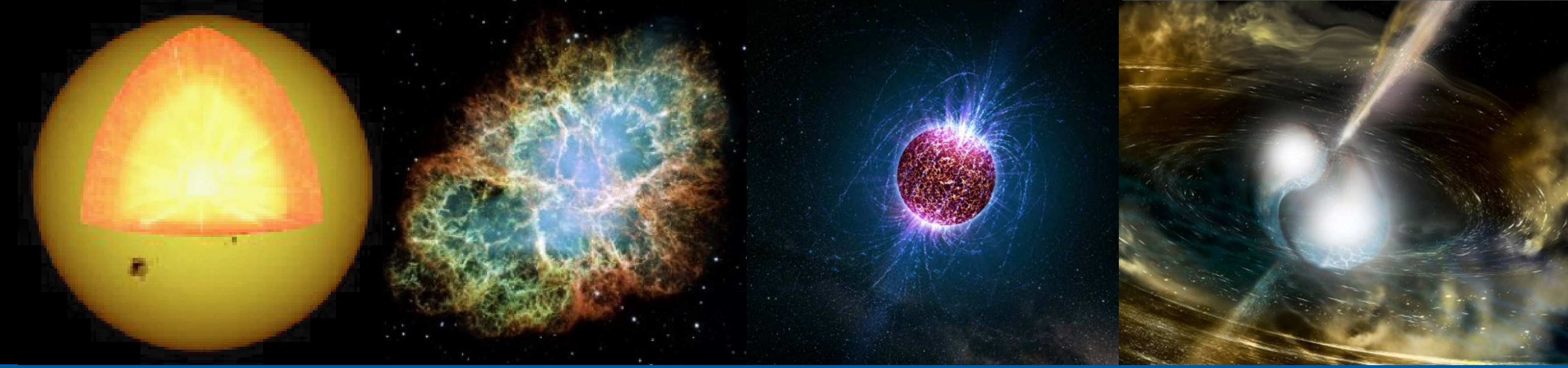


Cosmic matter in the laboratory – Science at FAIR

Peter Senger

Outline:

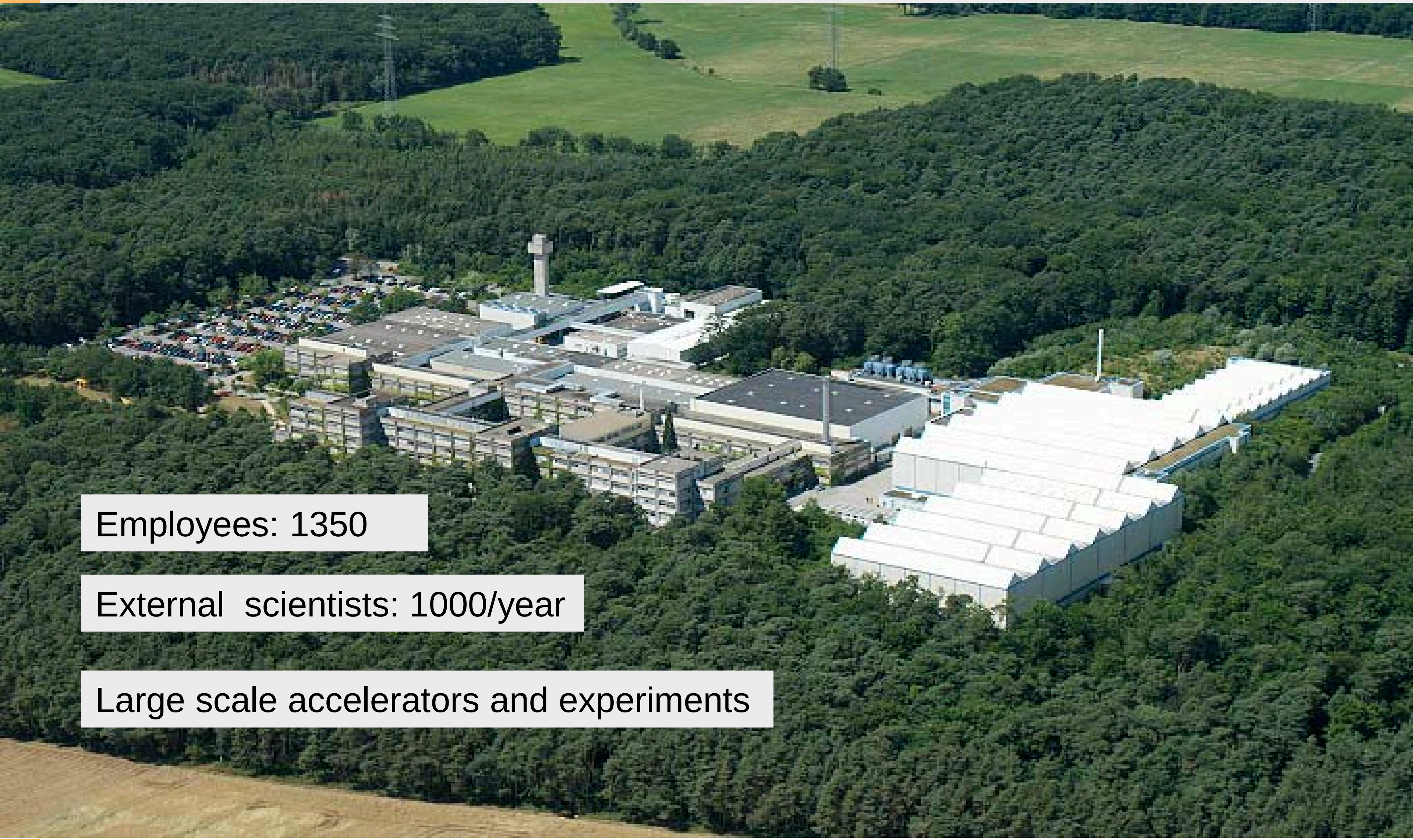
- GSI highlights
- Cosmic matter
- Research at FAIR

Eötvös University, 7th December 2017, Budapest, Hungary

Finland France Germany India Poland Romania Russia Slovenia Spain Sweden UK

FAIR

GSI Helmholtzzentrum für Schwerionenforschung

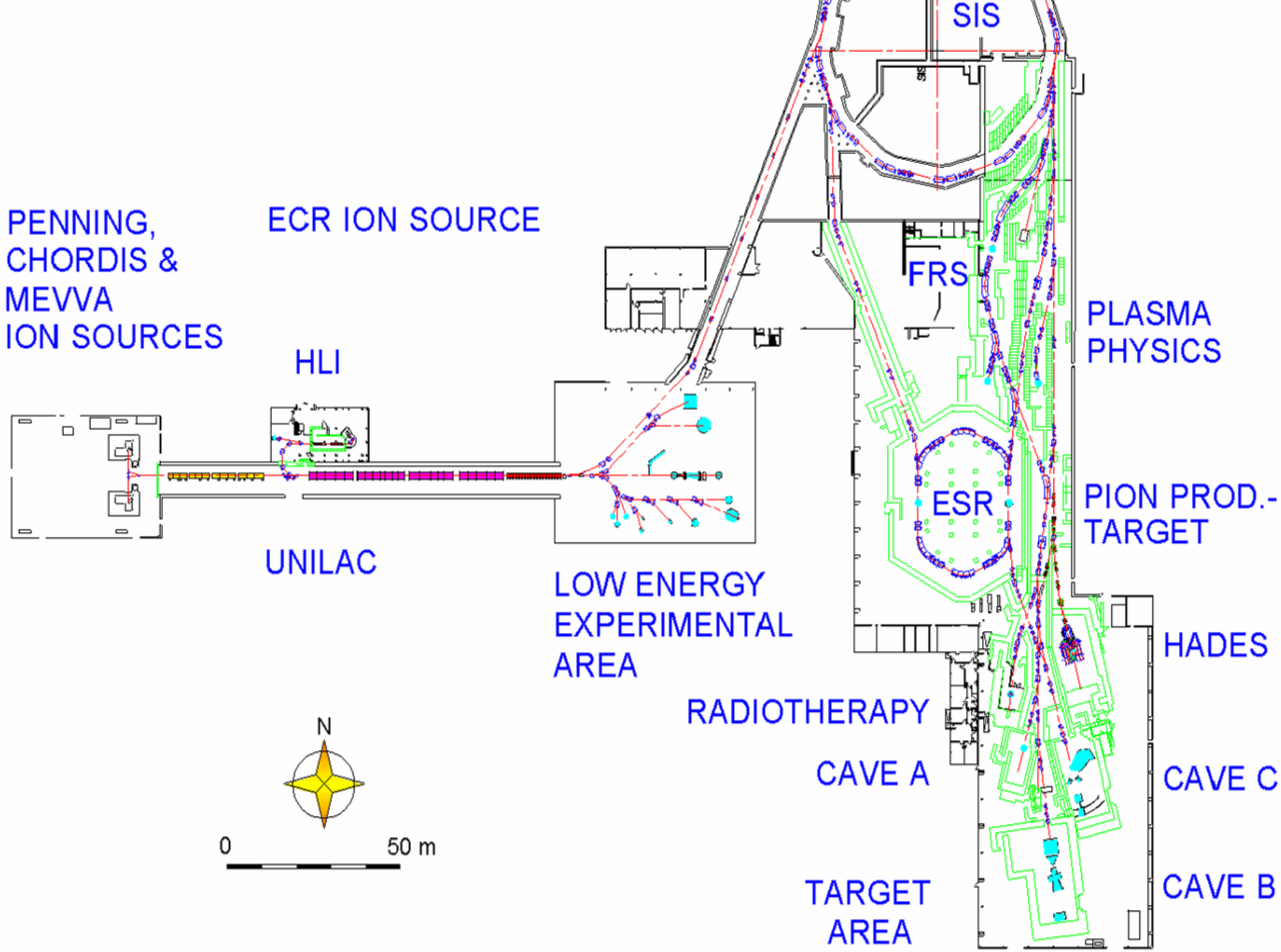


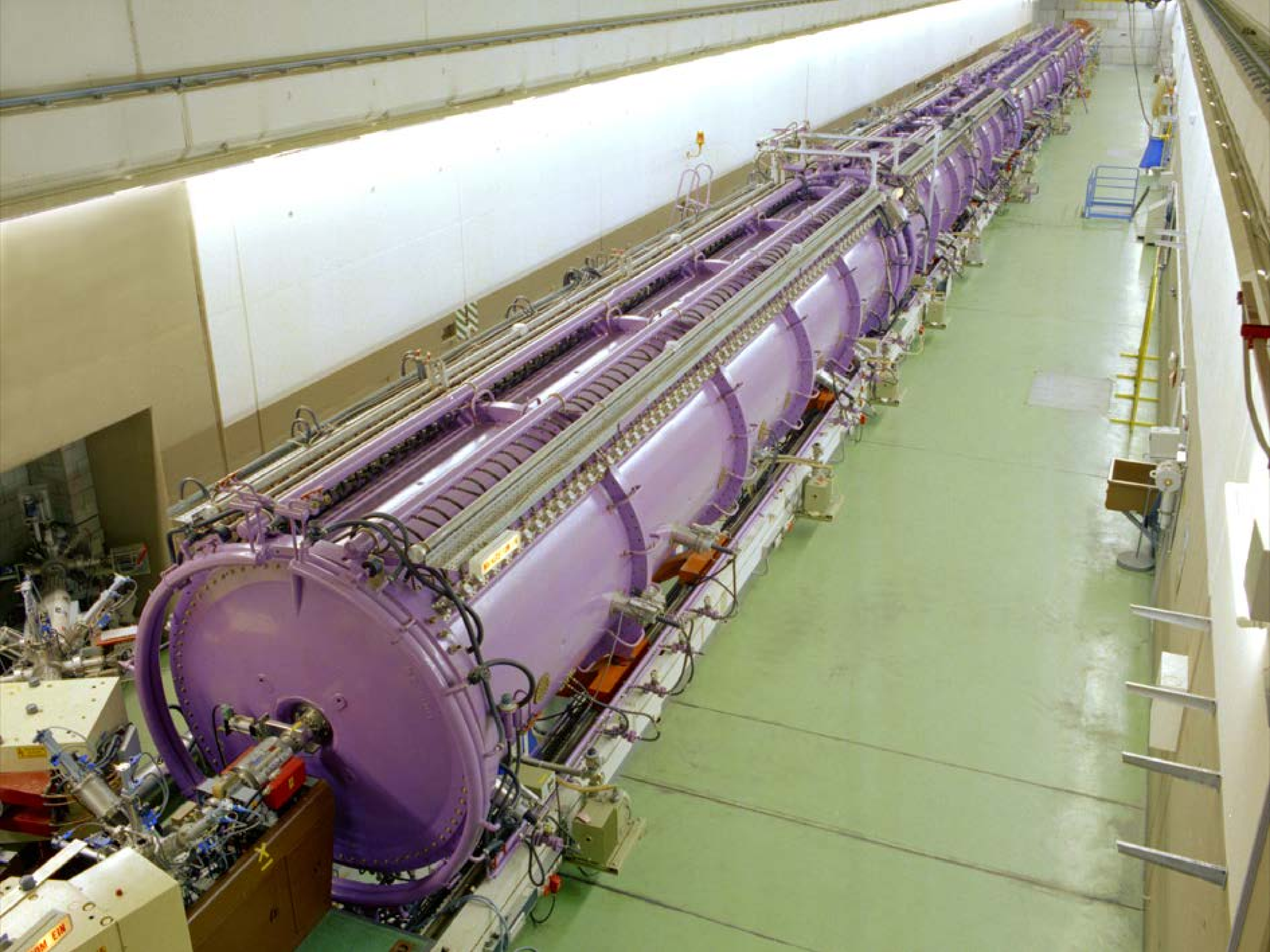
Employees: 1350

External scientists: 1000/year

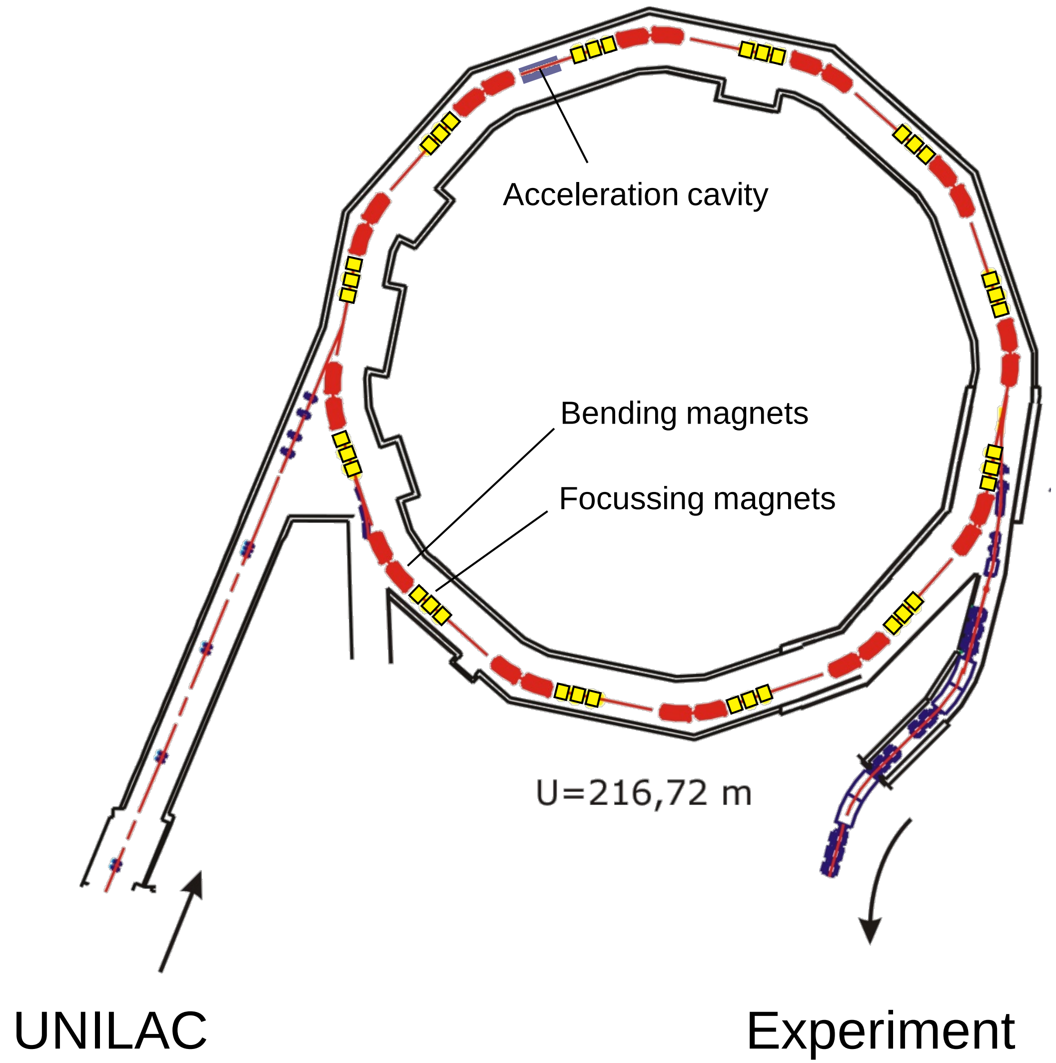
Large scale accelerators and experiments

ACCELERATOR FACILITIES AND EXPERIMENTAL AREAS



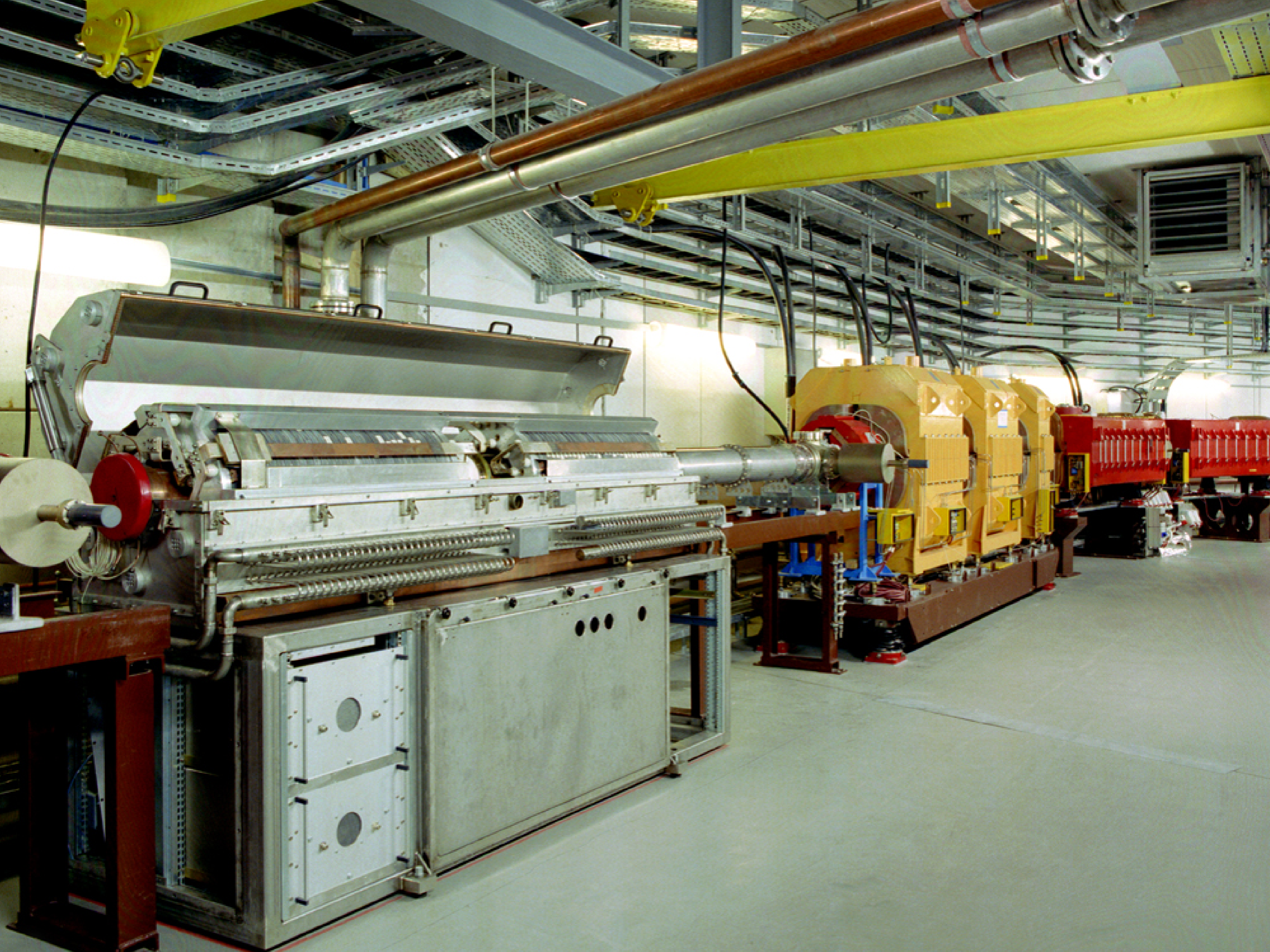


Heavy-ion synchrotron SIS18

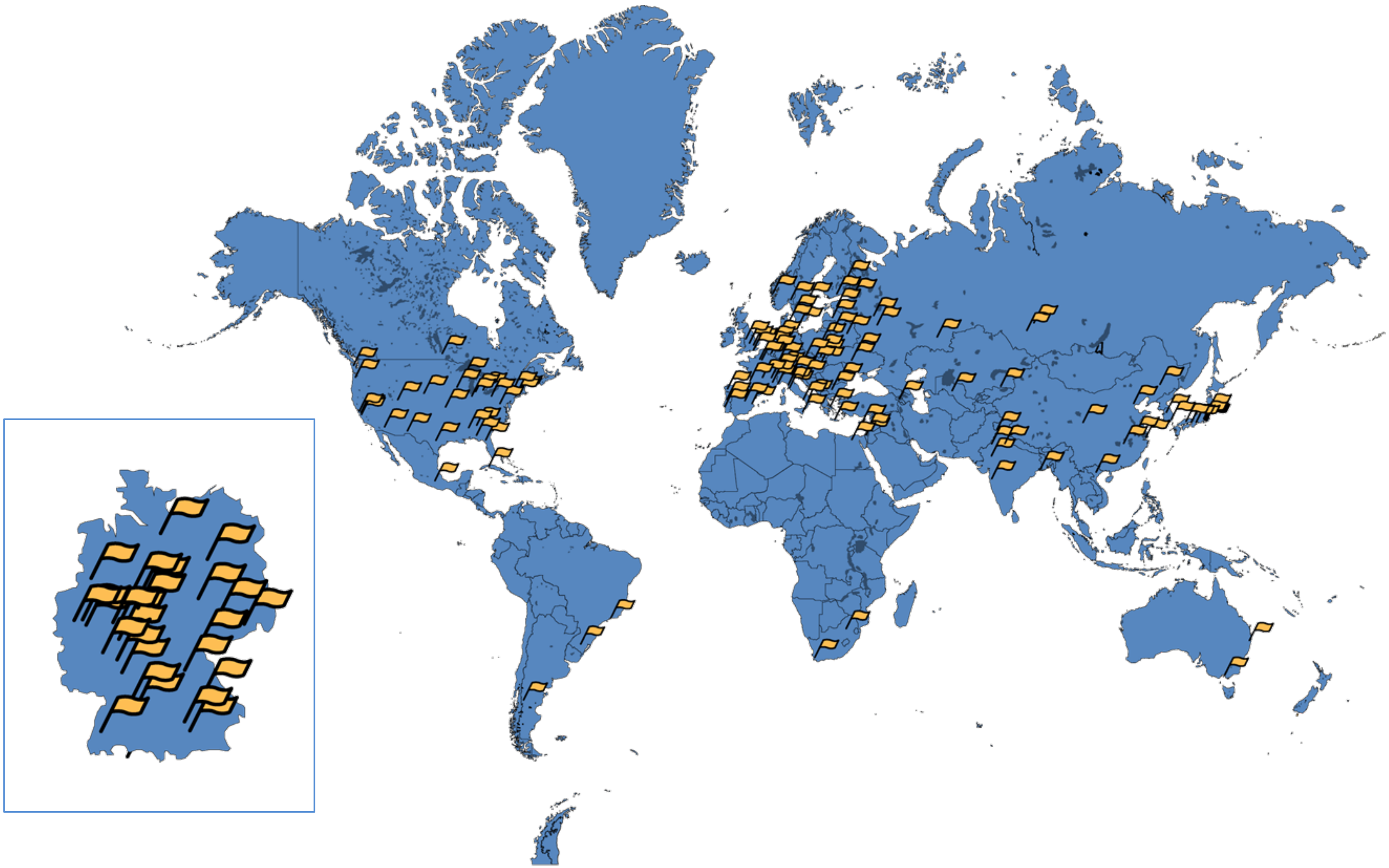


- Circumference: 216 m
- Acceleration: more than 100 000 turns per second
- Magnets: up to 1.8 T


ELIN
172 oben



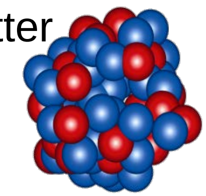
Worldwide Cooperations in more than 50 countries

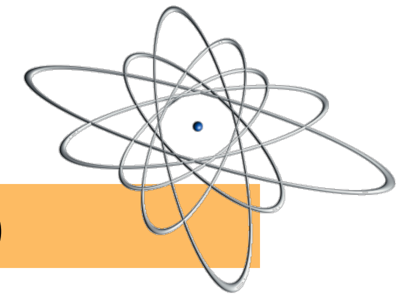


Research program

Nuclear physics (50%)

- Nuclear reactions
- hot and dense nuclear matter
- Superheavy elements





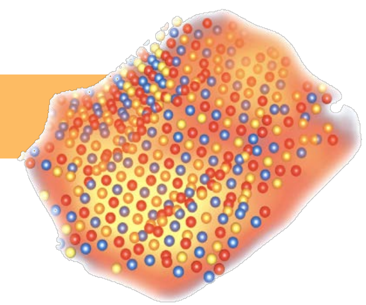
Atomic physics (15%)

- Atomic reactions
- Precision spectroscopy of highly charged ions

Biophysics and radiation physics (15%)

- Radiobiological effects of ions
- Tumor therapy twith ion beams

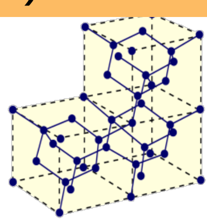
Plasma physics (5%)



- Hot and dense plasmas
- Ion-plasma interaction

Material research (5%)

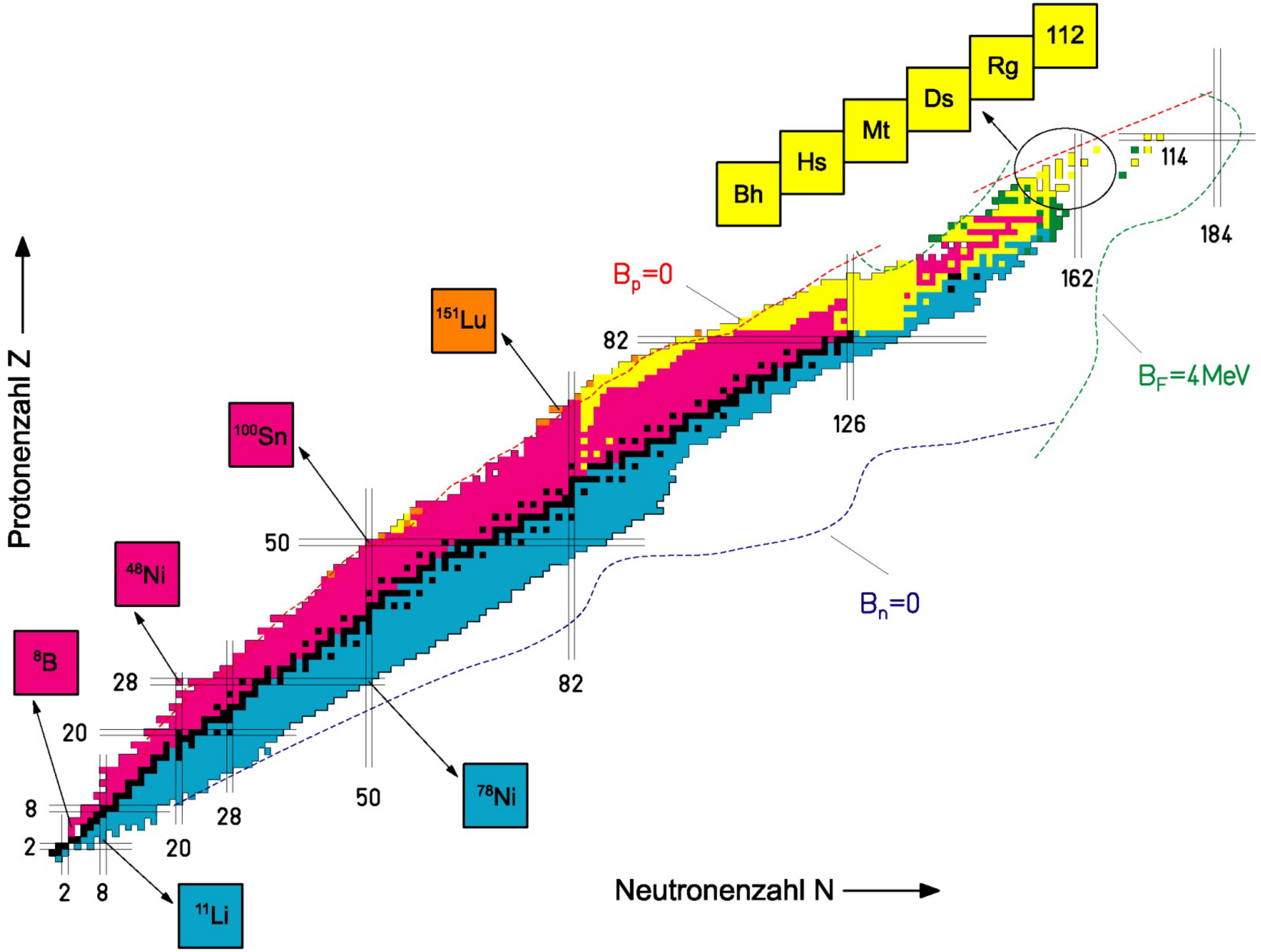
- Ion-material interaction
- Structuring of materials with ion beams



