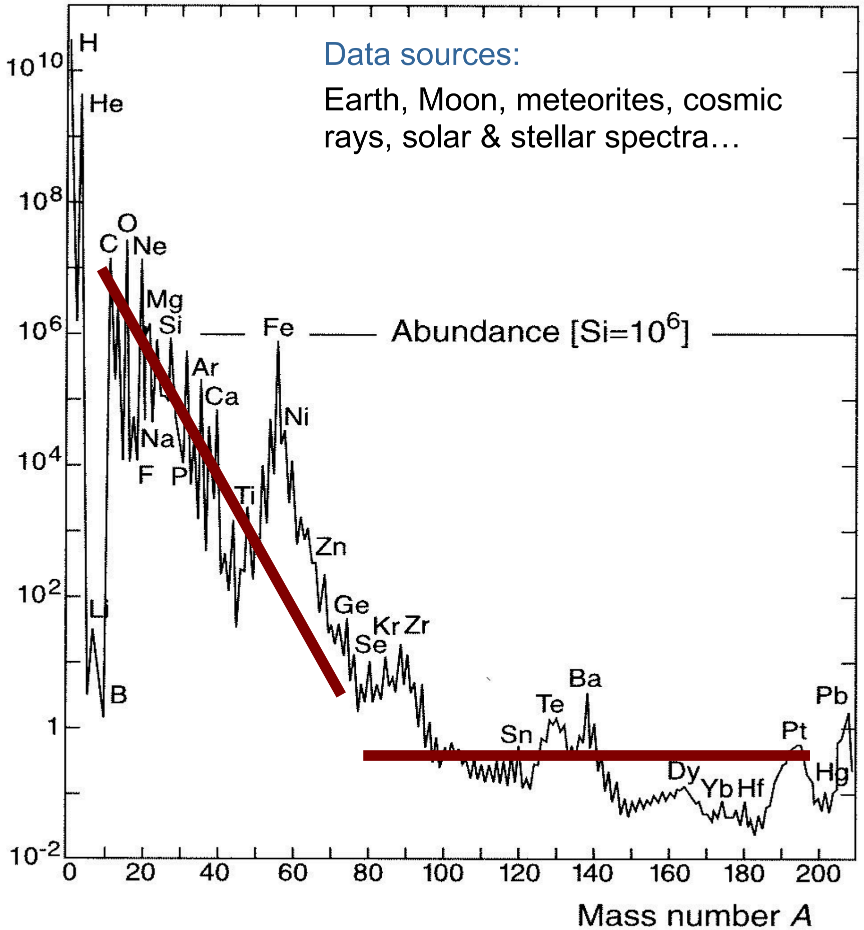
Fotos: Uranus, Jupiter, Erde Quelle: http://de.wikipedia.org

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***

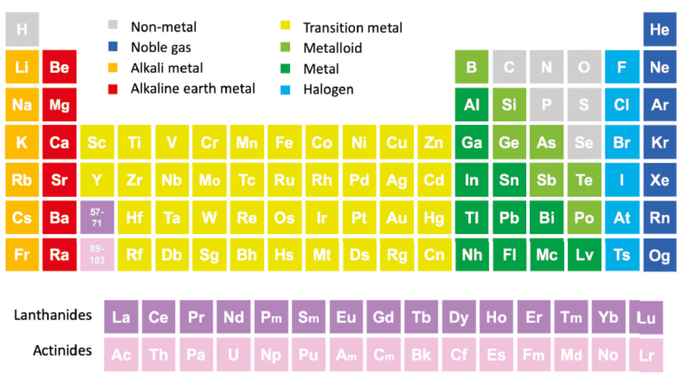
Solar Abundance Distribution



Features:

- distribution spans 12 orders of magnitude
- H ~ 75%, He ~ 23%
- C → U ~ 2% (“metals”)
- D, Li, Be, B under-abundant
- exponential decrease up to Fe
- almost flat distribution beyond Fe

Why these features?
Where do all elements come from?

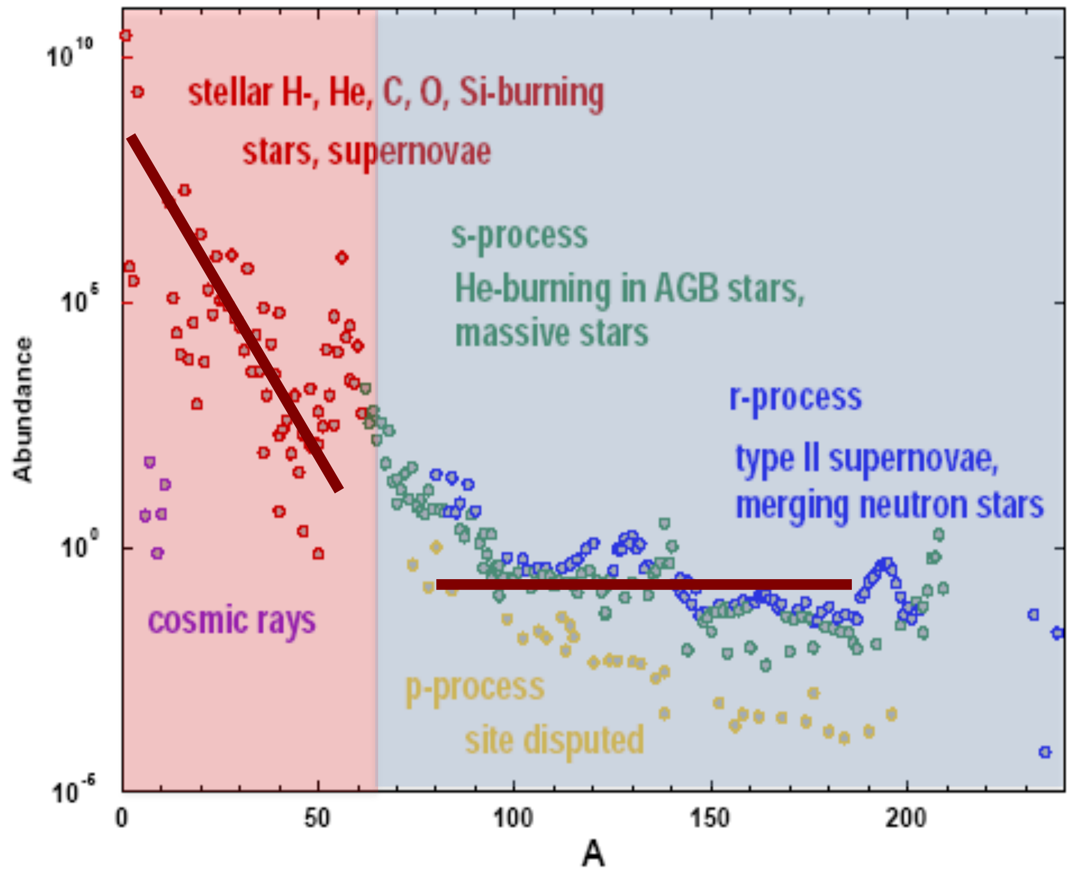


Stellar Nucleosynthesis: A Major Breakthrough

elements created by **nuclear reactions** in stars

fusion of charged particles

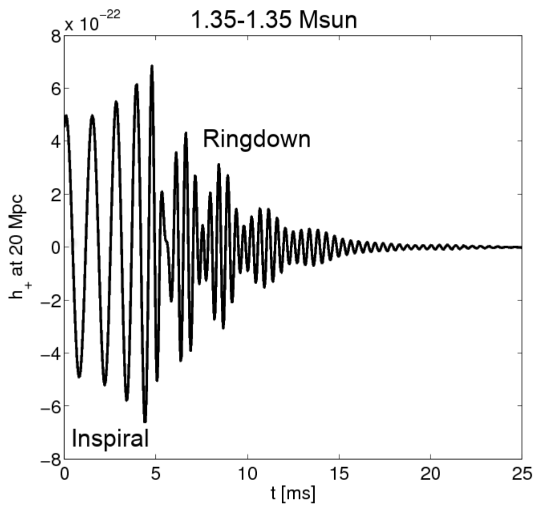
mainly **stable nuclei**



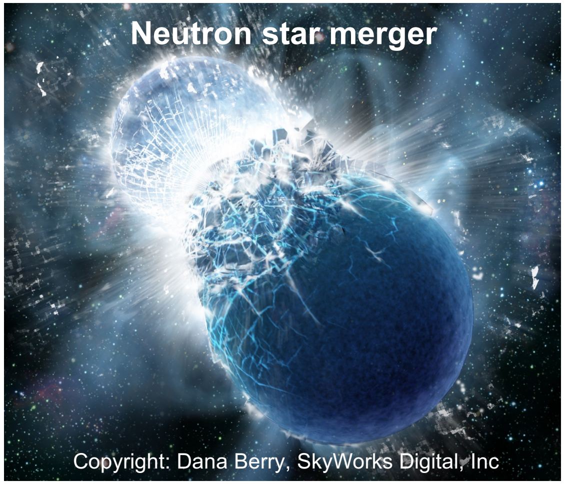
neutron-capture reactions

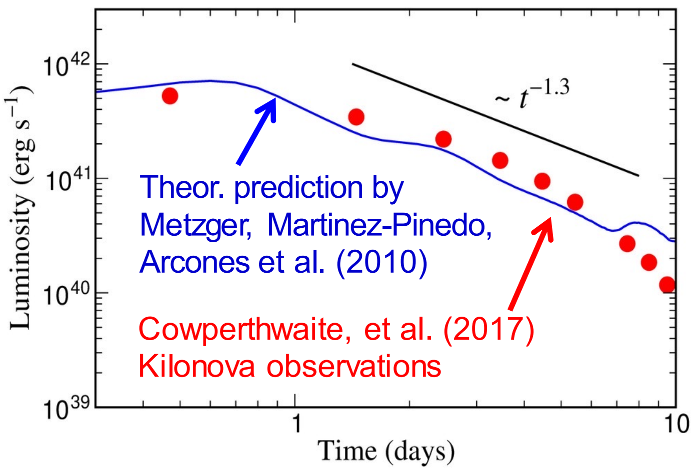
mainly **unstable nuclei**

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

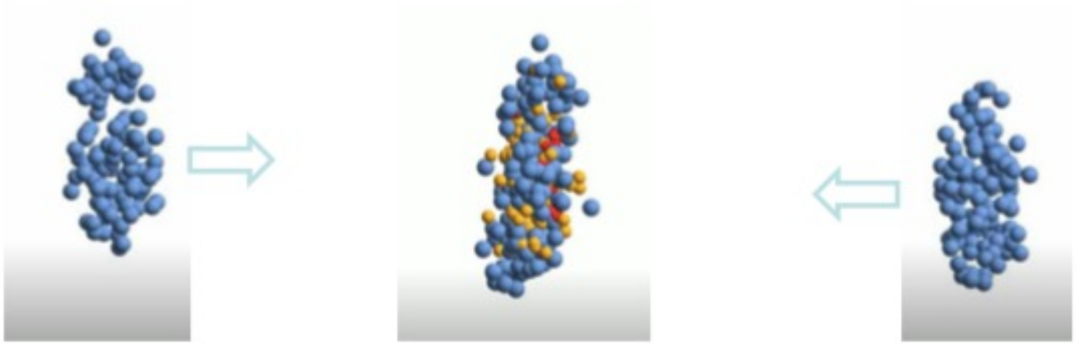
Neutron star merger

Temperature
T < 50 MeV

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

Reaction time
(GW170817)
T ~ 10 ms

Heavy ion collisions at SIS100



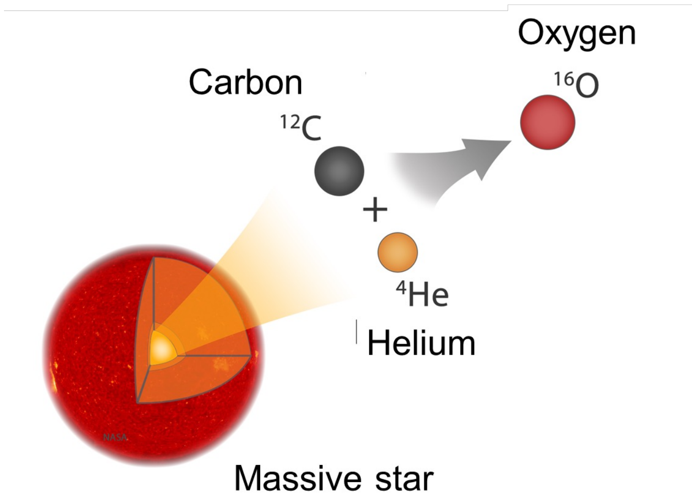
Compressed Baryonic Matter

Temperature
T < 120 MeV

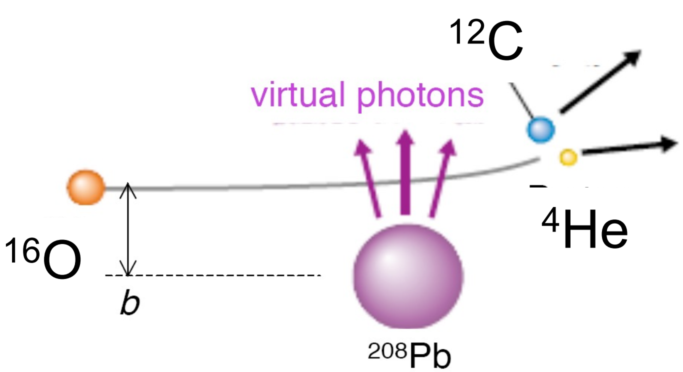
Density
$\rho < 8\rho_0$

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

How Nature makes the building blocks of life



rate insufficiently known at astrophysically energies

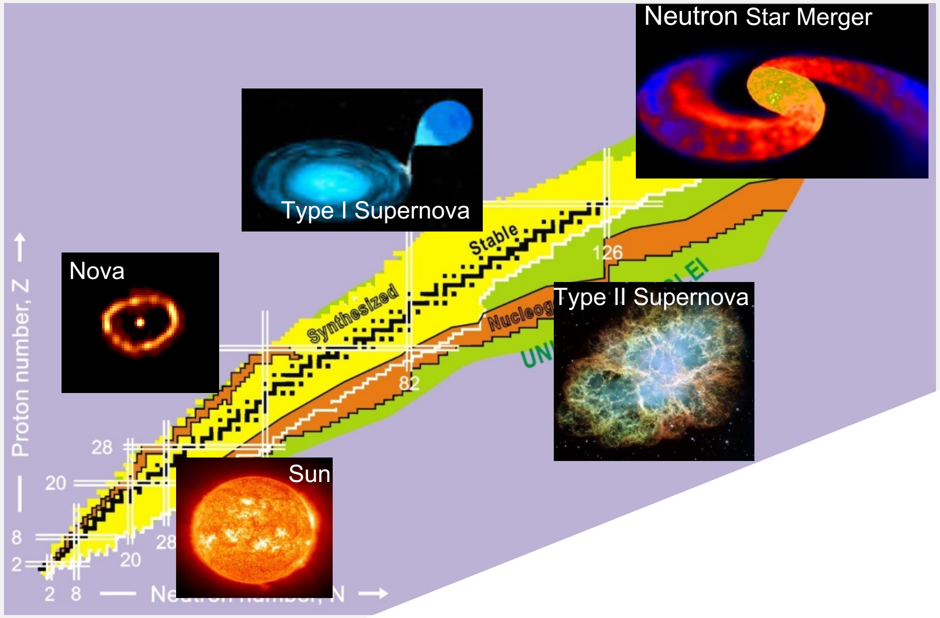


Alpha fusion on 12C is the stellar reaction of paramount importance,

W.A. Fowler, Nobel lecture 1983

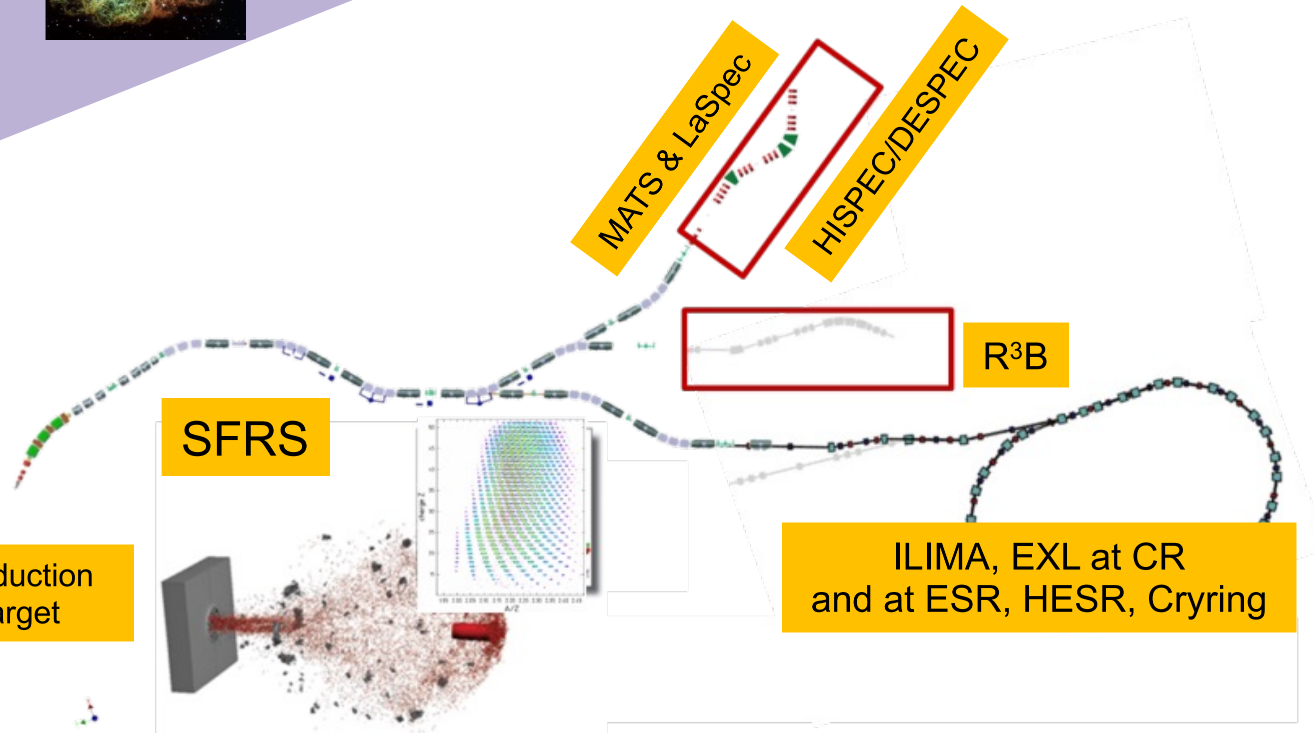
Experiment in inverse kinematics (Coulomb dissociation) requires high energies -> GSI/FAIR

