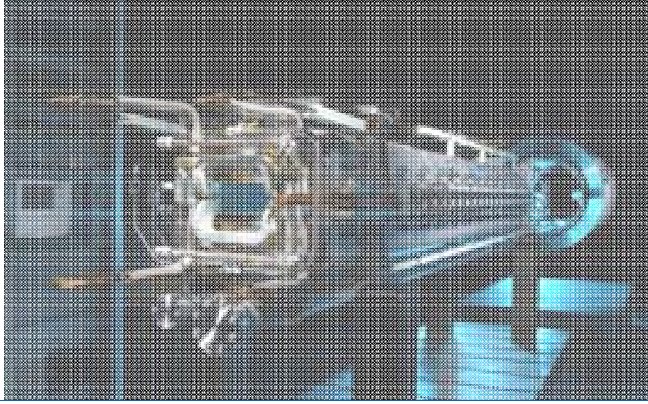




Extreme State of Matter Physics at FAIR

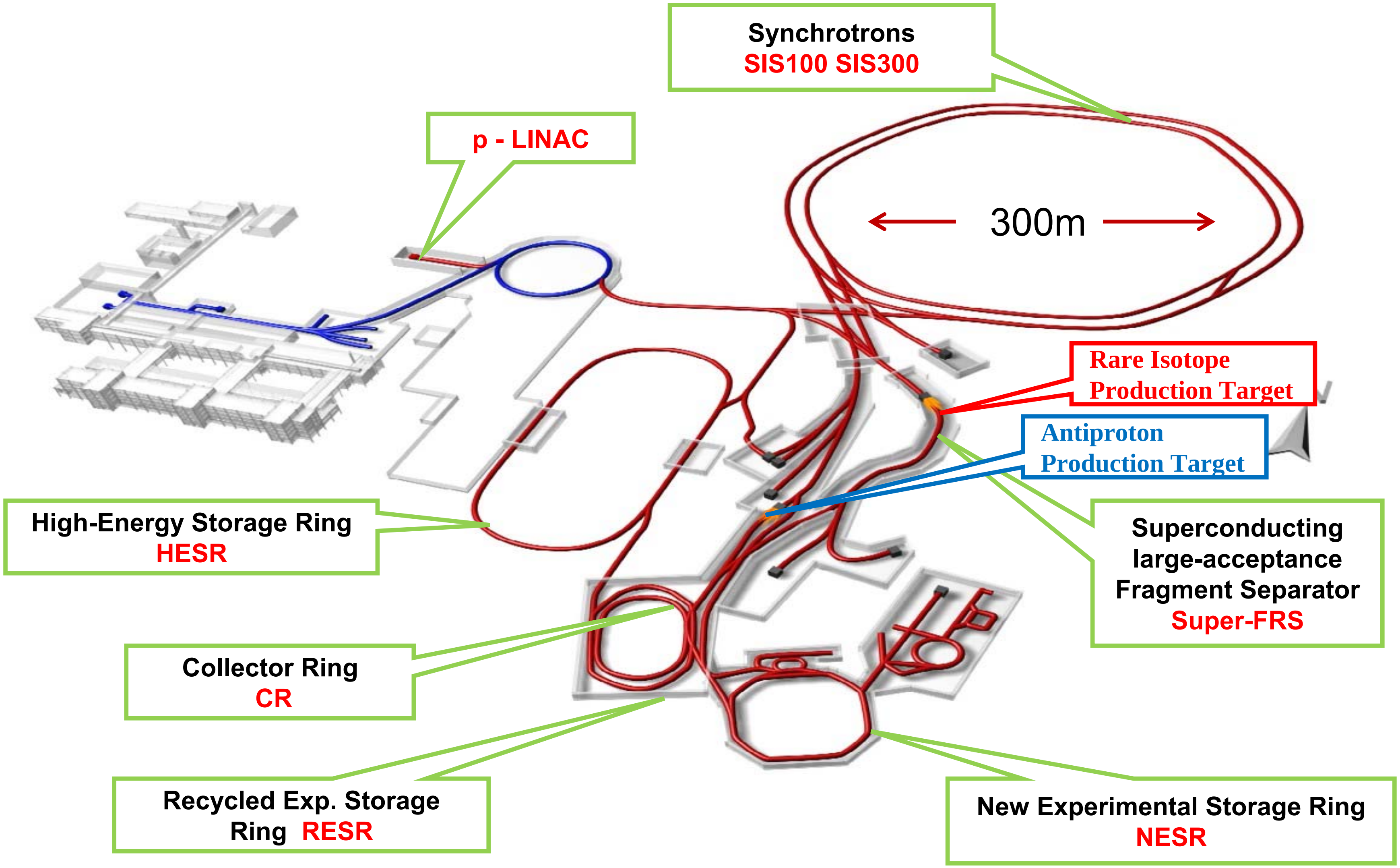
Boris Sharkov

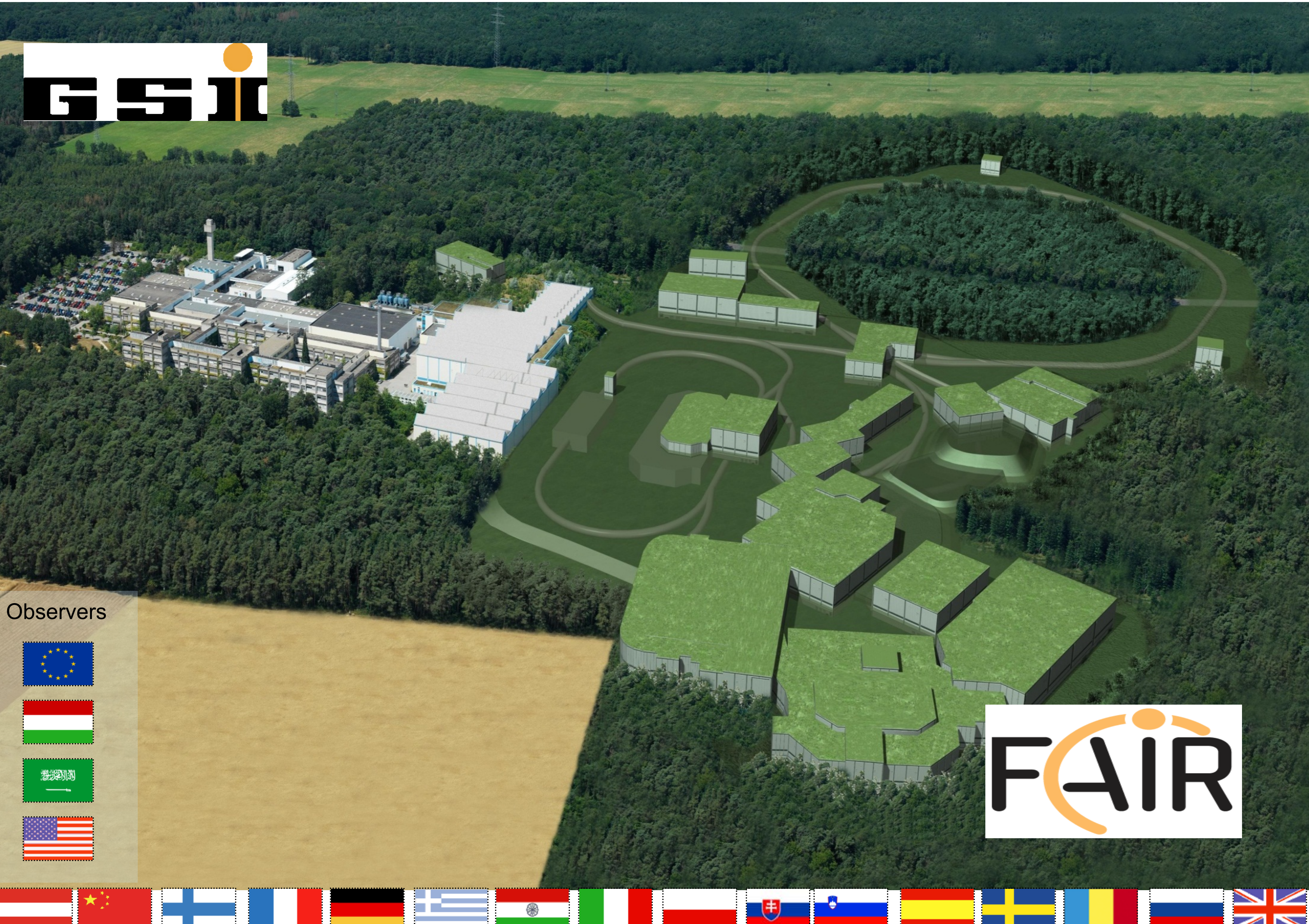
FAIR Scientific Director,
Chairman of the management board

31. 10. 2011 the NA, Washington

Facility for Antiproton and Ions Research – the light tower of the ESFRI Roadmap

New accelerator systems to be constructed in Darmstadt





Austria China Finnland France Germany Greece India Italy Poland Slovakia Slovenia Spain Sweden Romania Russia UK