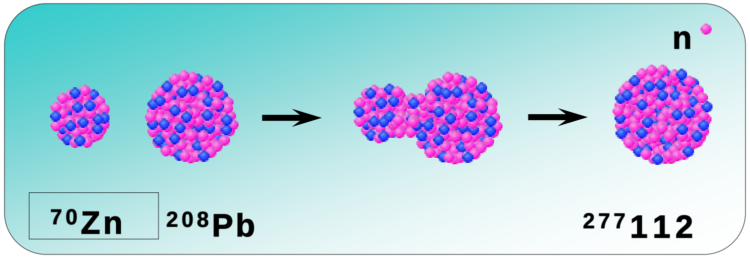
Accelerator technology (10%)

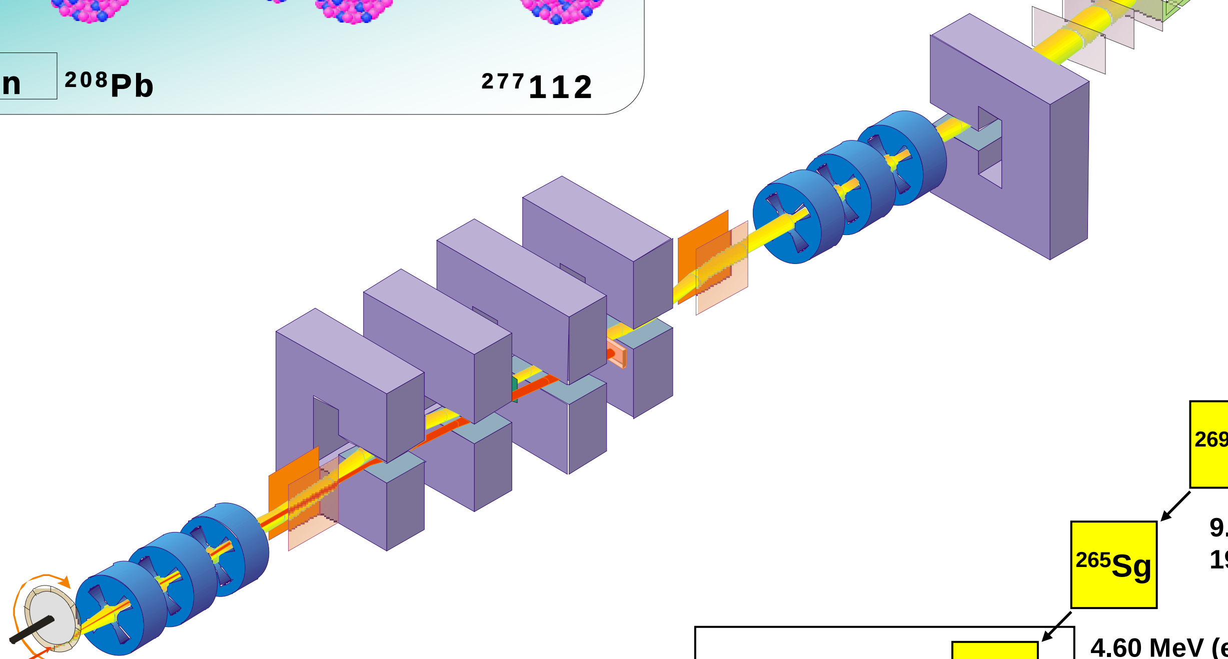
- Linear accelerators
- Synchrotrons und storage rings

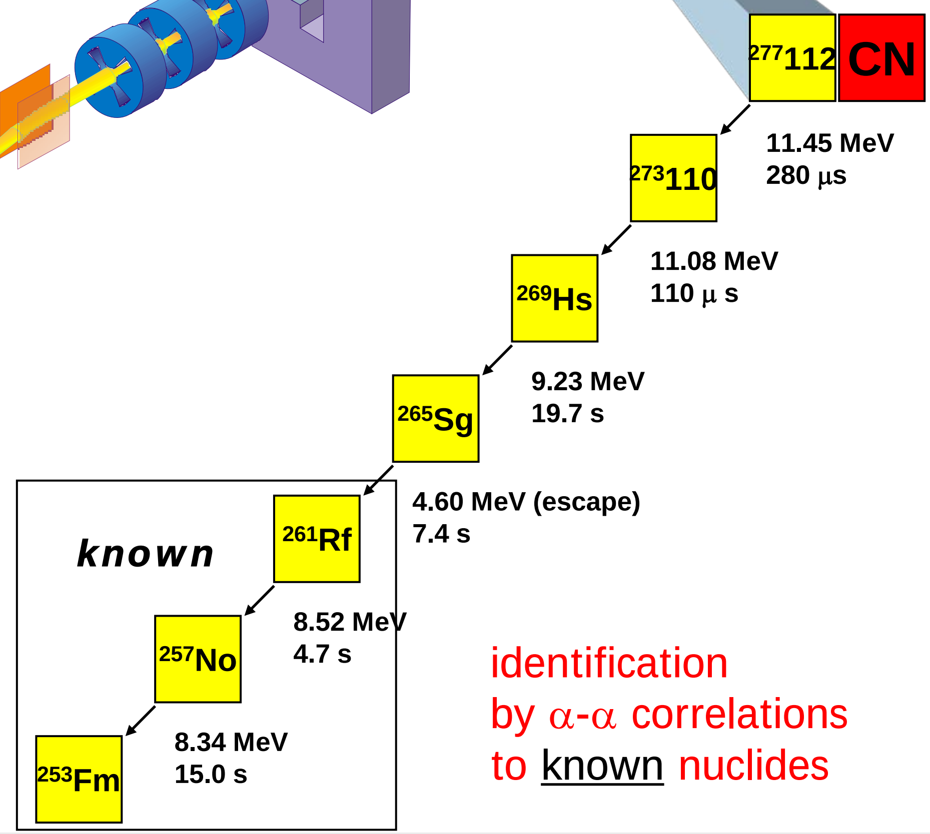
Superheavy elements



Superheavy elements







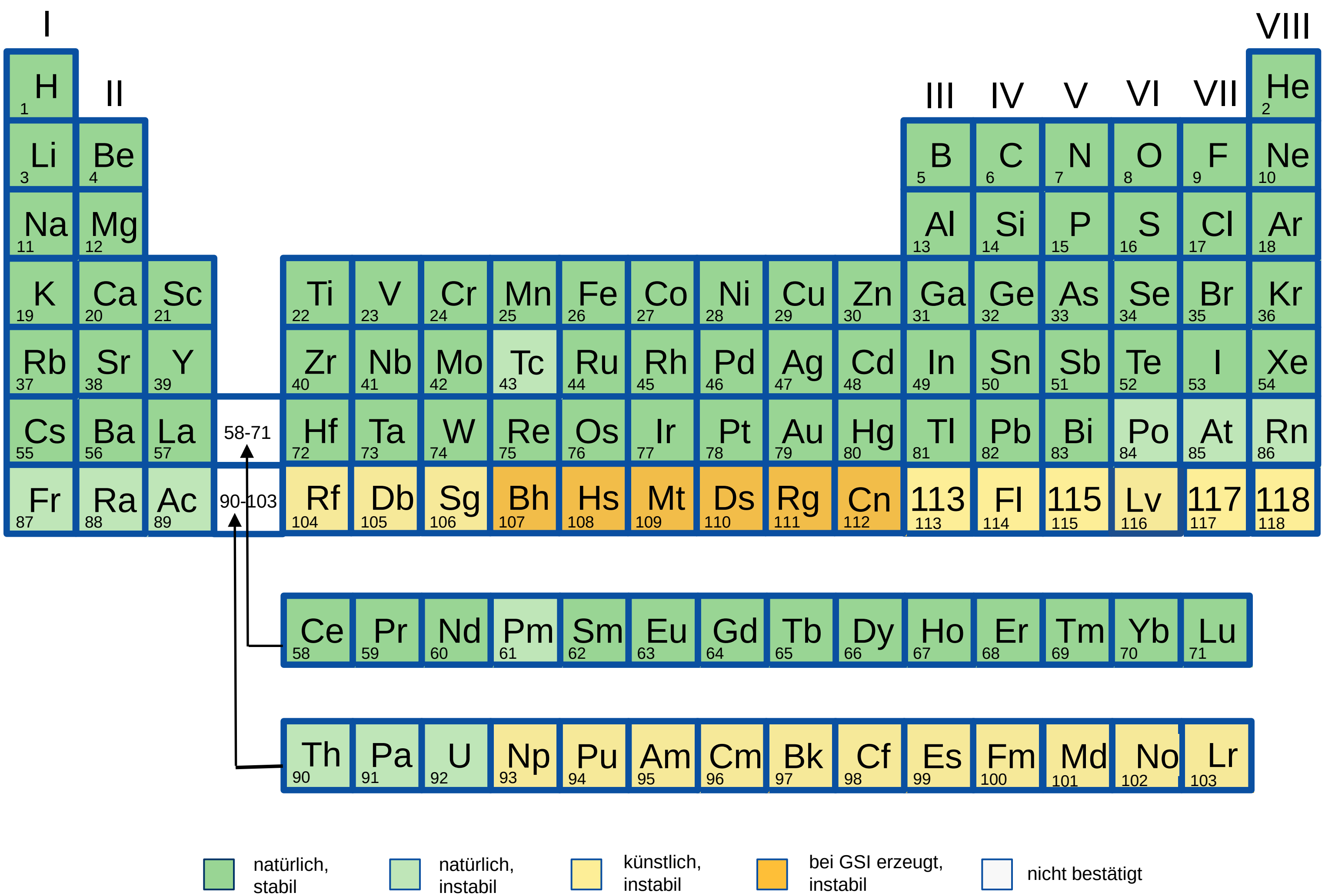
SHIP: kinematic separation in flight

Date: 09-Feb-1996
Time: 22:37 h

identification
by α-α correlations
to <u>known</u> nuclides

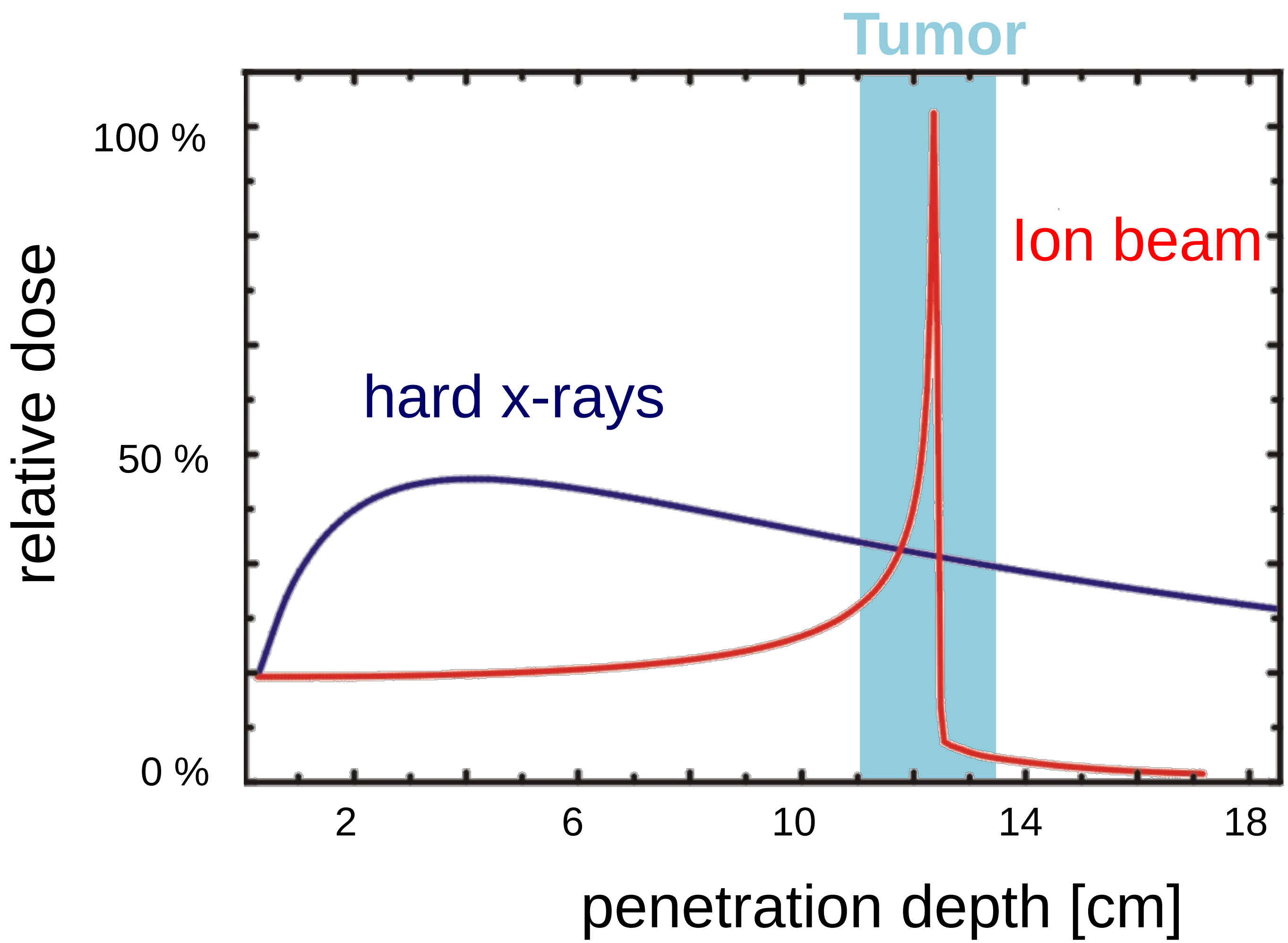
Superheavy elements

Periodic system of elements

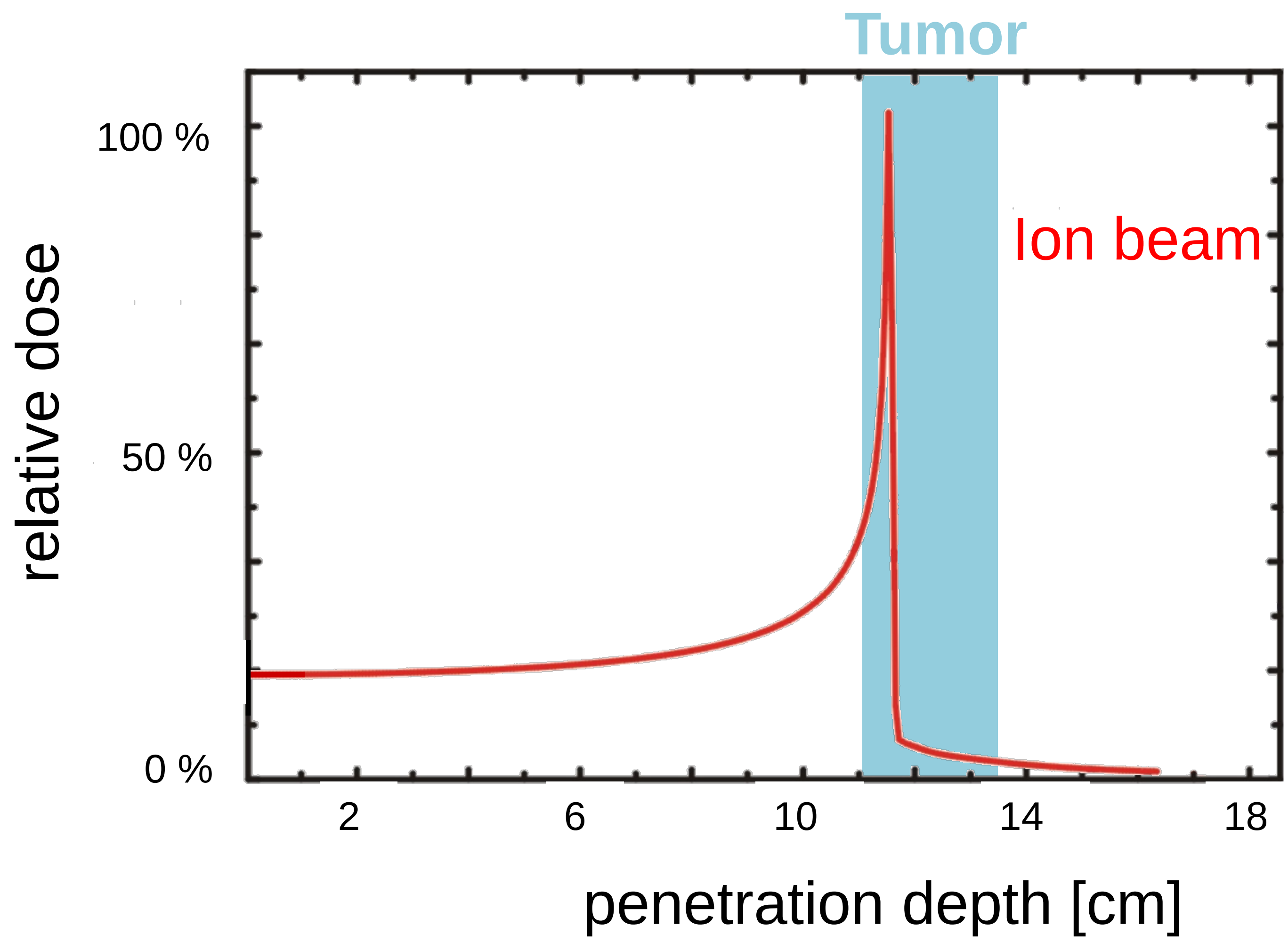


Tumor therapy with heavy ions

Radiation effects



Radiation effects

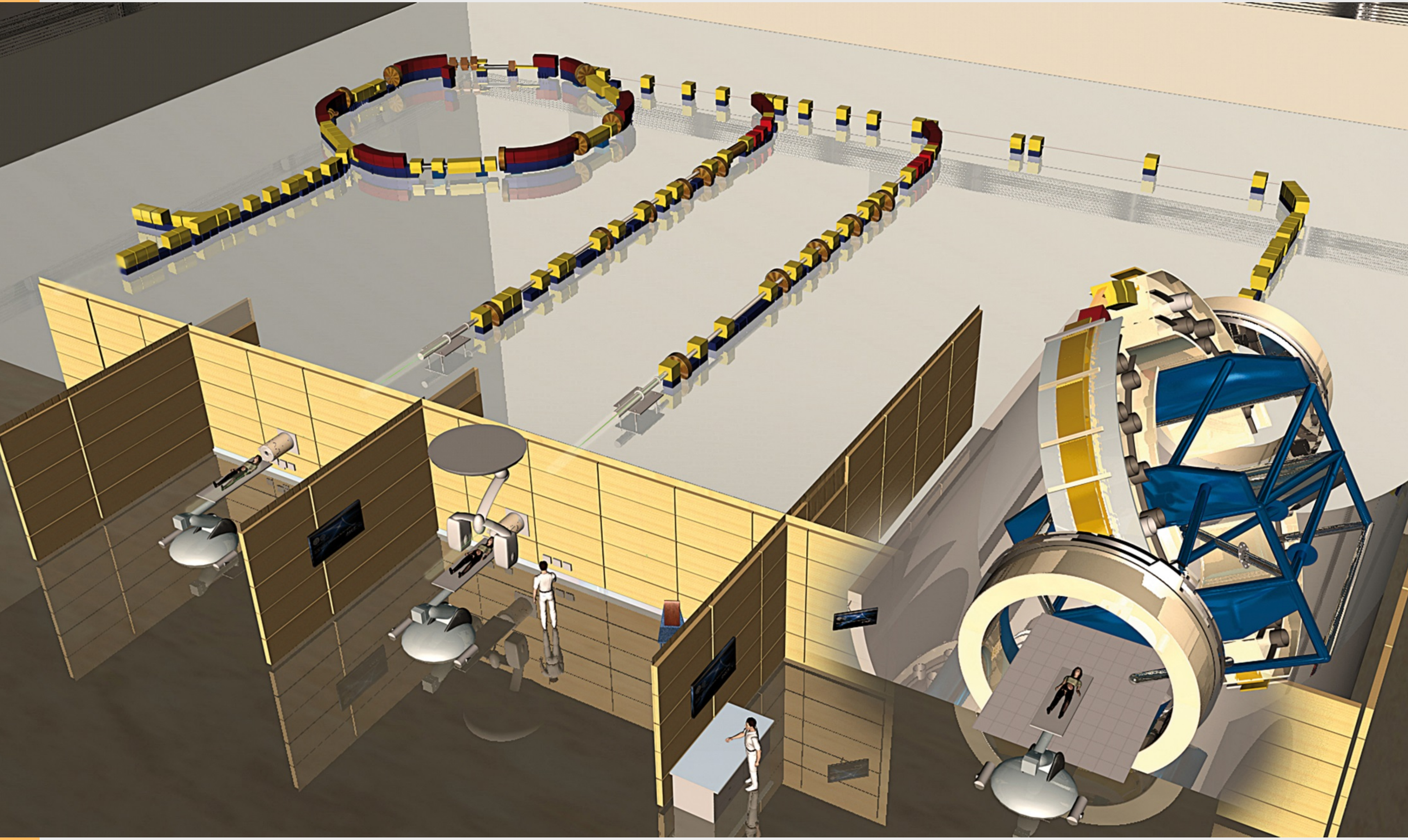


Course of desease

Prior to Carbon therapy

6 weeks after
Carbon therapy

Heidelberger Ionenstrahl-Therapiezentrum (HIT)



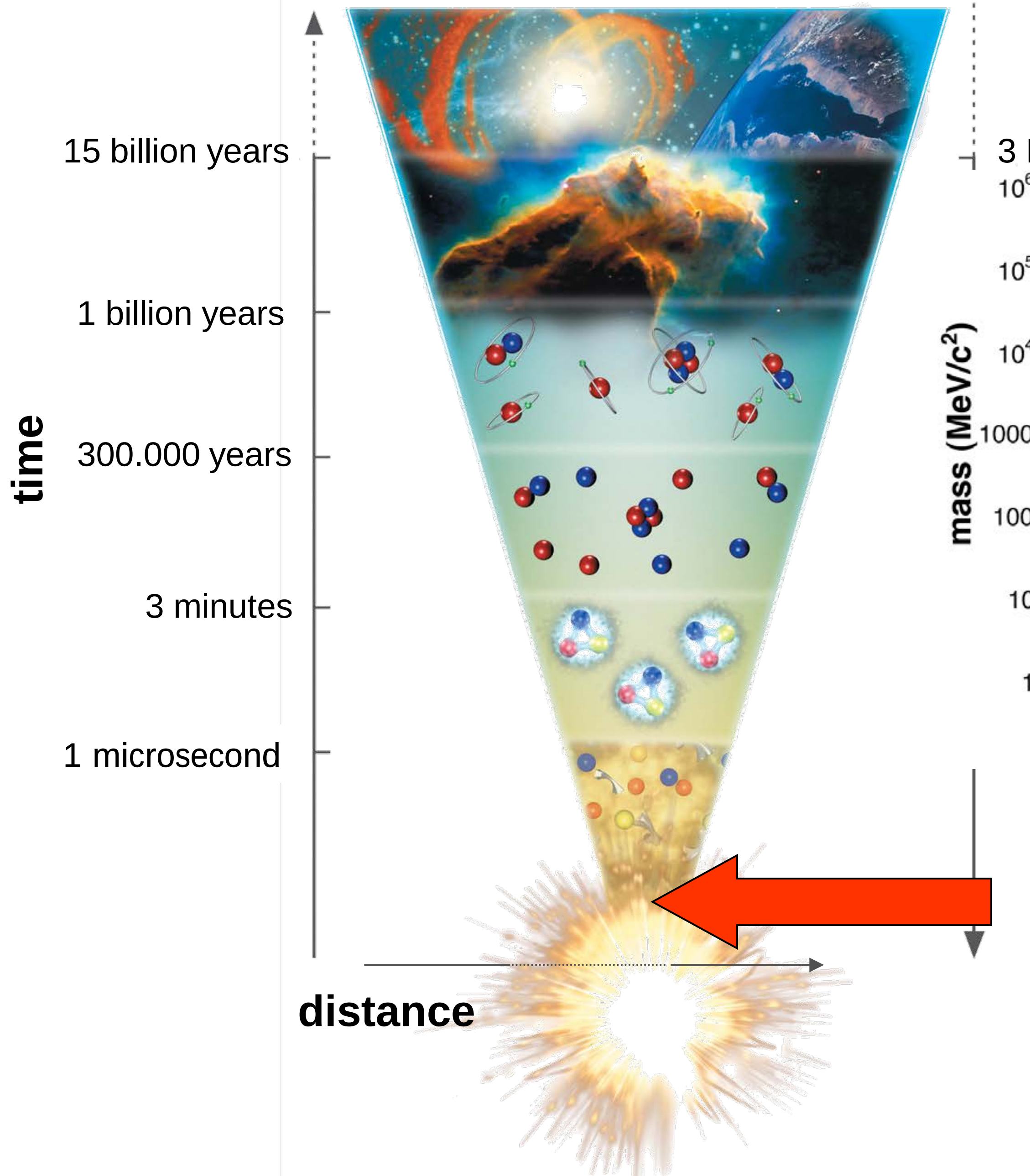
Heidelberger Ionenstrahl Therapiezentrum (HIT)

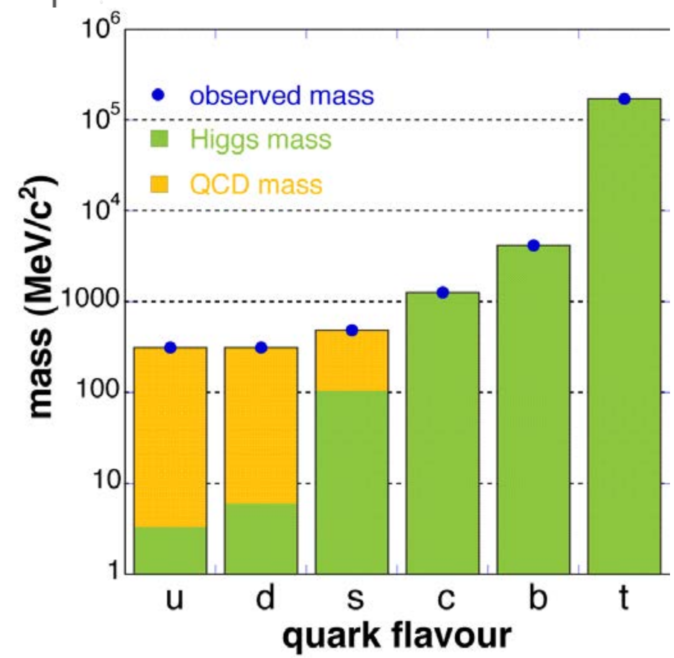
Inauguration Nov. 2, 2009
1000 patients per year

Facility for Antiproton and Ion Research: Cosmic matter in the laboratory

- FAIR is worldwide the largest project in fundamental science.
- Forefront research in nuclear, hadron, atom, plasma, antimatter, and applied physics.
- Member states: Germany, Russia, India, Poland, Romania, France, Finland, Sweden, Slovenia, Great Britain.
- 2500 – 3000 users per year.
- Total costs ca. 1.7 Mrd. €, full completion in 2025.
- Financing: Fed. Rep. Germany 60%, Hesse 10%, partner countries 30%