NUSTAR
- Origin of Elements in the Universe



„Nucleosynthesis sites“ in the universe

„Nucleosynthesis sites” at FAIR



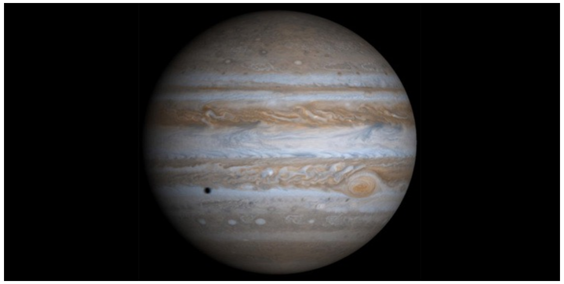
Primary intensities vs. GSI: x 100

SIS 100 → production target

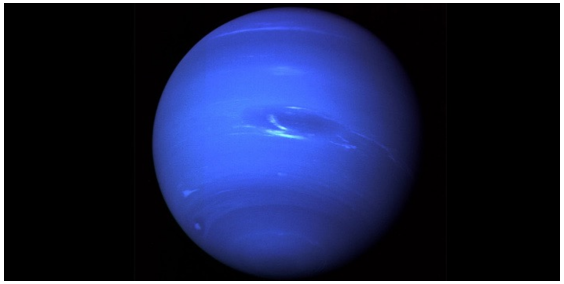
Questions about the Universe

Matter in the interior of the Earth and of large planets

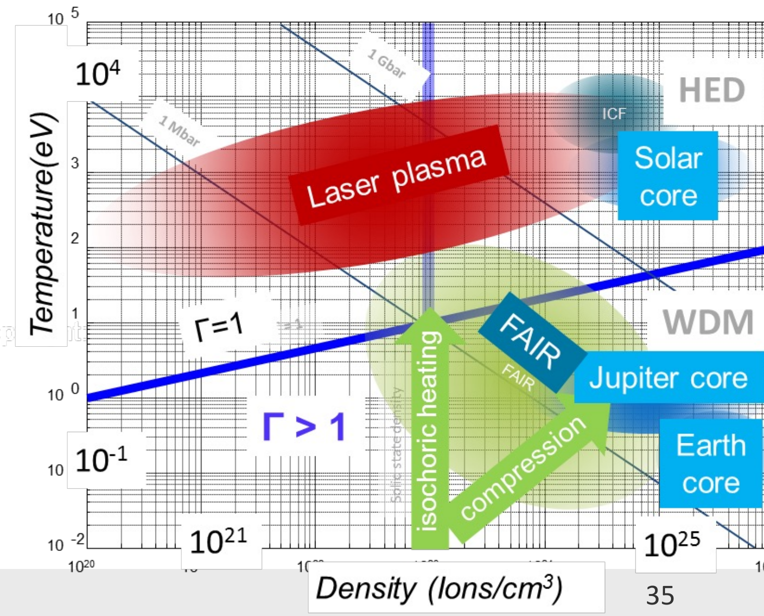
- The interior of our Earth is most likely composed of liquid iron. What is exactly the melting curve for iron?



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



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



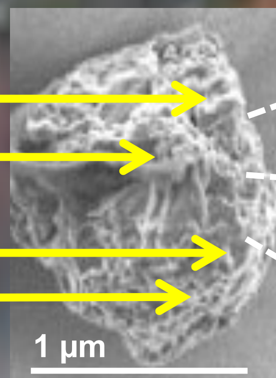
With direct applications in Inertial Fusion….

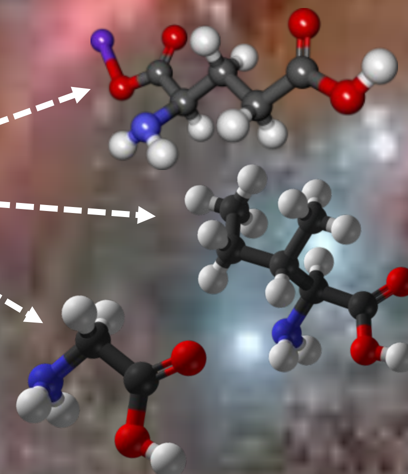
Studying cosmic radiation induced processes

FAIR GSI

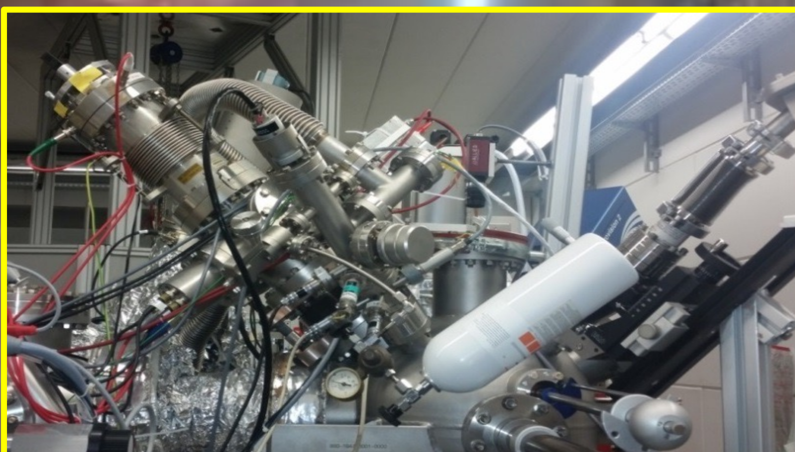
astrophysical ice grains (H_2O, CH_4, CO_2, NH_3, SO_2...)

200 MeV Ca ions



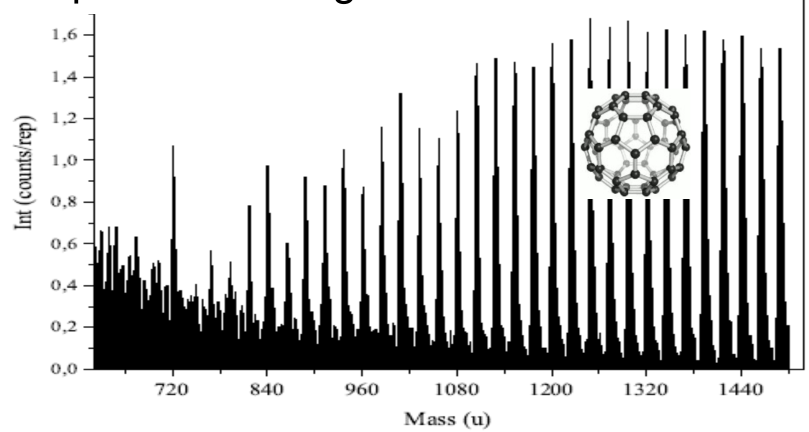


- C_nH_m polyaromatic hydrocarbons
- $C_6H_{13}NO_2$ amino acids
- C_{60}, C_{70} fullerenes

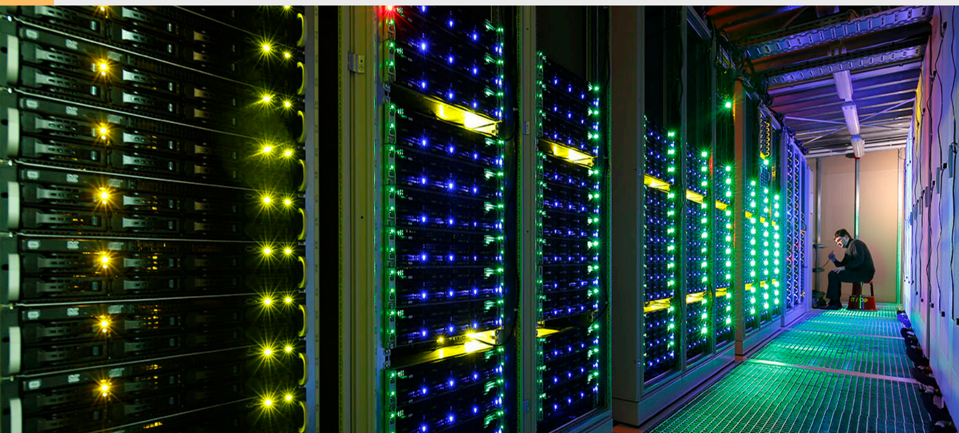


irradiation chamber and spectrometer

spectrum of large desorbed molecules

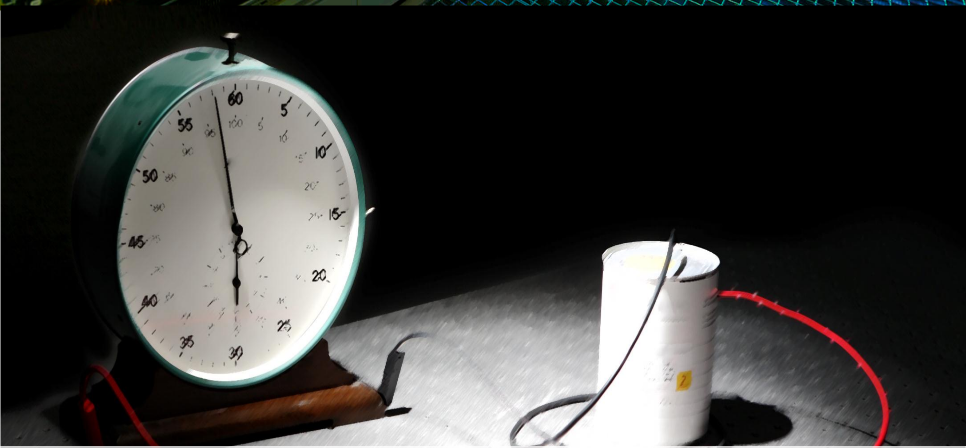


... with direct applications

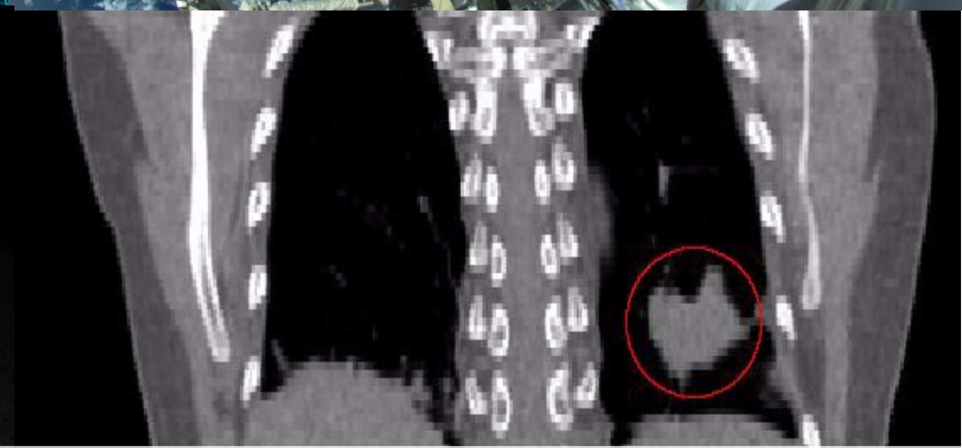


High-performance and scientific computing, big data, green IT

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

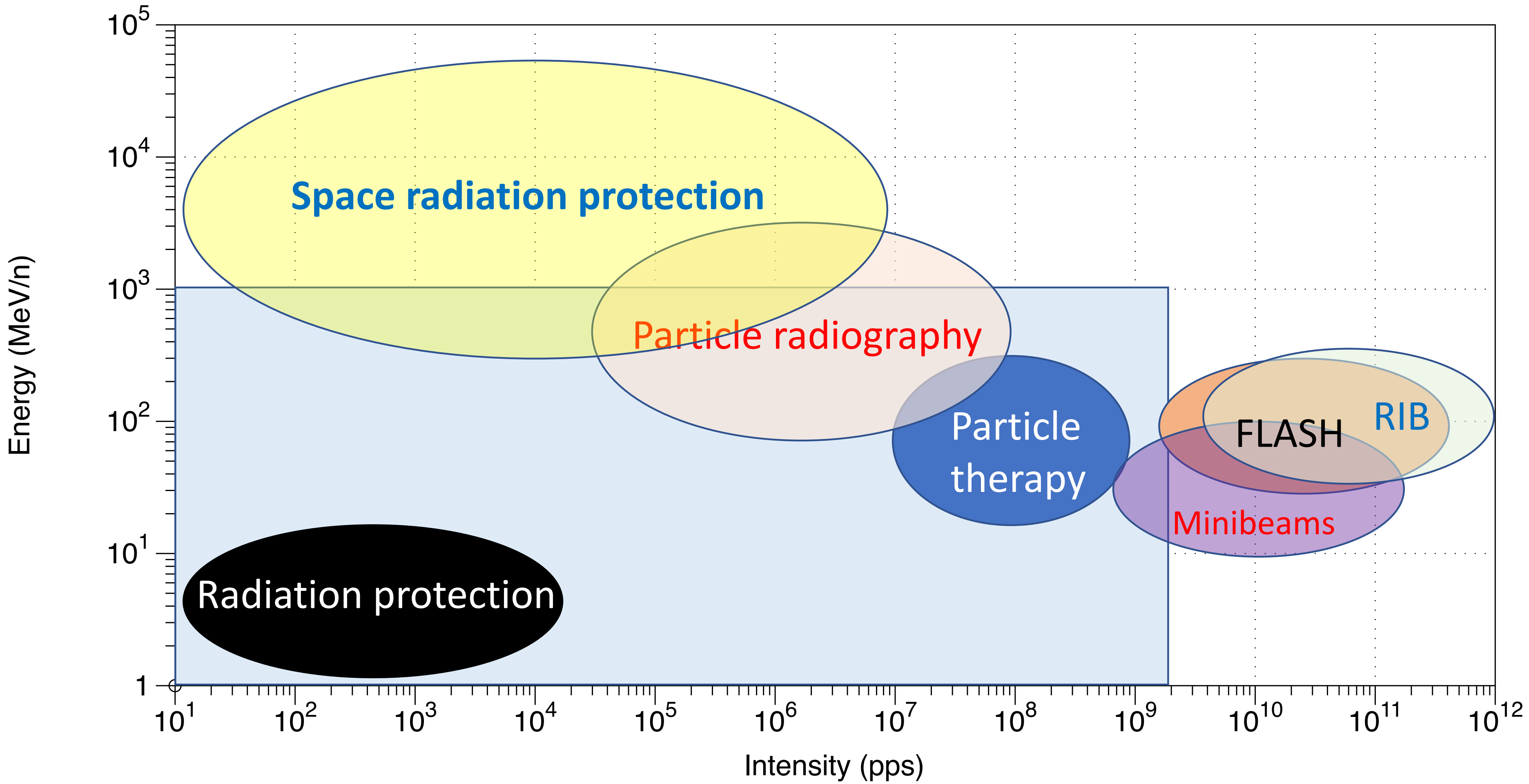


Development of nuclear clock: Promising candidate thorium-229



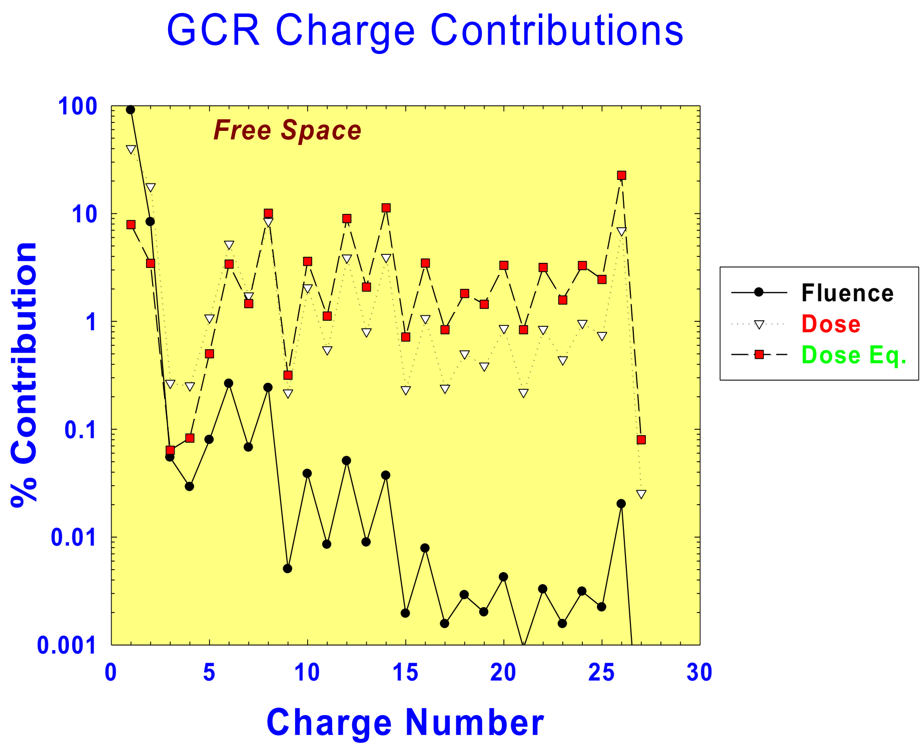
Novel applications for tumor and non-tumor diseases