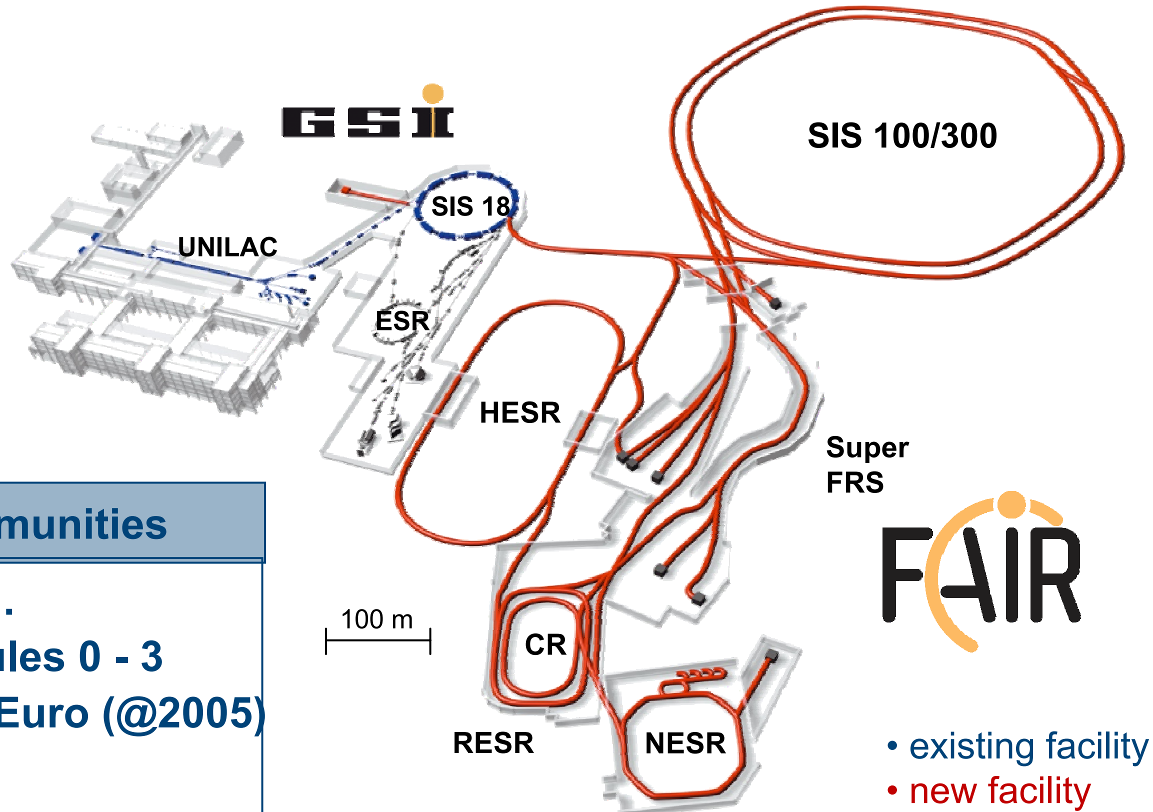
04.10.2010 Castle Biebrich, Wiesbaden
Signing Ceremony of FAIR international Convention

Finland, France, Germany, India, Poland, Romania, Russia, Slovenia and Sweden

The present Main Project: FAIR – the intensity frontier

Added value

- § Beam intensity by a factor of 100 - 10000
- § Beam energy by a factor of 20
- § Anti-matter beams
- § Unique beam quality
- § Parallel operation



Construction, cost, scientific communities

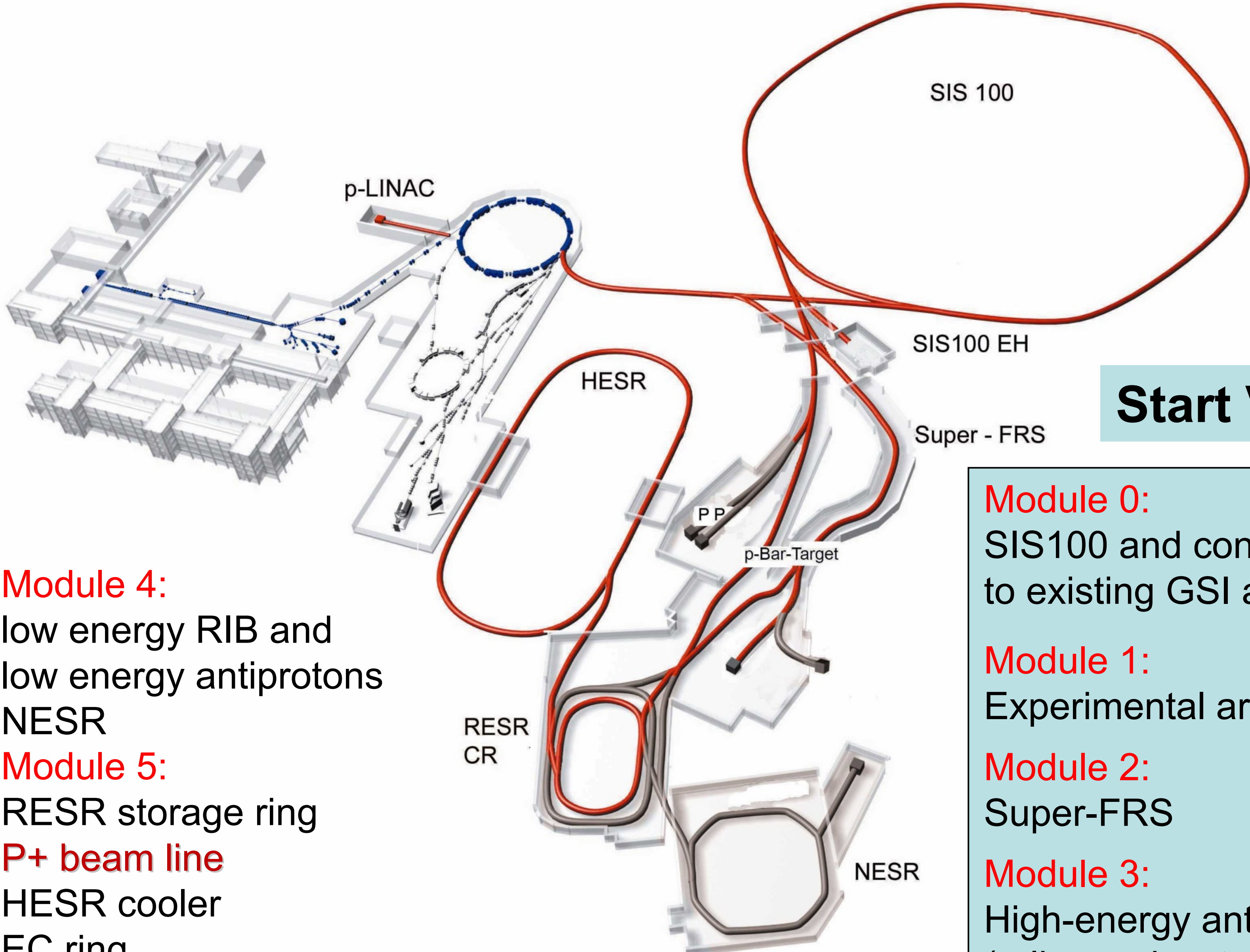
- § **Construction in modules 0 – 6, …**
- § **Modularized Start Version: Modules 0 - 3**
  Construction cost: 1.027 Billion Euro (@2005)
- § **Scientific Pillars:**

- **APPA:** Atomic Physics, **Plasma Physics**, Applic.
- **CBM:** Compresed Baryonic Matter
- **NuSTAR:** Nucl Structure & Astrophysics
- **PANDA:** Hadron Structure & Dynamics

In total: 2500 – 3000 Users

Funding (Construction)

- § 65 % Federal Republic
- § 10 % State of Hessen
- § 25 % International Partners



Start Version

Module 4:
low energy RIB and
low energy antiprotons
NESR
Module 5:
RESR storage ring
P+ beam line
HESR cooler
EC ring

Module 0:
SIS100 and connection to existing GSI accel.

Module 1:
Experimental areas CBM,APPA

Module 2:
Super-FRS

Module 3:
High-energy antiprotons (p-linac, pbar-target, CR, HESR)

Financial Constrains

Cost of Modularized Start Version = 1027 M€

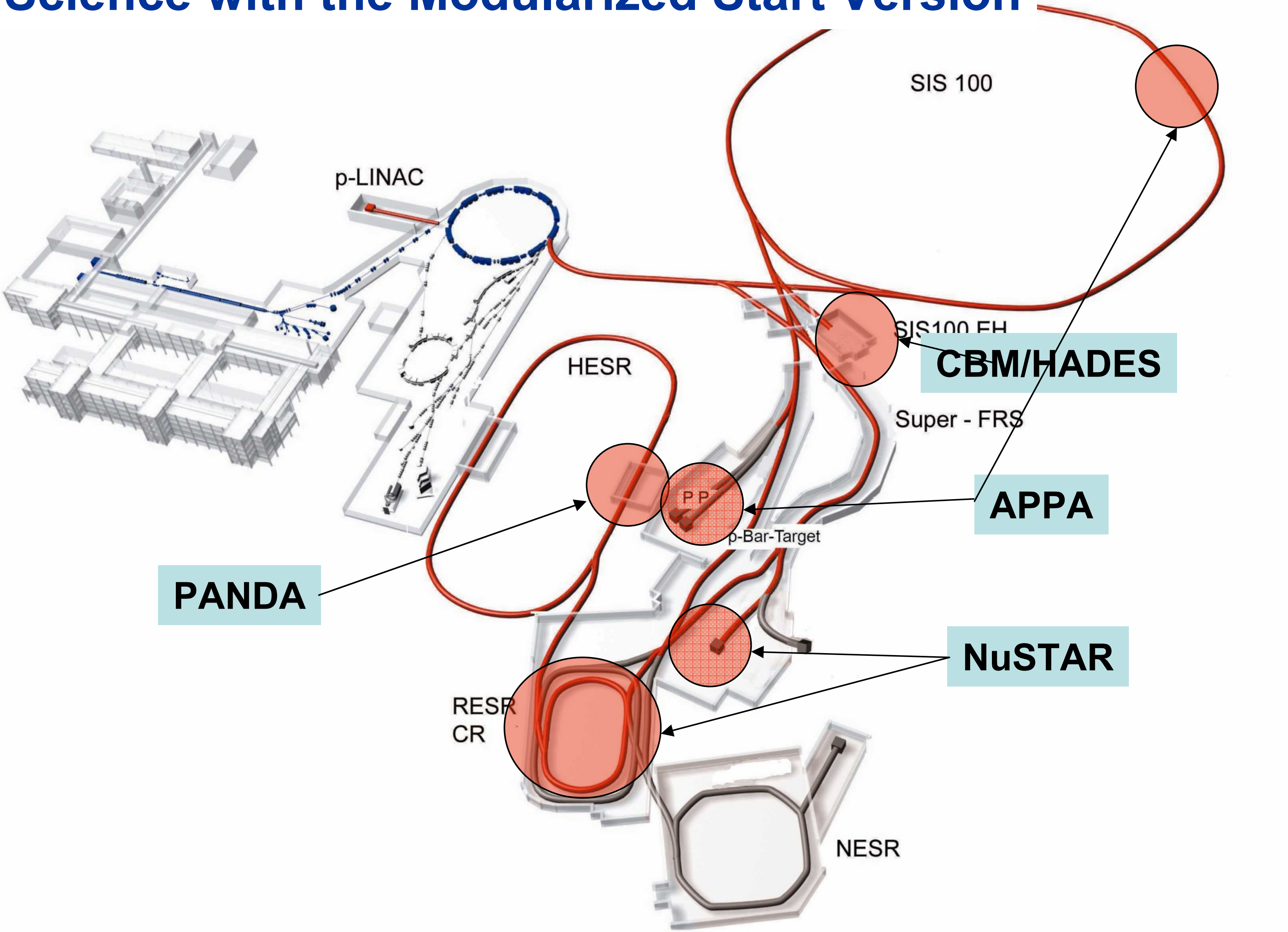
Firm funding commitments of FAIR Partners = 1026,5 M€