The evolution of matter in the universe





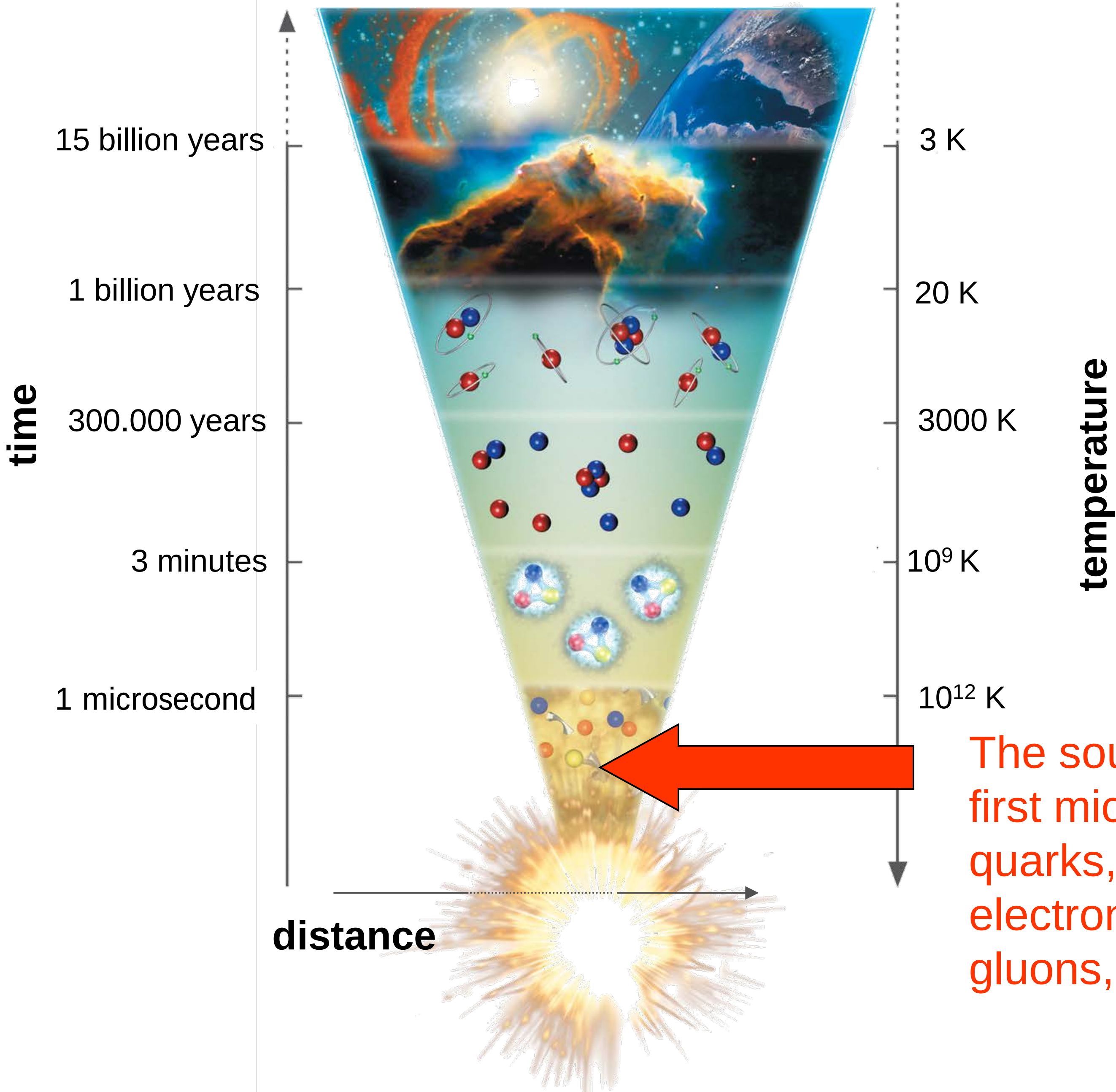
Explicit breaking of Chiral Symmetry (Higgs mechanism)

$m_u \approx 5$ MeV,

$m_d \approx 10$ MeV,

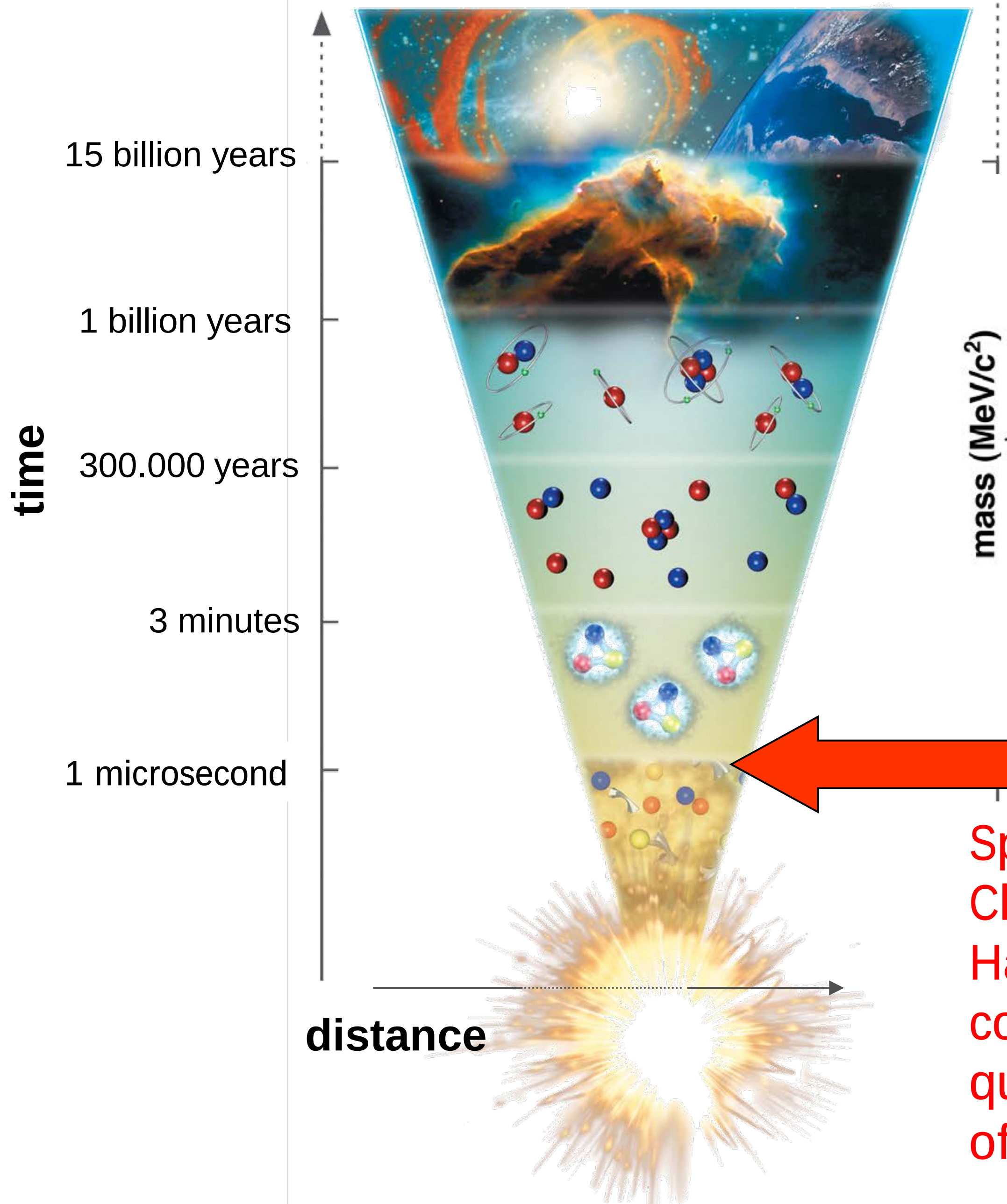
$m_s \approx 150$ MeV

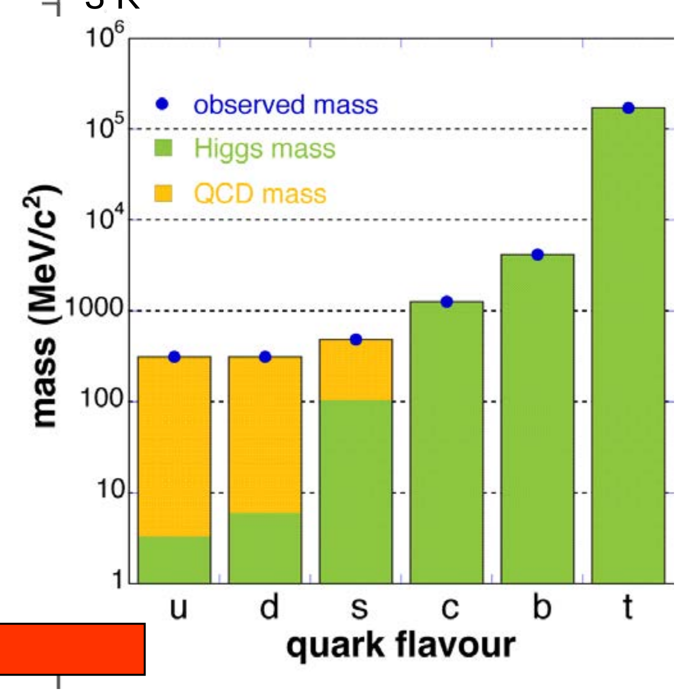
The evolution of matter in the universe



The soup of the first microsecond: quarks, antiquarks, electrons, positrons, gluons, photons

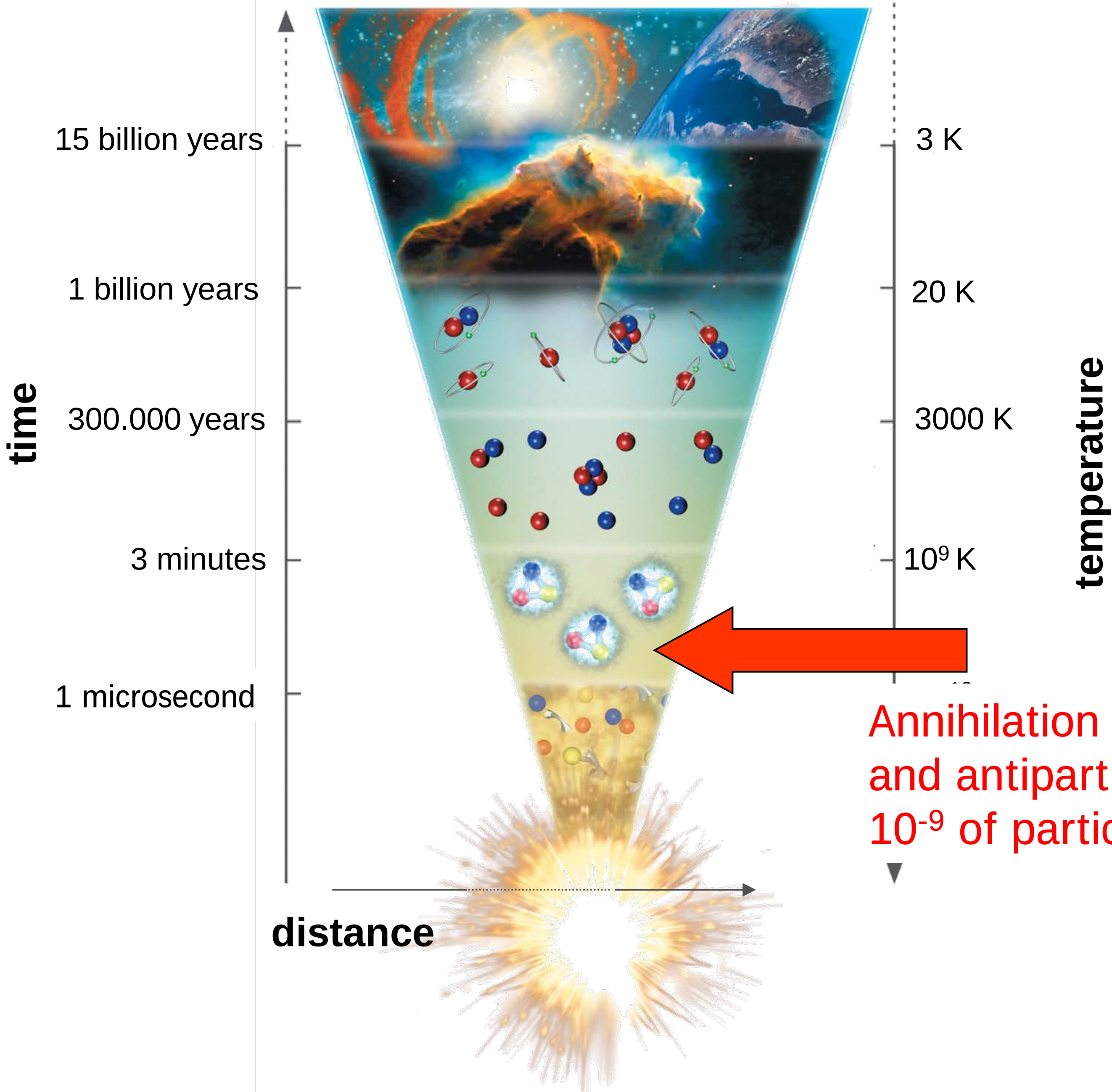
The evolution of matter in the universe





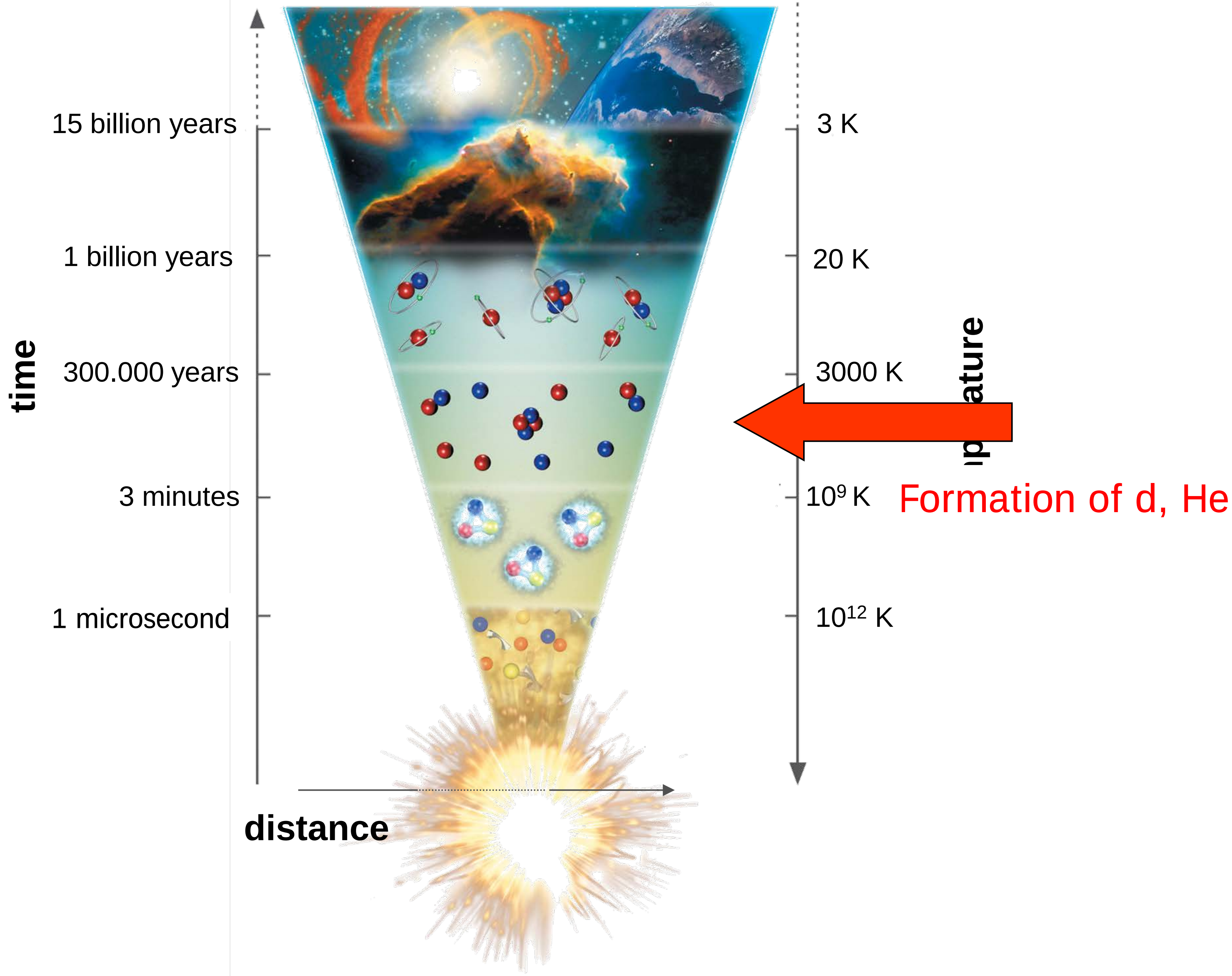
Spontaneous/dynamical
Chiral Symmetry breaking:
Hadrons acquire mass by
coupling to the virtual
quark-antiquark pairs
of the chiral condensate

The evolution of matter in the universe

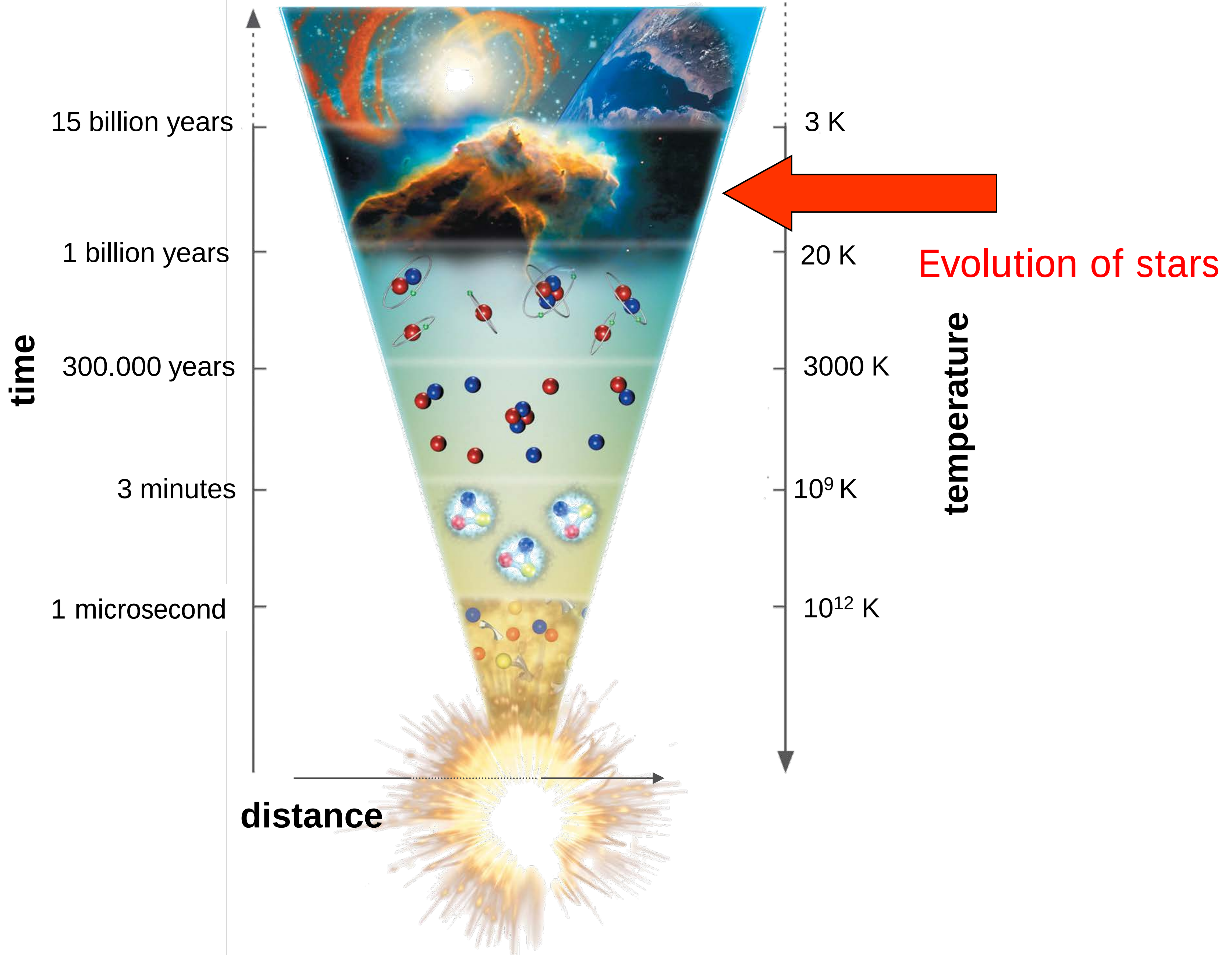


Annihilation of particles and antiparticles, only 10^{-9} of particles survived

The evolution of matter in the universe



The evolution of matter in the universe

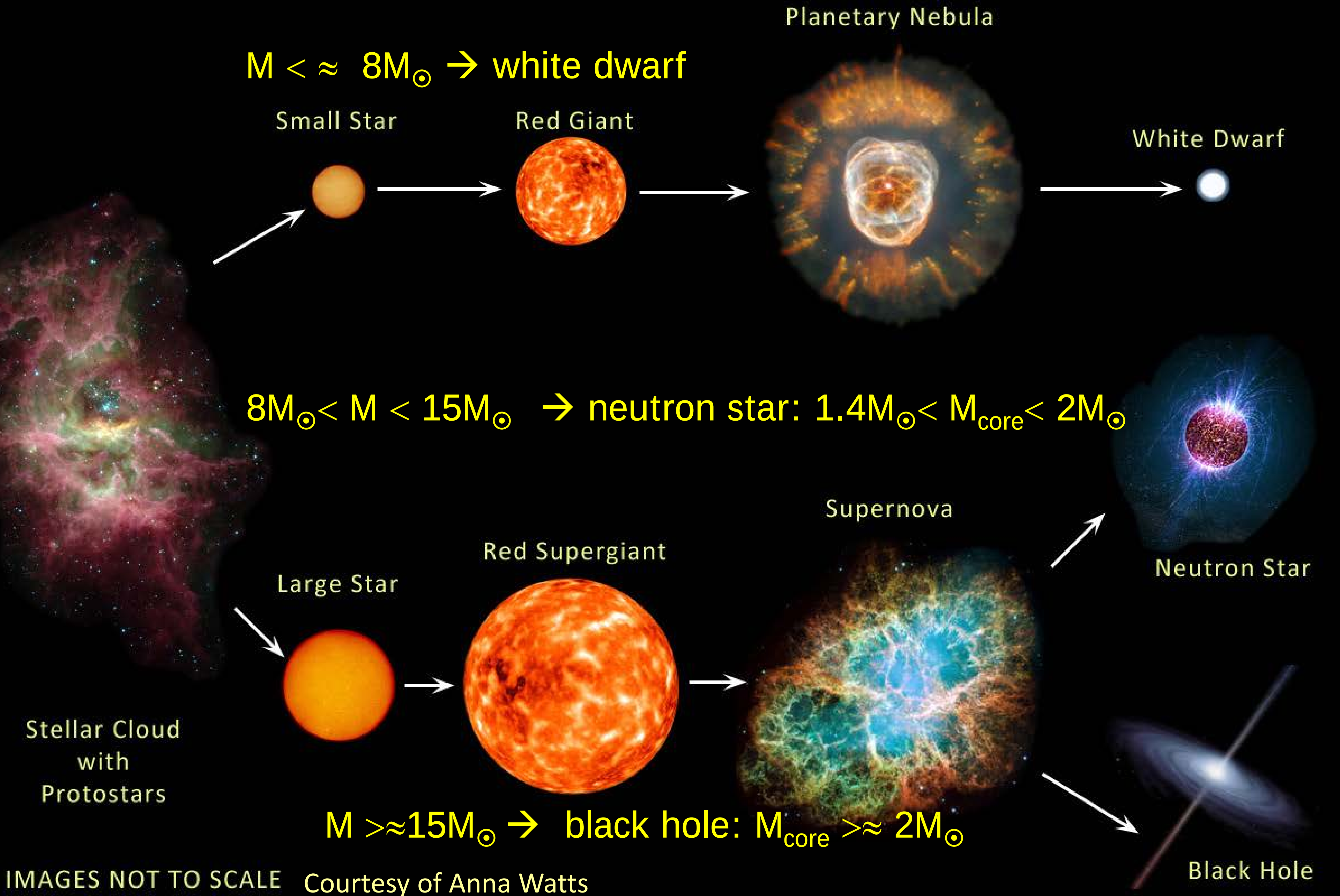


The evolution of stars

$M < \approx\ 8M_\odot \rightarrow$ white dwarf

$8M_\odot < M < 15M_\odot \rightarrow$ neutron star: $1.4M_\odot < M_{core} < 2M_\odot$

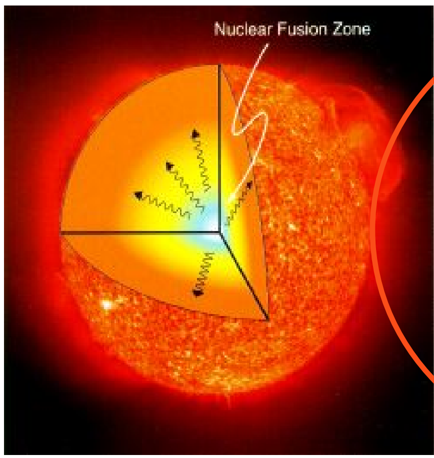
$M > \approx 15M_\odot \rightarrow$ black hole: $M_{core} > \approx 2M_\odot$



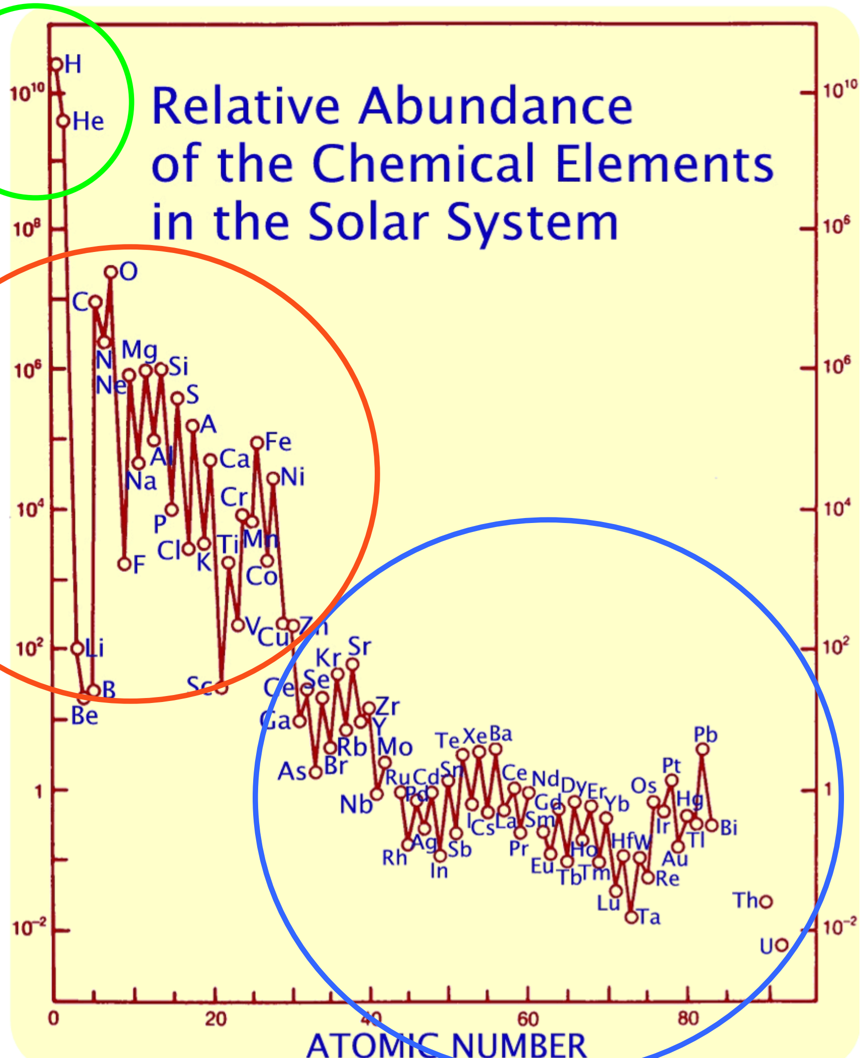
Courtesy of Anna Watts

The Origin of Elements

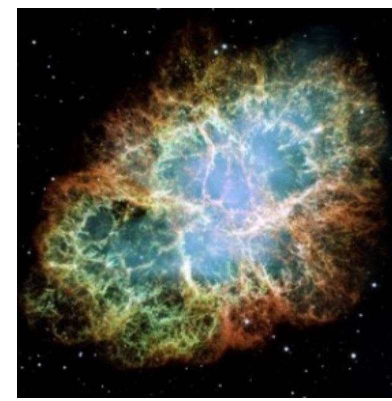
Nukleosynthesis after the Big Bang



Nuclear fusion in stars

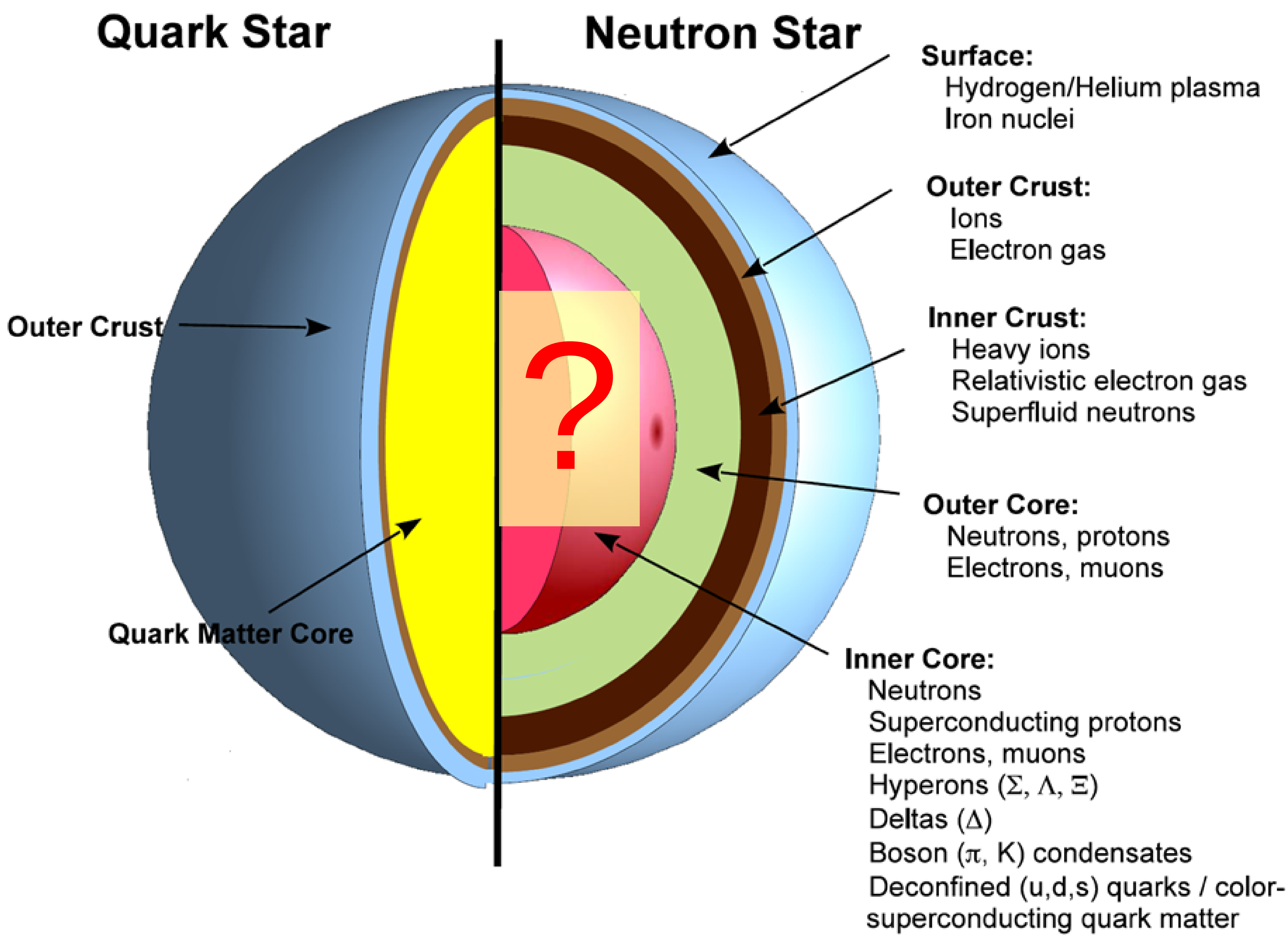


Neutron capture in Red Giants (s-process) or in supernovae or neutron star mergers (r-process)



Discovery of the first pulsar in 1968

Crab nebula:
ashes of a core collapse supernova observed in 1054 by Chinese astronomers.
The “visiting star” was as bright as the Venus for more than 20 days.