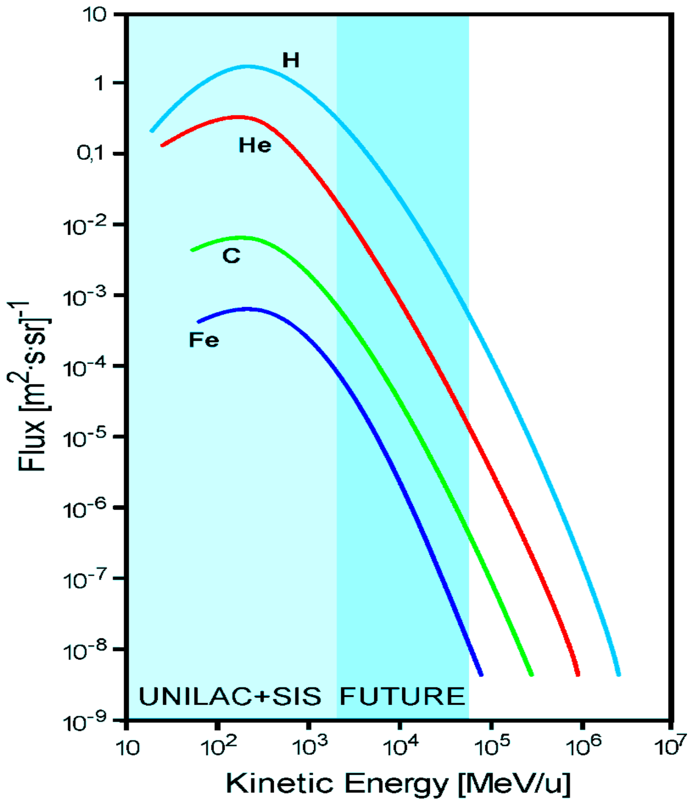
GSI/FAIR for Biophysics



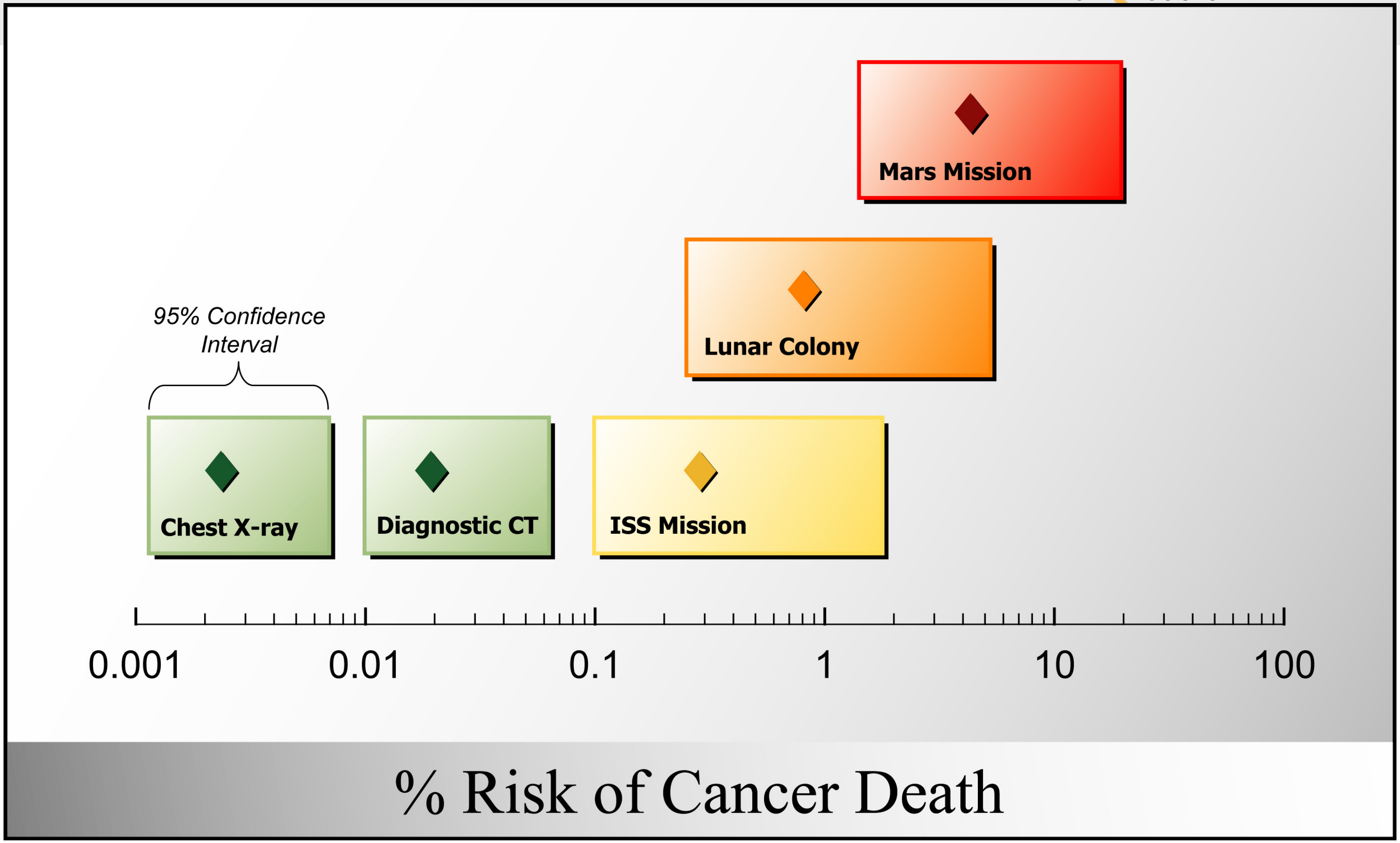
MoU FAIR-ESA, 2018

Galactic Cosmic Radiation





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



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

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

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

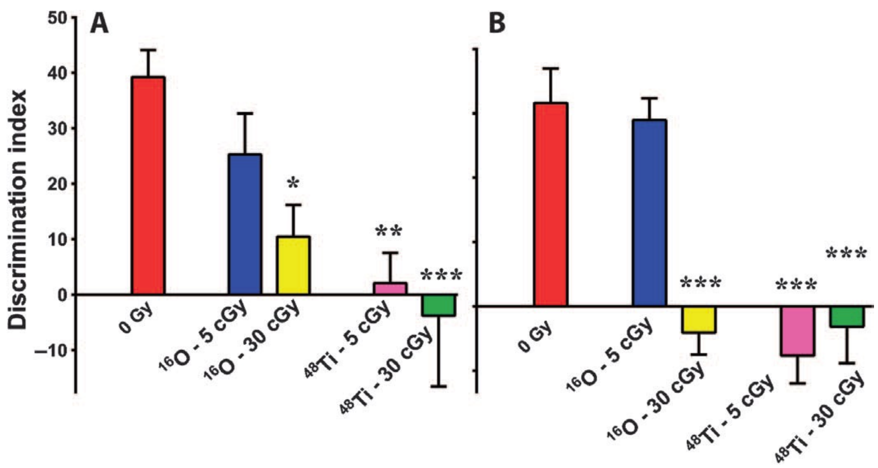
RESEARCH ARTICLE

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

COGNITIVE NEUROSCIENCE

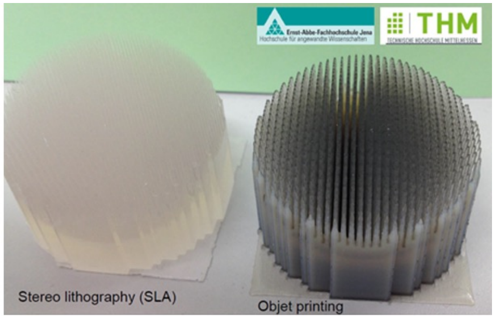
What happens to your brain on the way to Mars

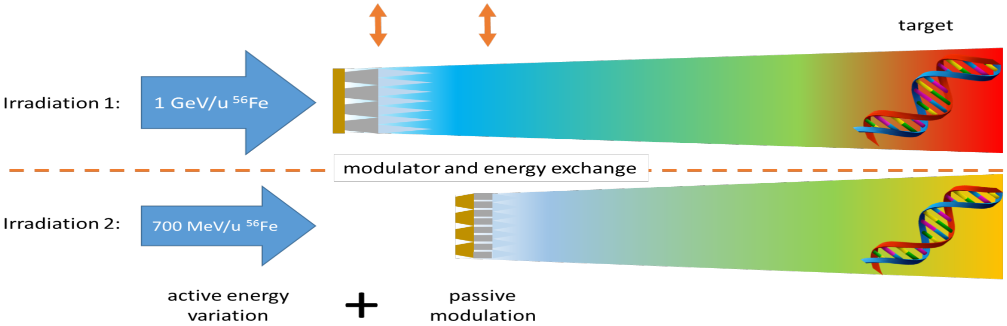
Vipan K. Parihar,[1] Barrett Allen,[1] Katherine K. Tran,[1] Trisha G. Macaraeg,[1] Esther M. Chu,[1] Stephanie F. Kwok,[1] Nicole N. Chmielewski,[1] Brianna M. Craver,[1] Janet E. Baulch,[1] Munjal M. Acharya,[1] Francis A. Cucinotta,[2] Charles L. Limoli[1]*

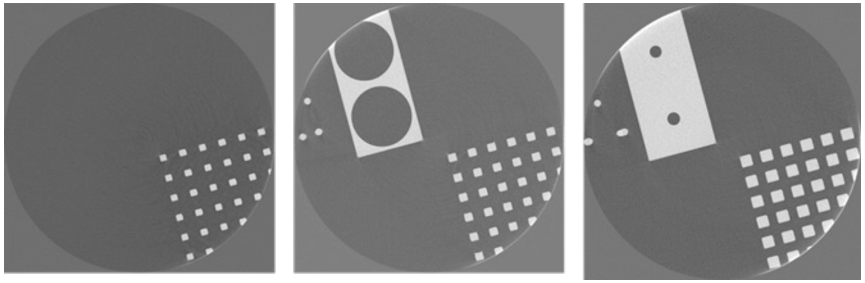


New infrastructures for FAIR tested in FAIR-phase-0 (March-June 2021)

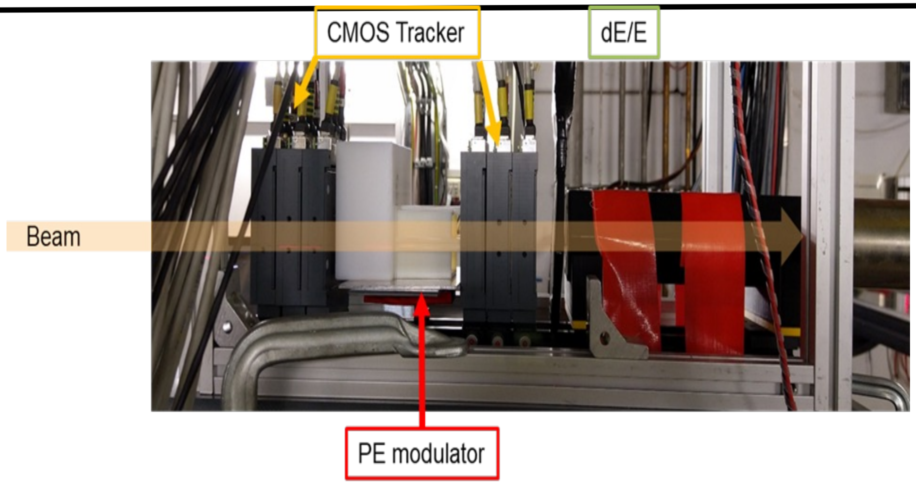
GCR simulator







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



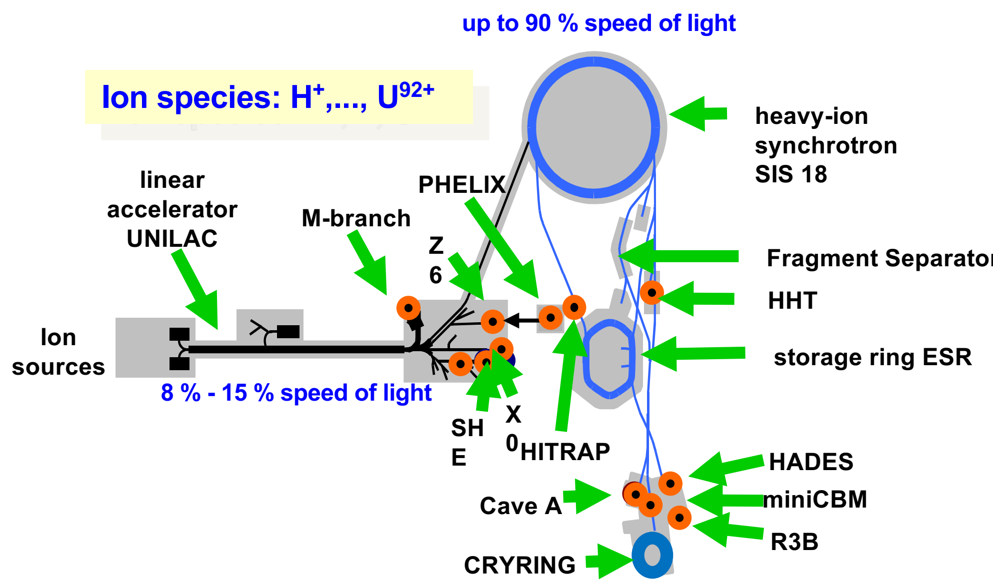
news….

- **Synthetic hibernation could provide protection from cosmic radiation**
- **14.11.2022 |**
  - **Astronauts could be put into artificial hibernation and in this state be better protected from cosmic radiation. An international research team led by the Biophysics Department of the GSI Helmholtzzentrum in Darmstadt now has found decisive indications of the possible benefits of artificial hibernation for radiation resistance.**
  - The main results of the research team after irradiation and induction of a synthetic torpor proved the hypotheses: Synthetic hibernation may have protective effects on a lethal dose of C-ions. In addition, synthetic hibernation reduces the tissues damage from total body irradiation. Furthermore, GSI scientists were able to characterize the underlying mechanism in their studies on rat tissue cells.

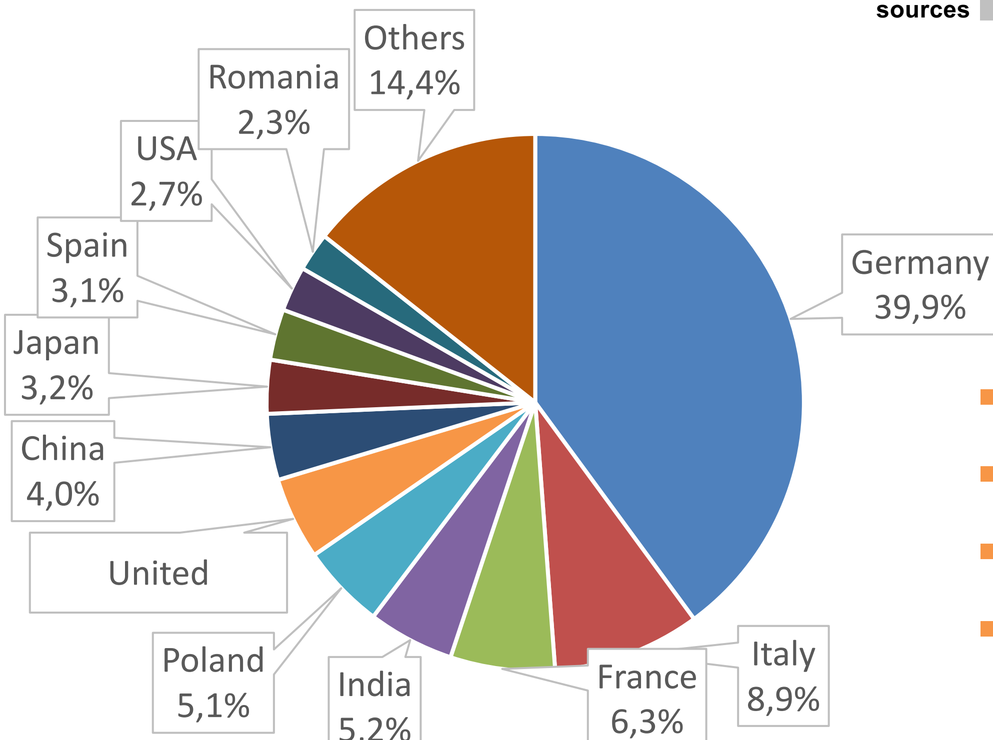
- https://www.gsi.de/en/start/news/details/2023/02/09/esa-wissenschaftsprogramm-fair-forschung-winterschlaf
- https://www.gsi.de/en/start/news/details/2022/11/14/schutz-vor-kosmischer-strahlung
- ESA VIDEO:
- https://www.youtube.com/watch?v=3cTWF6ws450