Modularized Start Version secures a swift start within the current funding commitments

Basic criteria of new FAIR construction scenario:

The Modularized Start Version should enable realization of outstanding forefront research program to <u>all four</u> scientific communities of FAIR

Science with the Modularized Start Version



FAIR – new international research laboratory to explore the nature of matter in the Universe

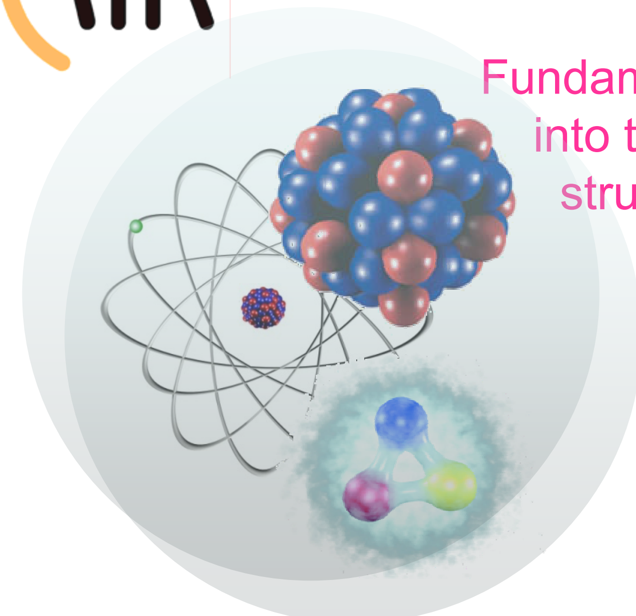
The main research thrust of FAIR focuses on the **structure and evolution of matter** on both a **microscopic and a cosmic scale**

Scientific Pillars:

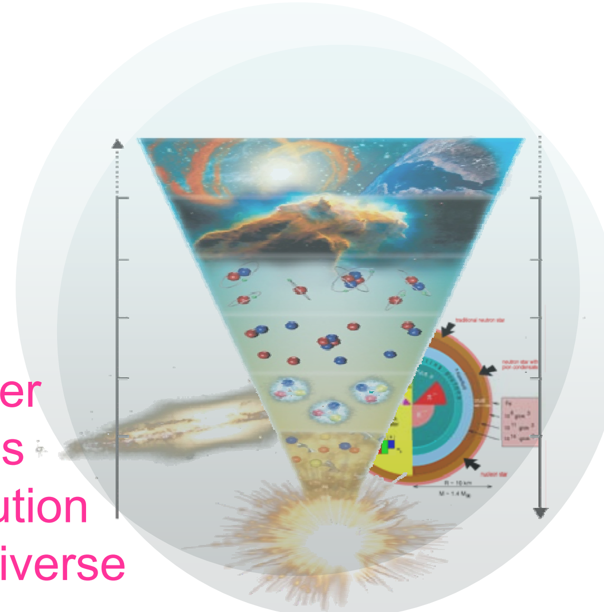
- **APPA:** Atomic Physics, **Plasma Physics**, Applic.
- **CBM:** Compressed Baryonic Matter
- **NuSTAR:** Nucl Structure & Astrophysics
- **PANDA:** Hadron Structure & Dynamics

In total: 2500 – 3000 Users

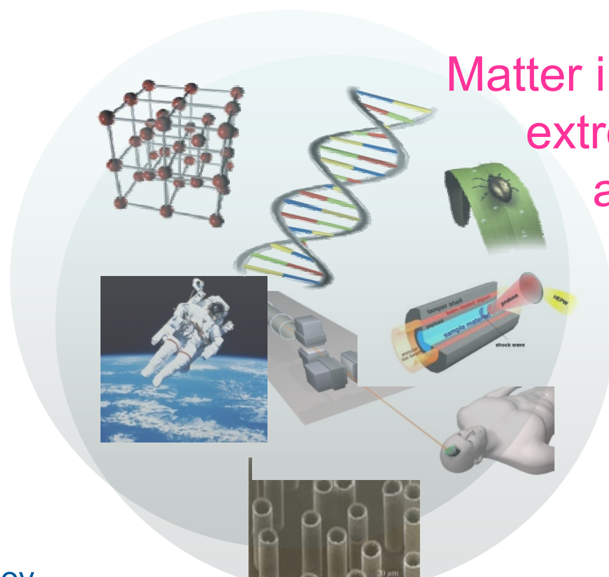
Highest Intensity Precision Beams of Energetic Ions and Antiprotons



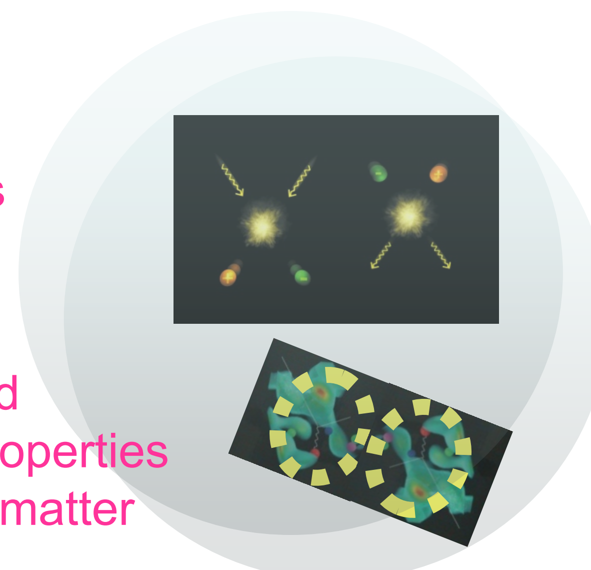
Fundamental Research
into the microscopic
structure of matter



Creation of matter
nucleosynthesis
and the evolution
of the Universe



Matter in
extreme states
and material studies
& applications



Structure and
fundamental properties
of anti-matter

Nuclear STructure, Astrophysics and Reactions

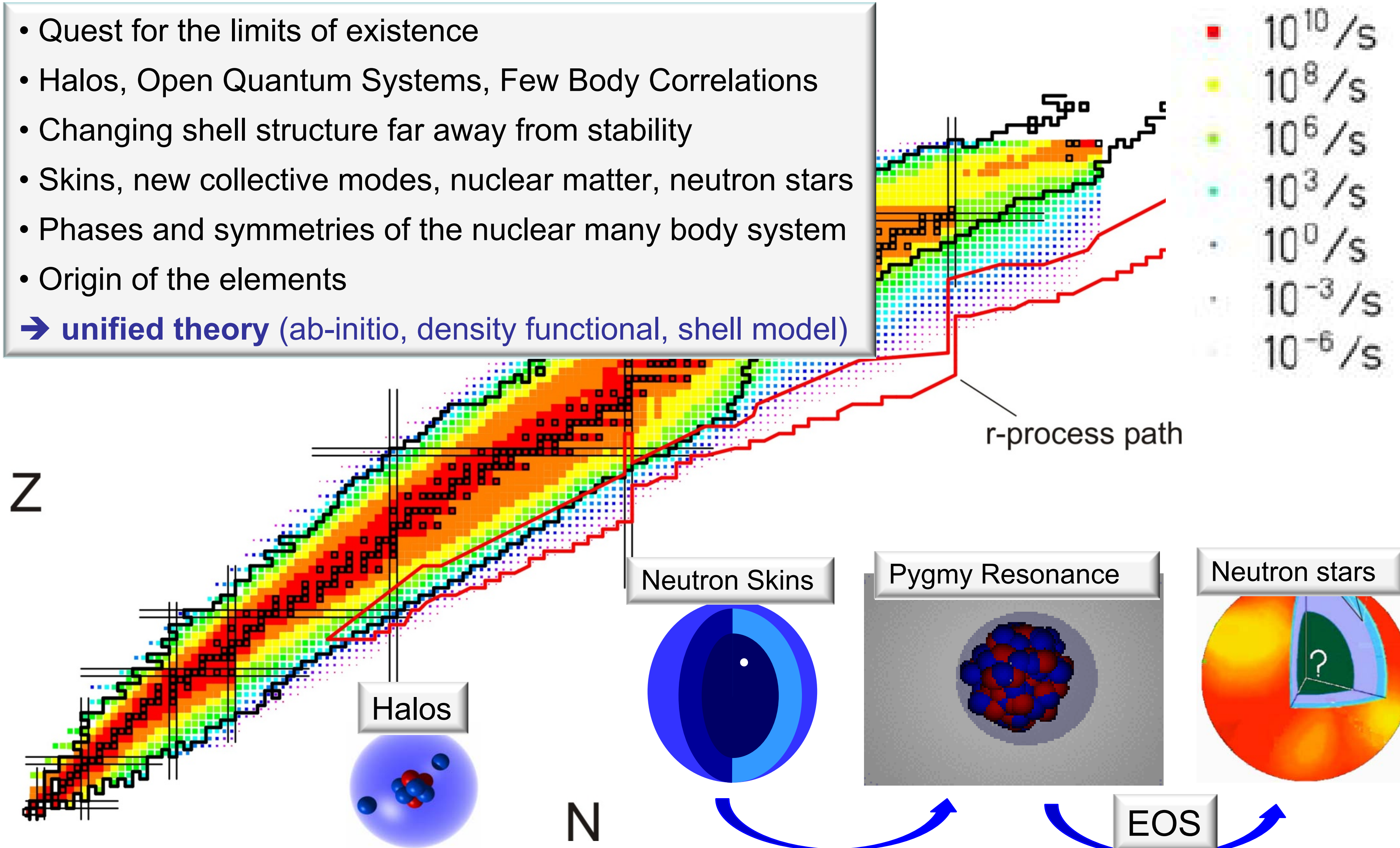
> 800 members from 37 countries and 146 institutions