Quark Star
Neutron Star
Surface:
Hydrogen/Helium plasma
Iron nuclei
Outer Crust:
Ions
Electron gas
Inner Crust:
Heavy ions
Relativistic electron gas
Superfluid neutrons
Outer Core:
Neutrons, protons
Electrons, muons
Inner Core:
Neutrons
Superconducting protons
Electrons, muons
Hyperons (Σ, Λ, Ξ)
Deltas (Δ)
Boson (π, K) condensates
Deconfined (u,d,s) quarks / color-superconducting quark matter
Outer Crust
Quark Matter Core
?

Fundamental questions

What is the origin of the mass of the universe?

What is the origin of the elements ?

What is the structure of neutron stars?

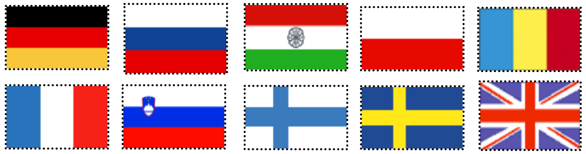
Can we ignite the solar fire on earth ?

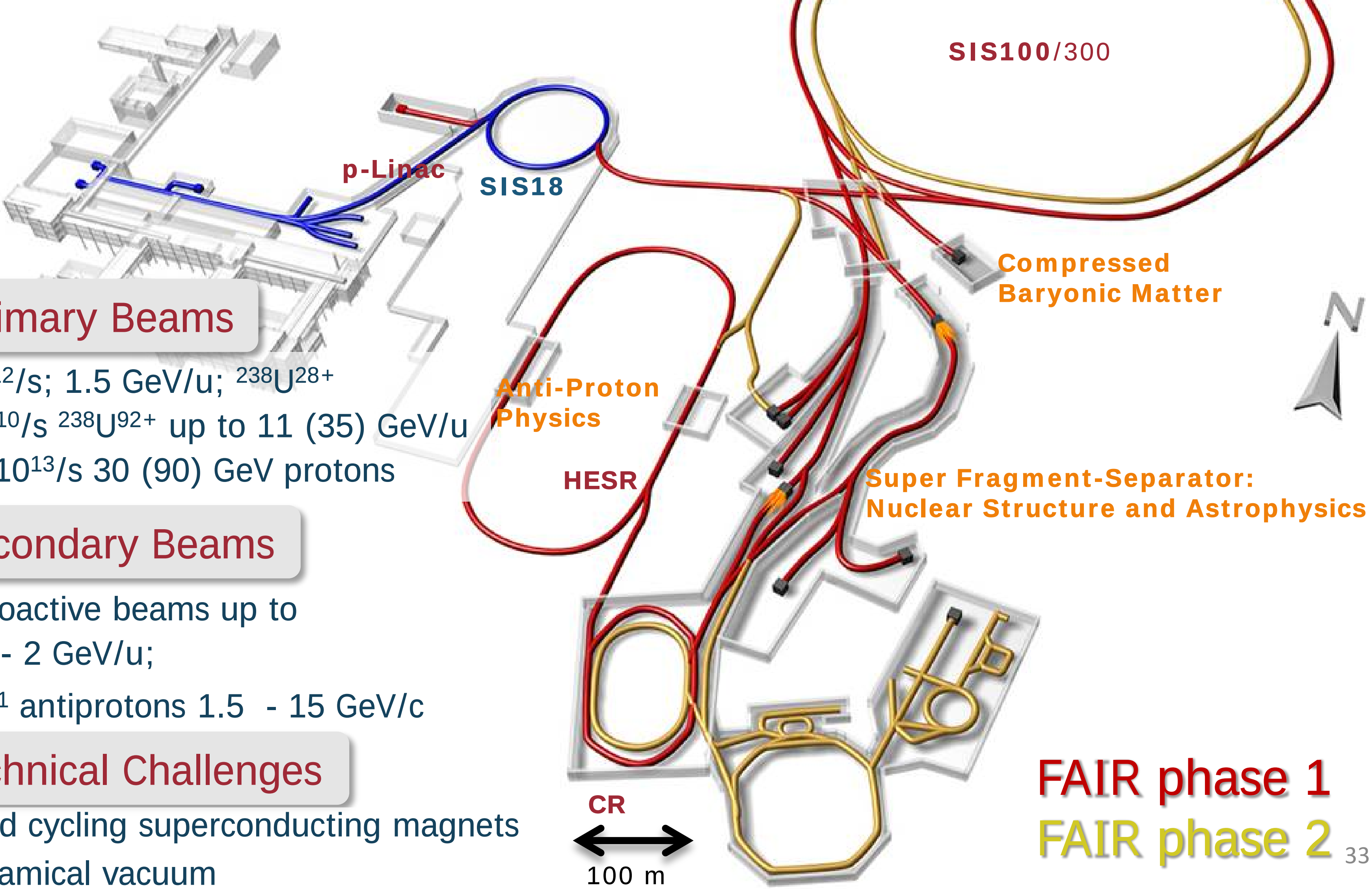
Does matter differ from antimatter ?

Why do we not observe individual quarks ?

→ to be explored at the future international Facility for Antiproton and Ion Research (FAIR)

Facility for Antiproton & Ion Research





Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{92+}$ up to 11 (35) GeV/u
- 3×10^{13}/s 30 (90) GeV protons

Secondary Beams

- radioactive beams up to 1.5 - 2 GeV/u;
- 10^{11} antiprotons 1.5 - 15 GeV/c

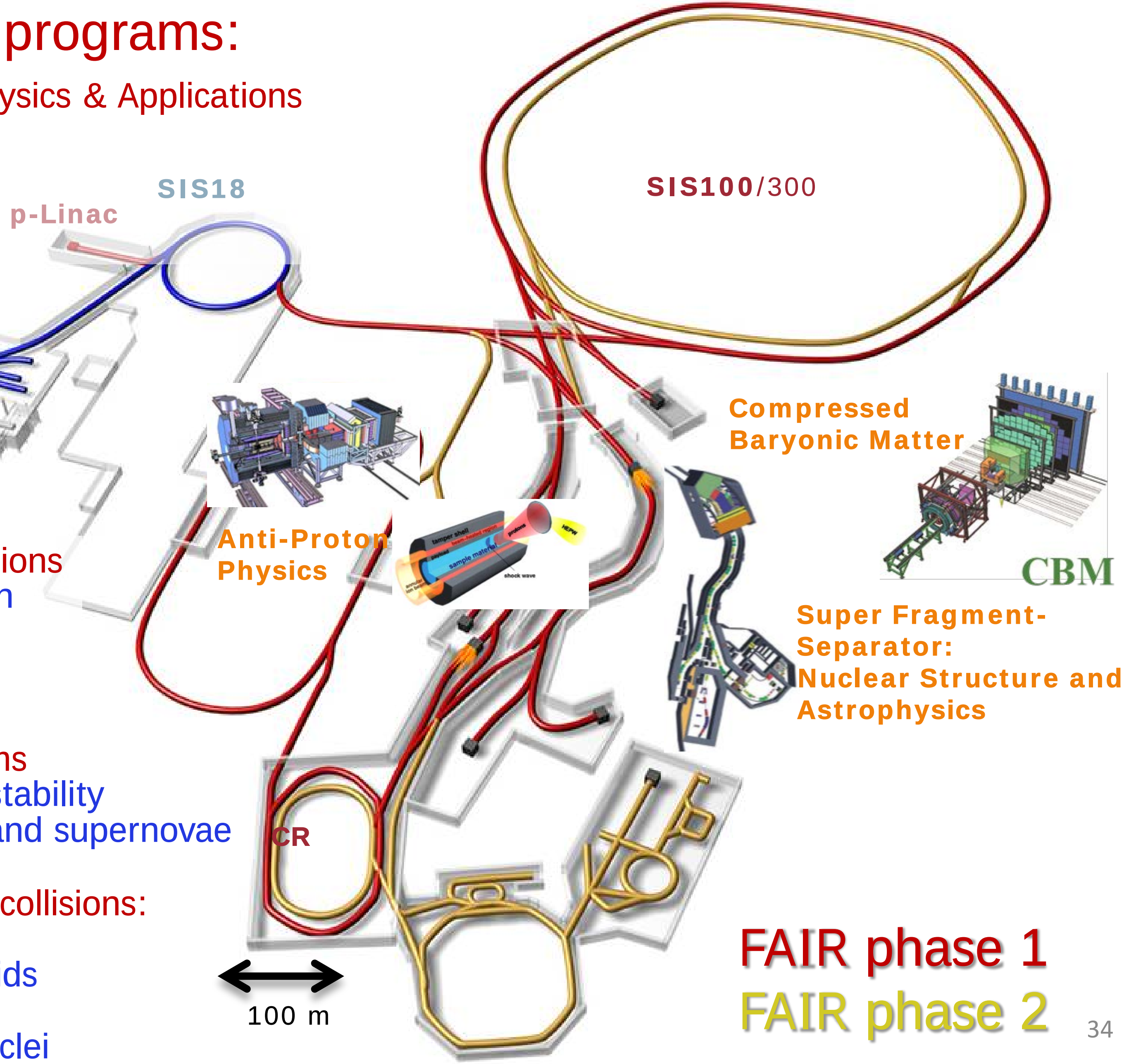
Technical Challenges

- rapid cycling superconducting magnets
- dynamical vacuum

Facility for Antiproton & Ion Research

Experimental programs:

APPA: Atomic & Plasma Physics & Applications
- Highly charged atoms
- Plasma physics
- Radiobiology
- Material science



CBM: Nucleus-nucleus collisions
- Nuclear matter at neutron star core densities
- Phase transitions from hadrons to quarks

NUSTAR: Rare Isotope beams
- Nuclear structure far off stability
- Nucleosynthesis in stars and supernovae

PANDA: Antiproton-proton collisions:
- Charmed hadrons (XYZ)
- Gluonic matter and hybrids
- Hadron structure
- Double Lambda hypernuclei

NUclear **ST**ructure **A**strophysics and **R**eactions

How are complex nuclei built from their basic constituents?

– What is the effective nucleon-nucleon interaction and how does QCD constrain its parameters?

– How does the three-nucleon force modify the picture?

How does the effective nuclear force depend on varying proton-to-neutron ratios?

– What is the isospin dependence of the spin-orbit force?

– How does shell structure change far from stability?

– How does the role of N-N correlations in nuclei and nuclear matter change with isospin?

How to explain collective phenomena from individual motion?

– What are the phases, relevant degrees of freedom, and symmetries of the nuclear many-body system?

What are the limits of existence of nuclei?

– Where are the proton and neutron drip lines situated?

– What are the heaviest elements?

Which nuclei are relevant for astrophysical processes, what are their properties and what is their impact on nucleosynthesis modeling?

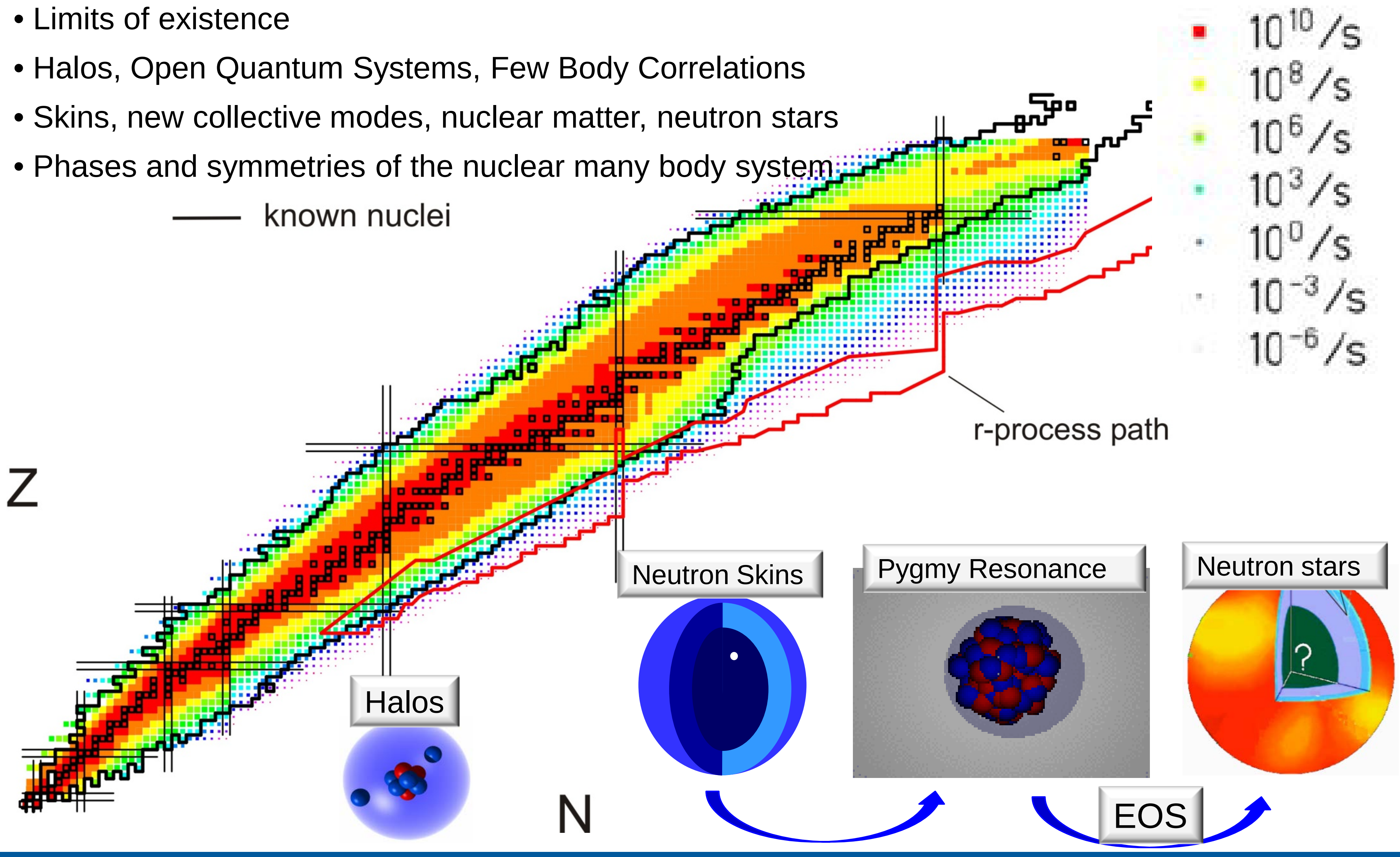
How does the equation of state of nuclear matter change with neutron-to-proton asymmetry?

– How large is the symmetry energy and its density dependence?

– What are the properties of neutron-rich matter?

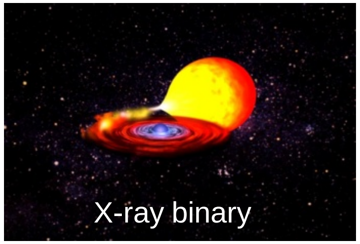
Nuclear structure research at FAIR

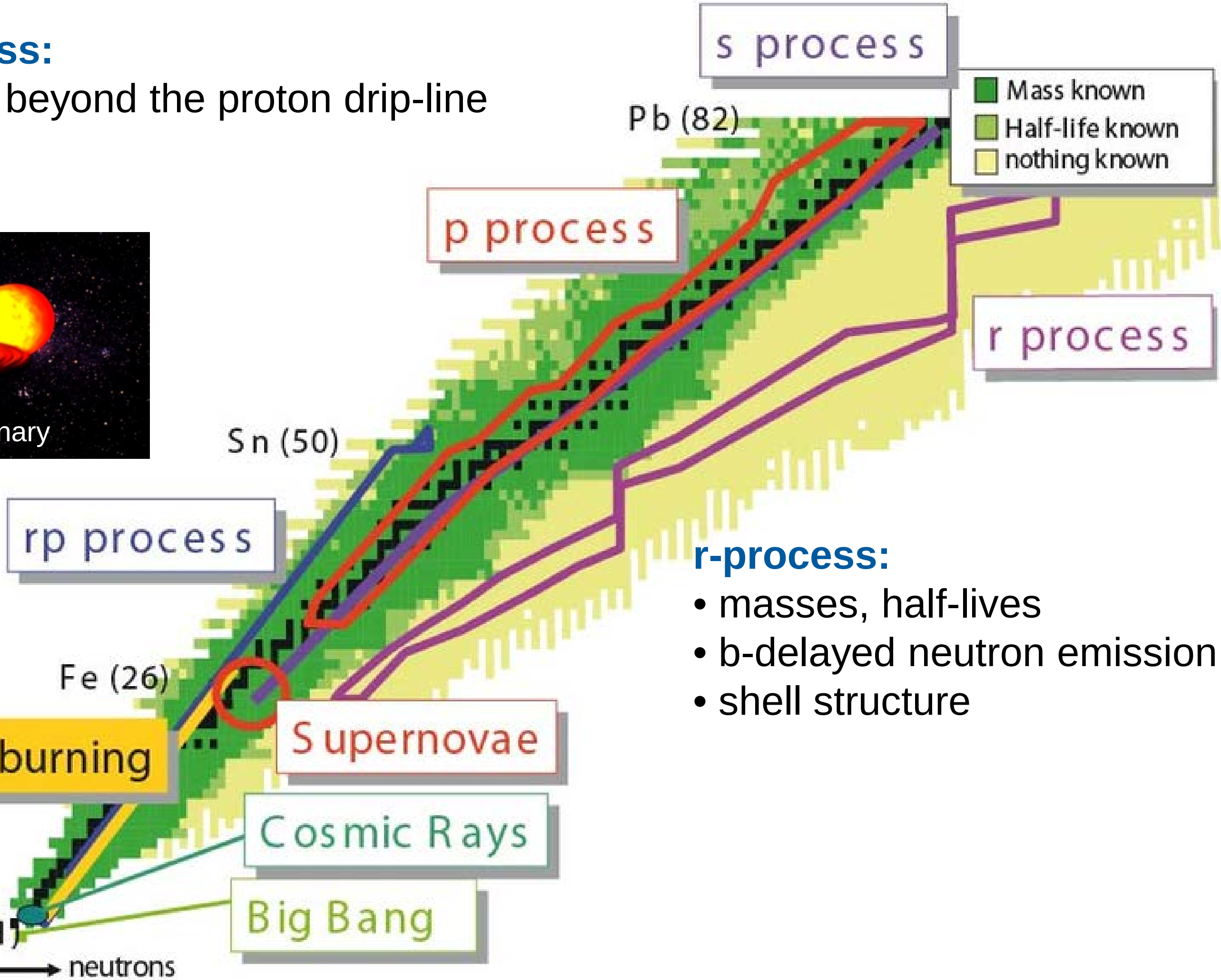
- Limits of existence
- Halos, Open Quantum Systems, Few Body Correlations
- Skins, new collective modes, nuclear matter, neutron stars
- Phases and symmetries of the nuclear many body system

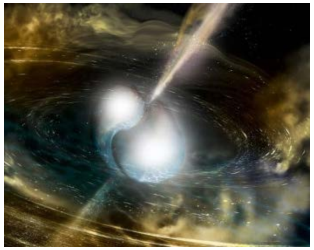


Nuclear Astrophysics at FAIR

rp-, p-process:
masses at & beyond the proton drip-line

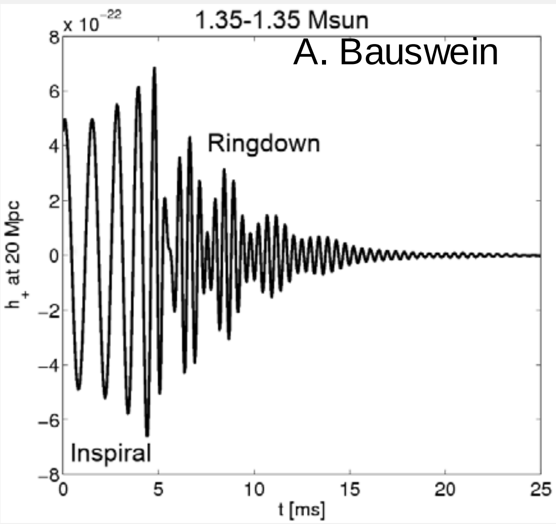




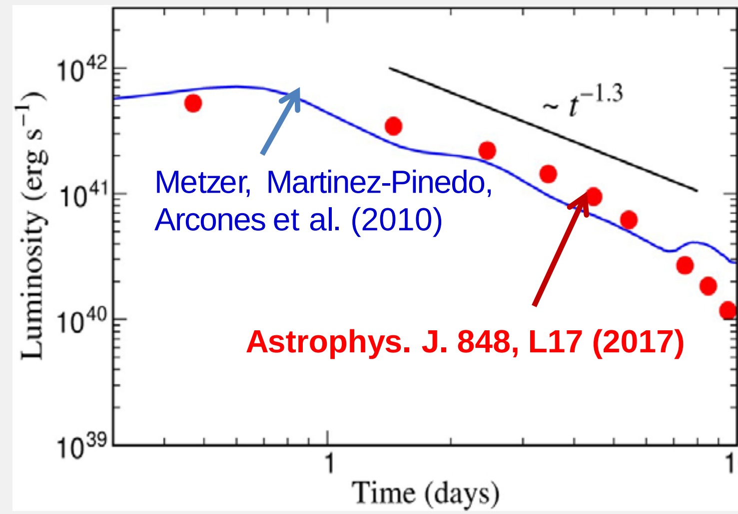


r-process:
- masses, half-lives
- b-delayed neutron emission
- shell structure

Astrophysical site of heavy element production (r process) in the universe: Neutron star merger !



Gravitational Wave Signal

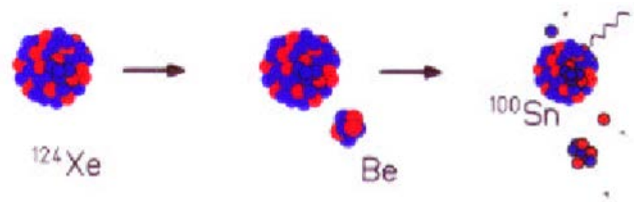


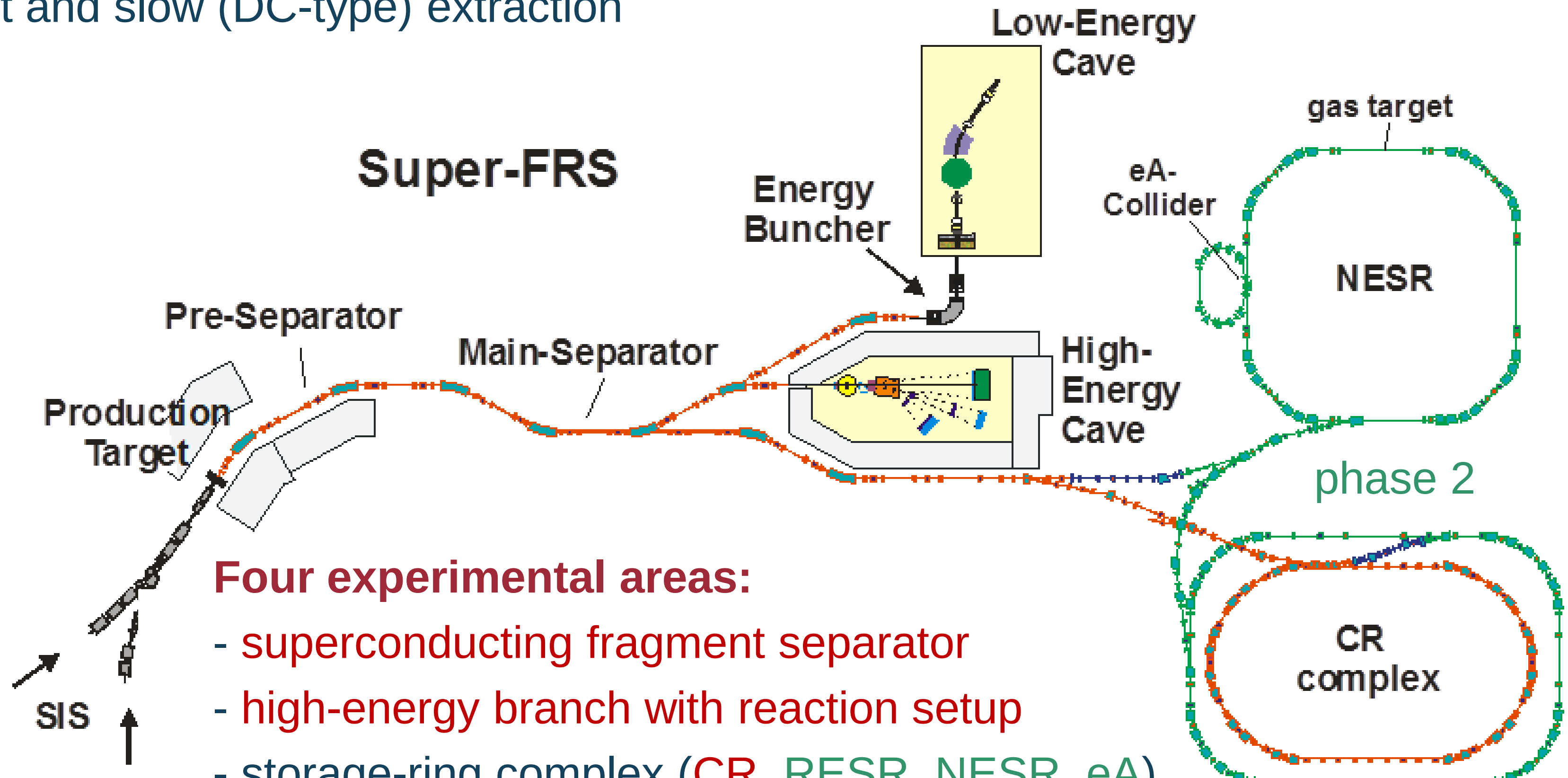
Electromagnetic "Kilonova" Signal

- Electromagnetic "Kilonova" signal due to "r process" in neutron star merger theoretically predicted by GSI scientists in 2010.
- Confirmation by recent astronomical observations after gravitational wave detection from GW170817 (September 2017).
- Source of heavy elements including gold, platinum and uranium.