Ongoing: Early science program FAIR Phase-0

- Started in 2019, annual runs of ~110 days until FAIR operation



Phase 0 Research Program

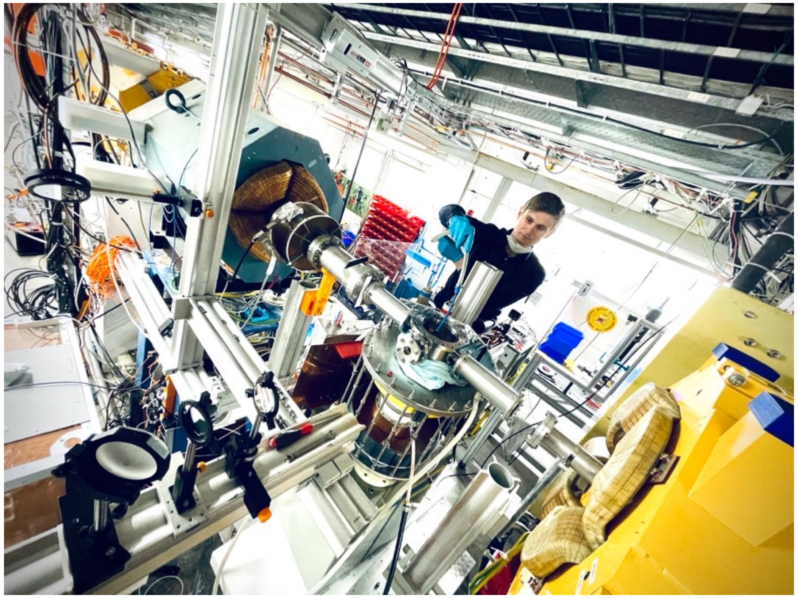


- Science while commissioning FAIR
- latest call: 124 proposals submitted
- 1729 participants of proposals
- From institutes in 45 countries

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

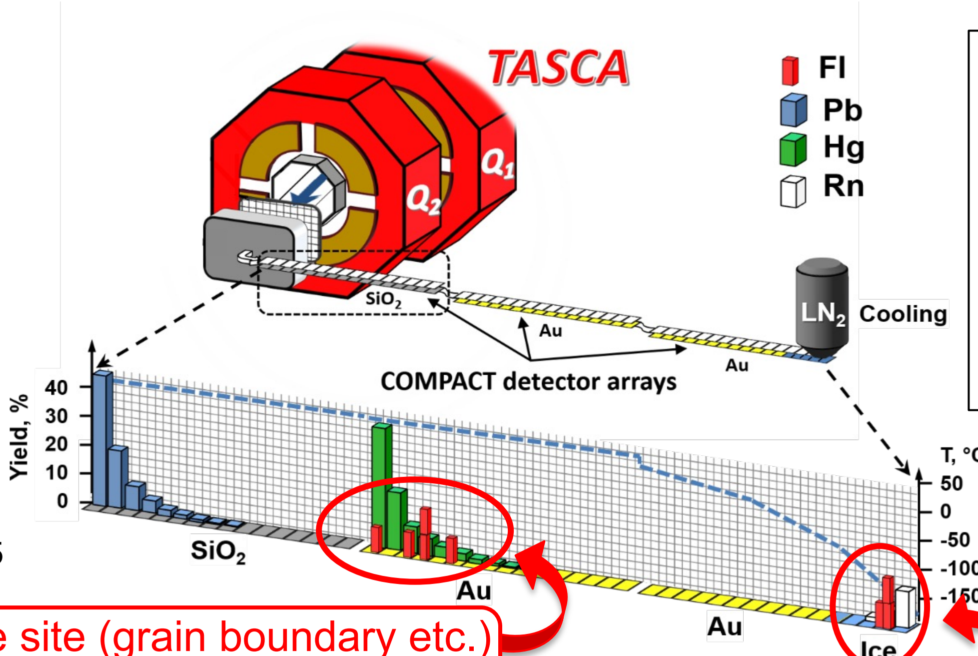
Chemical properties of element 114, Flerovium

- Flerovium: heaviest element with experimentally studied chemical properties
- Eight registered atoms in three beamtimes of total 2.5 months duration

Production:
$^{244}Pu(^{48}Ca,3\text{-}4n)$
^{288}Fl: $t_{1/2}$ ~0.7 s
^{289}Fl: $t_{1/2}$ ~2.0 s

Isolation in **TASCA**; Chemical study and detection: COMPACT

A. Yakushev *et al.*, Front. Chem. 10 (2022) 976635



Volatility:
Rn > **Fl** > Hg >> Pb

Reactivity:
Rn < **Fl** < Hg << Pb

Fl is the most volatile metal in the periodic table

Atoms hitting a reactive site (grain boundary etc.) on the inhomogeneous Au surface bind like Hg

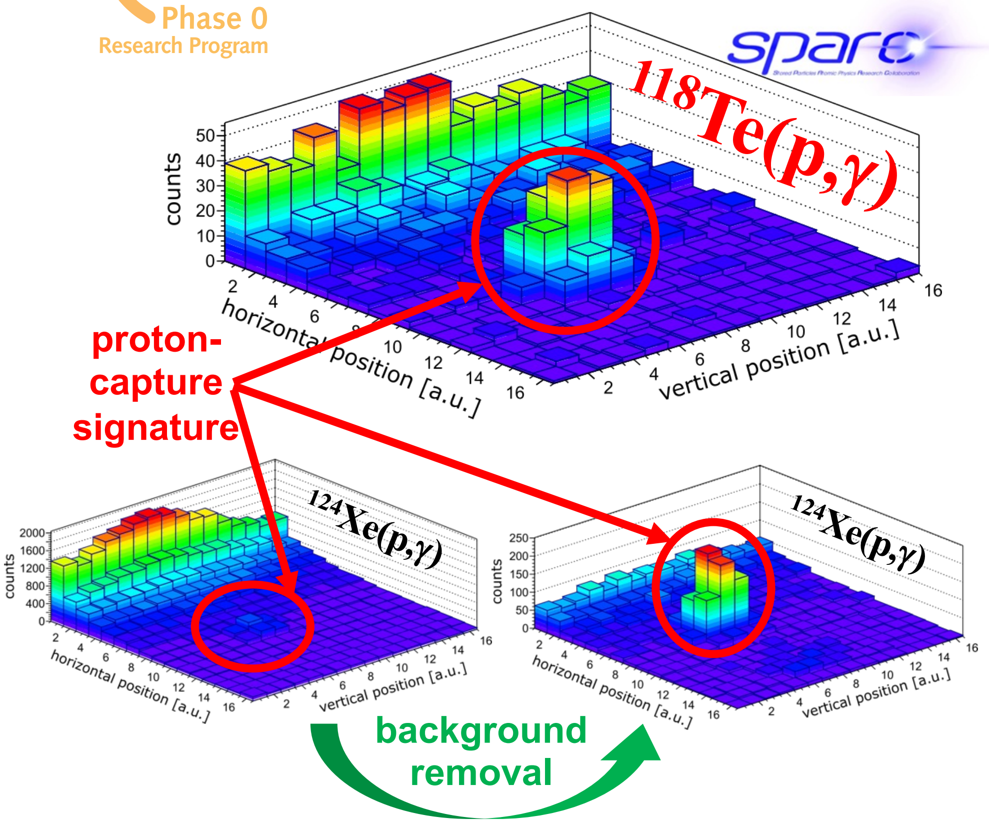
Other atoms reach location of Rn adsorption

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

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

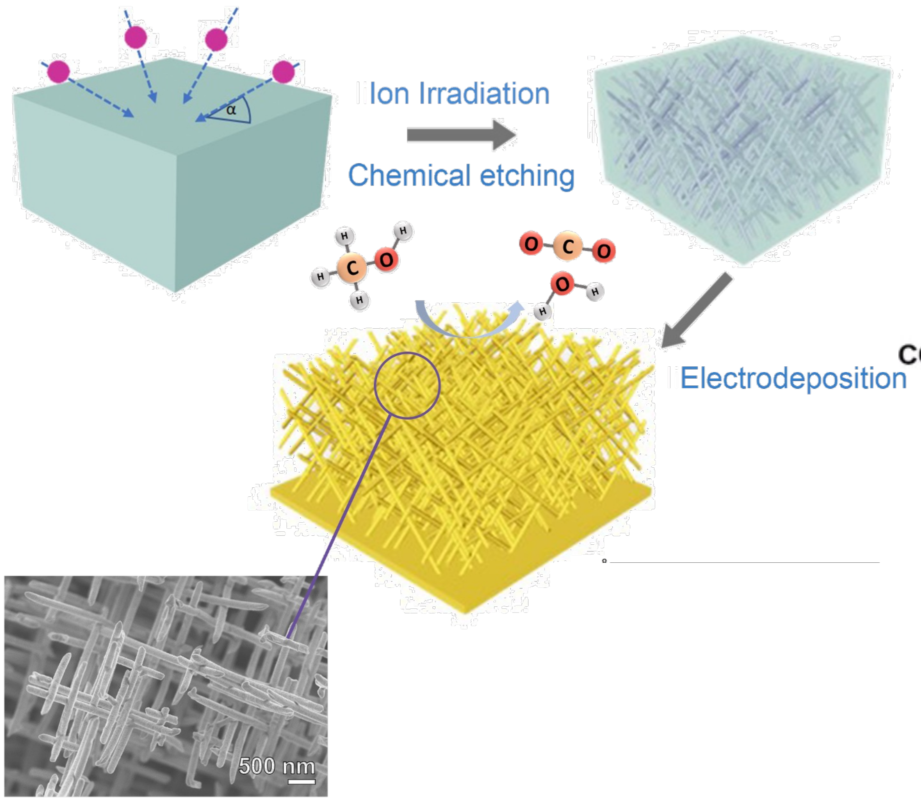
FAIR Phase 0 Research Program



Jan Glorius et al.

SPONSORED BY THE Federal Ministry of Education and Research

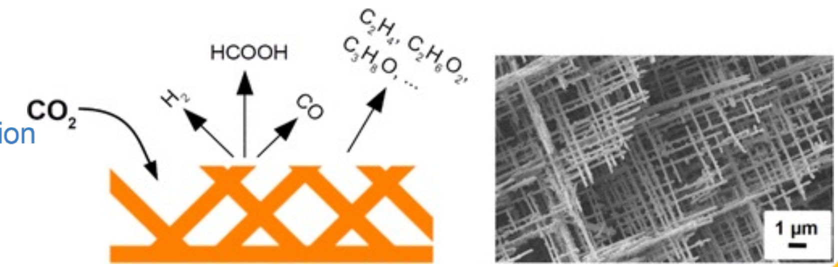
Materials Research
3d, highly interconnected nanowire networks



Li et al, RSC Advances 13 (2023) 4721-4728

3D nanowire networks with high surface area for catalytical applications

Copper nanowire-electrodes:
CO_2 reduction and formation of commodity chemicals

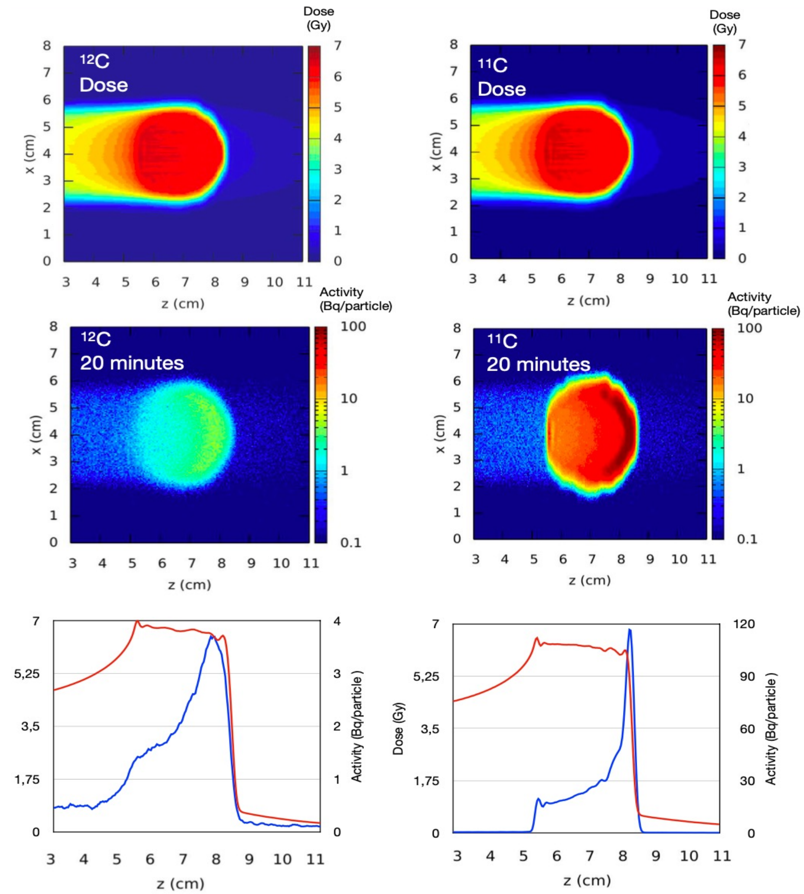


Ulrich et al, ACS Applied Nano Materials 6 (2023) 4190–4200

Advantages:
- Tailored nanowire density and diameter
- Excellent interconnectivity
- Surface area network > 500 larger than planar
- High current densities
- Excellent stability during performance

Breaktrhoughs: RIB in cancer therapy

- Motivation: **PET-based range monitoring: stable ions vs. β+ emitters**



- Uncertainties in CT number conversion
- Quality of the CT
- Anatomical changes and misalignments

↓

RANGE UNCERTAINTY

↓

Adding margins to the tumor contour

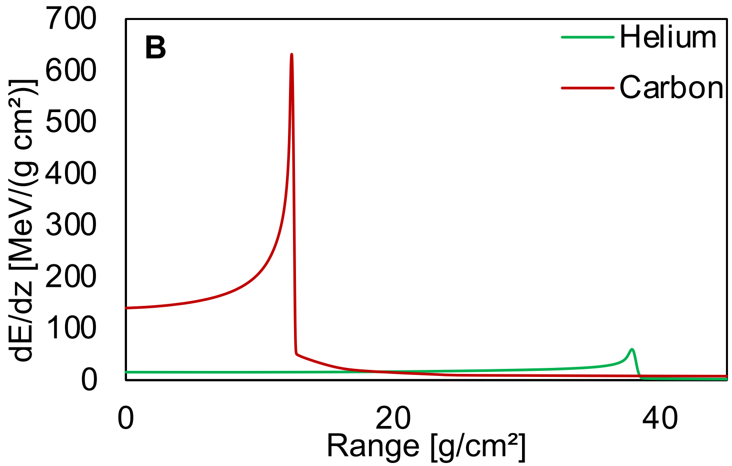
↓

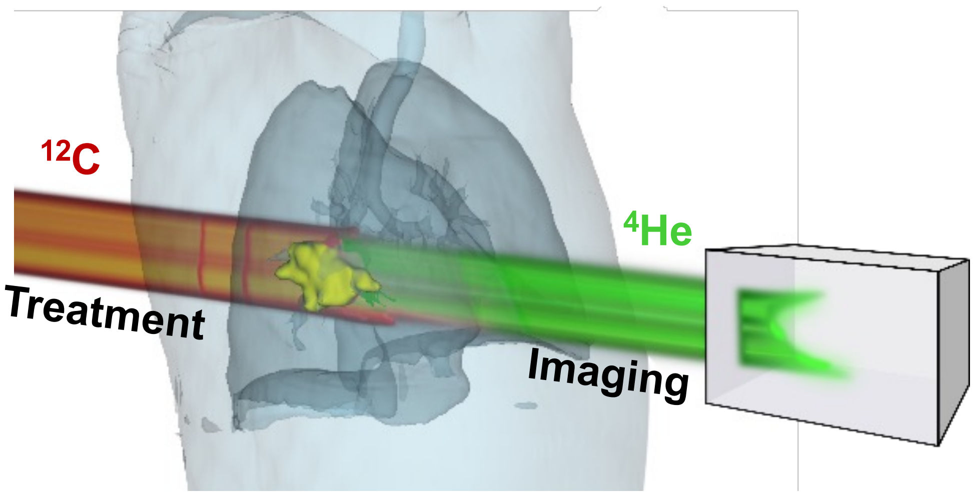
More damage to normal tissue

Boscolo *et al.*, *Front. Oncol*. 2021
Boscolo *et al.*, *NIM-A* 2022

Breaktrhoughs: combined imaging and therapy beams

- PROMISE will result in a new paradigm in carbon ion therapy: **combined imaging and therapy beams**



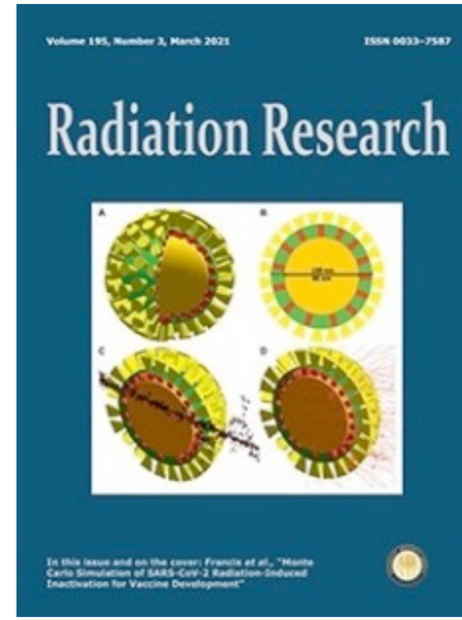


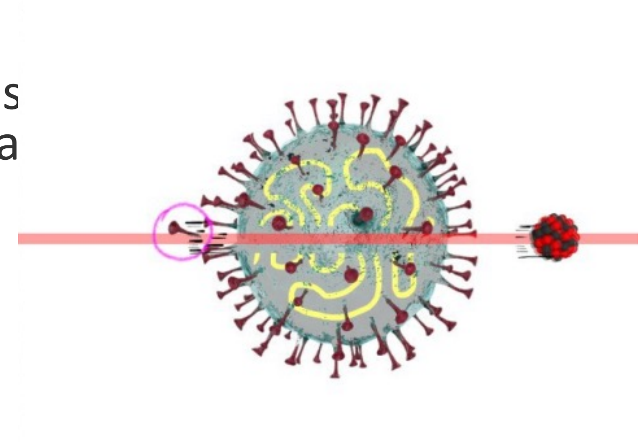
- Online **image guidance** and **range detection** will reduce uncertainty permitting highly **conformal planning** and **increased tumor control**

Breakthroughs:

Use heavy ion beams to inactivate viruses for vaccine development (published on Pharmaceutics)

- Study launched in response to the COVID pandemic
- Energetic ions are able to inactivate the virus by inducing breaks in the viral RNA with only minimal membrane damage and thus protecting the surface structures.
  - In the experiment at the GSI/FAIR accelerator facilities, an Influenza virus was irradiated with the iron isotope Fe-56, which was accelerated at 1 GeV/n at the SIS18 synchrotron.
  - Based on the resulting viruses, HZI produced a flu vaccine inactivated with heavy ions and examined it for its ability to promote the formation of virus-binding and neutralizing antibodies after vaccination.
  - Immunization of mice with the inactivated virus res in the stimulation of strong, antigen-specific cellula immune responses.
- heavy ion beams can be an innovative and effective method for inactivating viruses and developing more effective vaccines.