Annual NUSTAR Collaboration Meeting

Central Topics for NuSTAR at FAIR *How are nuclei made?*

- Quest for the limits of existence
- Halos, Open Quantum Systems, Few Body Correlations
- Changing shell structure far away from stability
- Skins, new collective modes, nuclear matter, neutron stars
- Phases and symmetries of the nuclear many body system
- Origin of the elements

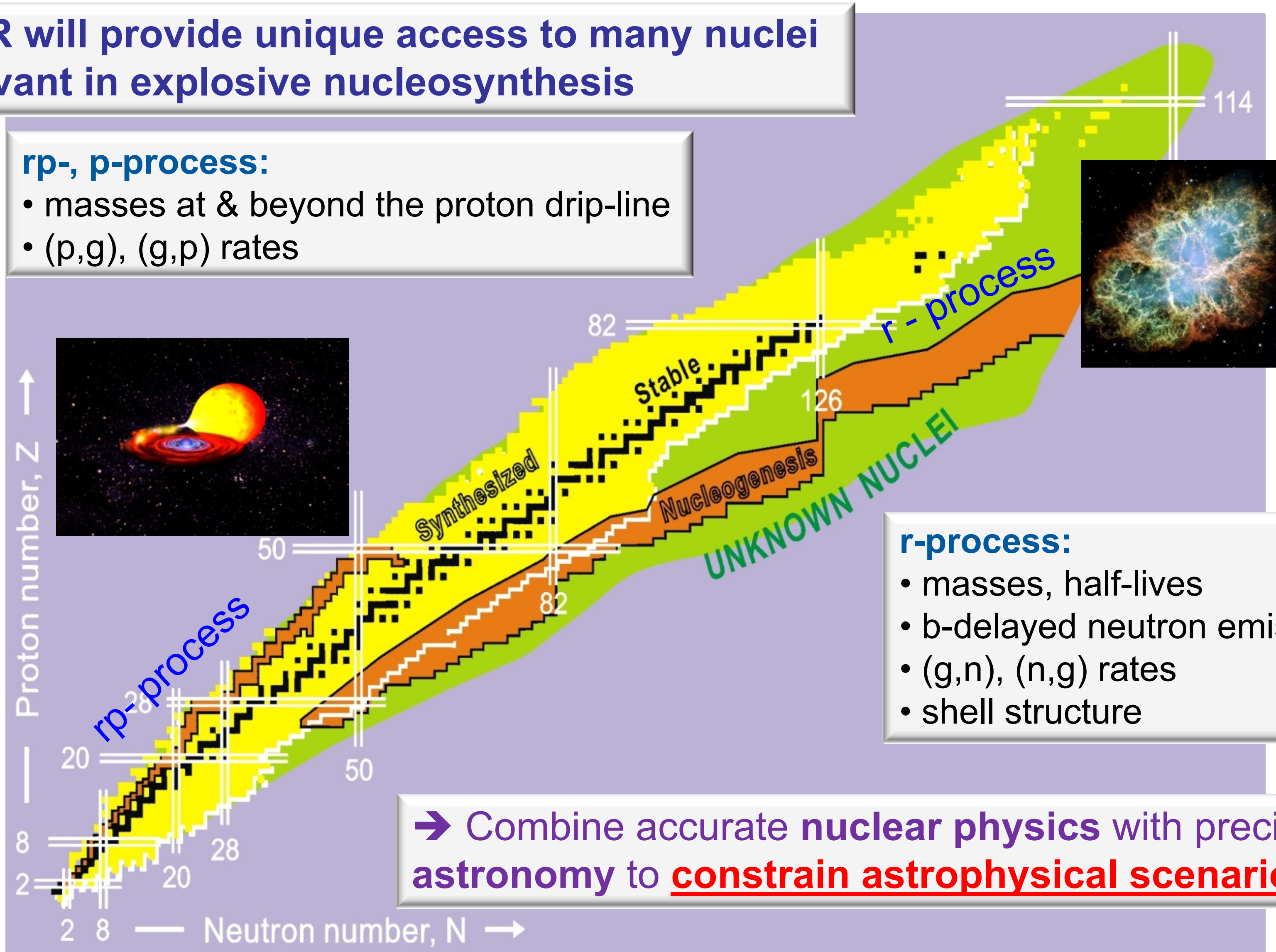
➔ **unified theory** (ab-initio, density functional, shell model)



Nuclear Astrophysics at FAIR

FAIR will provide unique access to many nuclei relevant in explosive nucleosynthesis

rp-, p-process:
- masses at & beyond the proton drip-line
- (p,g), (g,p) rates

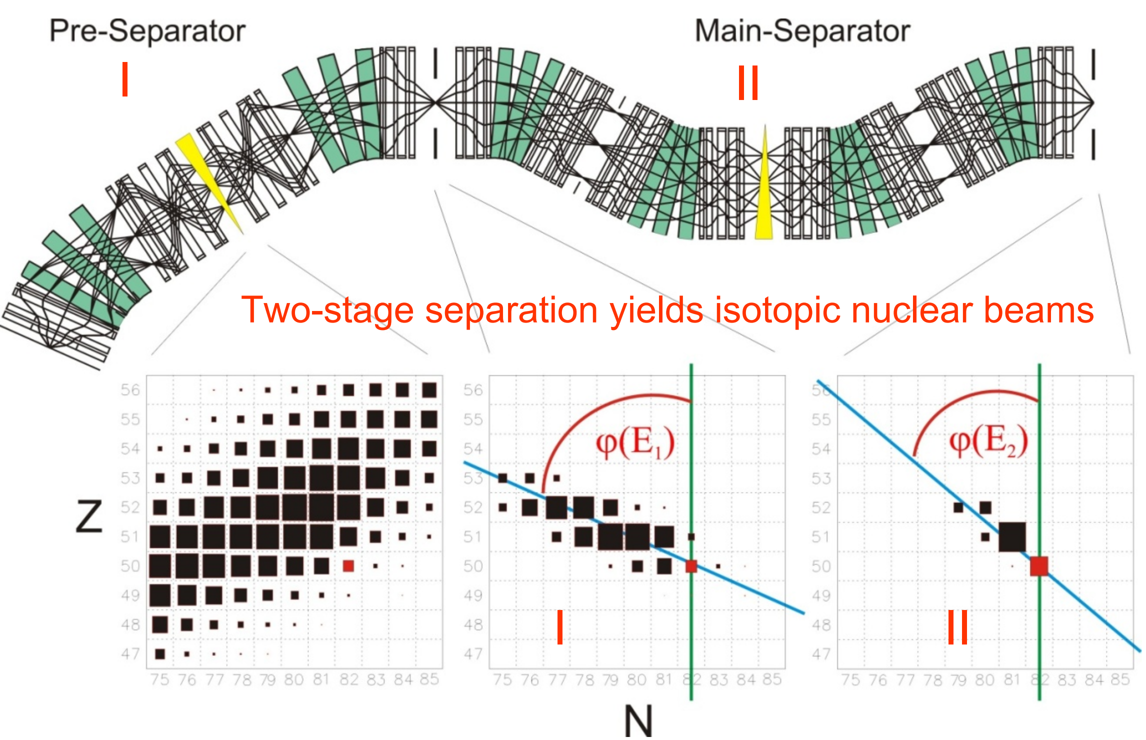


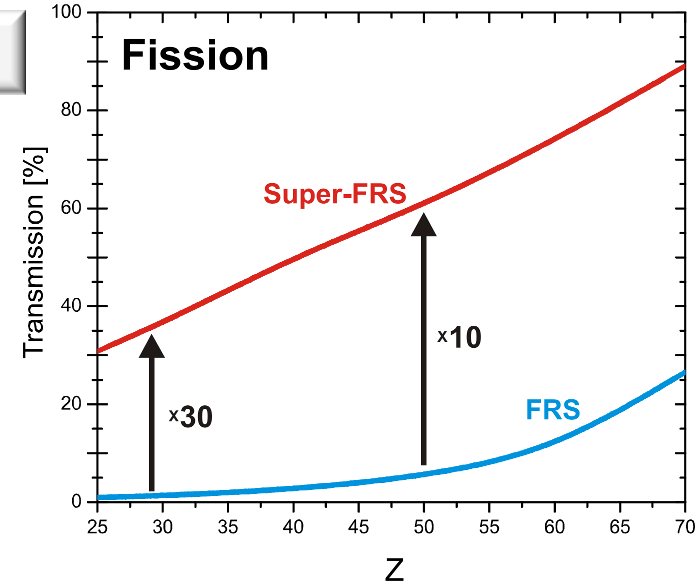
r-process:
- masses, half-lives
- b-delayed neutron emission
- (g,n), (n,g) rates
- shell structure

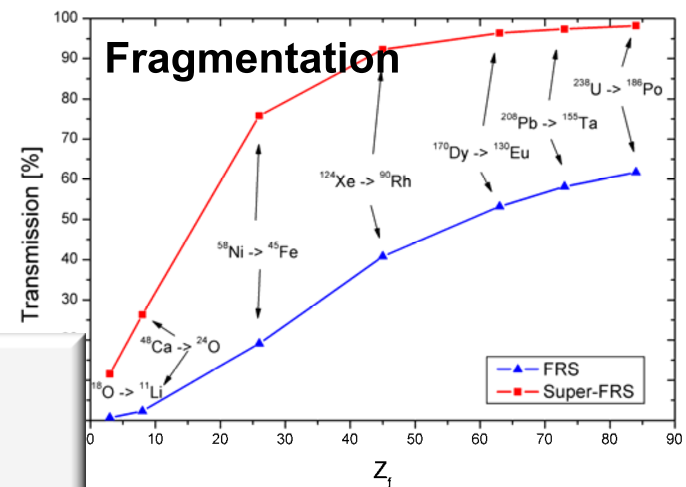
➔ Combine accurate **nuclear physics** with precision **astronomy** to <u>**constrain astrophysical scenarios**</u>

The Super-FRS

Central instrument for the NuSTAR program!!