The NUSTAR experimental facilities at FAIR

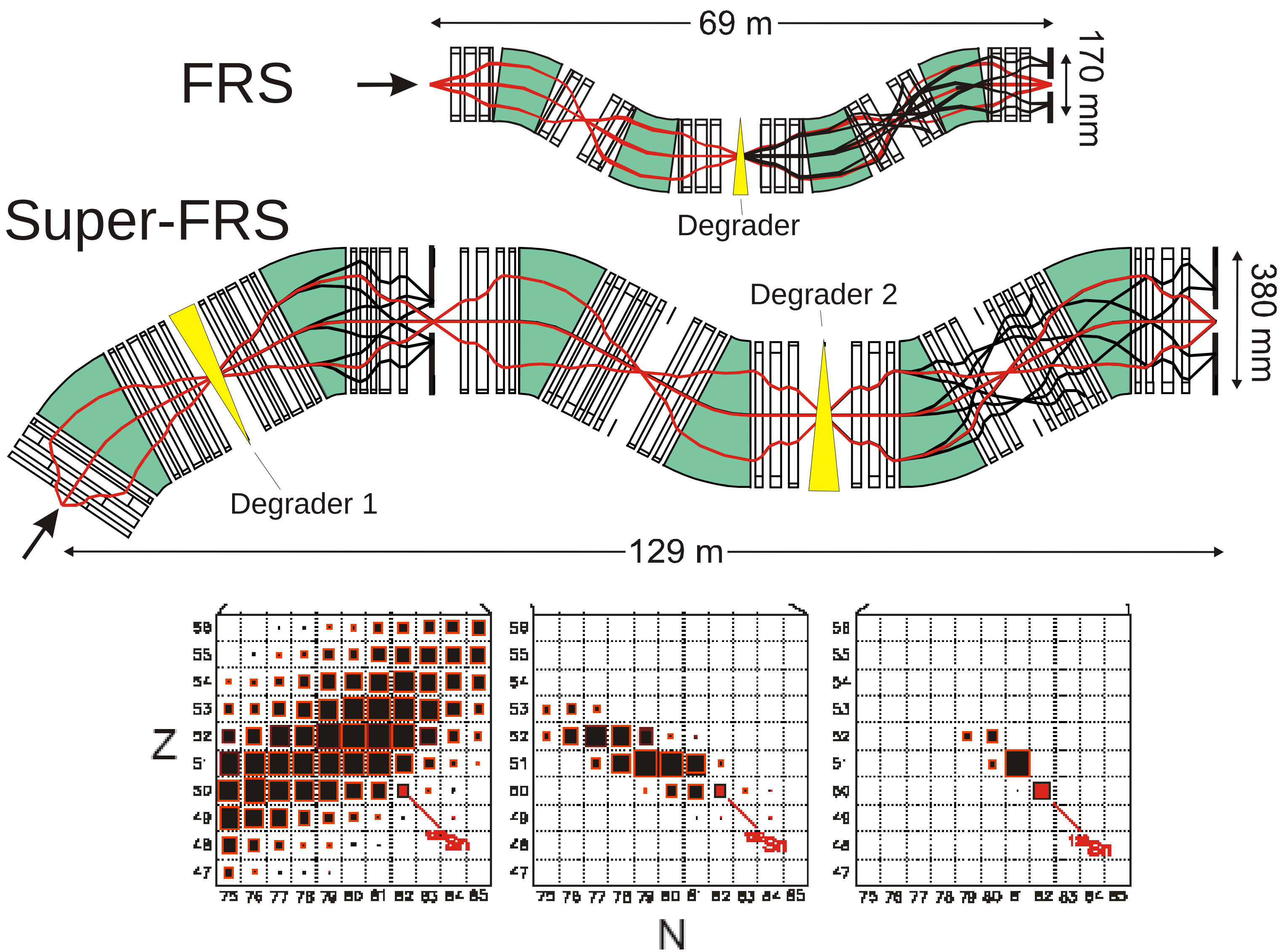
Important beam parameters:
- all elements (H through U)
- intensity ~ 10^{12} ions/sec.
- beam energies up to 1.5 GeV/u
- fast and slow (DC-type) extraction



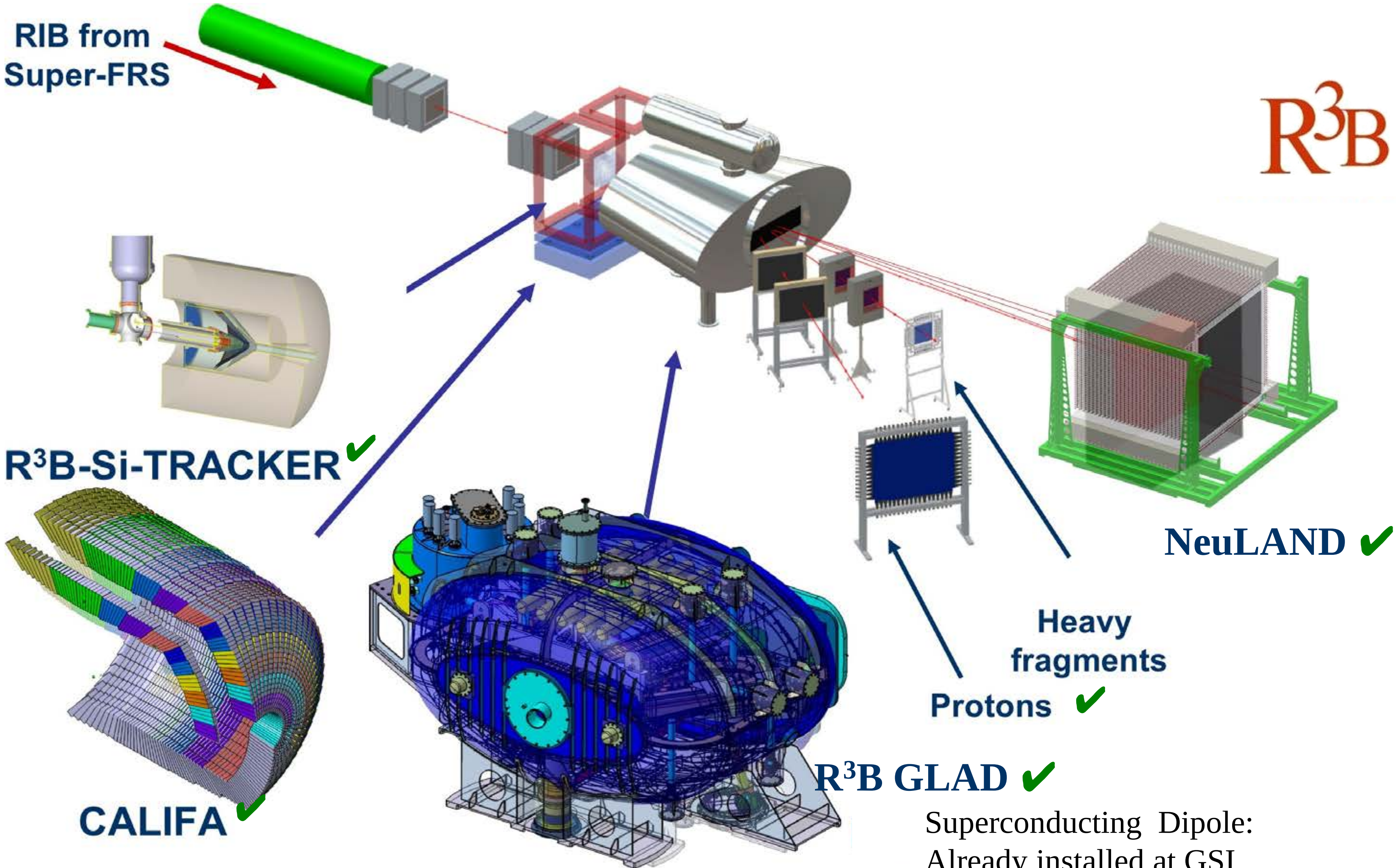


Four experimental areas:
- superconducting fragment separator
- high-energy branch with reaction setup
- storage-ring complex (CR, RESR, NESR, eA)
- low-energy branch with energy focusing and re-acceleration

Fragment-Separators at GSI and FAIR



Reactions with Relativistic Radioactive Beams R3B

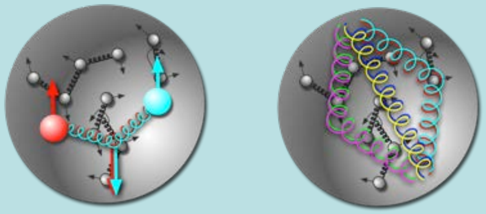


Superconducting Dipole:
Already installed at GSI
Construction by CEA Saclay

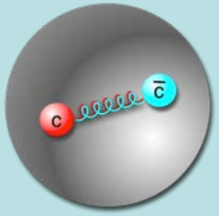
GLAD magnet at GSI

Hadron Physics with antiprotons at FAIR

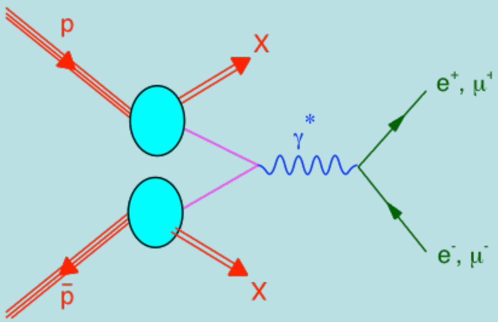
Gluonic excitations: Hybrids, glueballs



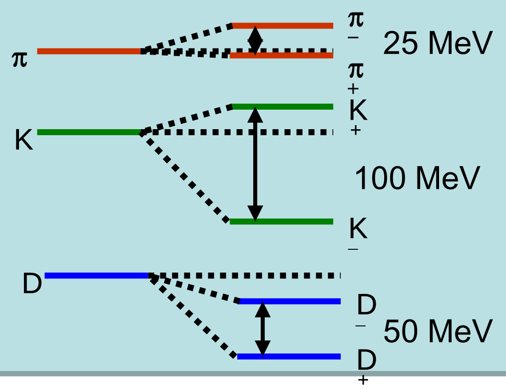
Charmonium states: Precision spectroscopy



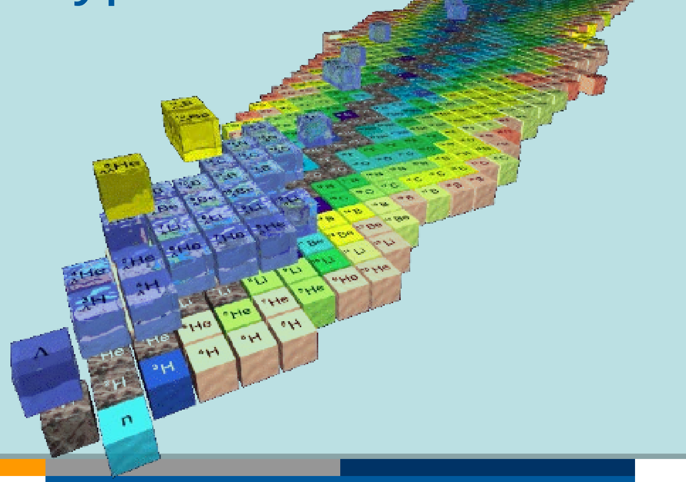
Time-like form factors, nucleon structure



In medium mass modifications: Extension to the charm sector

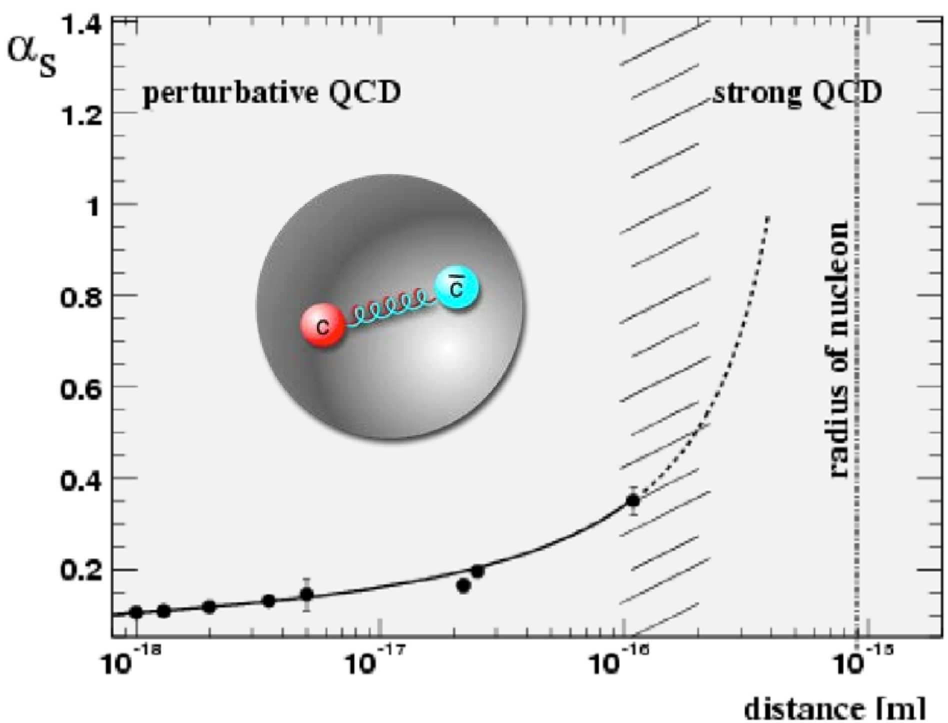


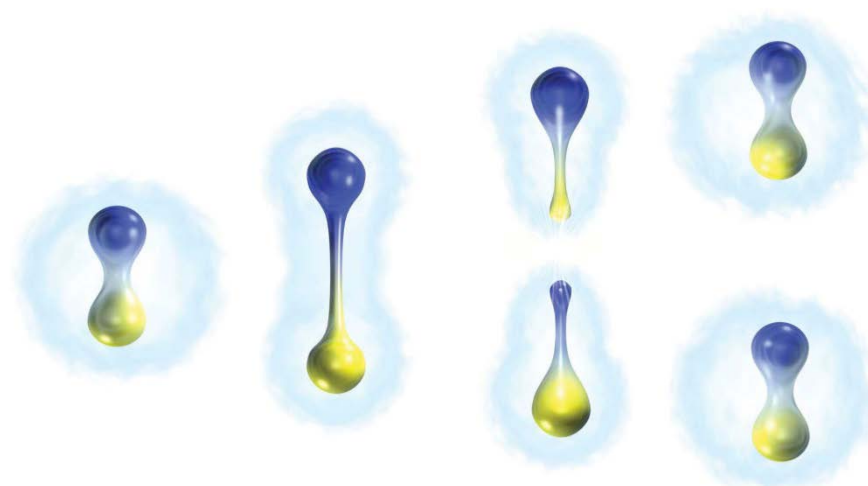
Extension of nuclear chart: Double hypernuclei



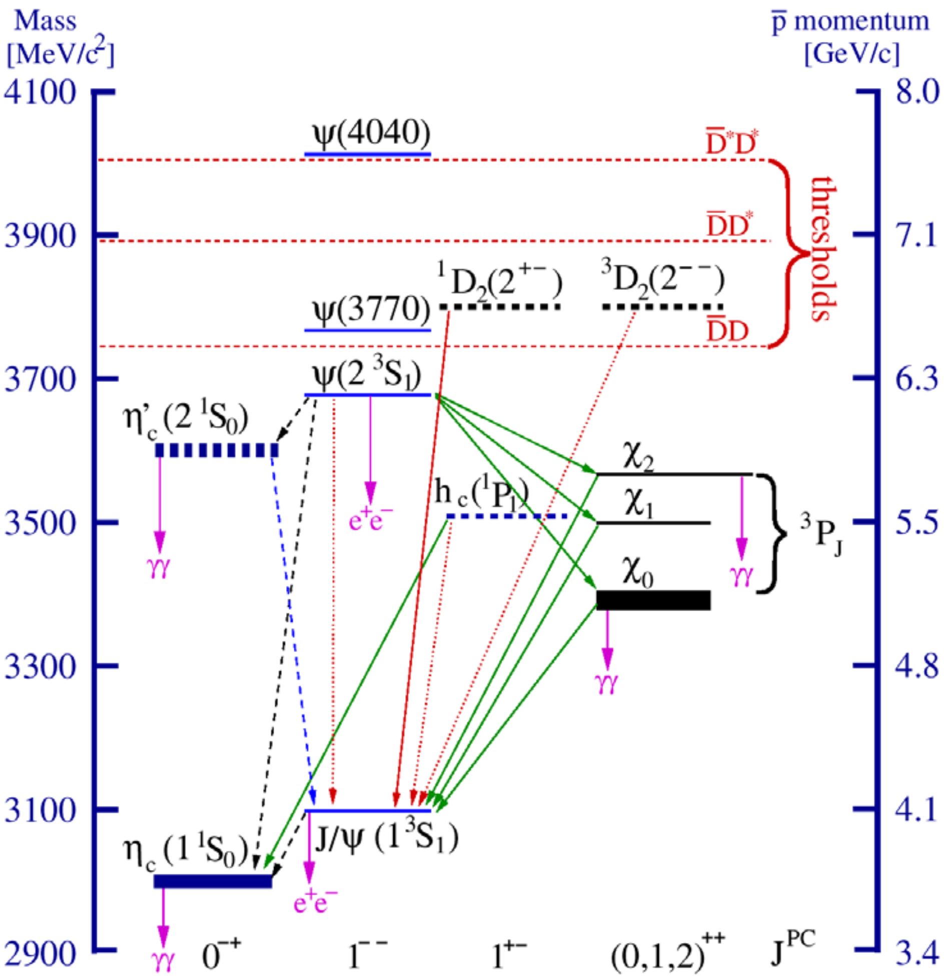
Confinement and Charmonium spectroscopy

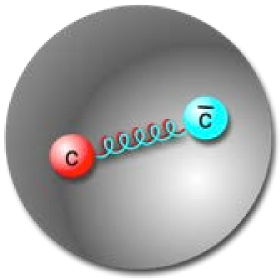
Coupling strength between two quarks

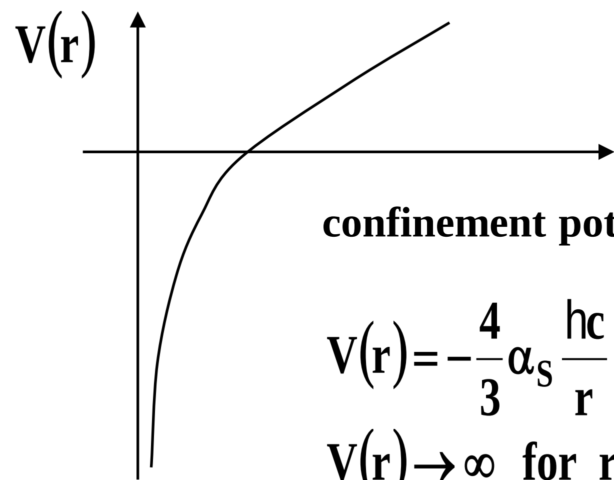




Confinement and Charmonium spectroscopy





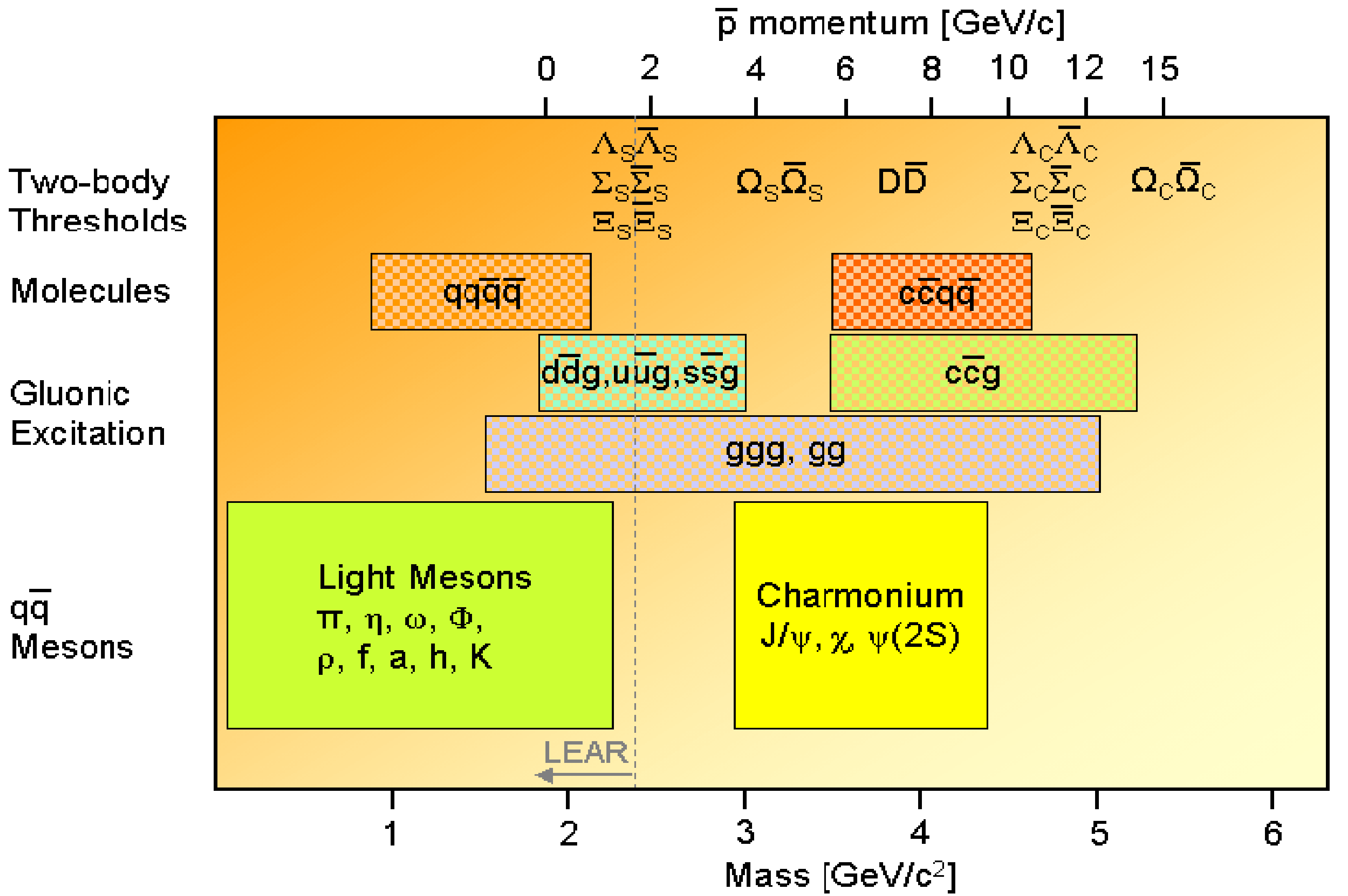


confinement potential

$$V(r) = -\frac{4}{3}\alpha_S \frac{\hbar c}{r} + K \cdot r$$

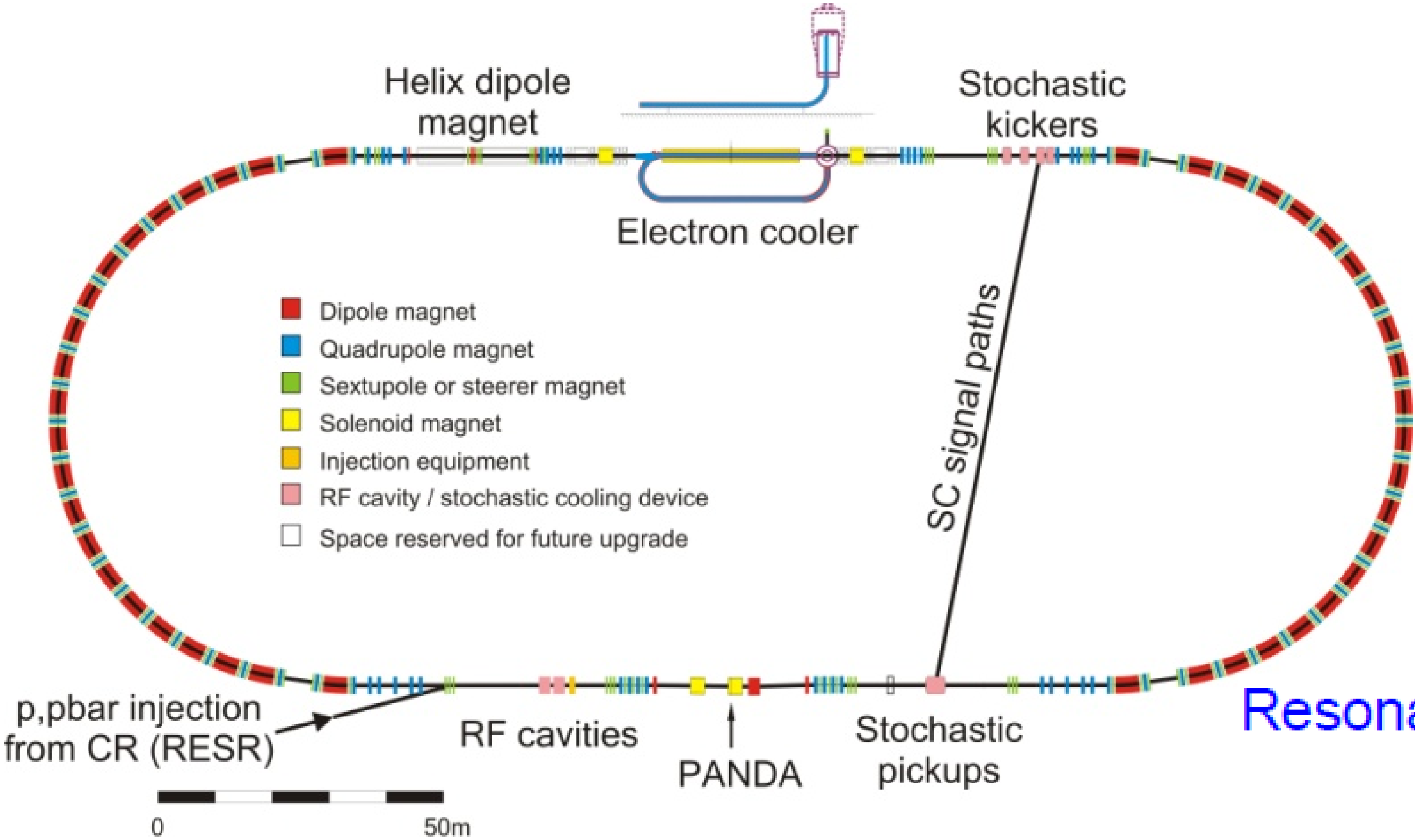
$$V(r) \rightarrow \infty \quad \text{for} \quad r \rightarrow \infty$$

Antiproton momenta up to 15 GeV/c

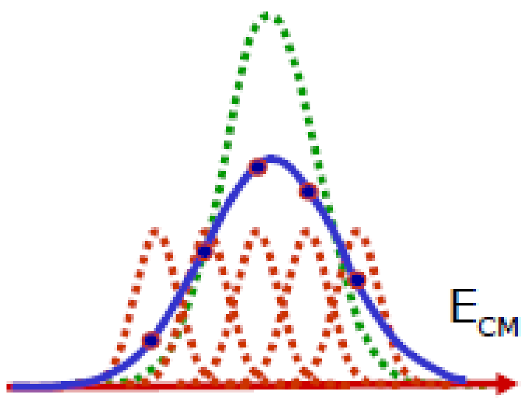


Antiproton-Proton-Annihilation in Darmstadt

The High Energy Storage Ring

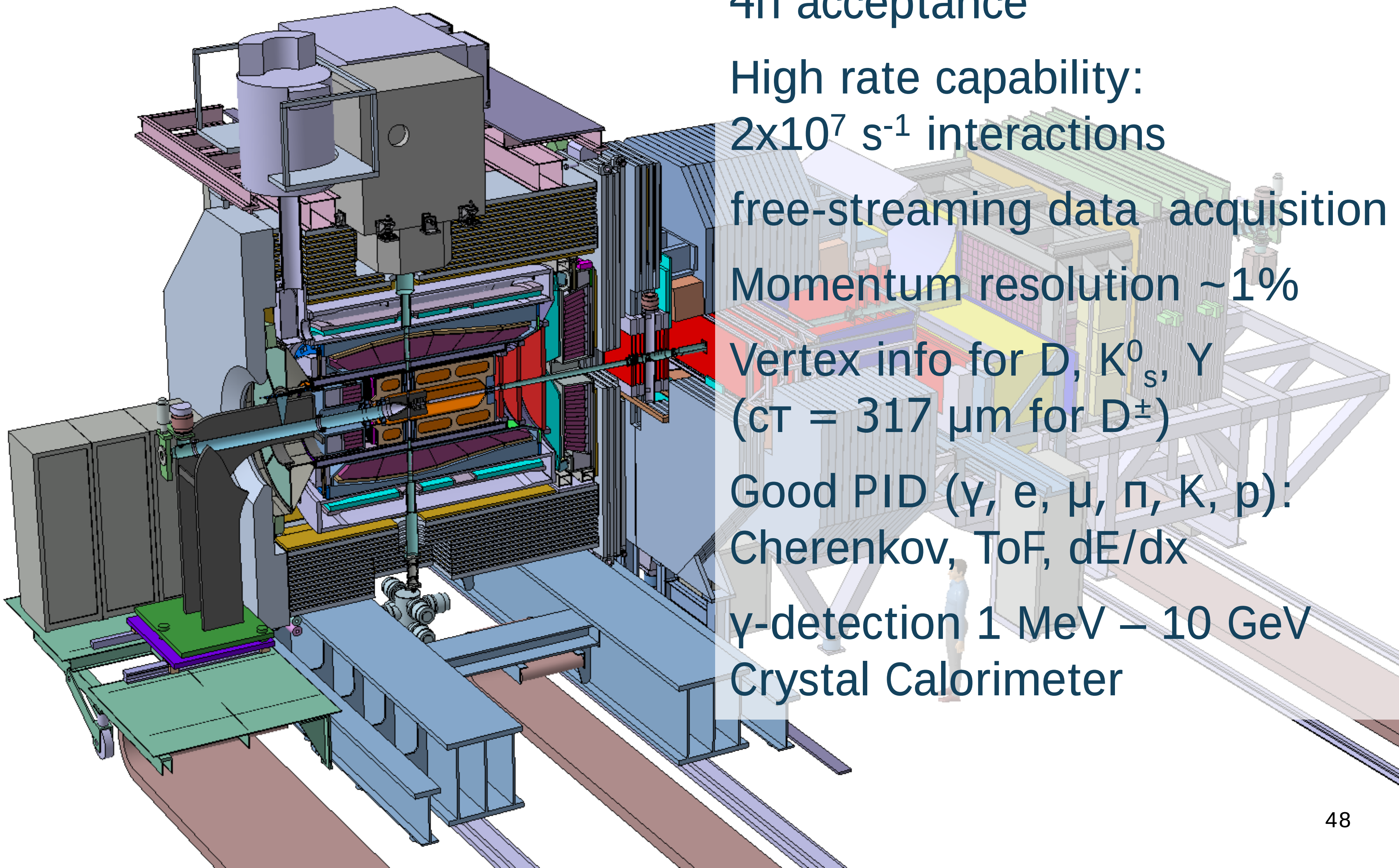


Resonance Scan



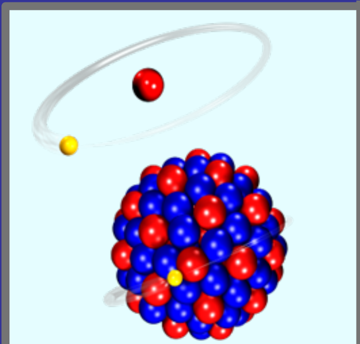
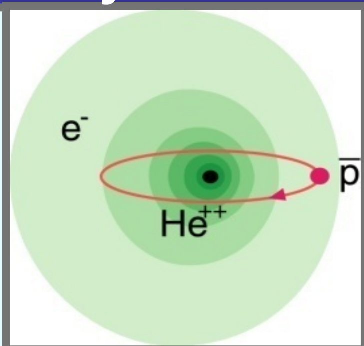
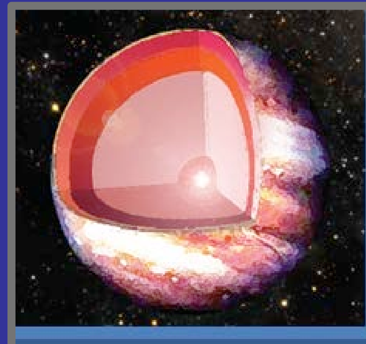
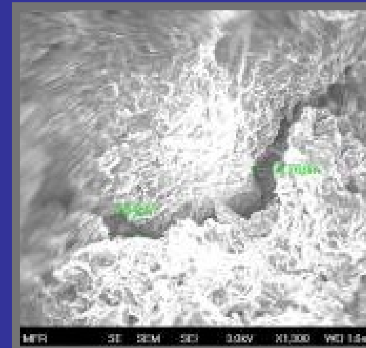
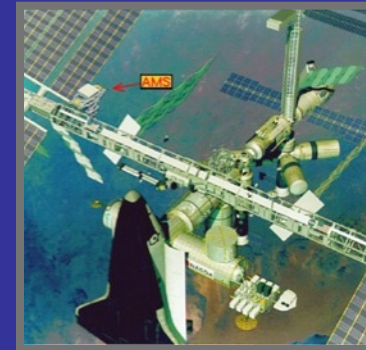
- Luminosity up to L~ $2x10^{32}$ $cm^{-2}s^{-1}$
- Stochastic & electron cooling
- Resolution ~50 keV
- Tune E_{CM} to scan resonance: precise mass and width