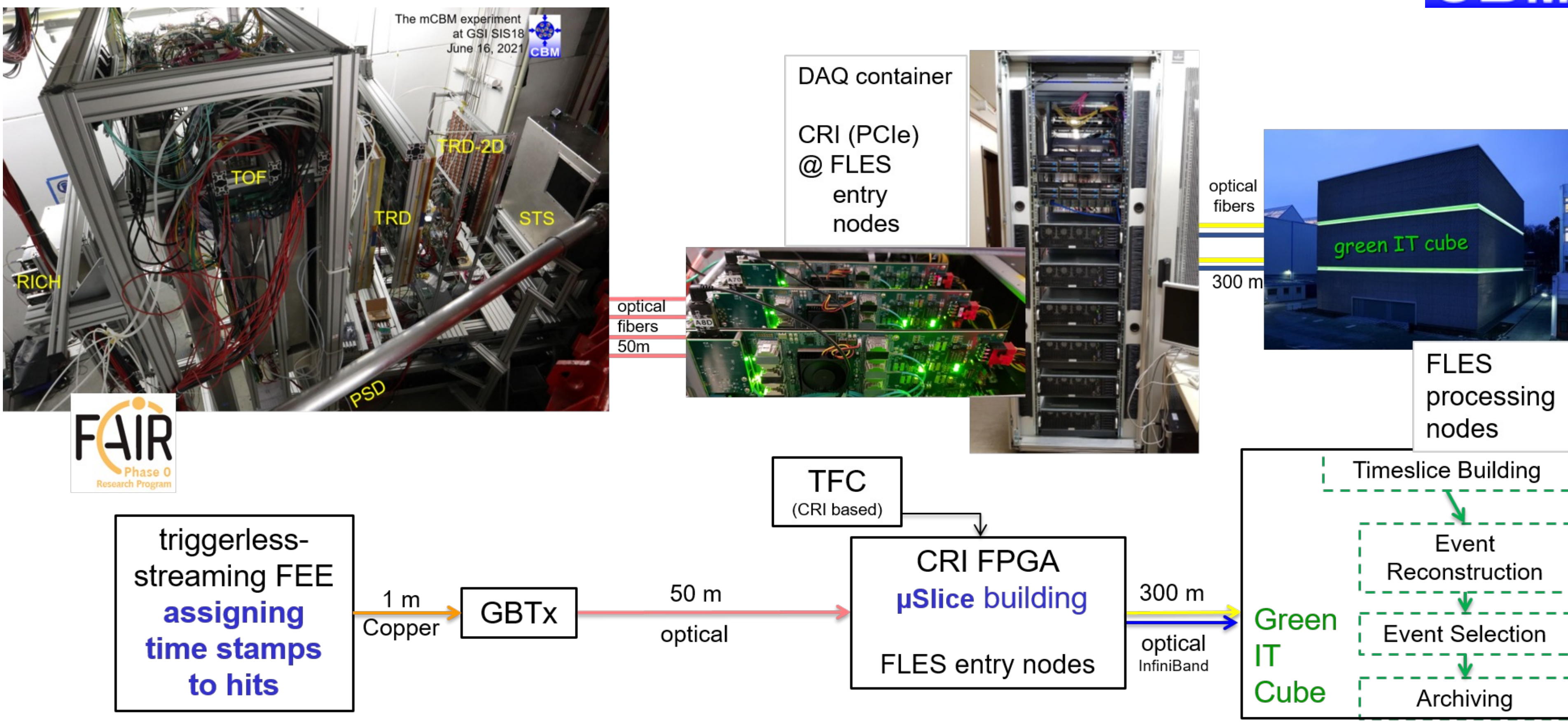
- FLASH Radiotherapy, is a novel approach of RT using ultra-high dose rate aiming to get **unchanged tumor control protection (TCP)** and **decreased normal tissue complication probability (NTCP).**

- GSI has demonstrated for the first time that the FLASH effect can be obtained with accelerated carbon ions (18 Gy in one spill of 150 ms) paving the way to clinical translation in particle therapy

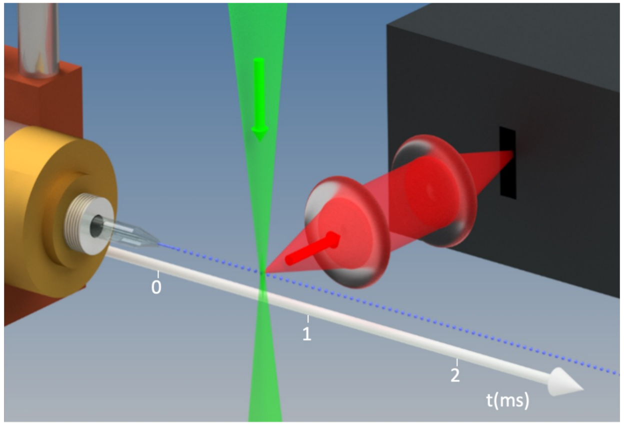
- The paper made the cover of the prestigious *Nature Reviews Clinical Oncology*

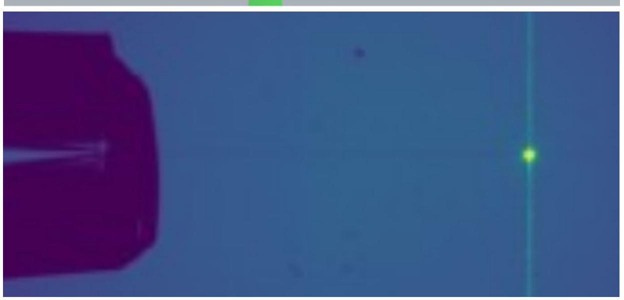
CBM in Phase-0: mCBM

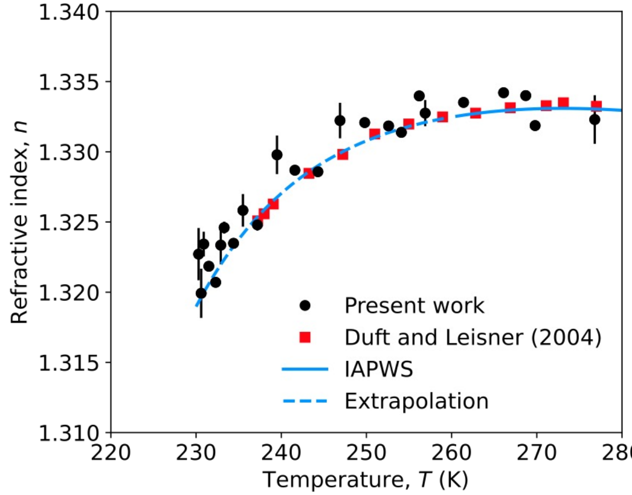
- During the last campaign, mCBM was successfully tested with the highest collision rates available in FAIR Phase-0
- Customised chain of electronics to process and transfer the data of all subsystems to the final data processing proven its capability



Refractive index of supercooled water down to 230 K (- 43,15° C)







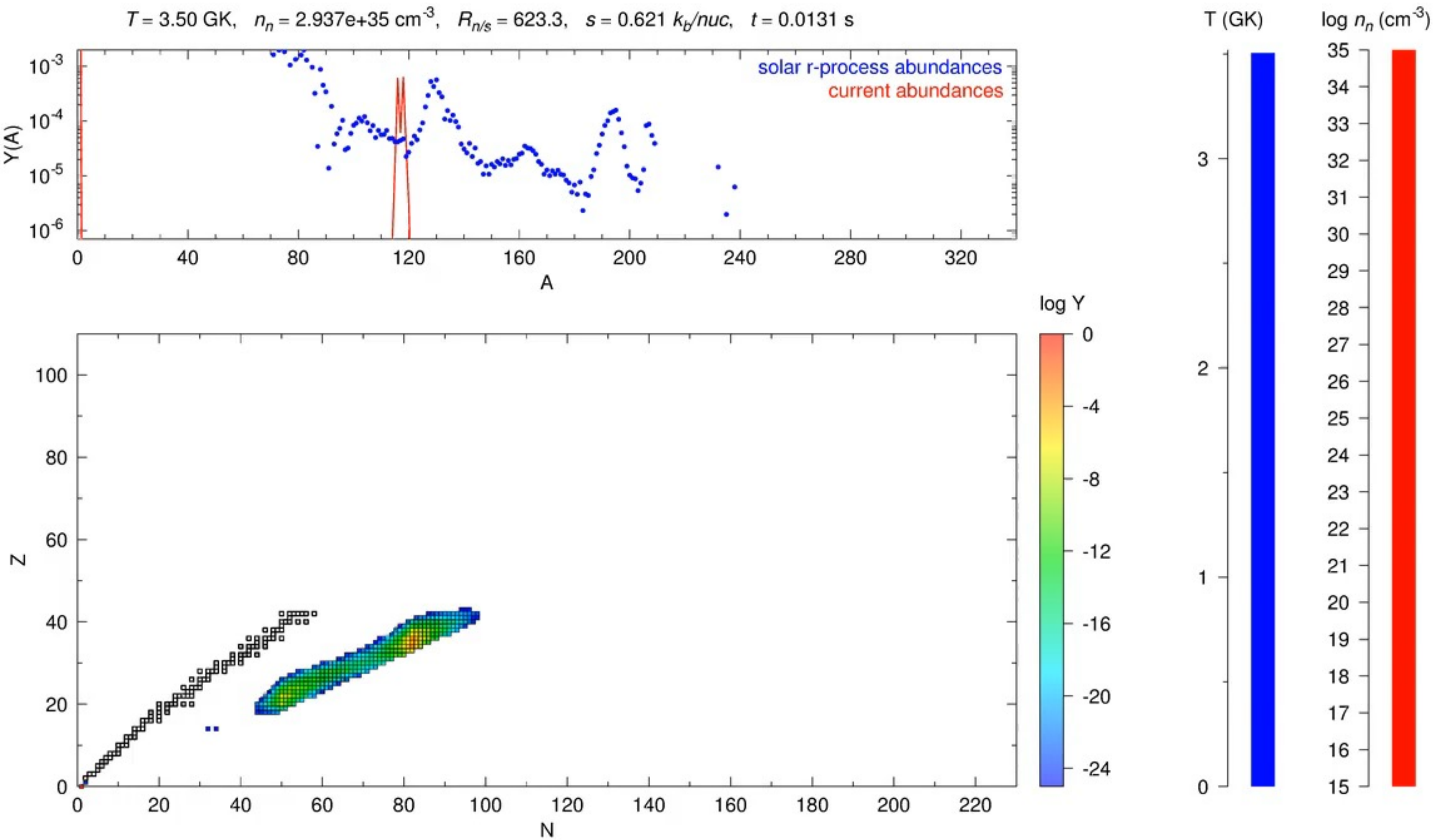
- Knowledge of the refractive index *n* of supercooled water is crucial for improving climate models.
- Water microjets in vacuum probed by Raman scattering allowed the determination of refractive index n for visible light down to 230 K.

Goy *et* al., J. Phys. Chem. Lett. **13**, 11872 (2022)

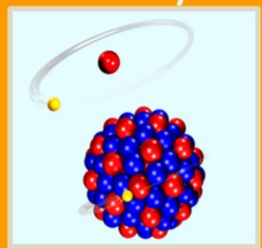
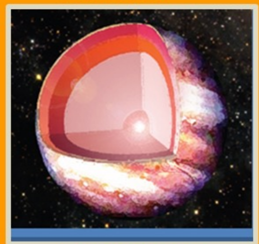
FAIR: Unique Opportunities . . . & Challenges

Backup

The theory:
where the elements come from ...



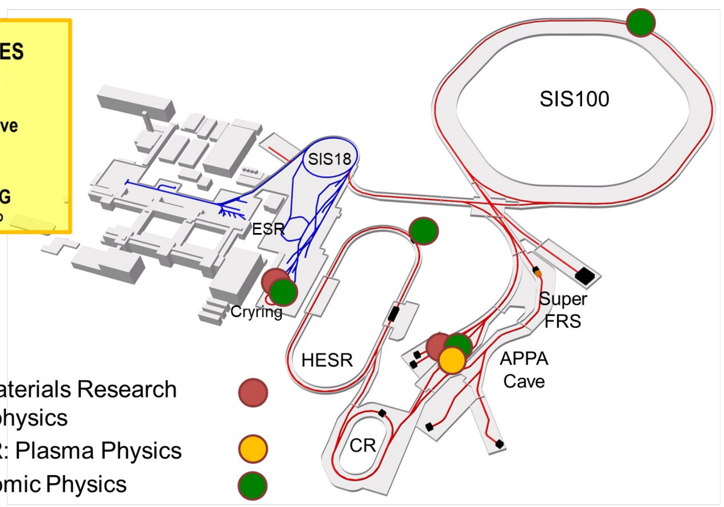
APPA - Atomic Physics, Plasma Physics, and Applied Sciences

Atomic Physics	Plasma	Materials	Bio
			
SPARC	HED@FAIR	MAT/BIOMAT	BIO/BIOMAT

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

FACILITIES
SIS100
HESR
APPA-Cave

ESR
CRYRING
HITRAP

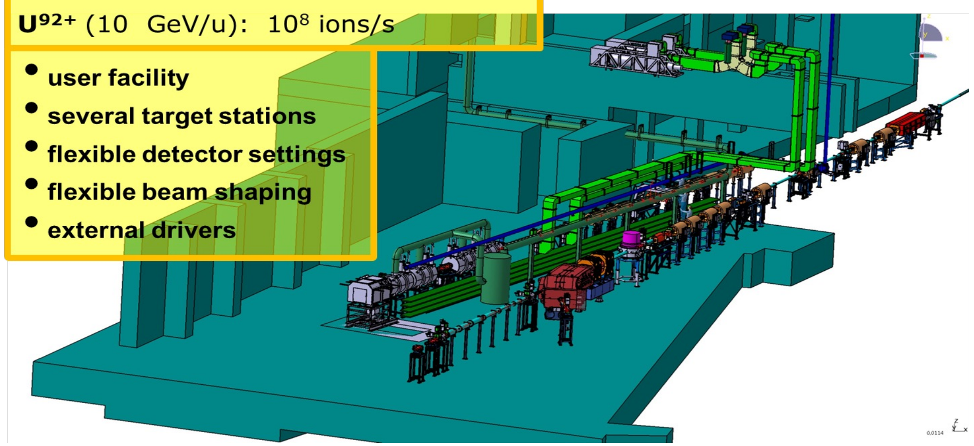


BIOMAT: Materials Research and Biophysics
HED@FAIR: Plasma Physics
SPARC: Atomic Physics

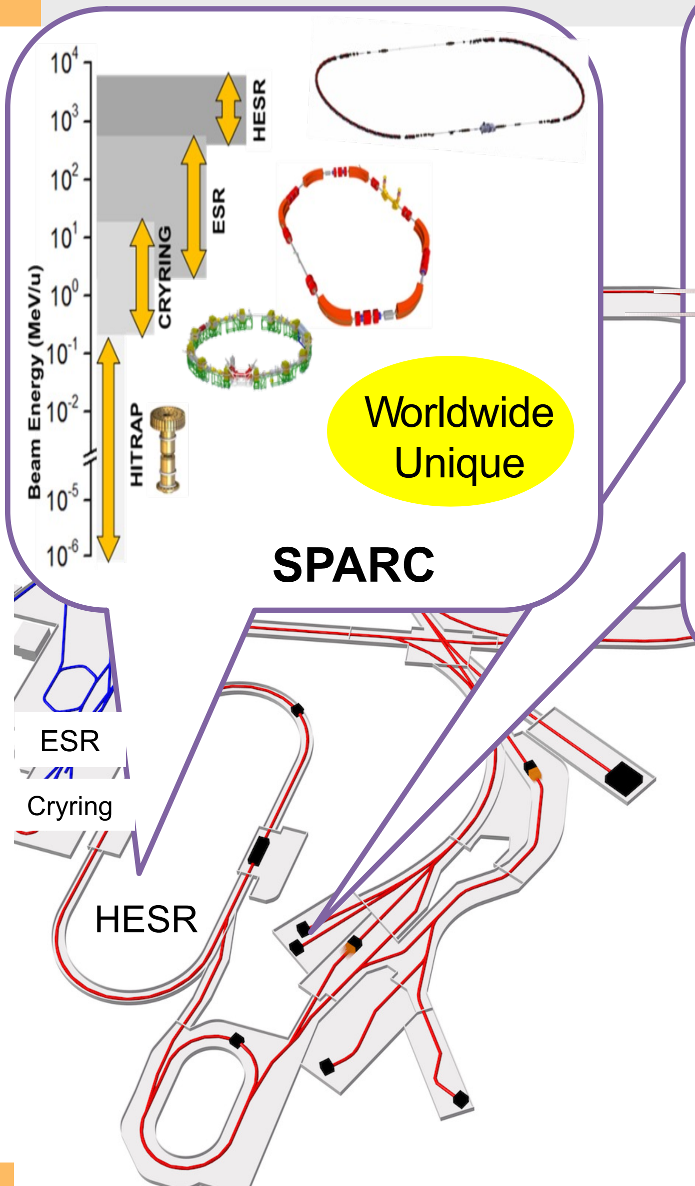
protons (10 GeV): 2 x 10^{13} p/bunch
U^{28+} (2 GeV/u): 5 × 10^{11} ions/bunch
U^{92+} (10 GeV/u): 10^{8} ions/s