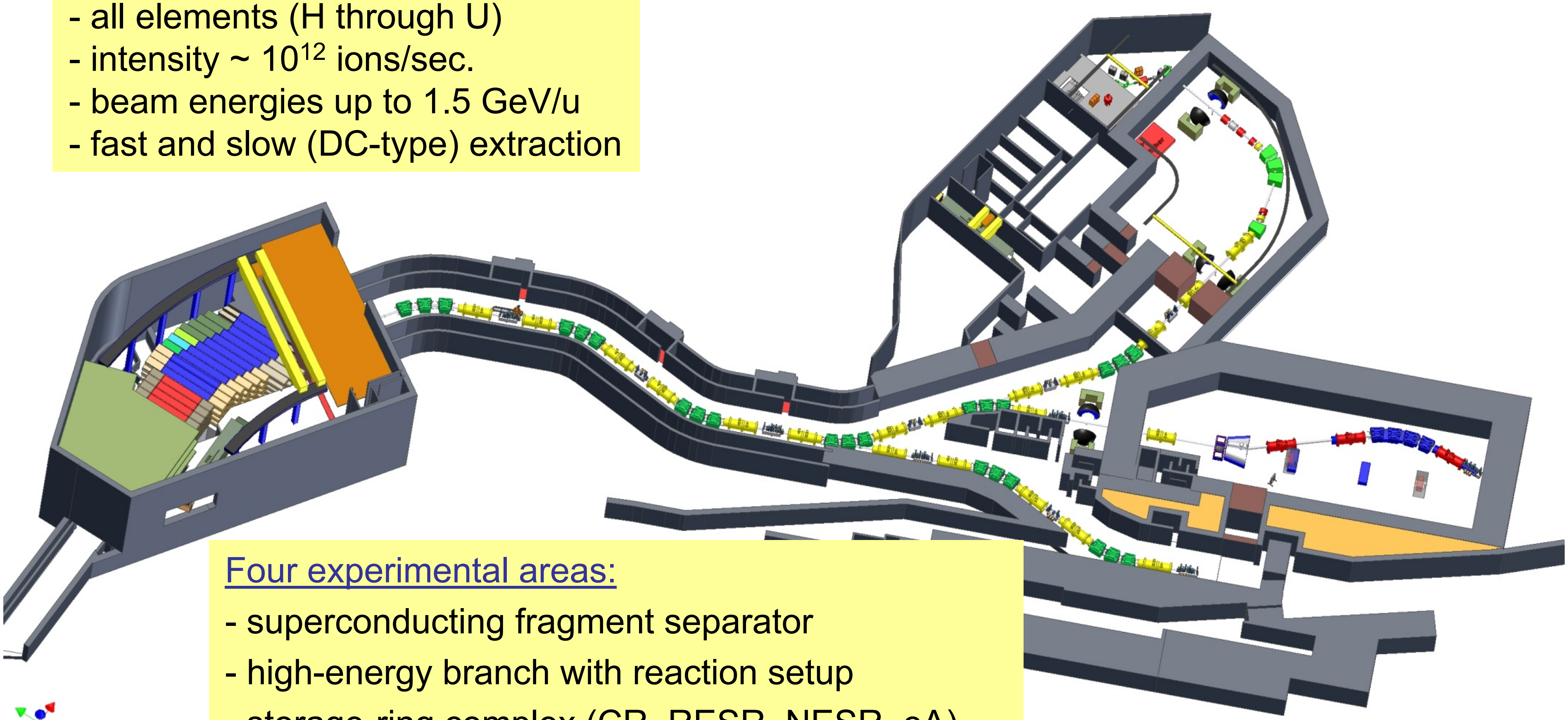




- High acceptance for projectile fragments and fission products
- Two-stage separation absolutely needed for clean beams
- **More than one order of magnitude <u>transmission gain</u> relative to FRS**

The NUSTAR experimental facilites at FAIR

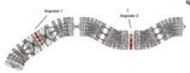
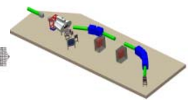
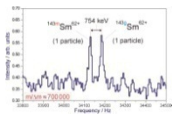
Important beam parameters:
- all elements (H through U)
- intensity ~ 10^{12} ions/sec.
- beam energies up to 1.5 GeV/u
- fast and slow (DC-type) extraction

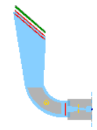
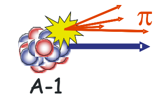


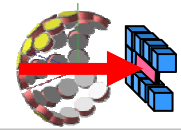
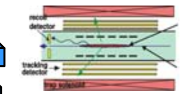
Four experimental areas:
- superconducting fragment separator
- high-energy branch with reaction setup
- storage-ring complex (CR, RESR, NESR, eA)
- low-energy branch with energy focusing and re-acceleration

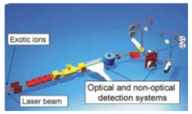
Complementarity of NUSTAR experiments

Super-FRS | R3B | ILIMA | EXL | ELISE | AIC | HISPEC/ DESPEC | exo+ pbar | MATS | LASPEC

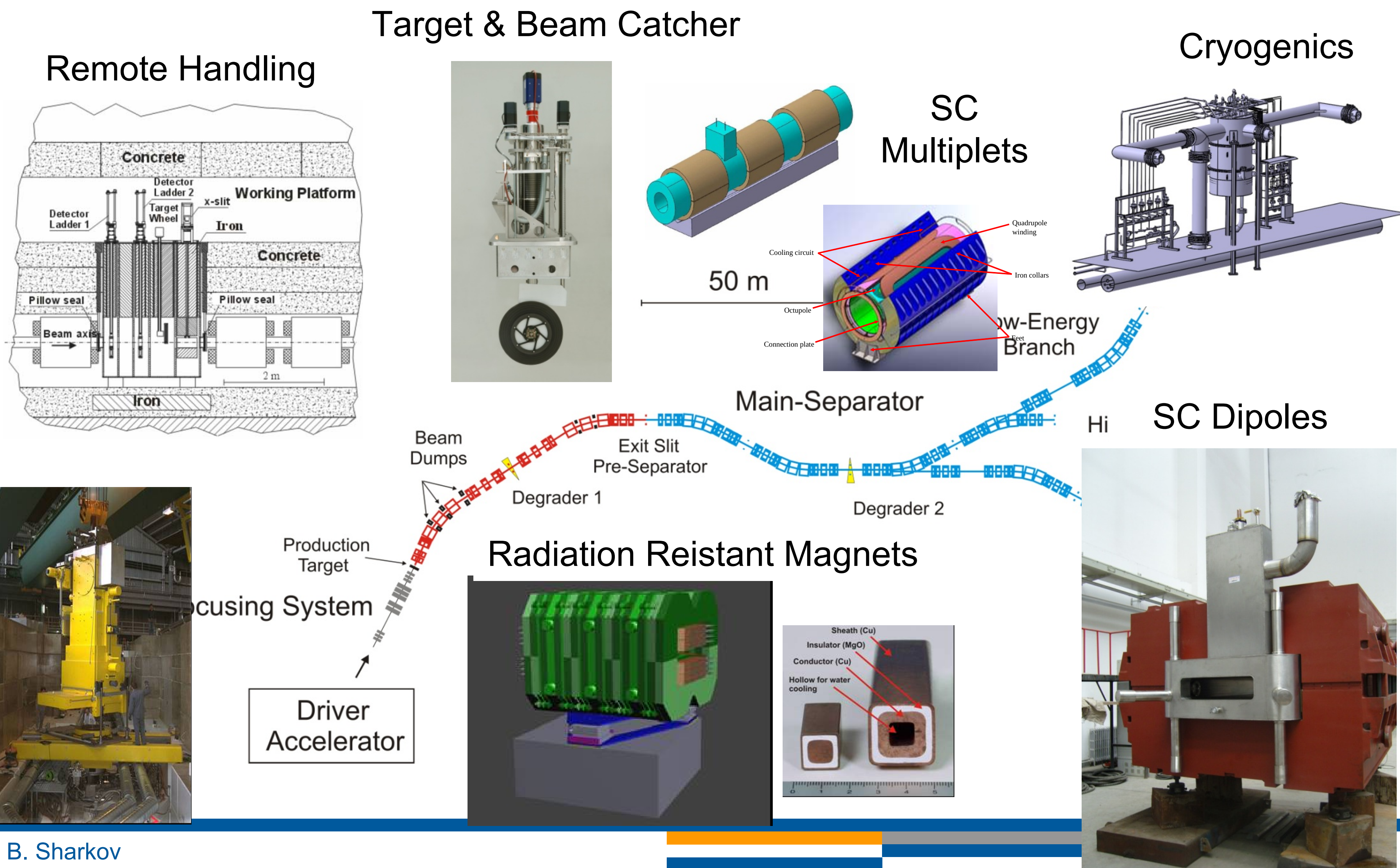


	Super-FRS	**R3B**	**ILIMA**	**EXL**	**ELISE**	**AIC**	**HISPEC DESPEC**	**exo+pbar**	**MATS**	**LASPEC**
Masses			bare ions, mapping study				Q-values, isomers		dressed ions, highest precision	
Half-lives	ps…ns-range		bare ions, s…h				dressed ions, μs…s			
Matter radii	interaction x-sect	matter radii		matter densitiy distributions		matter radii from absorption		nuclear periphery		
Charge radii					charge density distribution					mean square radii
Single-particle structure	high resolution, angular momentum	complete kinematics, neutron detection		low momentum transfers			high-resolution spectroscopy			

- Highest intensity and transmission
- "High" energy (unambigous identification)
- World-wide unique storage-ring complex
- Exotic nuclei **and** antiprotons
- Complementary instruments, cutting-edge technology

- New isotopes (r-nuclides)
- Neutron radioactivity, neutron dripline
- Modification of shell structure, new excitation modes
- Unexpected observations and phenomena

Technical Challenges: contributions by partner countries



PANDA The Collaboration

At present 410 physicists from 53 institutions in 16 countries

Basel, Beijing, Bochum, IIT Bombay, Bonn, Brescia, IFIN Bucharest, Catania, IIT Chicago, Cracow, IFJ PAN Cracow, Cracow UT, Edinburgh, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, FZ Jülich, JINR Dubna, Katowice, KVI Groningen, Lanzhou, LNF, Lund, Mainz, Minsk, ITEP Moscow, MPEI Moscow,TU München, Münster, Northwestern, BINP Novosibirsk, IPN Orsay, Pavia, IHEP Protvino, PNPI St.Petersburg, KTH Stockholm, Stockholm, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, SINS Warsaw, TU Warsaw, AAS Wien