The PANDA spectrometer at FAIR



- 4π acceptance
- High rate capability: $2 \times 10^{7}\ s^{-1}$ interactions
- free-streaming data acquisition
- Momentum resolution ~1%
- Vertex info for D, K^{0}_{S}, Y ($c\tau$ = 317 μm for $D^{\pm}$)
- Good PID (γ, e, μ, π, K, p): Cherenkov, ToF, dE/dx
- γ-detection 1 MeV – 10 GeV Crystal Calorimeter

Atomic Physics, Plasma and Applied Sciences

Atomic Physics		Plasma	Materials	Bio
				
SPARC	FLAIR	HEDgeHOB/WDM	MAT/BIOMAT	BIO/BIOMAT
strong field research ... probing of fundamental laws of physics	**anti-matter** ... matter / anti-matter asymmetry	**planetary interiors** ... states of matter common in astrophysical objects	**extreme conditions** ... radiation hardness and modification of materials	**aerospace engineering** ... radiation shielding of cosmic radiation

Highest Charge States: Extreme Static Fields

Relativistic Energies: Extreme Dynamical Fields and Ultrashort Pulses

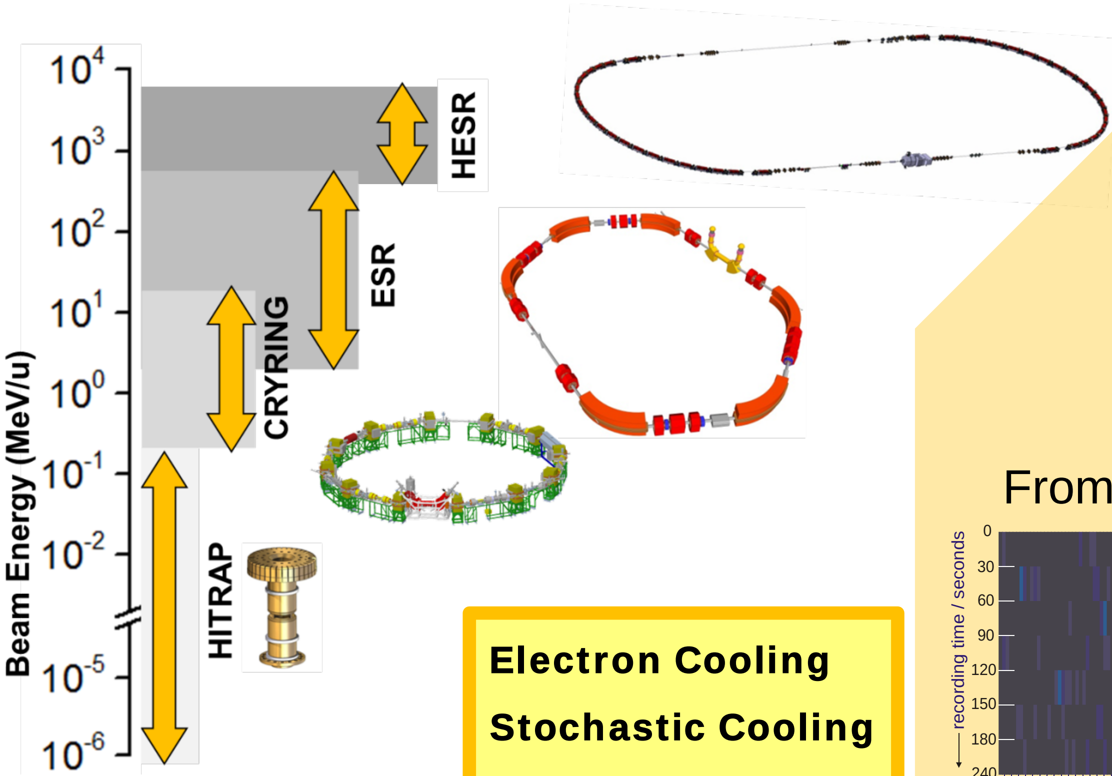
High Intensities: Very High Energy Densities and Pressures

High Charge at Low Velocity: Large Energy Deposition

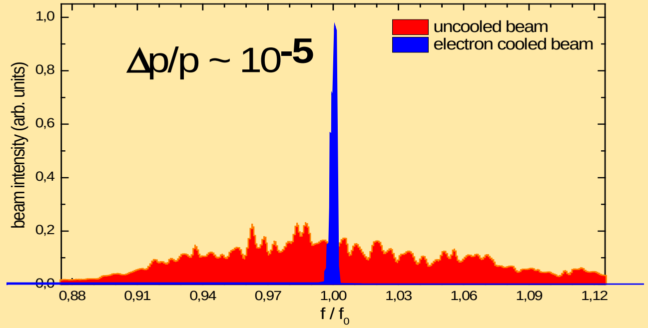
Low-Energy Anti-Protons: Antimatter Research

Atomic physics with stored and cooled ions

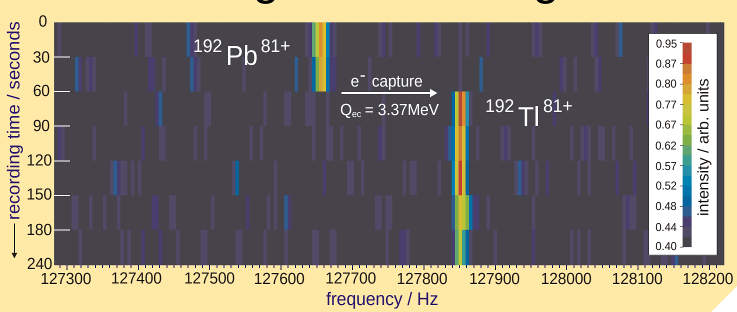
Stored and cooled highly charged ions and RIBs
Protons to Uranium in various charge states (U^{28+} to U^{92+})
Single to 10^9 stored ions
From rest to relativistic (γ=6) energies



Cooling: The Key for Precision

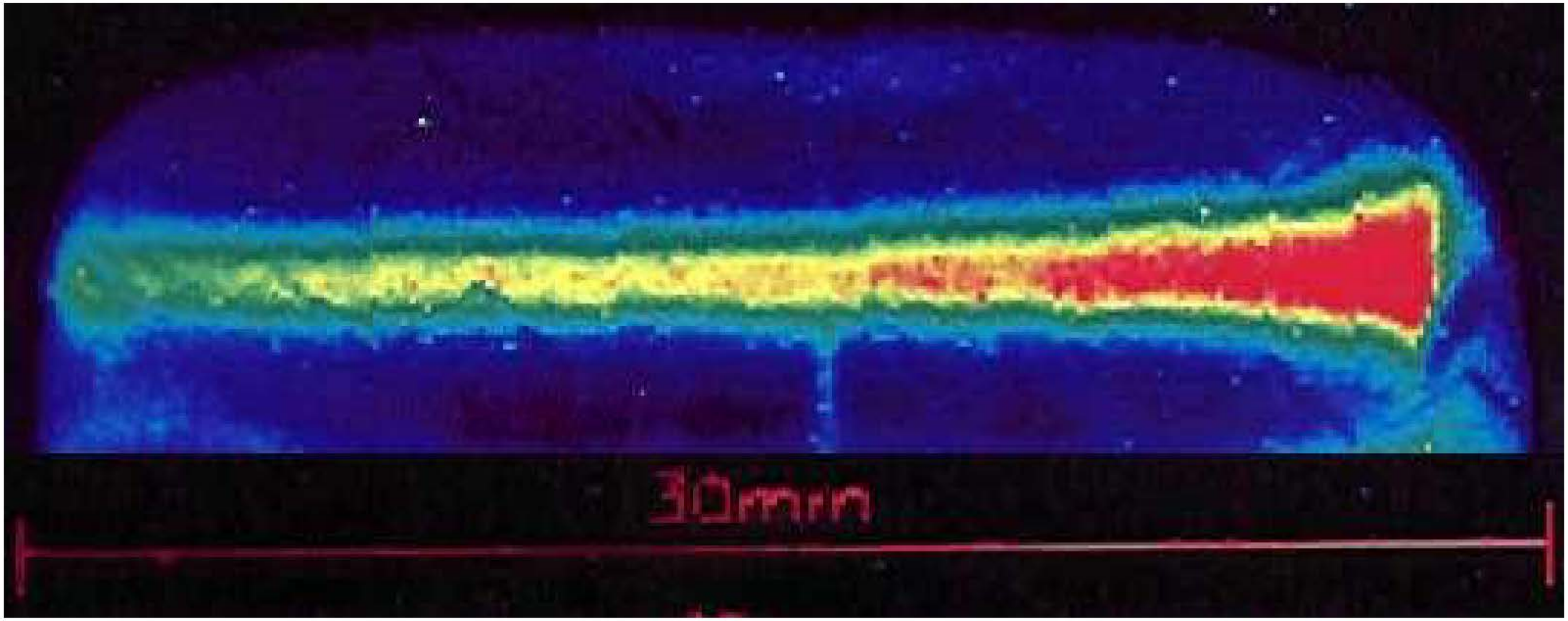


From Single Ions to Highest Intensities



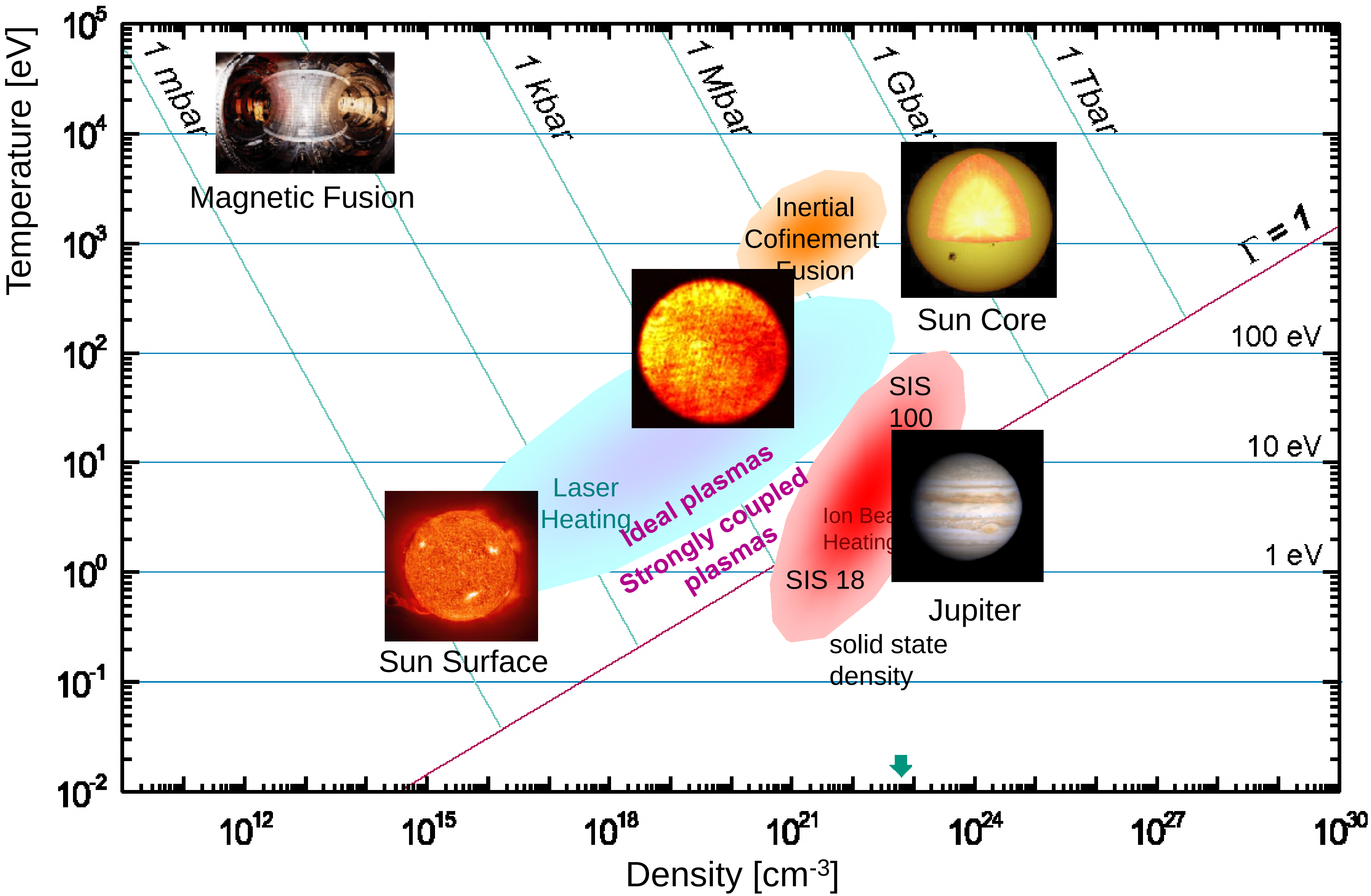
Electron Cooling
Stochastic Cooling
Laser Cooling

Plasma physics with heavy ion beams



Neon beam at 300 A MeV penetrating an Ar cristal

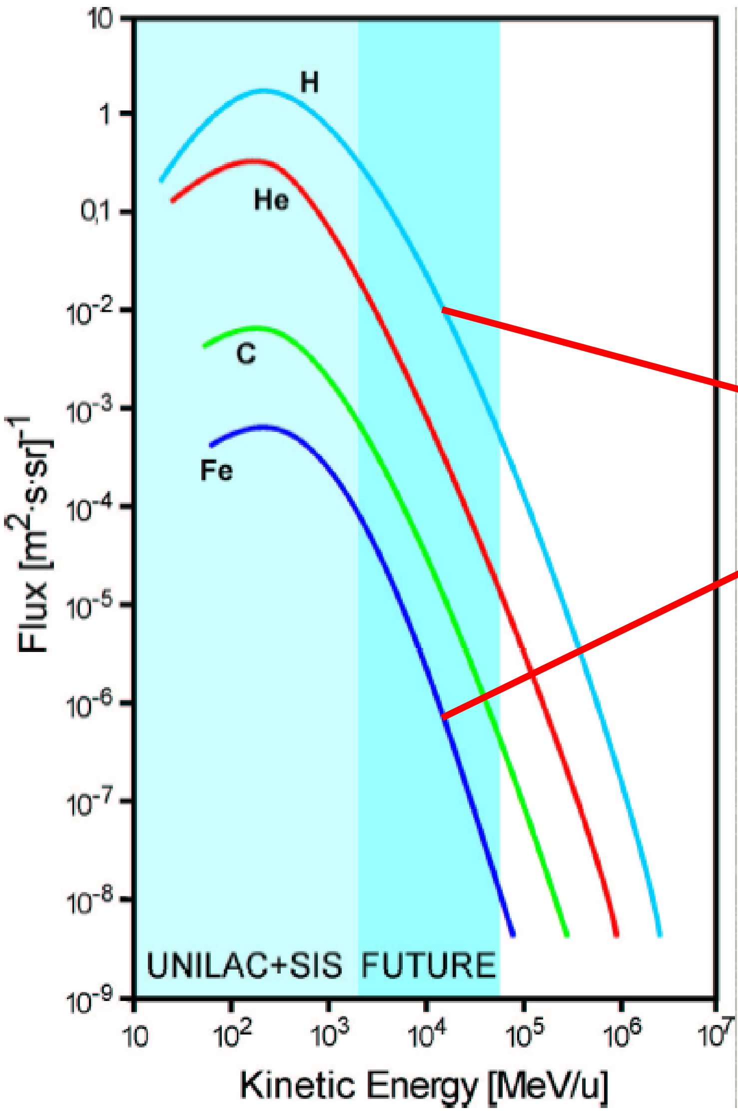
Hot electromagnetic plasmas: high-intensity ion beams + high-power laser



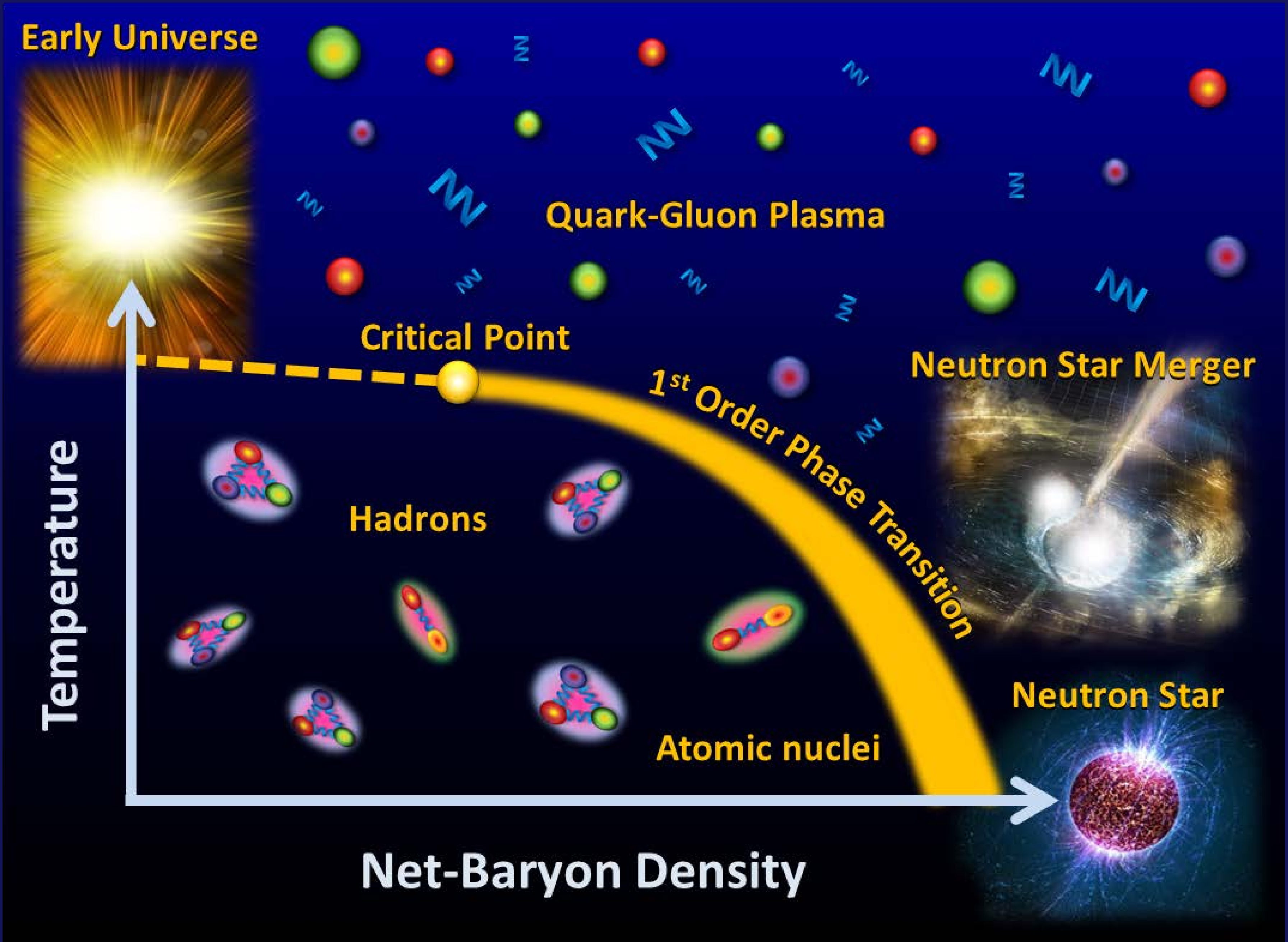
Radiobiology:

Radiation dose during long-term space missions ?

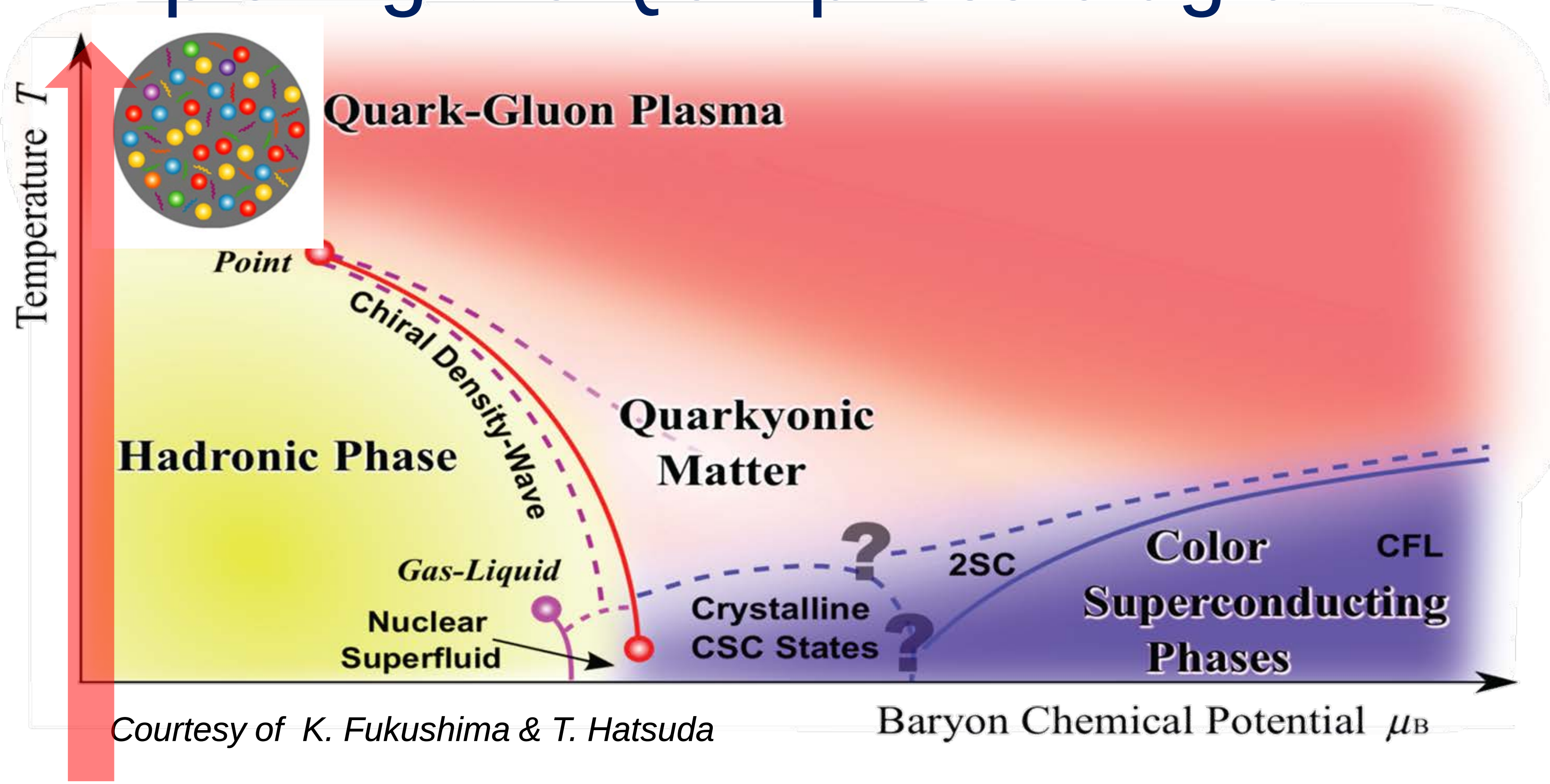
Cosmic radiation in space



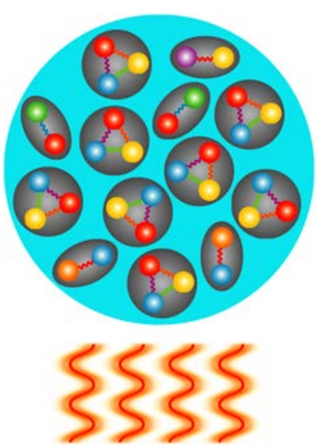
Exploring the QCD phase diagram



Exploring the QCD phase diagram



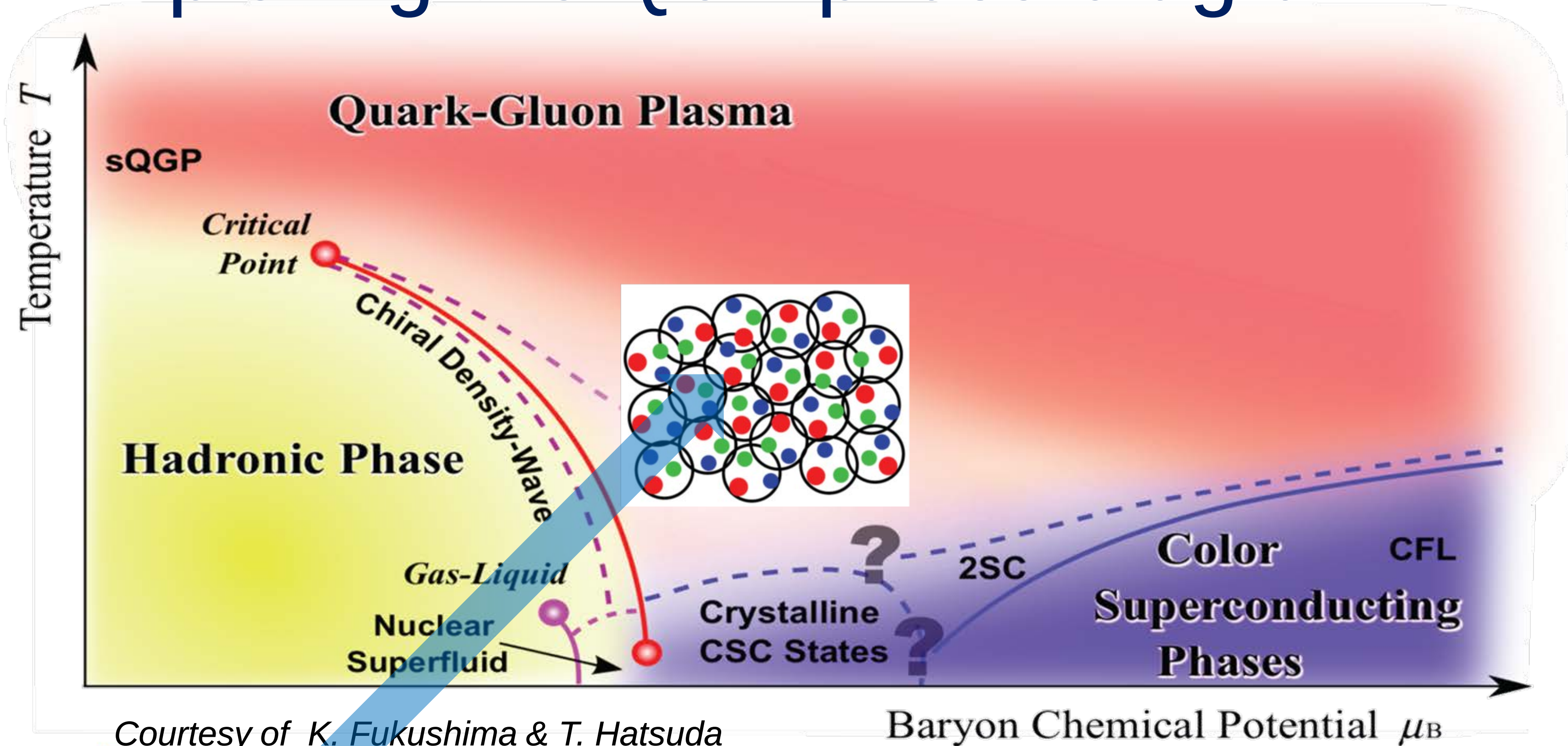
Courtesy of K. Fukushima & T. Hatsuda



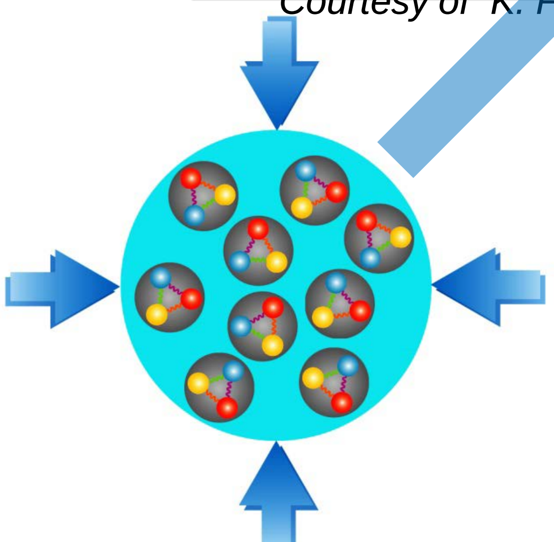
<u>At very high temperature:</u>

- N of baryons ≈ N of antibaryons
  Situation similar to early universe
- L-QCD finds crossover transition between
  hadronic matter and Quark-Gluon Plasma at T≈ 160 MeV
- Experiments: ALICE, ATLAS, CMS at LHC
  STAR, PHENIX at RHIC

Exploring the QCD phase diagram



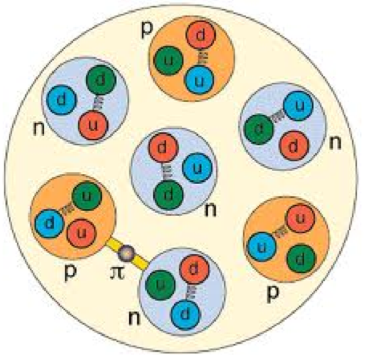
Courtesy of K. Fukushima & T. Hatsuda



<u>At high baryon density:</u>

- N of baryons >> N of antibaryons
  Densities like in neutron star cores
- L-QCD not (yet) applicable
- Models predict first order phase transition with mixed or exotic phases
- Experiments: BES at RHIC, NA61 at CERN SPS, CBM at FAIR, NICA at JINR

Density estimates



Atomic nucleus:

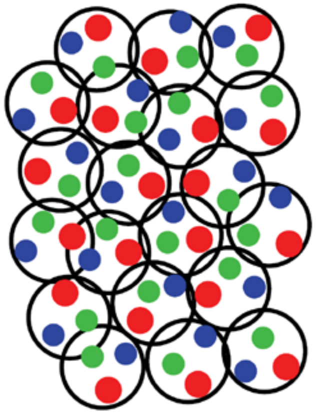
Radius $R = 1.2 \text{ fm } A^{1/3}$ $(\sigma_{reac} = \pi R^2)$

Volume $V = 4/3 \, \pi R^3 = 4/3 \, \pi \, 1.2^3 \, A \text{ fm}^3$

Nucleon density $\rho_0 = A/V = 3/(4 \pi \, 1.2^3) \text{ fm}^{-3} \approx 0.14 \text{ fm}^{-3}$

Mass of nucleon $m = 1.67 \cdot 10^{-24}$ g

Mass density of cold nuclear matter $\rho_0 \cdot m \approx 270$ Mio t/cm^3



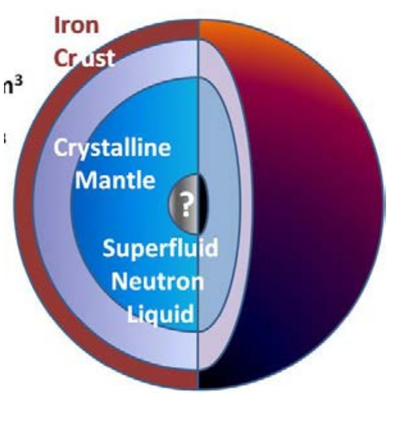
Limits of nucleon density:

Au-nucleus: $R \approx 7$ fm, $V \approx 1400 \text{ fm}^3$

Nucleon: $R \approx 0.8$ fm, $V \approx 2 \text{ fm}^3$

200 Nucleons: $V \approx 400 \text{ fm}^3$

At $3 - 4 \, \rho^0$: nucleons overlap, Fermi see of quarks?