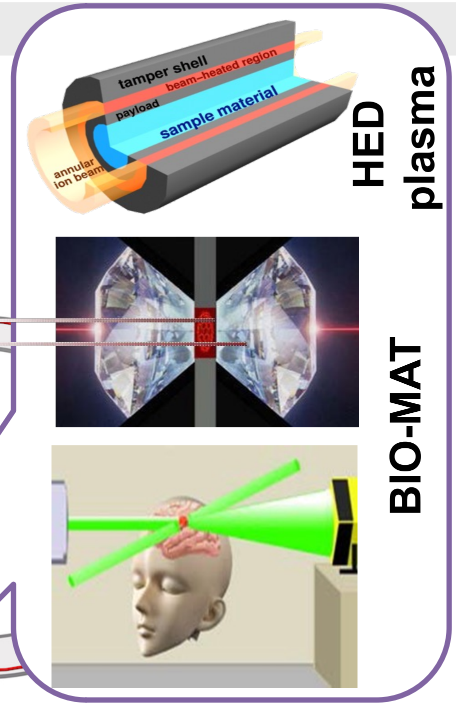
- **user facility**
- **several target stations**
- **flexible detector settings**
- **flexible beam shaping**
- **external drivers**

APPA Cave



APPA





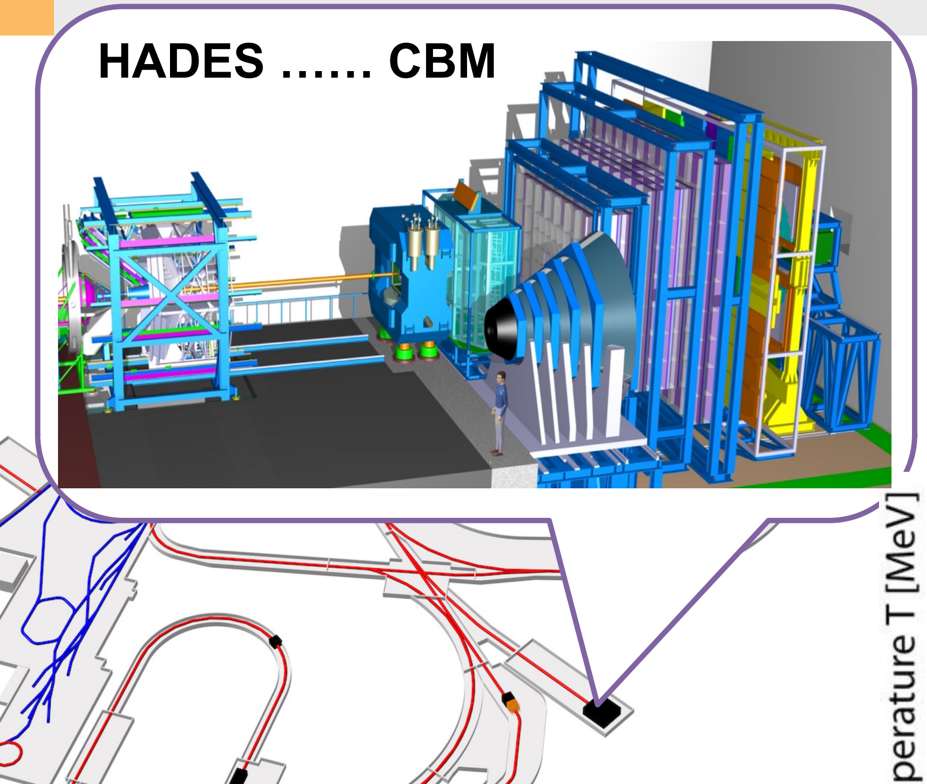
- Atomic, Plasma Physics and Applications
  - About 800 members
  - Wide field of science
    - basic research into material, biological and medical applications and space research

Atomic Physics
SPARC: ~400 members from 26 countries

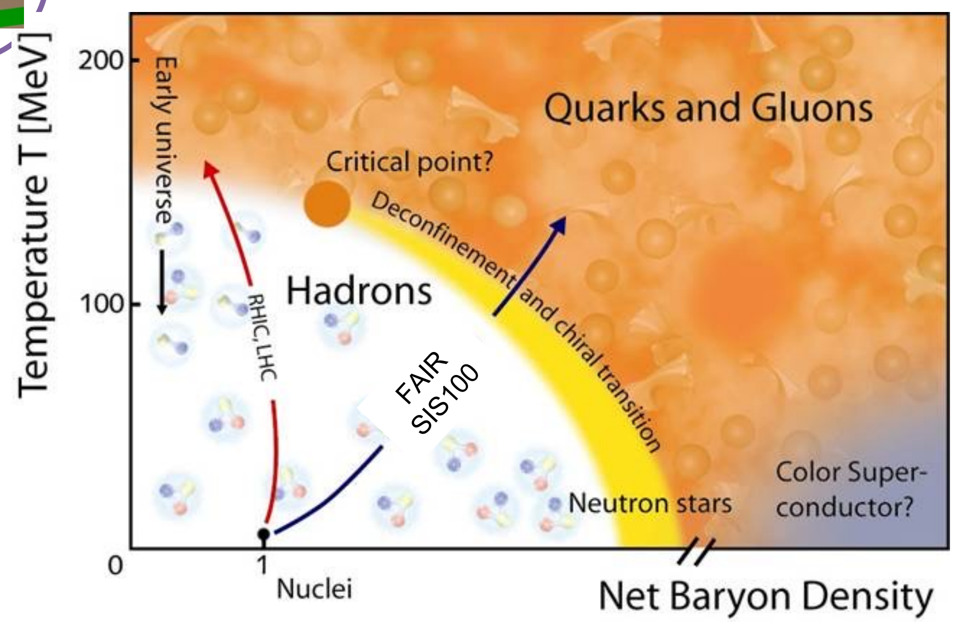
Plasma Physics
HED: ~300 members from 16 countries

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

C.B.M.



- Compressed Baryonic Matter Experiments
  - About 400 members

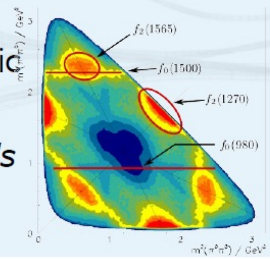


PANDA - AntiProton Annihilation at Darmstadt

Bound States of Strong Interaction

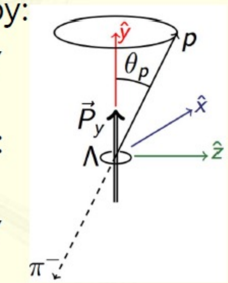
Spectroscopy

- 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*

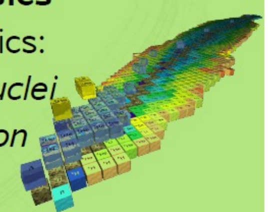


Nucleon Structure

- 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.

FAIR - The Universe in the Laboratory

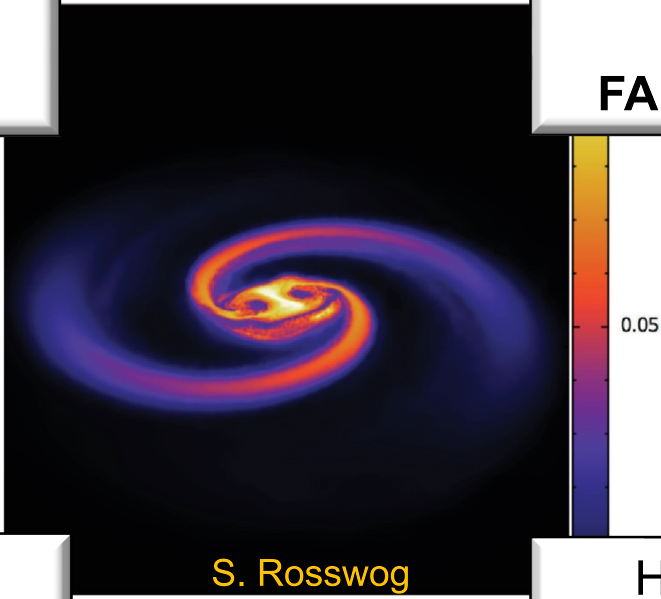
From Neutron Star Mergers to Platinum and Gold

How Matter behaves at extreme electromagnetic Field Strengths

FAIR/ APPA

How Matter behaves at extreme Densities and Temperatures

FAIR/ CBM-HADES

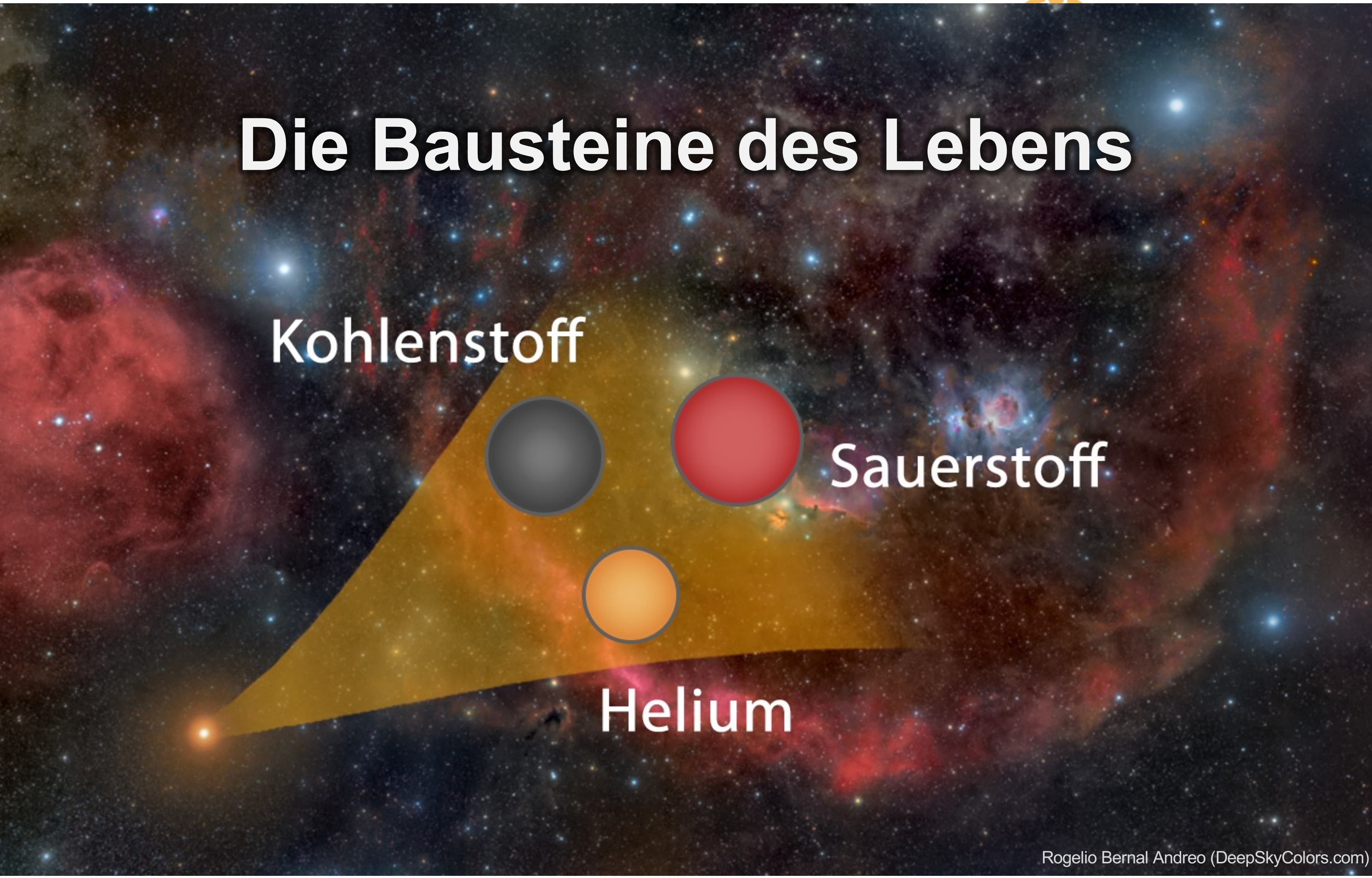


How the chemical elements evolve from Neutron-Star Matter

FAIR/ NUSTAR

How the Protons and Neutrons are formed

FAIR/ PANDA


Die Bausteine des Lebens
Kohlenstoff
Sauerstoff
Helium
Rogelio Bernal Andreo (DeepSkyColors.com)