High precision beams of Antiprotons

..allow in collisions with protons and nuclei the formation of

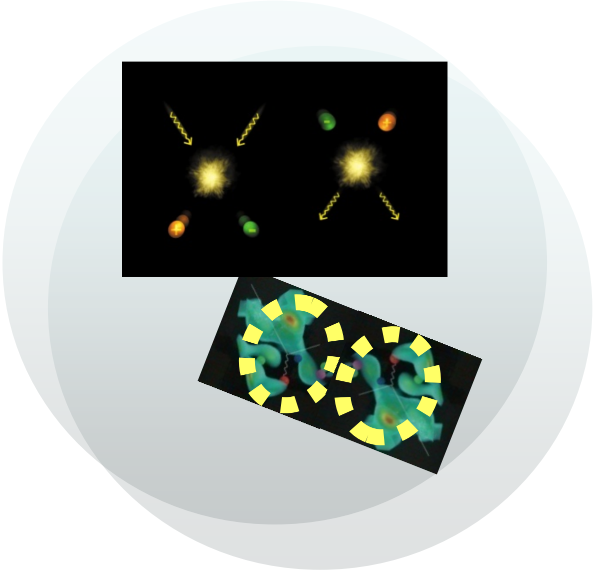
- pairs of sub-nuclear particles and their antiparticles
- high precision measurements of sub-nuclear masses and lifetimes

..allow at zero velocity the production of ***antihydrogen atoms and molecules***, the antimatter of hydrogen, and studies of, e.g.,

- gravity acting on ***antimatter***
- validity of our physics laws for ***antimatter***

Þ ***At FAIR: 100 times more abundant than at CERN***

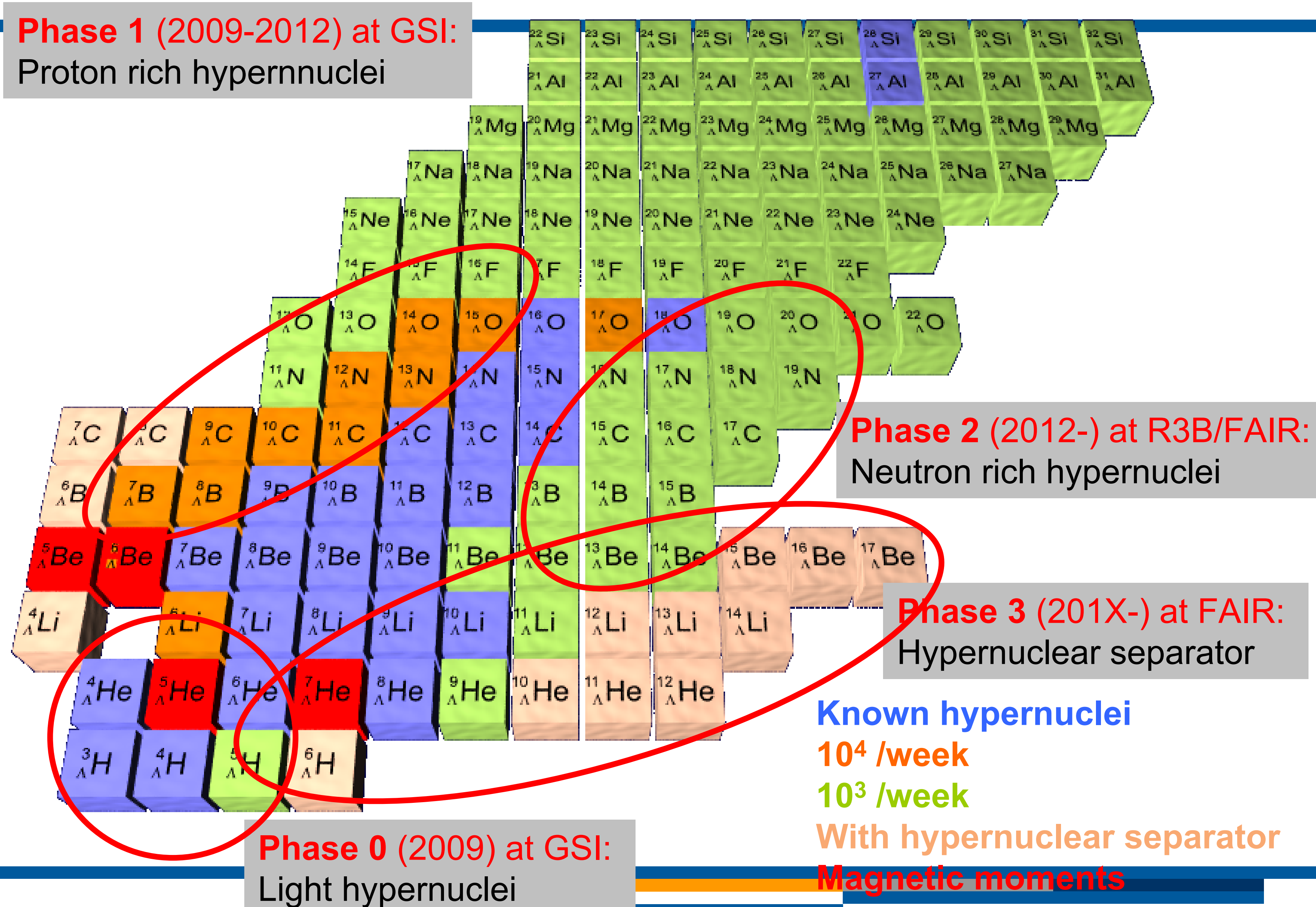
Structure and fundamental properties of anti-matter



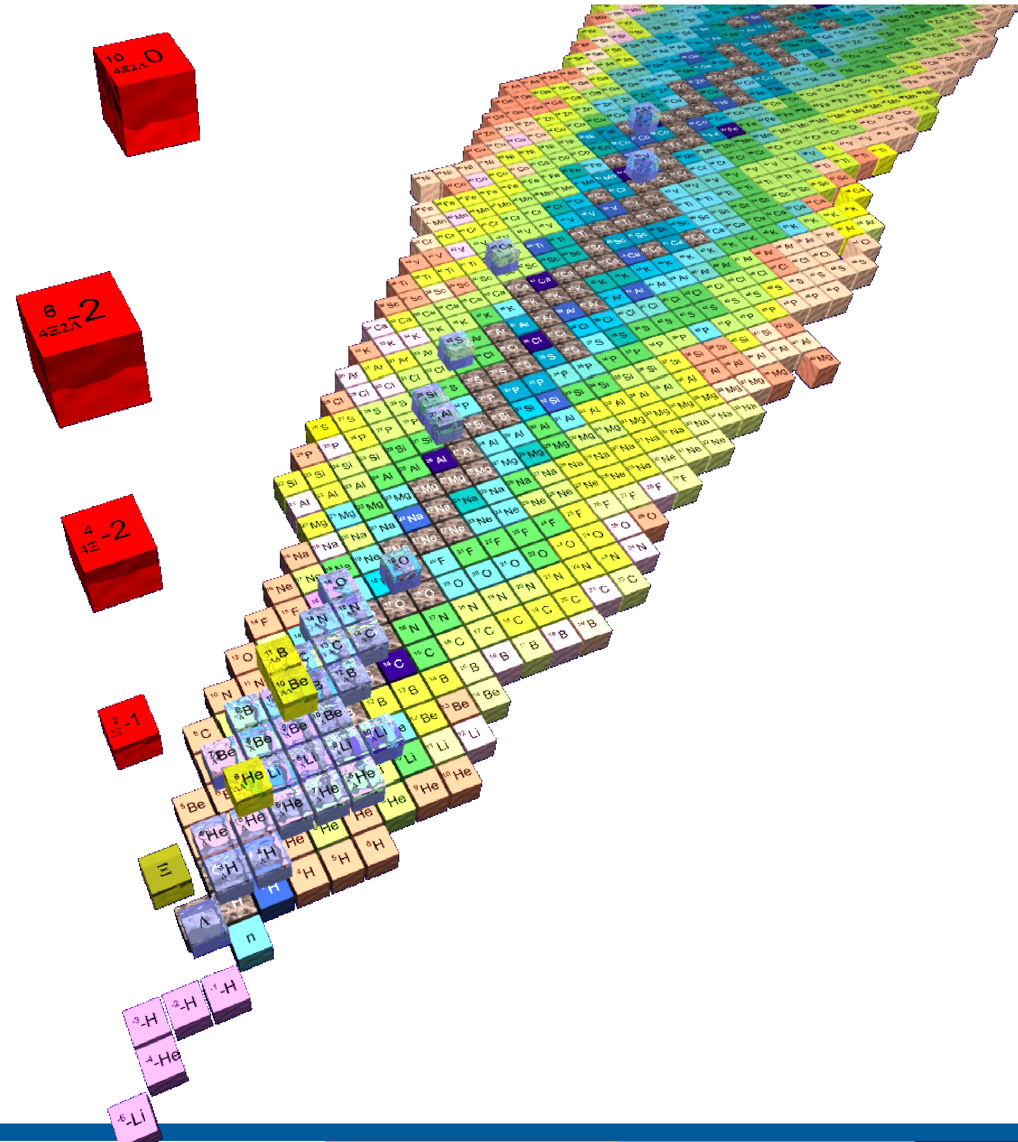
Scientific program (Highlights)

- Charmonium (ccbar)/open charm (c+other non c-quark) spectroscopy
- Non-pertubative QCD dynamics
- Nucleon Structure via electro-magnetic processes