Neutron star:

Radius $R \approx 10$ km,

Volume $V \approx 4200 \text{ km}^3$

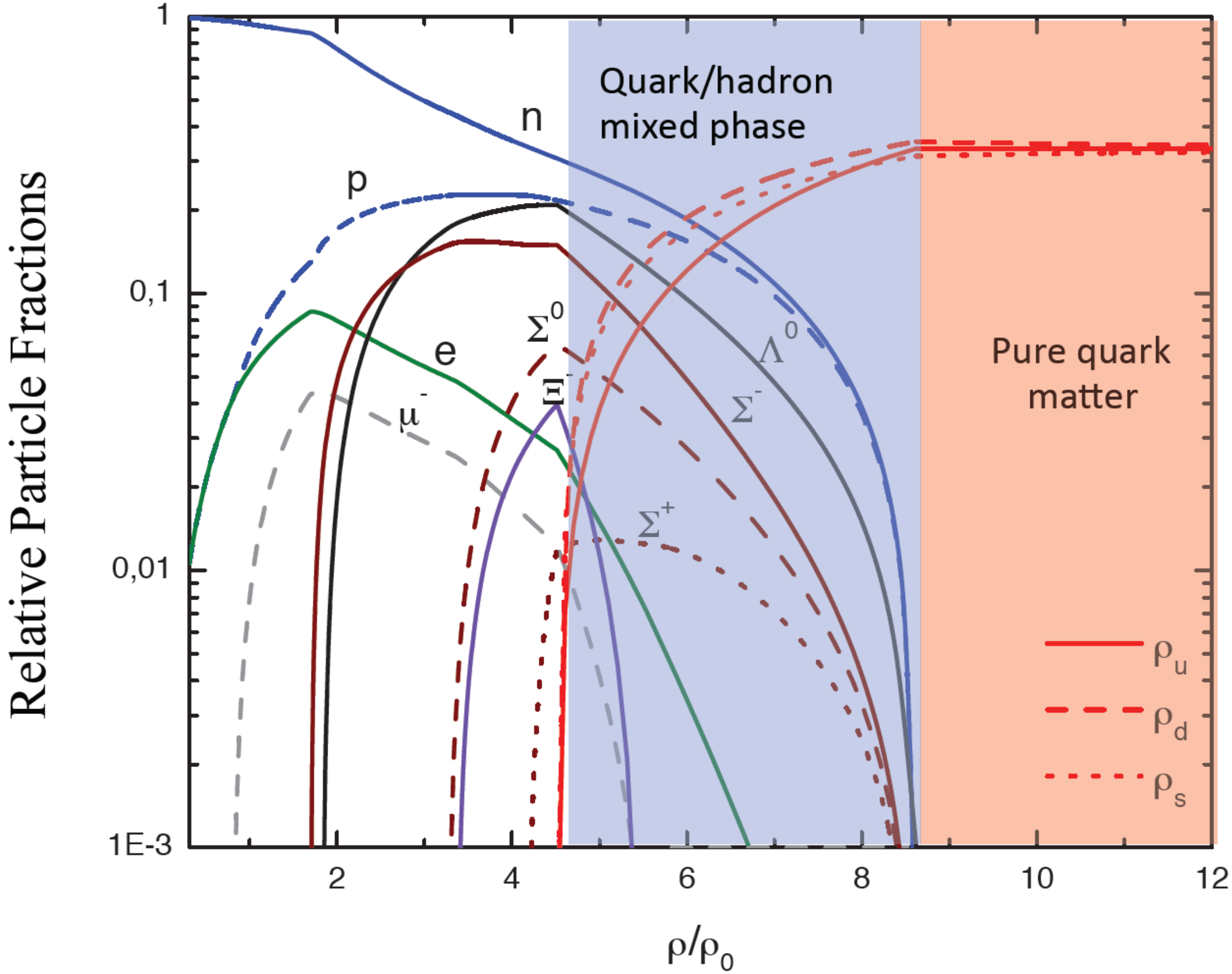
Mass $M \approx 2$ solar masses $= 2 \cdot 2 \cdot 10^{33}$ g

Average mass density $\rho = M/V \approx 1000$ Mio t/cm$^3 \approx 3.6 \, \rho^0 \cdot m$

Core density 5 – 10 times nuclear density

Quark matter in massive neutron stars?

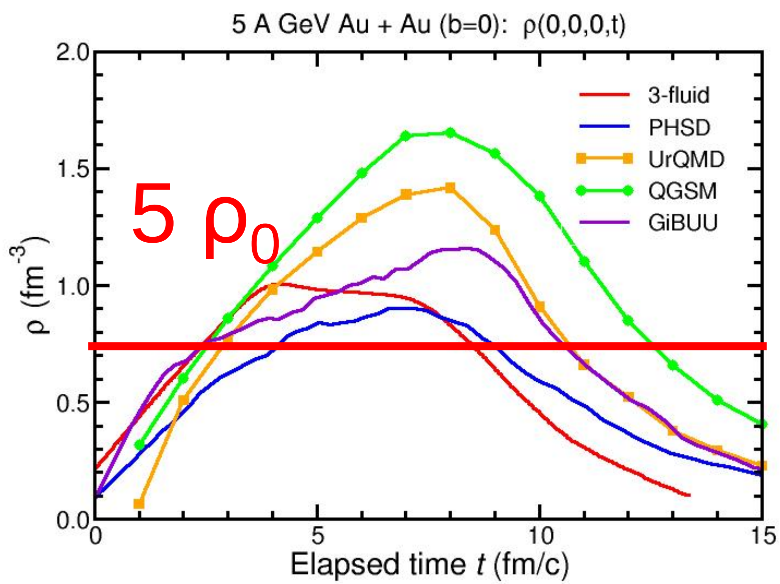
M. Orsaria, H. Rodrigues, F. Weber, G.A. Contrera, arXiv:1308.1657
Phys. Rev. C 89, 015806, 2014



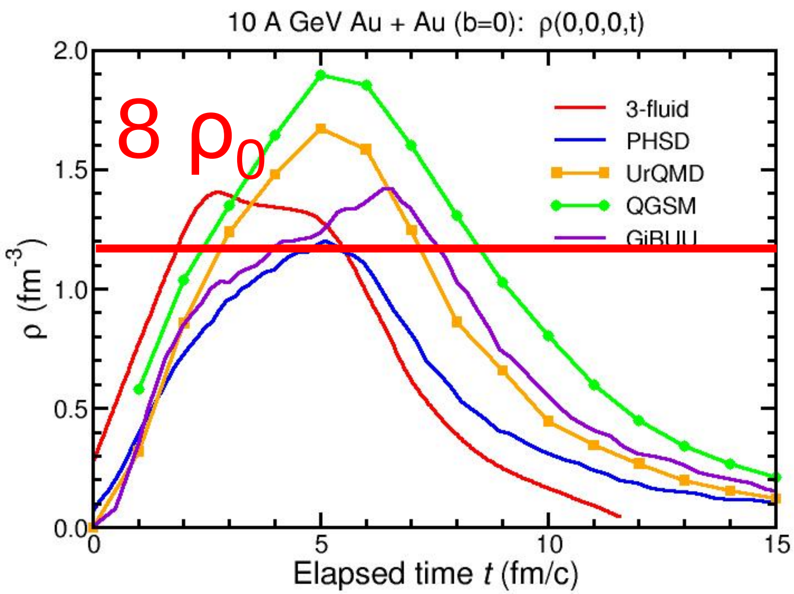
Baryon densities in central Au+Au collisions

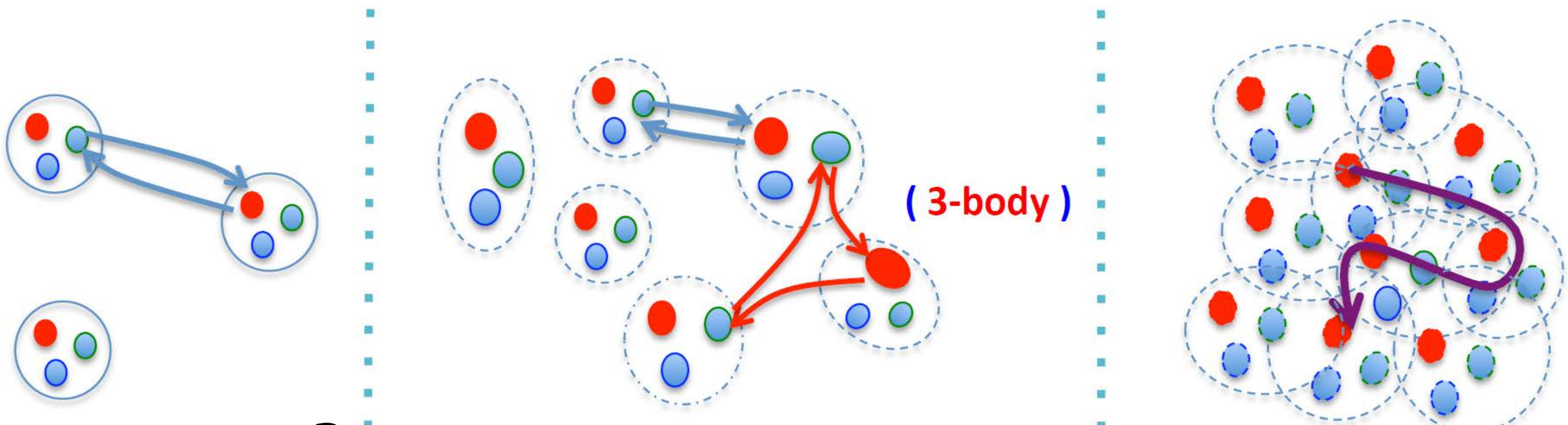
I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

5 A GeV



10 A GeV





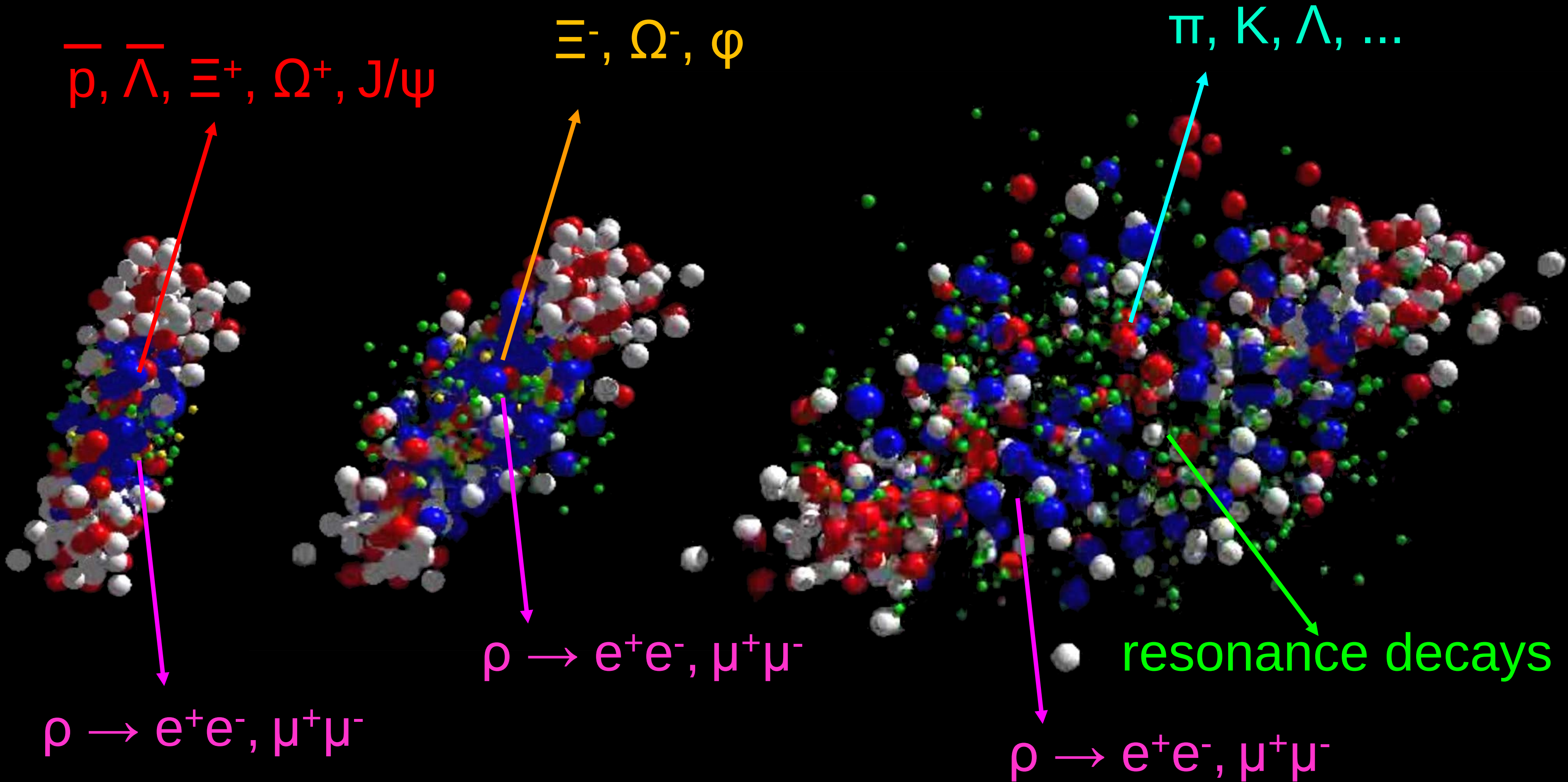
$\sim 2\ \rho_0$

$\sim 5\ \rho_0$

courtesy Toru Kojo (CCNU)

Messengers from the dense fireball:

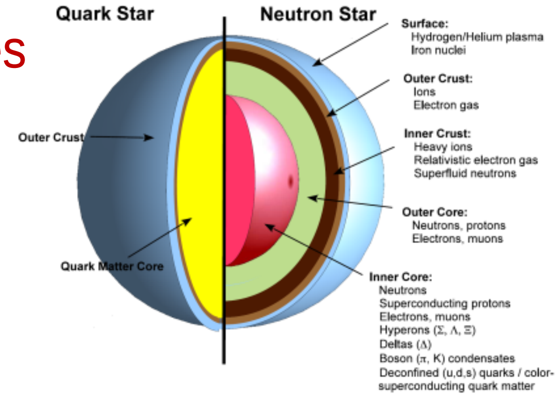
UrQMD transport calculation Au+Au 10.7 A GeV



The Compressed Baryonic Matter (CBM) experiment at FAIR: Physics case and observables

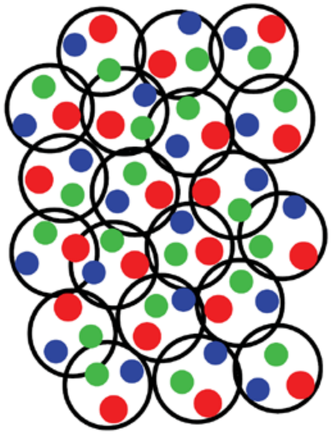
The QCD equation-of-state at neutron star core densities

- collective flow of identified particles (π,K,p,Λ,Ξ,Ω,…) driven by the pressure gradient in the early fireball
- particle production at threshold energies via multi-step processes (multi-strange hyperons, charm)



Phase transitions from hadronic matter to quarkyonic or partonic matter at high ρ_B, phase coexistence, critical point

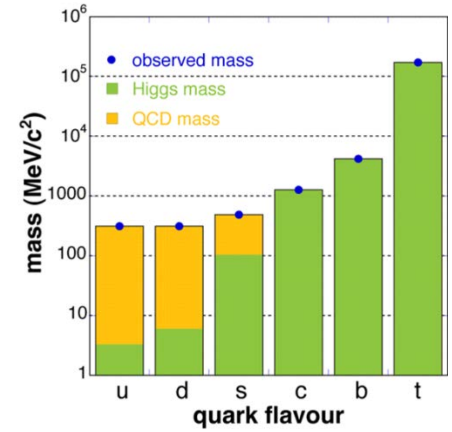
- excitation function of strangeness: $\Xi^-(dss)$,$\Xi^+(\overline{dss})$,$\Omega^-(sss)$,$\Omega^+(\overline{sss})$
  $\rightarrow$ chemical equilibration at the phase boundary
- excitation function (invariant mass) of lepton pairs: Thermal radiation from fireball, “caloric curve”
- anisotropic azimuthal angle distributions: ”spinodal decomposition”
- event-by-event fluctuations of conserved quantities: ”critical opalescence”



The Compressed Baryonic Matter (CBM) experiment at FAIR: Physics case and observables

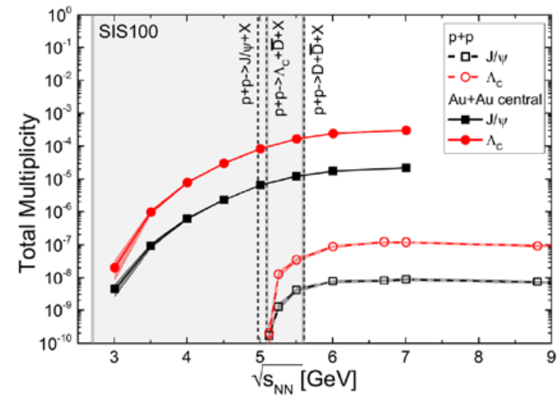
Onset of chiral symmetry restoration at high ρ_B

- in-medium modifications of hadrons ($\rho,\omega,\phi \rightarrow e^+e^-(\mu^+\mu^-)$)
- dileptons at intermediate invariant masses: $4\,\pi \rightarrow \rho\text{-}a_1$ chiral mixing



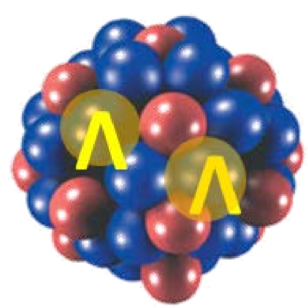
Charm production at threshold energies in cold and dense matter

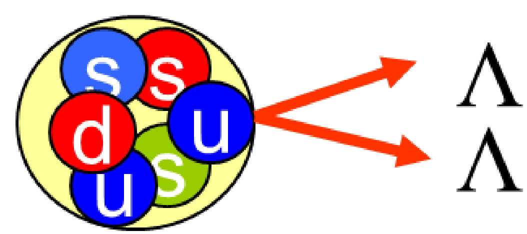
- excitation function of charm production in p+A and A+A   (J/ψ, D^0, $D^\pm$)



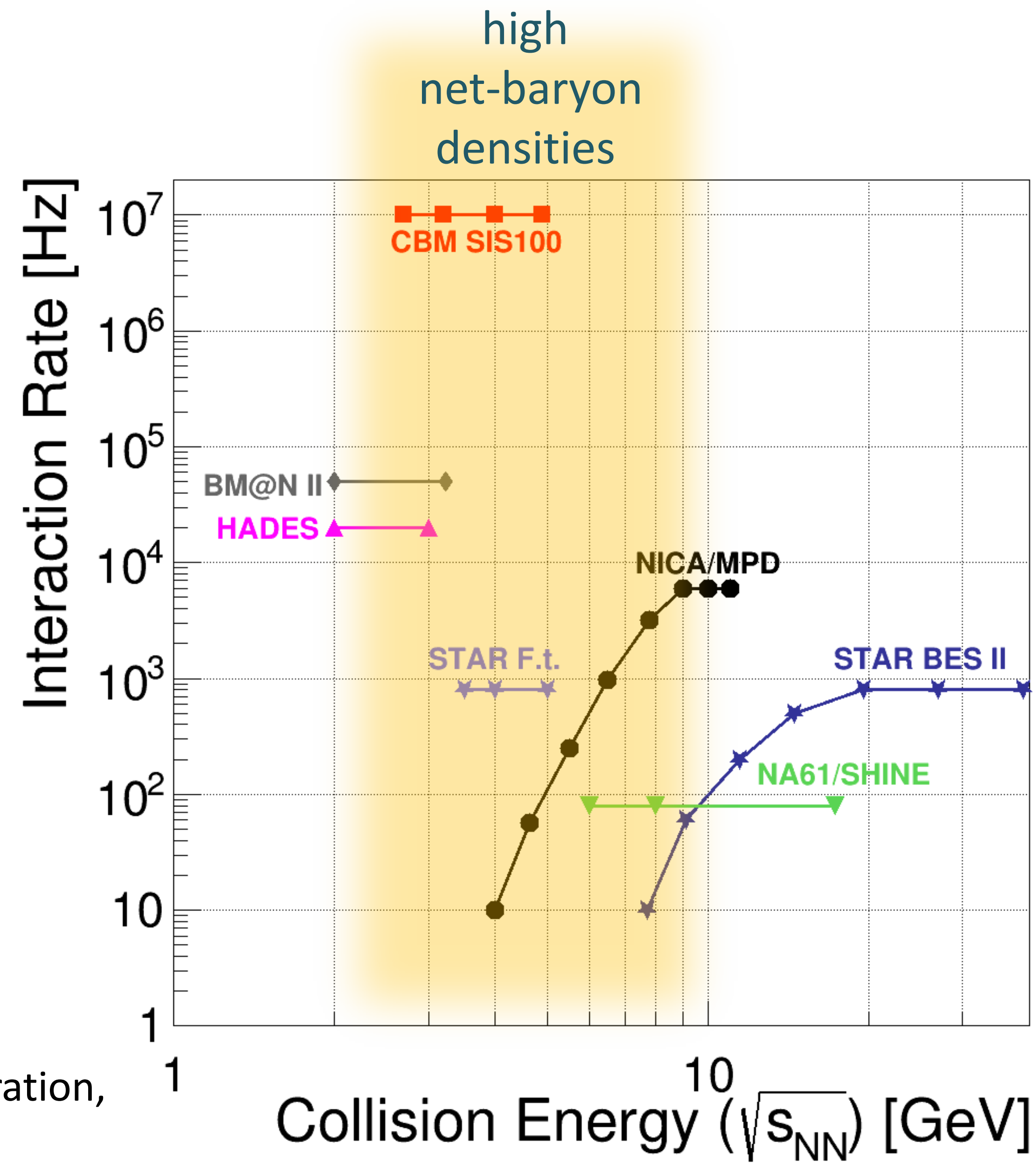
N-Λ, Λ-Λ interaction, strange matter

- (double-) lambda hypernuclei
- meta-stable objects (e.g. strange dibaryons)