Sauerstoff

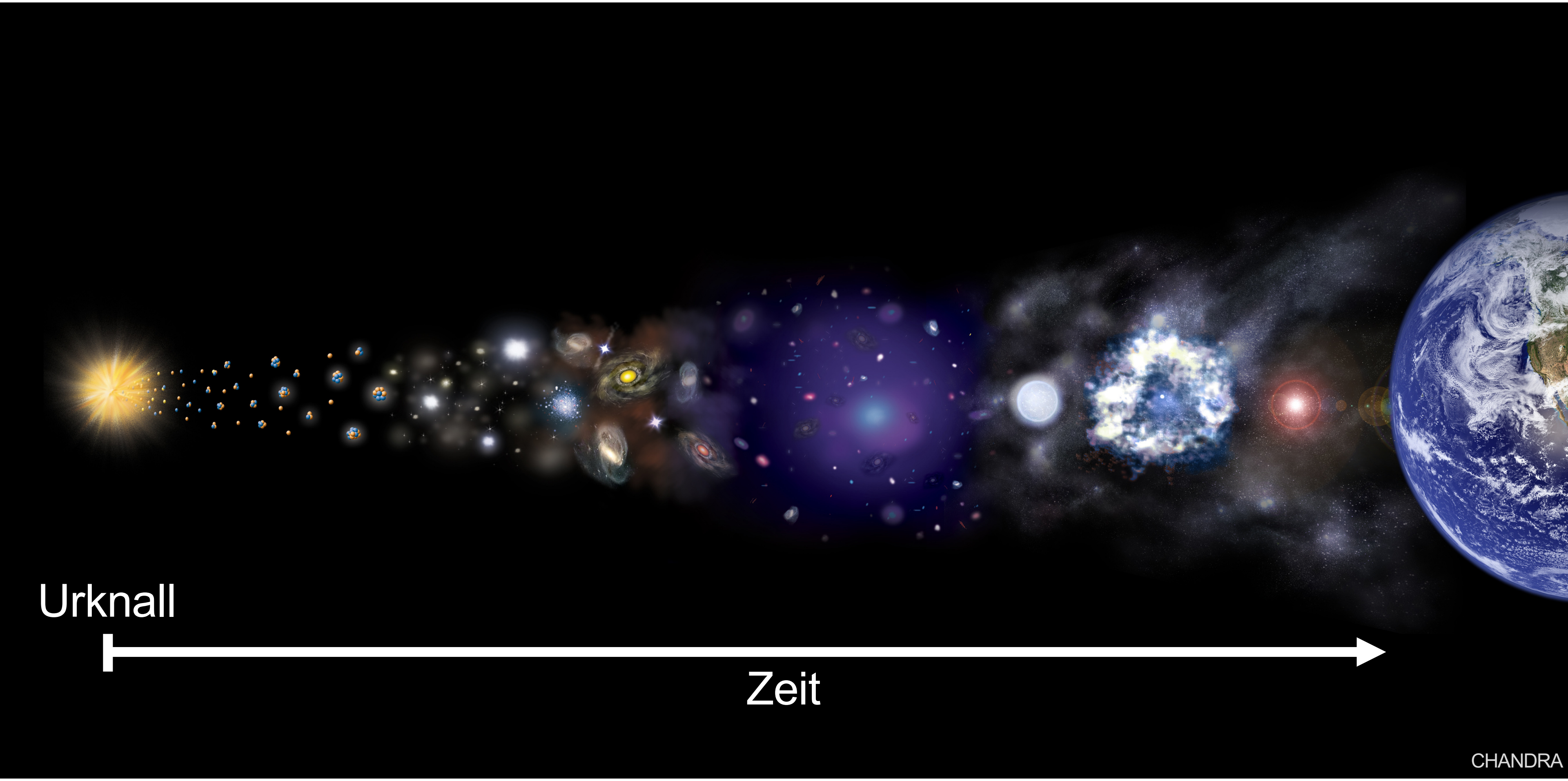
Kohlenstoff

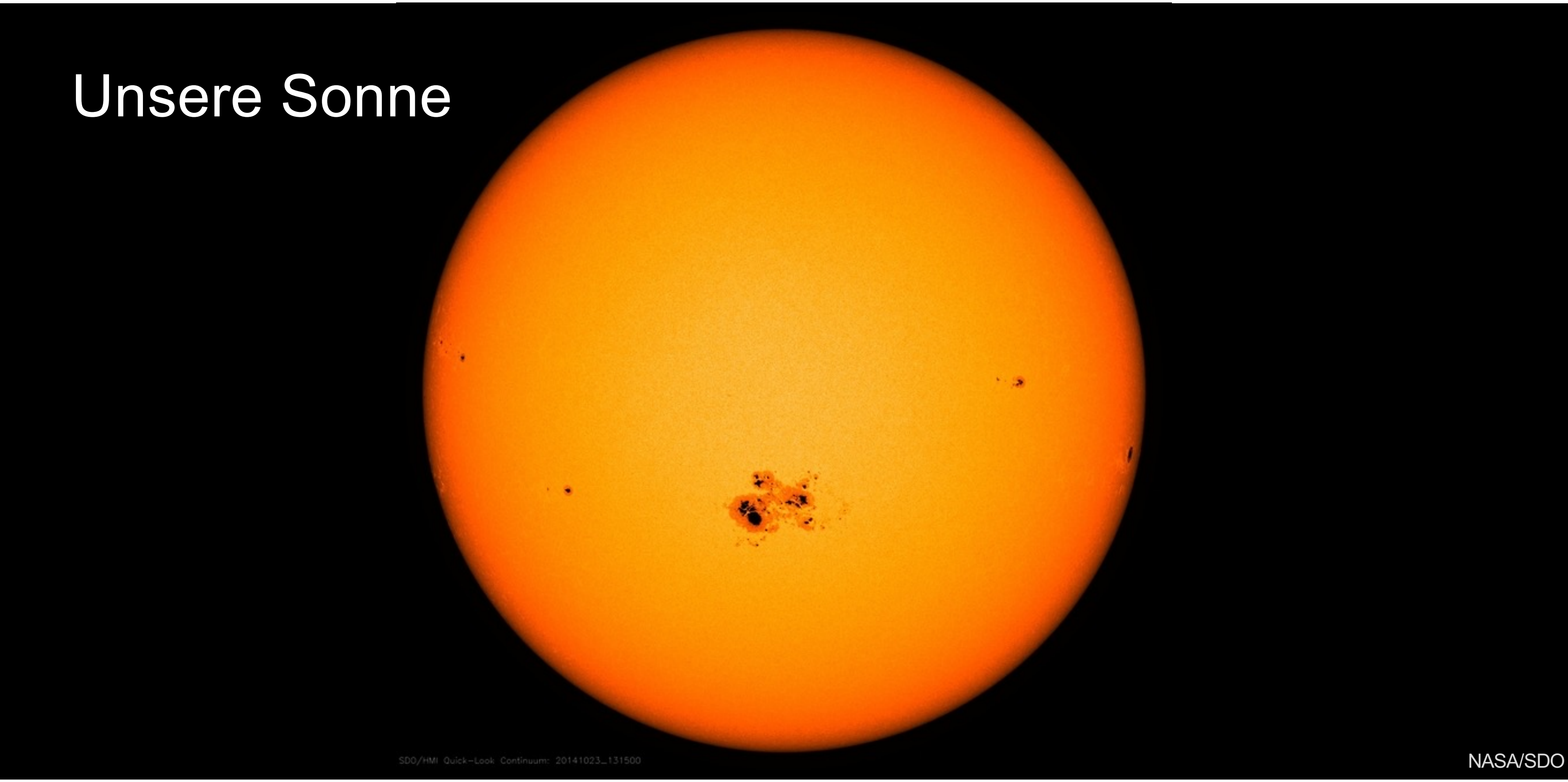
Wasserstoff

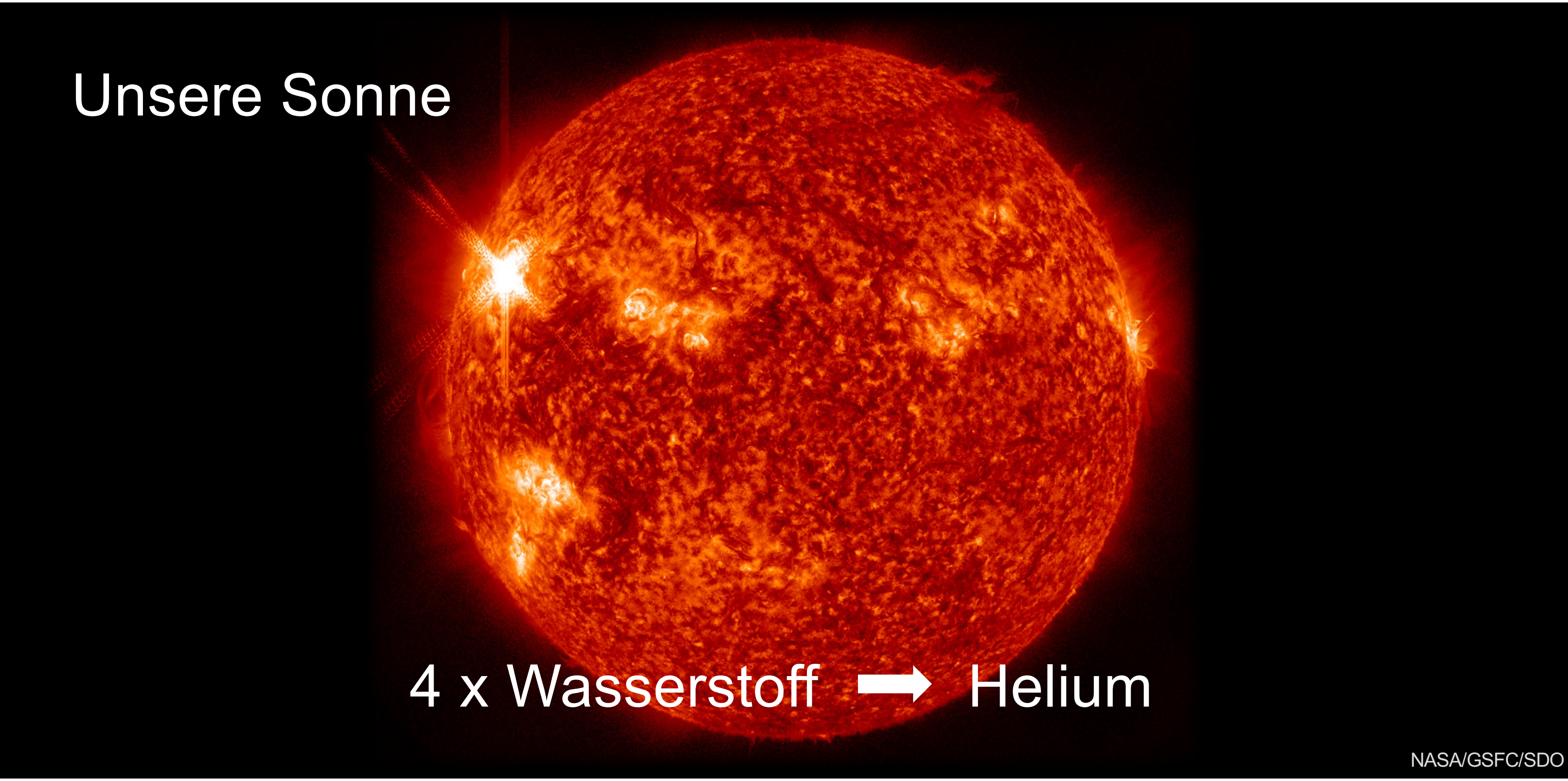
Stickstoff

Calcium
Chlor
Phosphor
...