Hypernuclear landscape with HypHI

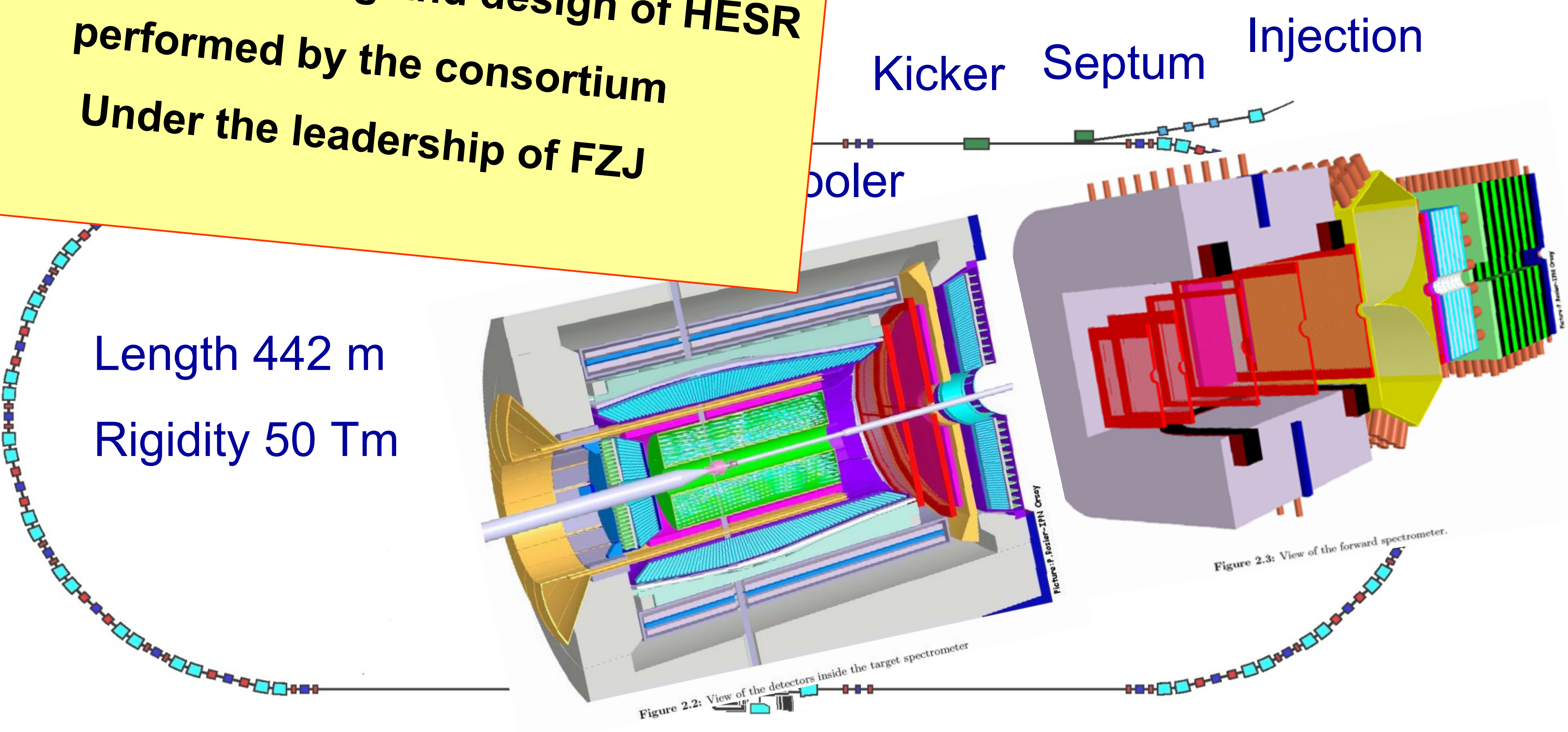


Exploring strange dimensions for the nuclear chart: Hyperon Clusters



HESR and PANDA

Working on planning and design of HESR performed by the consortium Under the leadership of FZJ



4π detector **PANDA Detector**

The CBM Collaboration: 55 institutions, 450 members

Croatia:
RBI, Zagreb
Split Univ.

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei

Czech Republic:
CAS, Rez
Techn. Univ.Prague

France:
IPHC Strasbourg

Hungaria:
KFKI Budapest
Budapest Univ.

Norway:
Univ. Bergen

India:
Aligarh Muslim Univ.
Panjab Univ.
Rajasthan Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
SAHA Kolkata
IOP Bhubaneswar
IIT Kharagpur
Gauhati Univ.

Korea:
Korea Univ. Seoul
Pusan Nat. Univ.

Germany:
Univ. Heidelberg, P.I.
Univ. Heidelberg, KIP
Univ. Heidelberg, ZITI
Univ. Frankfurt IKF
Univ. Frankfurt, FIAS
Univ. Münster
FZ Dresden
GSI Darmstadt
Univ. Wuppertal

Poland:
Jag. Univ. Krakow
Warsaw Univ.
Silesia Univ. Katowice
AGH Krakow

Portugal:
LIP Coimbra

Romania:
NIPNE Bucharest
Univ. Bucharest

Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
KRI, St. Petersburg
Kurchatov Inst., Moscow
LHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
Obninsk State Univ.
PNPI Gatchina
SINP MSU, Moscow
St. Petersburg P. Univ.

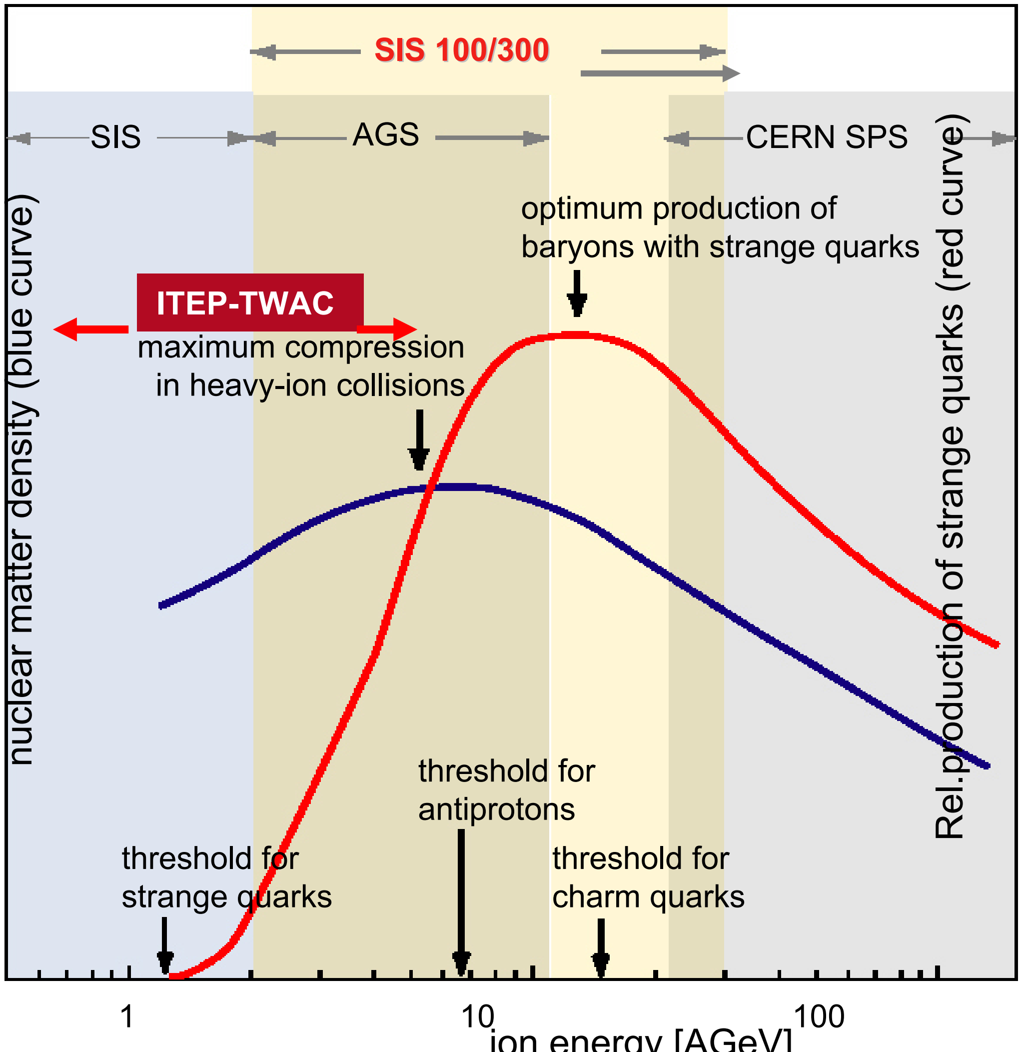
Ukraine:
T. Shevchenko Univ. Kiev
Kiev Inst. Nucl. Research