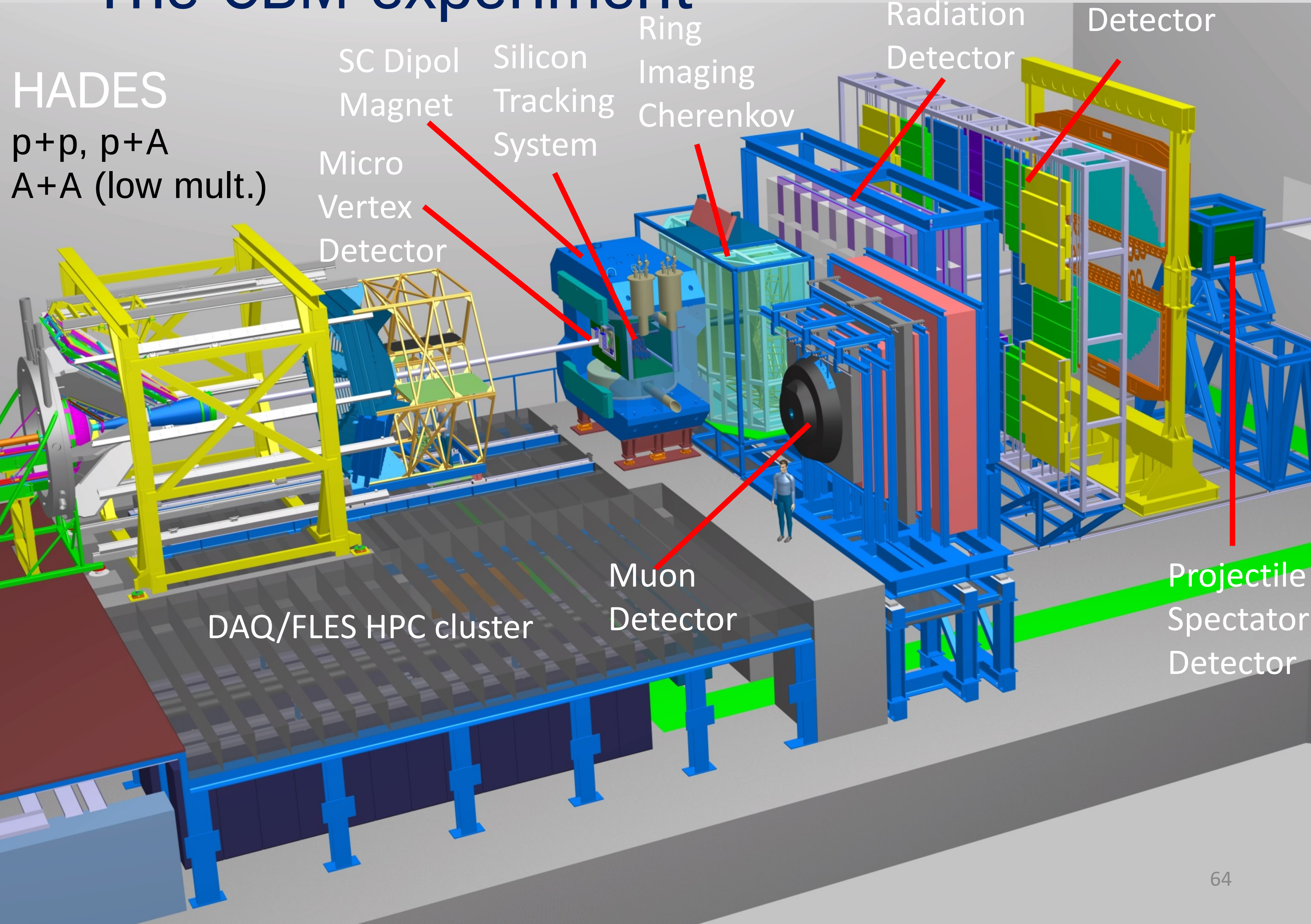


Experiments exploring dense QCD matter

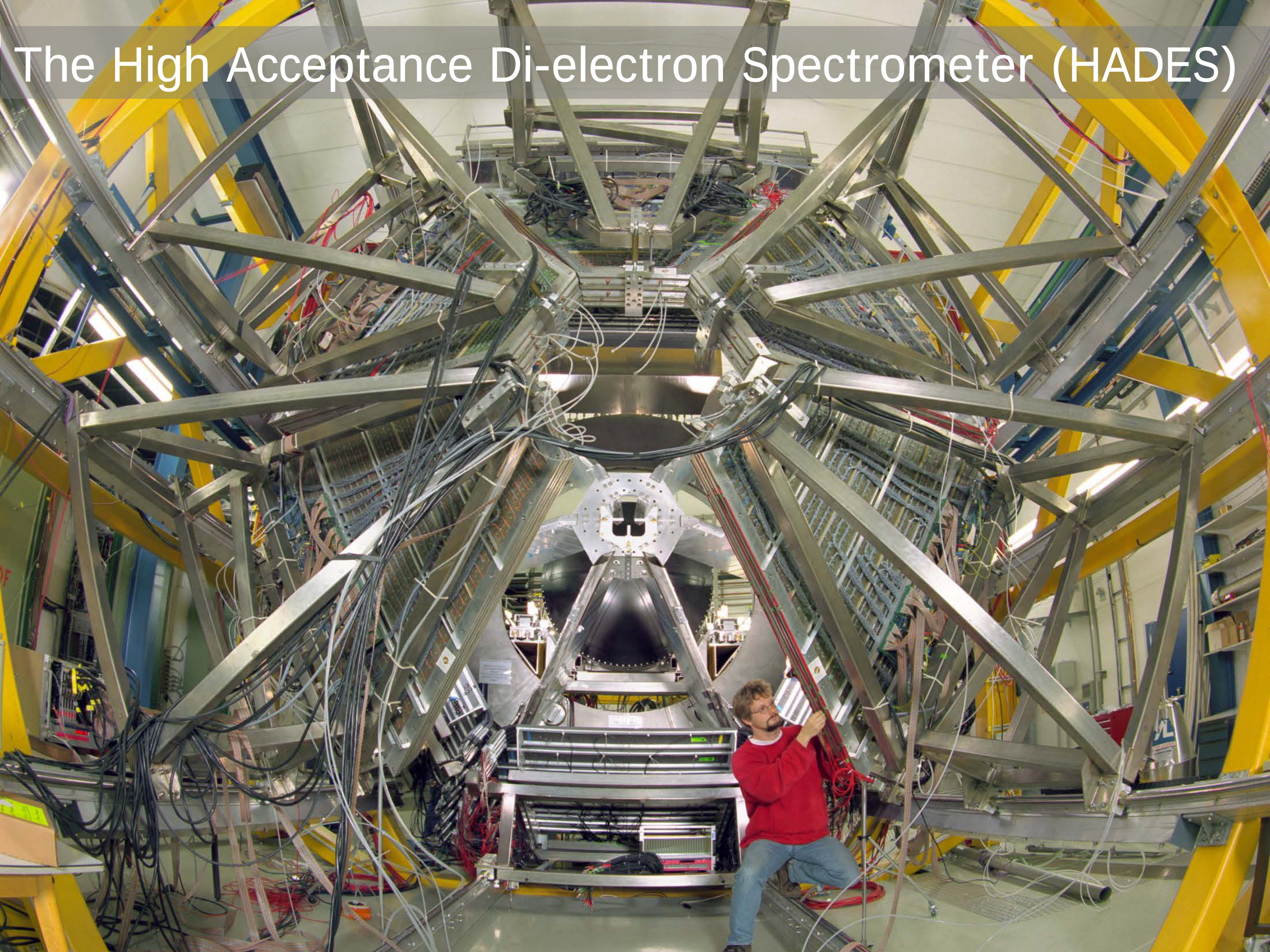


The CBM Collaboration, arXiv:1607.01487

The CBM experiment

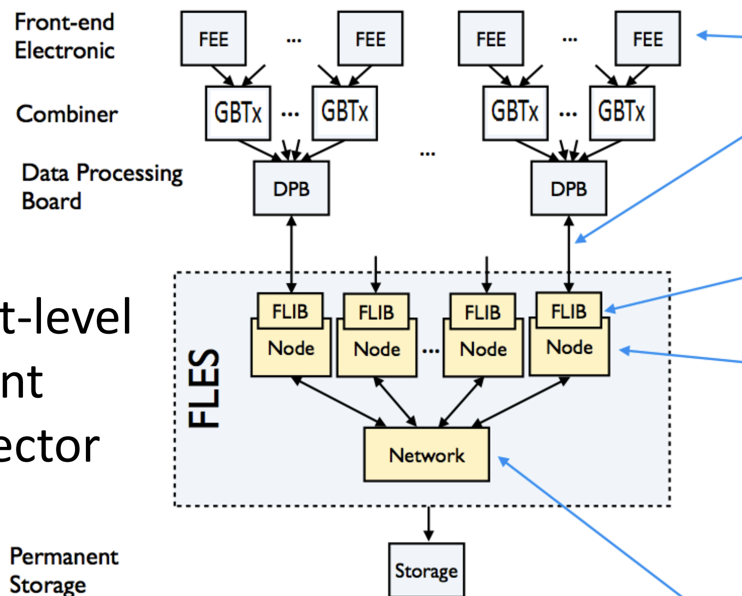


The High Acceptance Di-electron Spectrometer (HADES)



CBM DAQ and online event selection

First-level Event Selector



1 TByte/s Total Input Data Rate
- 1000 links

FLES Interface Board
- FPGA based
- Optical input links
- Fast PCIe interface
- Large buffer memory

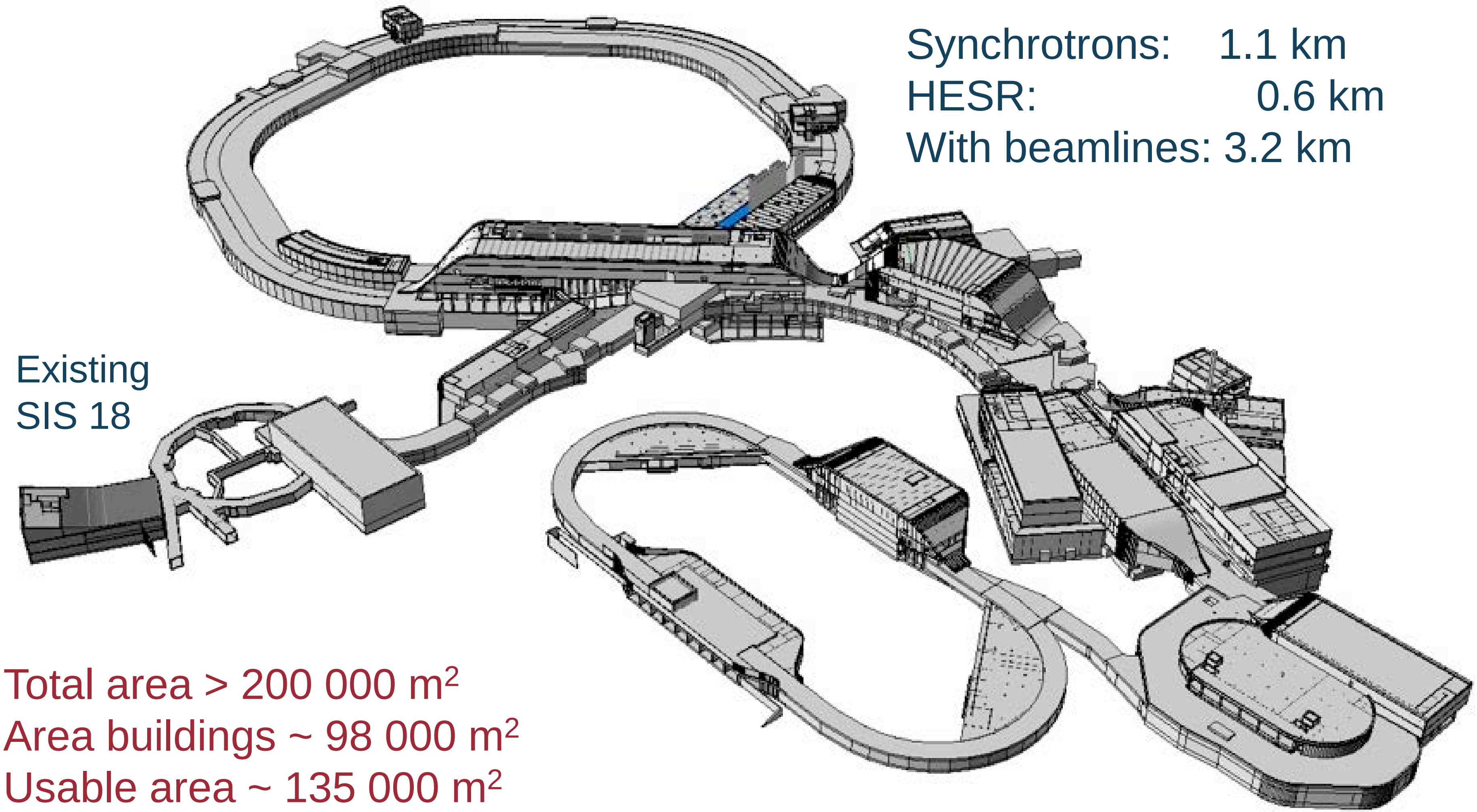
Event selection in FLES processor farm
- High-throughput online analysis
- **full event reconstruction**
- **10^7 Events/s**
- Vectorization and many-core architectures
- **~ 60.000 Cores**

High-throughput interval building
- InfiniBand

Novel readout system: no hardware trigger on events, detector hits with time stamps, full online 4-D track and event reconstruction.

FAIR Civil Construction

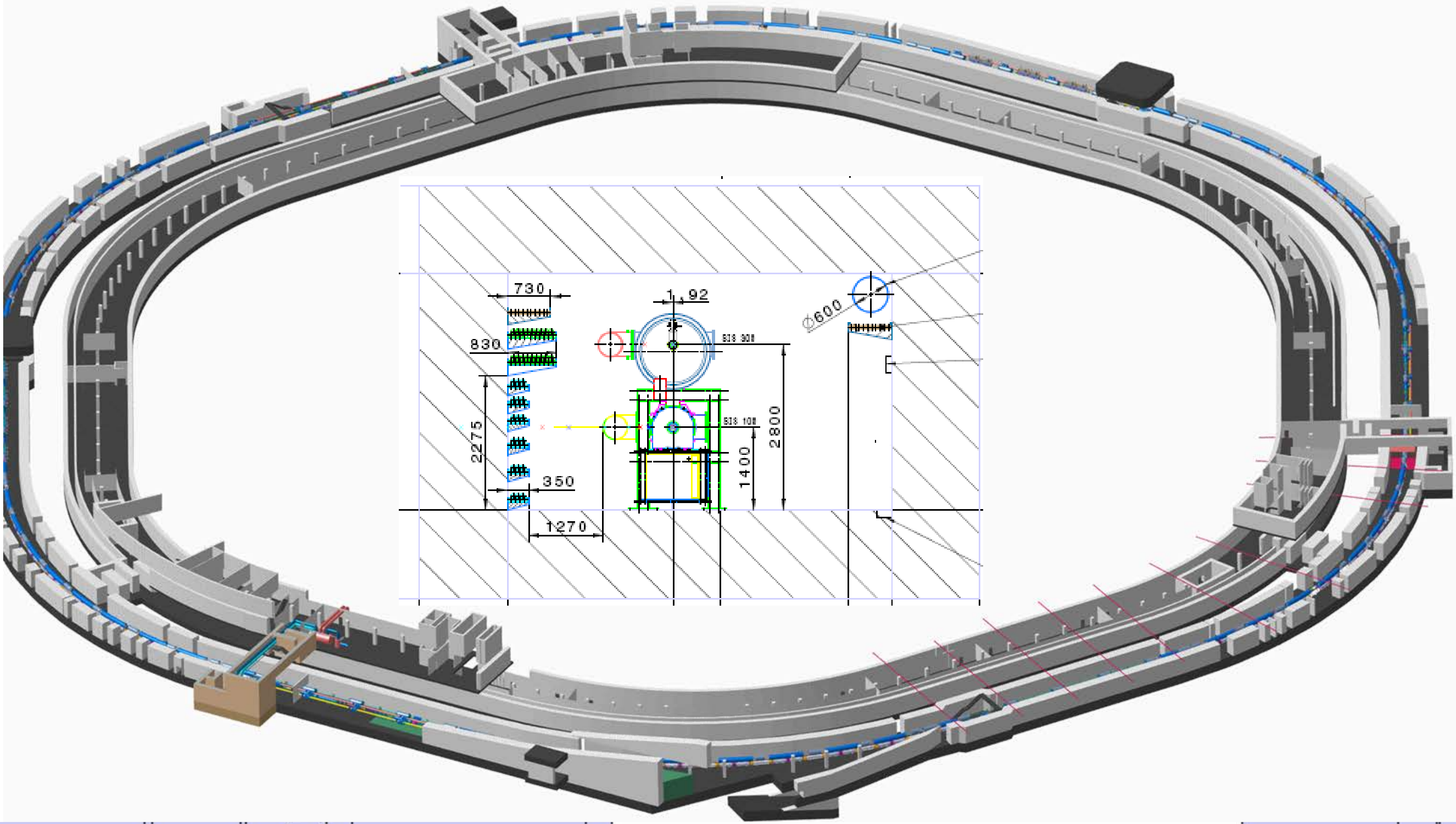
Synchrotrons: 1.1 km
HESR: 0.6 km
With beamlines: 3.2 km

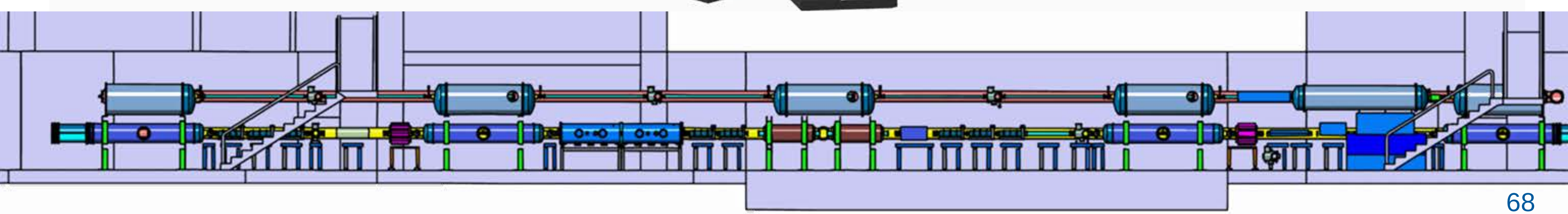


Existing
SIS 18

Total area > 200 000 m^2
Area buildings ~ 98 000 m^2
Usable area ~ 135 000 m^2
Volume of buildings ~ 1 049 000 m^3
Substructure: 1350 pillars, 60 m deep

Tunnel for SIS100/300





Civil construction (Status 2014)

The four most powerful drilling machines worldwide put down 1350 reinforced concrete pillars of 60 m depth and 1.2 m diameter.

FAIR Project Status 2017

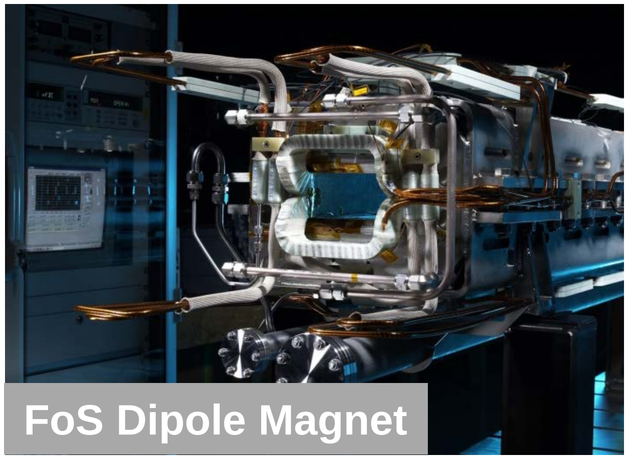
- Successful restart in 2015 and 2016
- Comprehensive civil construction plan: completion of all buildings by 2022
- Full integrated planning for construction and commissioning of the entire project: Completion of the full FAIR facility by 2025.
- Civil construction as well as procurement of accelerators and realization of experiments are progressing well …

Ground breaking - 4 July 2017

Excavation SIS100 tunnel - Nov 2017

Construction of accelerator components

- First of Series (FoS) of major components for SIS 100



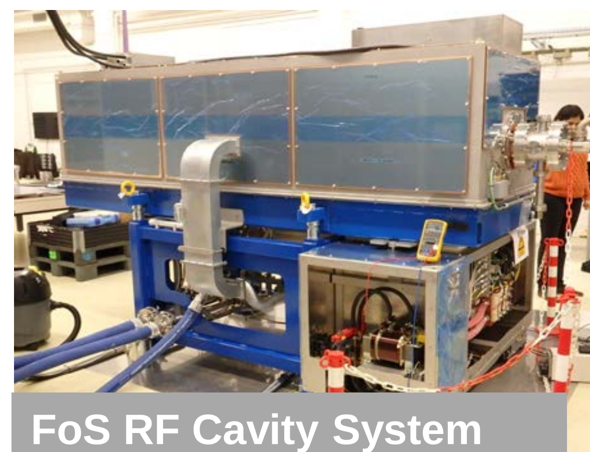
FoS Dipole Magnet

FoS Cryo Catcher

FoS Cro-Bypass Line

FoS Bunch Compressor

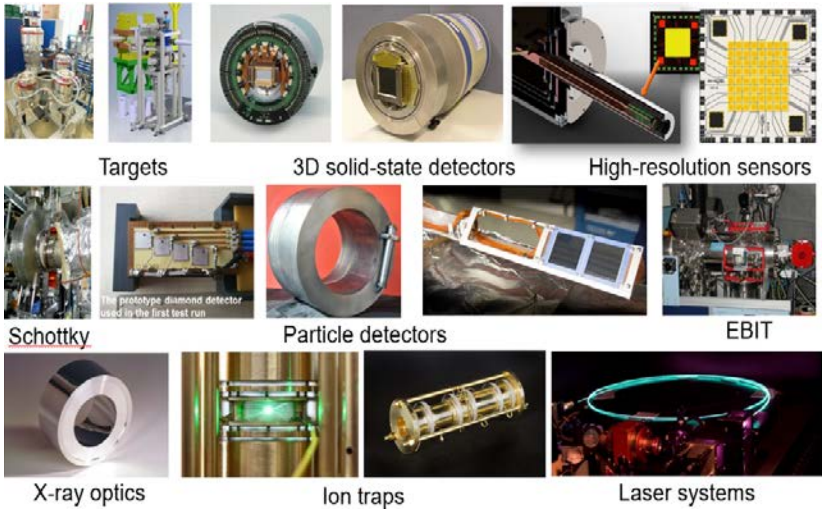
FoS Dipole Quadrupole Unit



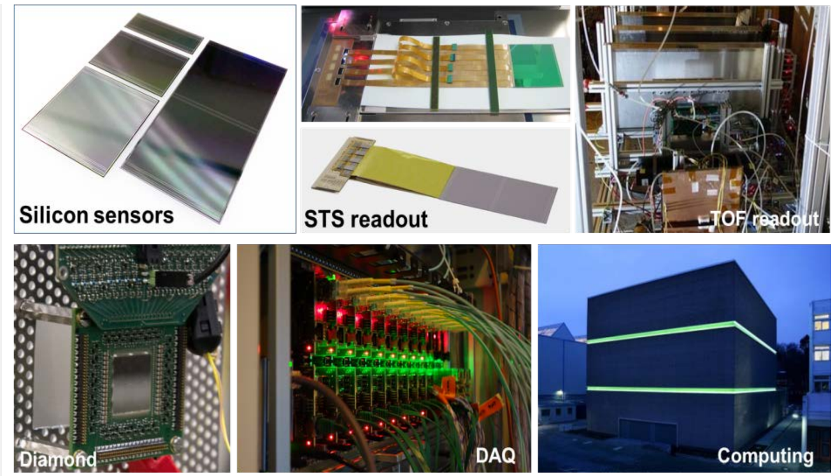
FoS RF Cavity System

Construction of detector components

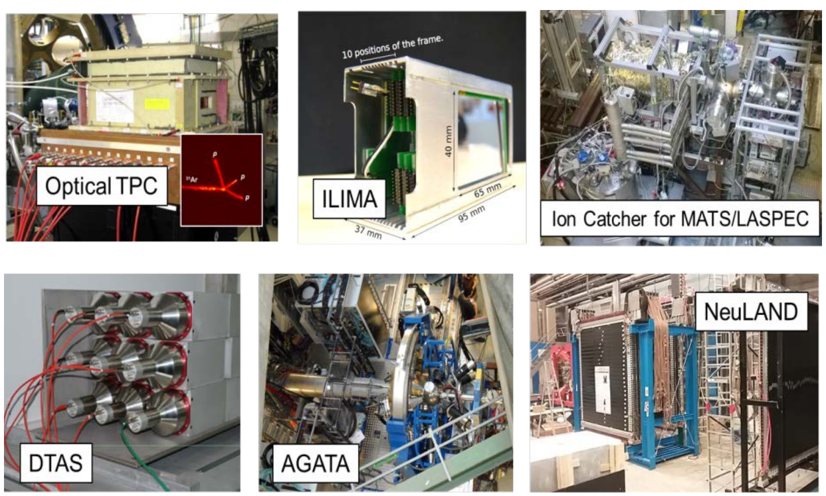
APPA



CBM

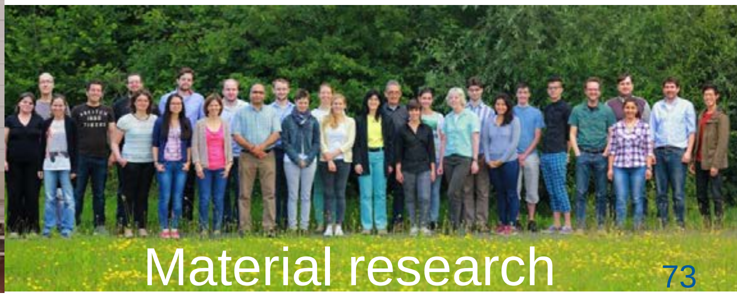


NUSTAR

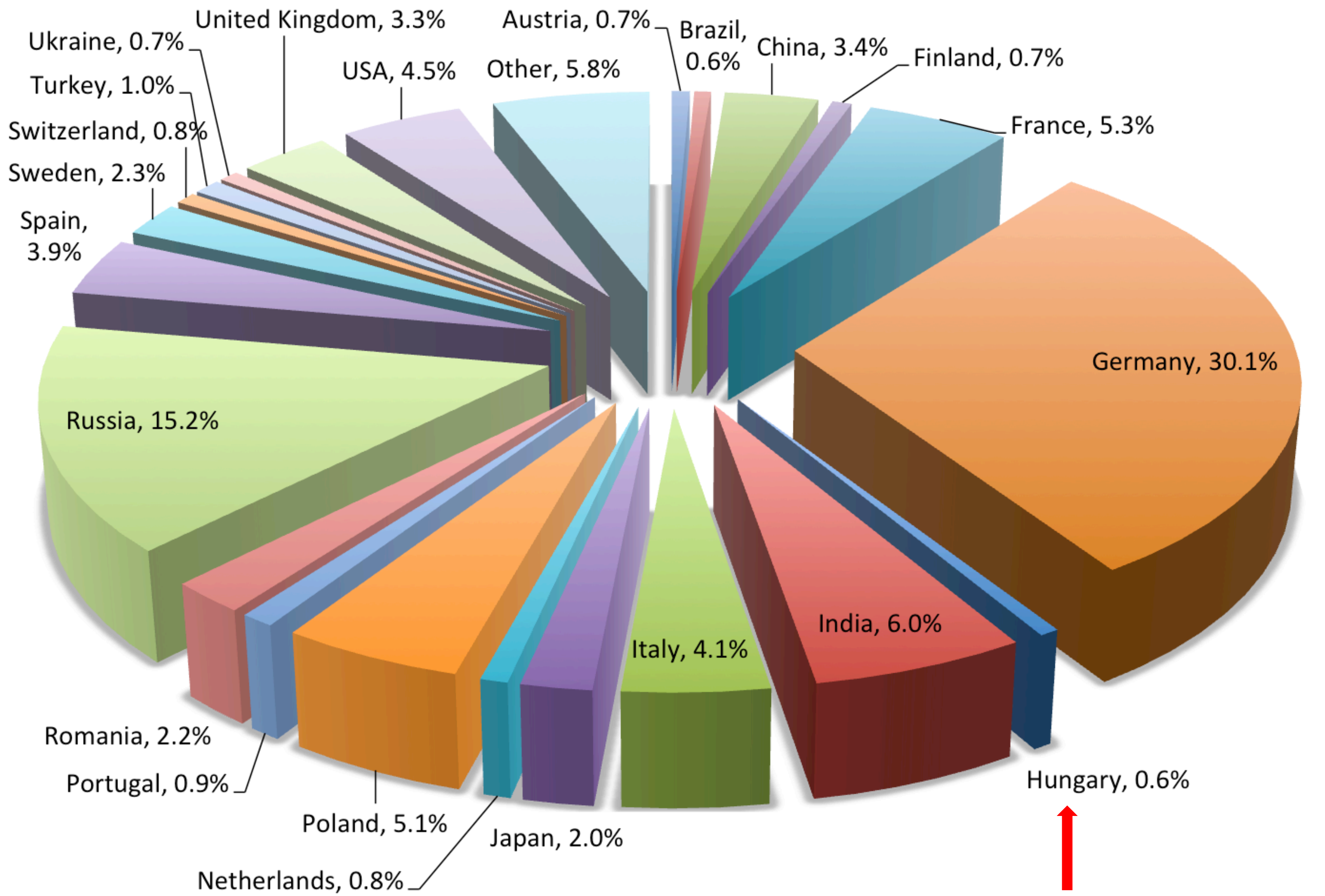


PANDA

FAIR International Collaborations

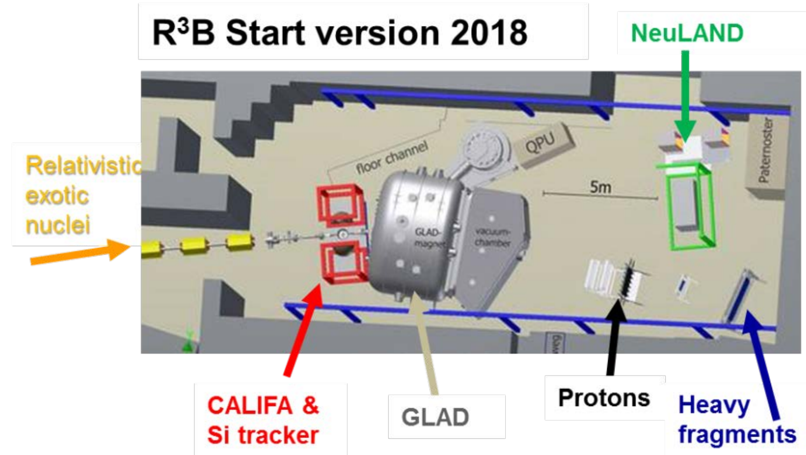


Collaboration Members by Country



room for improvement

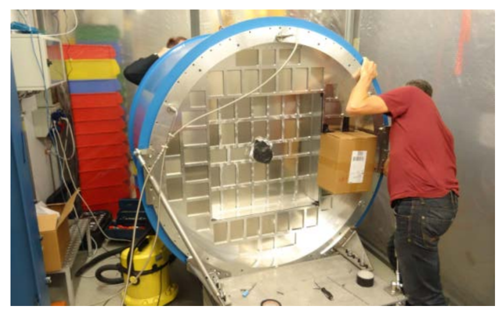
FAIR "Phase 0" - Detector commissioning and science starting 2018 (examples)



R^{3}B installation at GSI/Cave C:

Reactions at high beam energies up to 1-2 GeV/u
Identification capability even for the heaviest ions
Multiple neutron tracking capability

CBM detectors installed at HADES (GSI) and STAR (LBL)



Photon detectors for HADES RICH
MRPC-TOF detectors as STAR endcap

Atomic physics at the CRYRING installed being FRS-ESR at GSI

Precision collision spectroscopy of Be-like ions
Photoionization of C^+ ions
Ground-state Lamb Shift in Hydrogen-like U91+


Swedish contribution to FAIR

Instead of a summary …

Key Summary Recommendation of the NUPECC Long Range Plan 2017 presented in Brussels on Nov 27th :

Complete urgently the construction of the ESFRI* flagship FAIR and develop and bring into operation the experimental program of its four scientific pillars APPA, CBM, NUSTAR and PANDA.

FAIR is a European flagship facility for the coming decades. Worldwide unique it will allow for a large variety of unprecedented fore-front research in physics and applied science. It focuses on the structure and evolution of matter. Its multi- faceted research opens a new era in our understanding of the fundamental building blocks of matter and the forces as well as of the evolution of our Universe: the new possibilities for research in Darmstadt are unique and are expected to produce ground breaking new insights for nuclear research.

*European Strategy Forum on Research Infrastructures