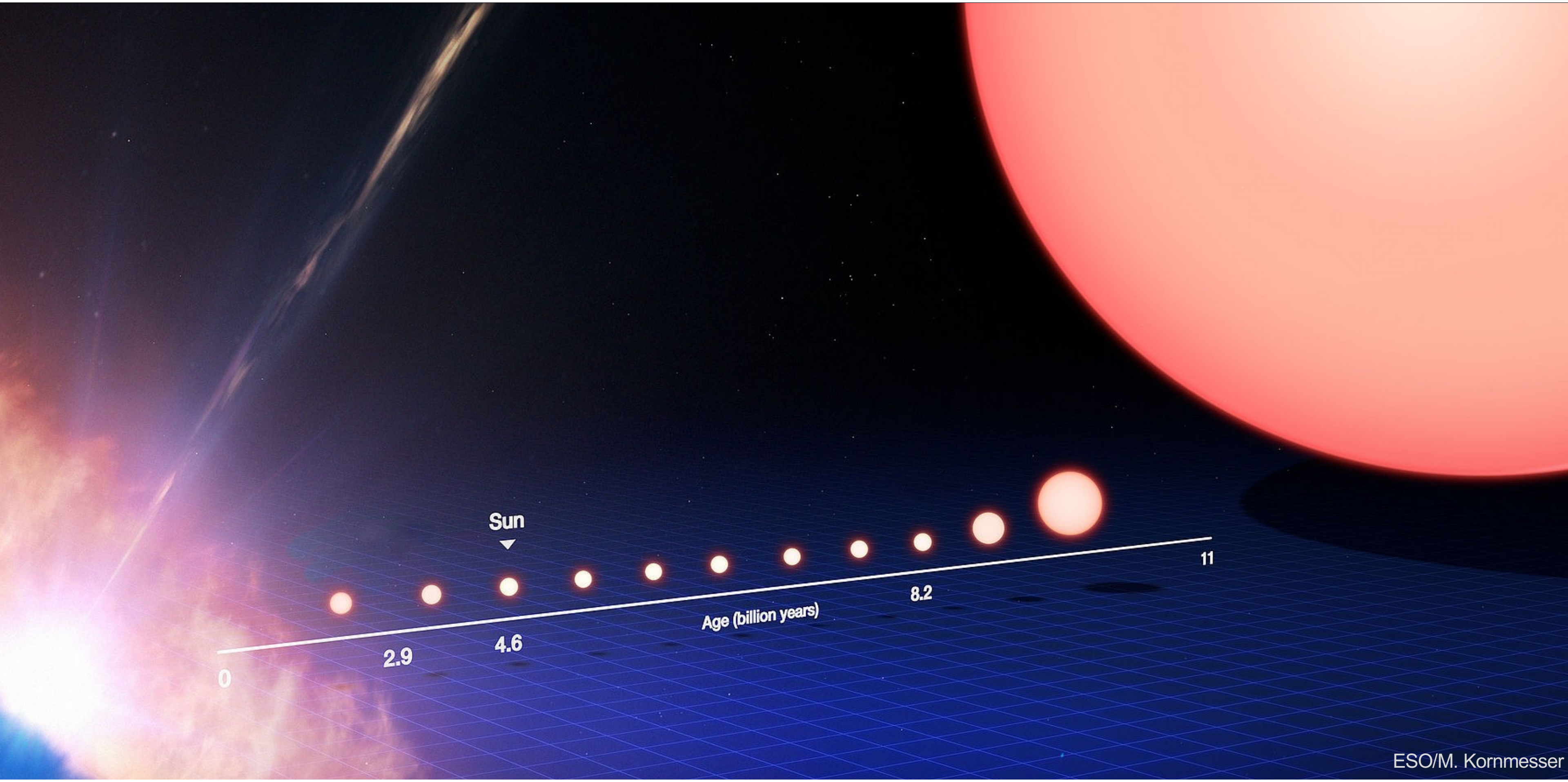
Der Ursprung der Elemente



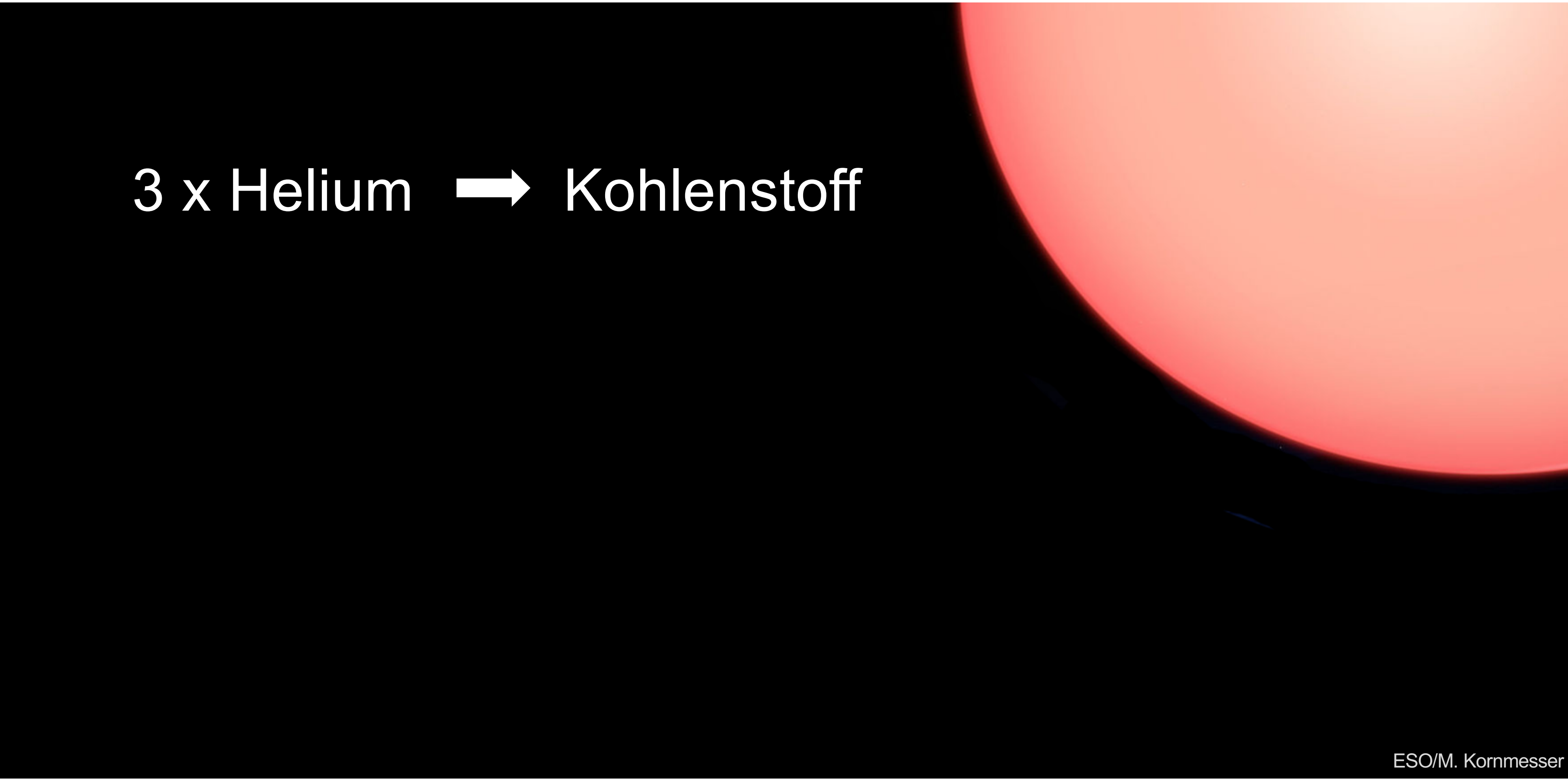

Unsere Sonne
SDO/HMI Quick-Look Continuum: 20141023_131500
NASA/SDO


Unsere Sonne
4 x Wasserstoff → Helium
NASA/GSFC/SDO

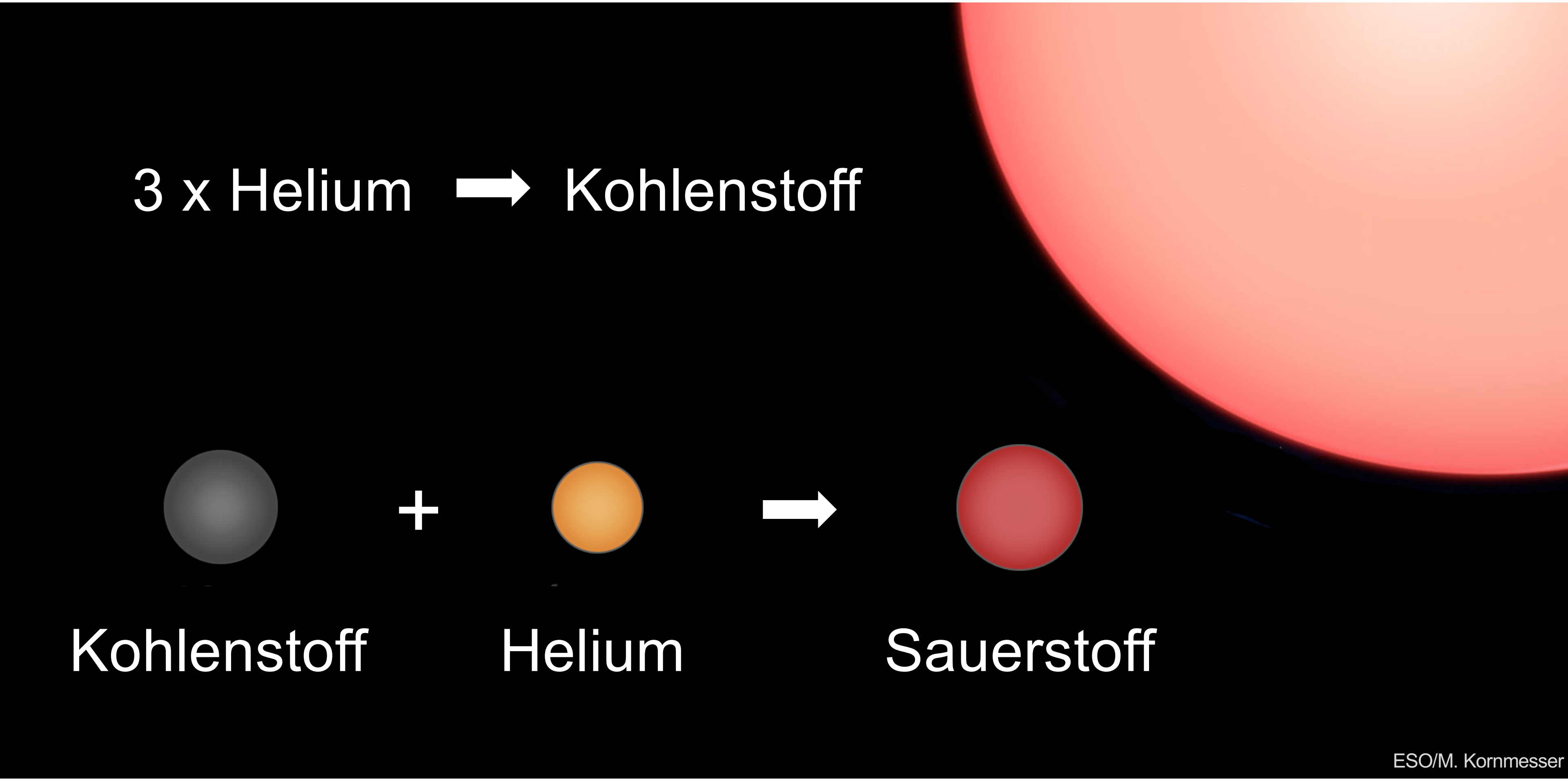
Die Sonne wird zum Roten Riesen

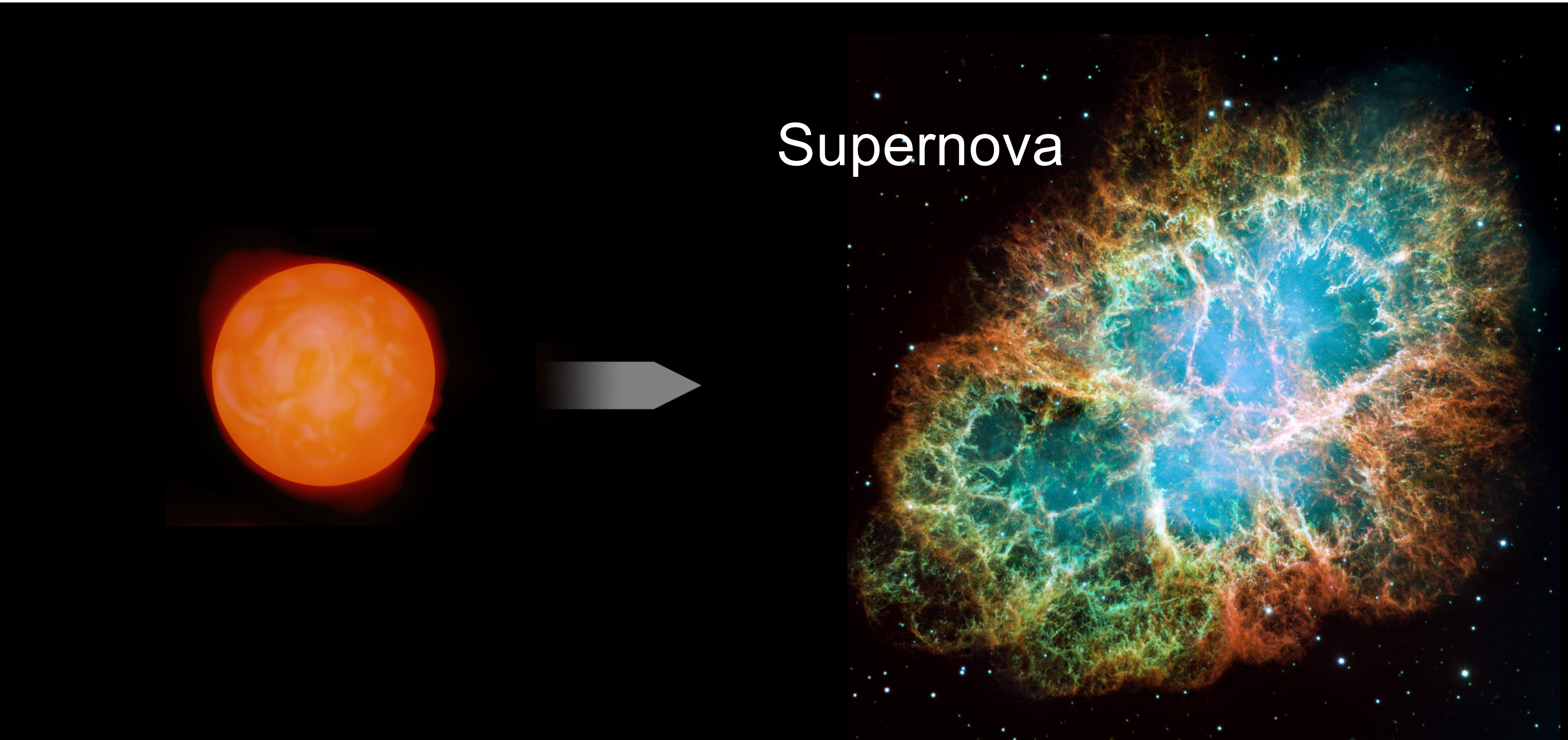


Fusionsreaktionen in Roten Riesen



Fusionsreaktionen in Roten Riesen

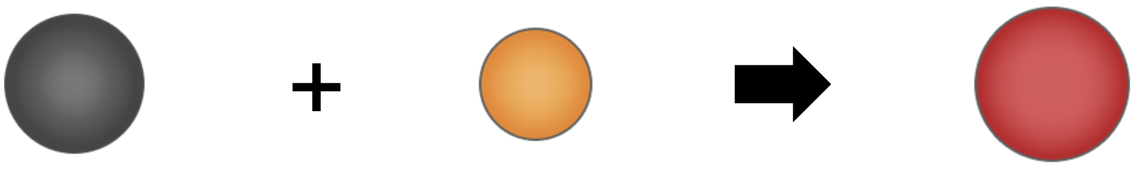




NASA/CXC/M.Weiss

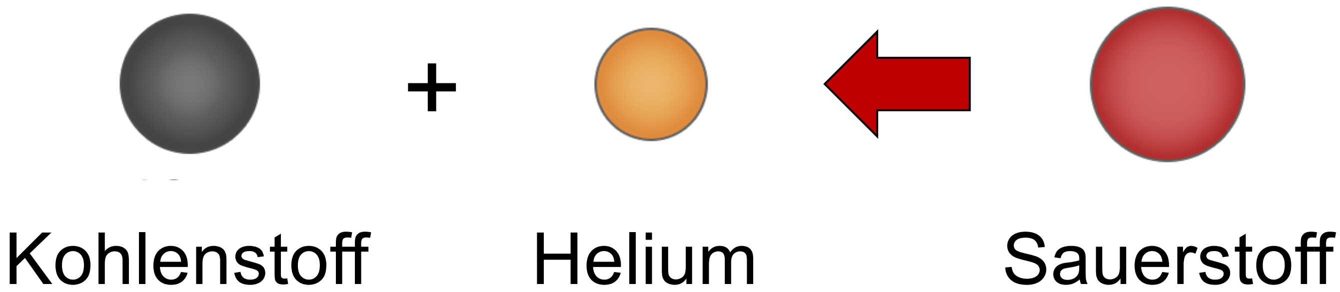
NASA, ESA, J. Hester and A. Loll (Arizona State University)

Die wichtigste Reaktion

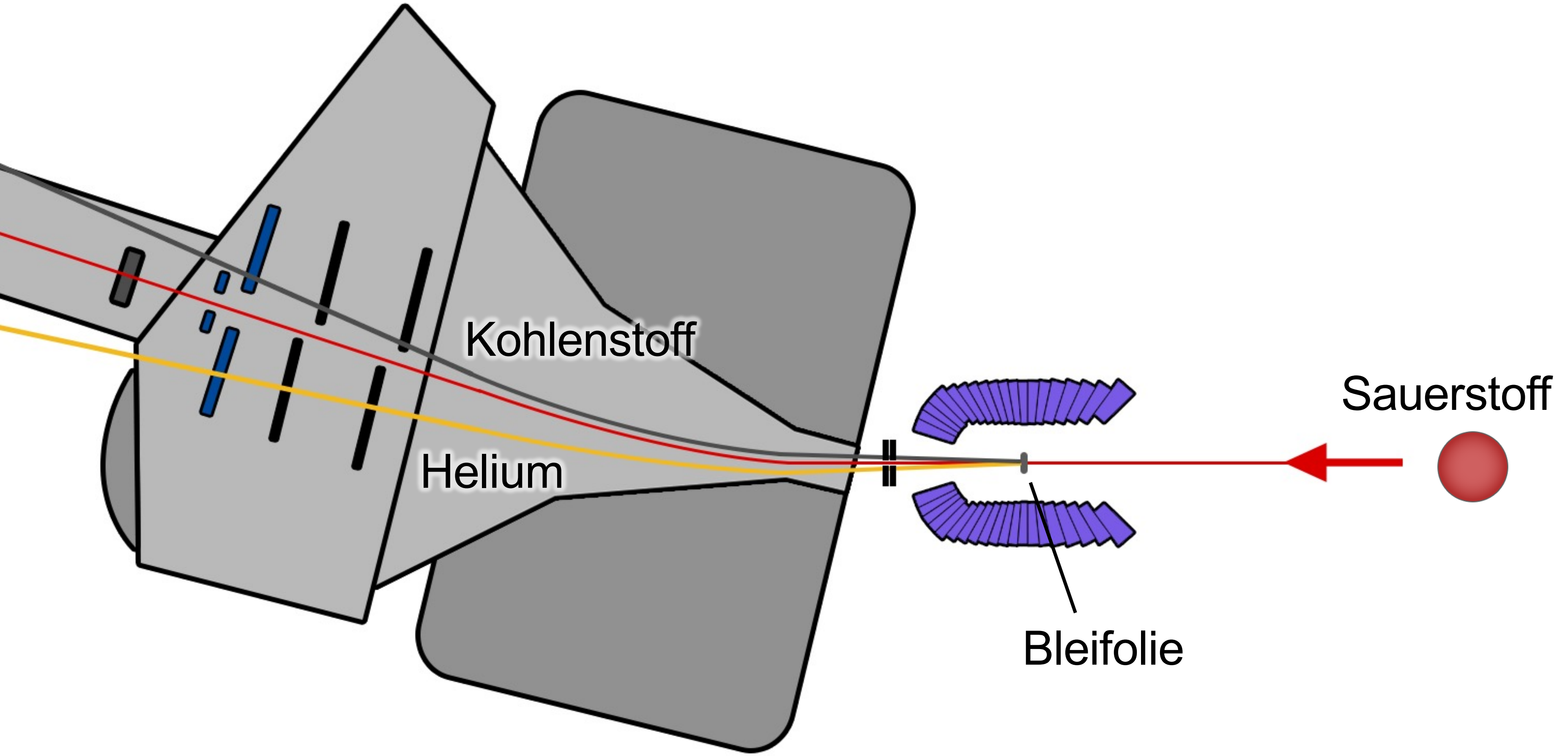


Kohlenstoff Helium Sauerstoff

Wir drehen es um:

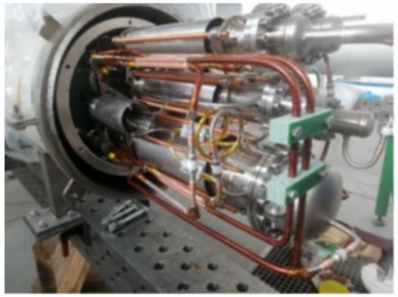


Das Experiment



Main FAIR accelerators

SIS100



- rigidity: 100 Tm
- super-conducting
- accelerating intermediate charge states of HIC
- cryogenic UHV system

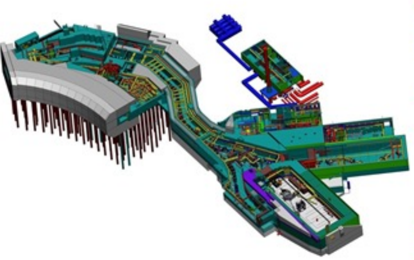
protons: 2.5 × 10^{13}/cy, 29 GeV
U^{28+} : 5 × 10^{11} /cy, 2.7 GeV/u
U^{92+} : 4 × 10^{10} /cy, 10 GeV/u

ESR – CRYRING

ESR
- rigidity: upto 10 Tm
- electron cooling
- typical energies ~ 300 MeV/u

CRYRING
- rigidity 0.04 – 1.44 Tm
- ion source for stand alone operation

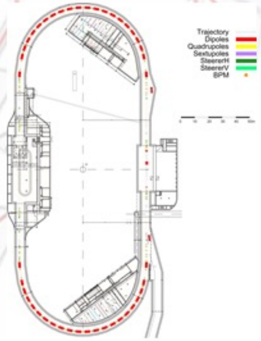
Super-FRS



ACCEPTANCE
- horizontal Φ_x = ±40 mrad
- vertical Φ_y = ±20 mrad
- momentum $\Delta P/P$ = ±2.5 %
- magnetic rigidity 2 - 20 Tm

MOMENTUM RESOLUTION
- first stage = 750
- second stage = 1500

CR - HESR



CR
- max. rigidity 13 Tm
- fast bunch rotation, coasting beam
- stochastic cooling

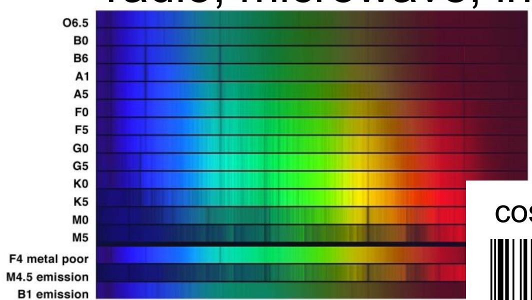
HESR
- rigidity: 5-50 Tm
- accelerating p, anti-p and highly charged ions
- stochastic (and electron) cooling

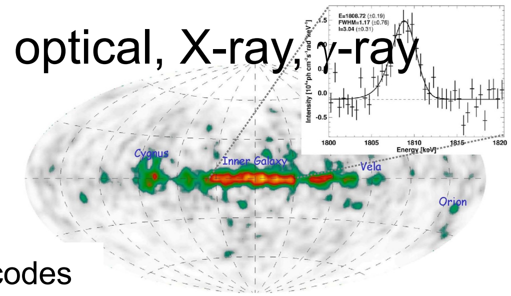
M Aliotta

The Messengers of the Universe

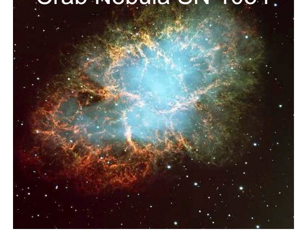
electromagnetic emissions

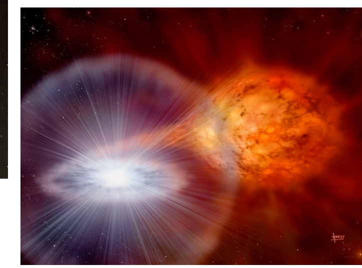
…rared, optical, X-ray, γ-ray





Crab Nebula SN 1054



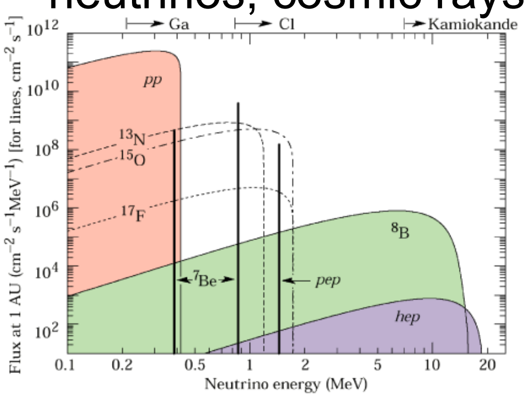


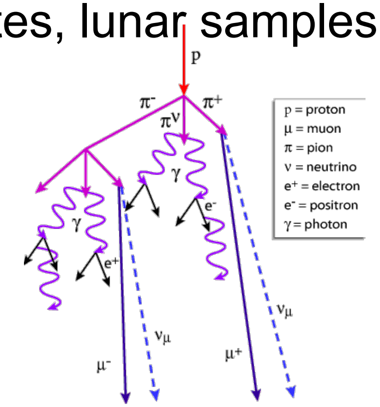
cosmic bar codes

9 771144 875007

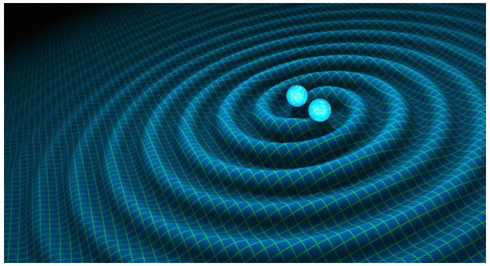
direct messengers

neutrinos, cosmic rays, meteorites, lunar samples, …





gravitational waves



On the Origin of the Chemical Elements

REVIEWS OF
MODERN PHYSICS
VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

Rev. Mod. Phys. 29 (1957) 547

(B^2FH, 1957)

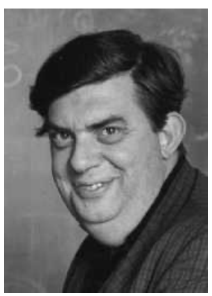
PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC
Vol. 69 June 1957 No. 408

NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS*

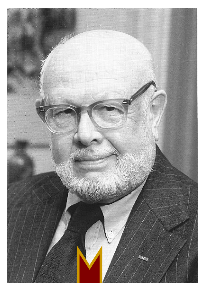
A. G. W. CAMERON
Atomic Energy of Canada Limited
Chalk River, Ontario

Burbidge

Burbidge



Fowler



Hoyle

1983
Nobel Prize

"for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"