14st CBM Collaboration meeting
5-9 Oct. 2009, Split, Croatia

Relativistic Nuclear Physics

Studies of hadronic matter at high densities

Motivation for NN collisions at 2-40 AGeV

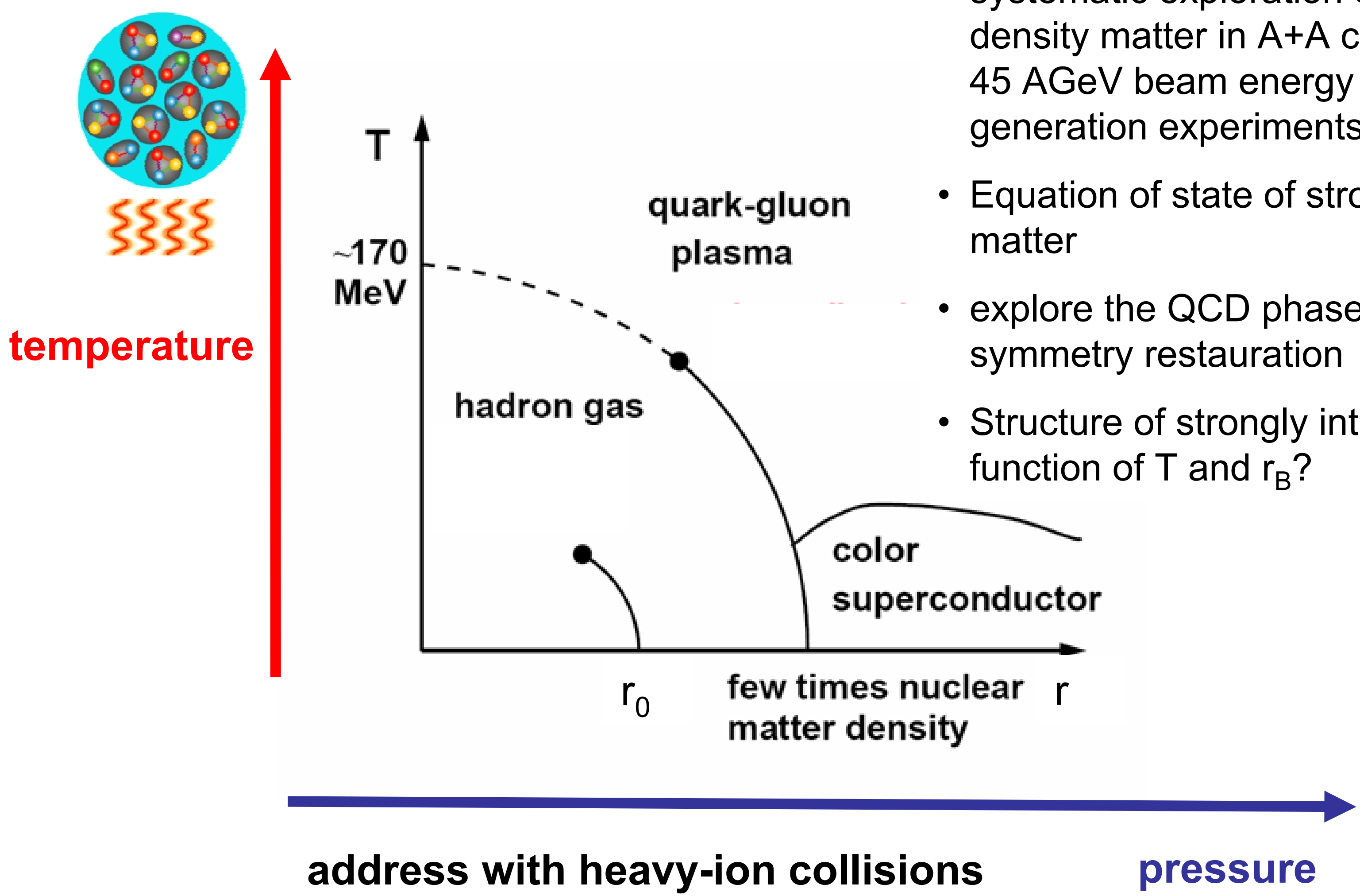


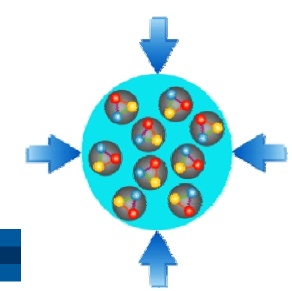
Phasediagram of strongly interacting matter

Fundamental questions of QCD

CBM and HADES at SIS 100 and SIS 300

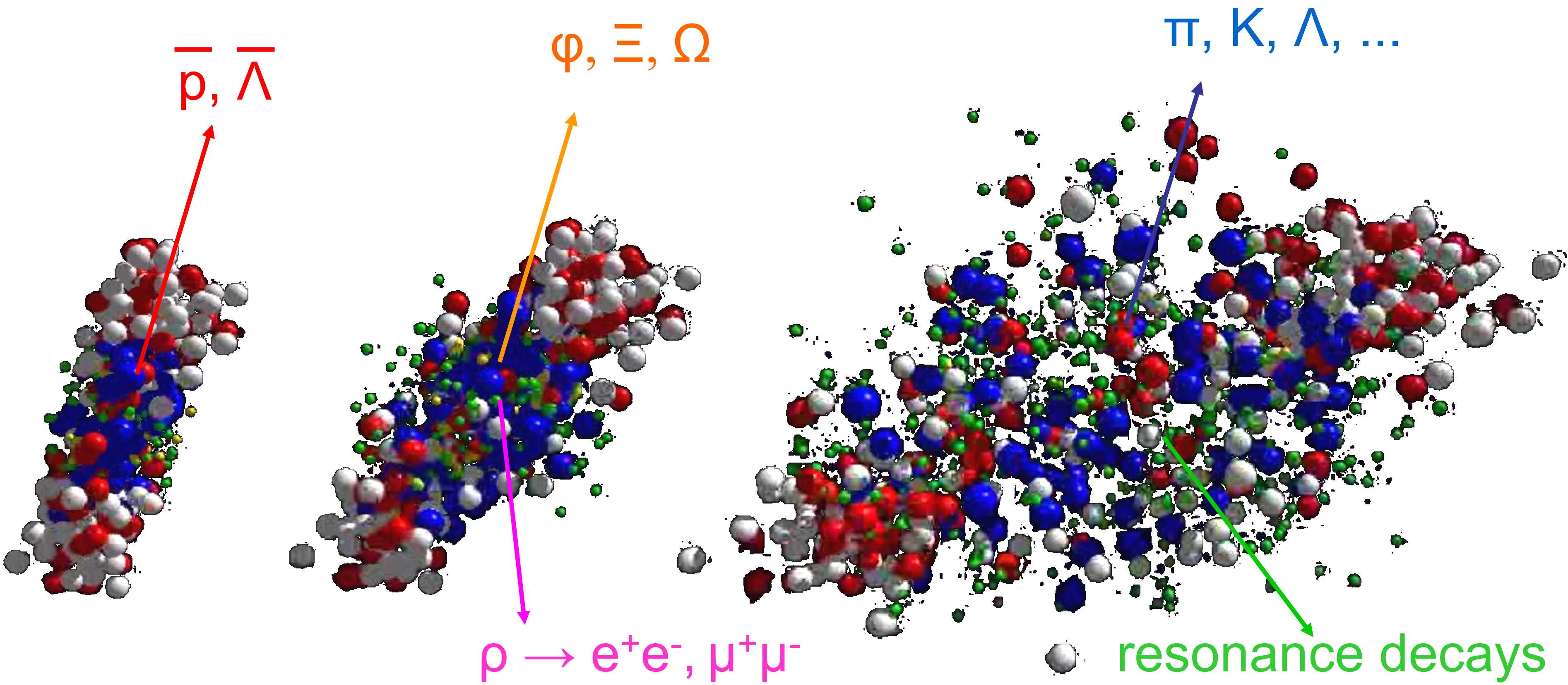
- systematic exploration of high baryon density matter in A+A collisions from 2 – 45 AGeV beam energy with 2nd generation experiments
- Equation of state of strongly interacting matter
- explore the QCD phase diagram, chiral symmetry restauration
- Structure of strongly interacting matter as function of T and r_B?





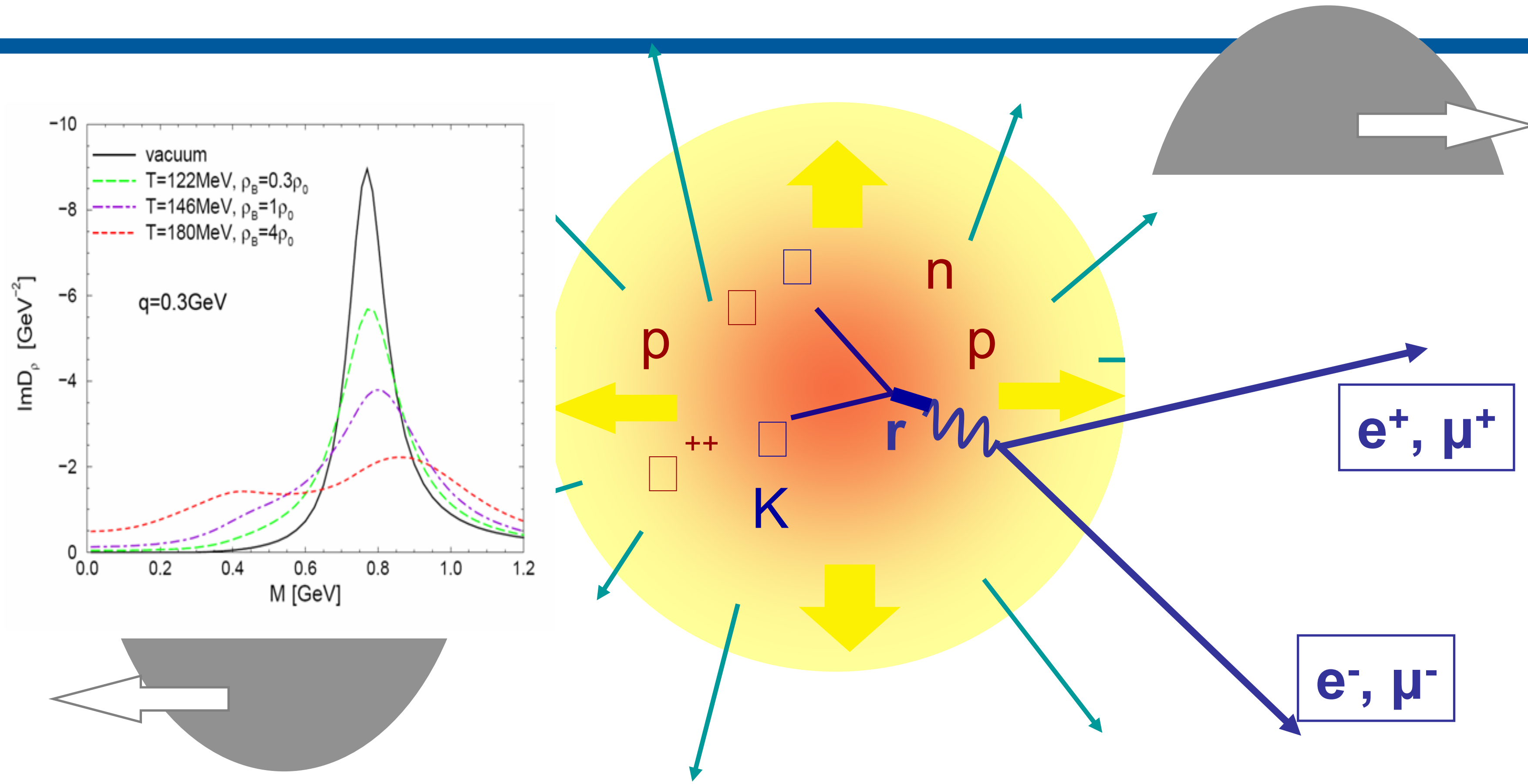
The evolution of the fireball

Au+Au collision at 10.7 A GeV from UrQMD



... using multistrange particles: equation of state at high baryon densities

Looking into the fireball ...



… using penetrating probes: short-lived vector mesons decaying into electron-positron pairs

Atomic, Plasma Physics and Applied Physics (APPA)

Plasma-physics

- 246 scientists
- 55 institutions
- 16 countries

BIOMAT

- 110 scientists
- 28 institutions
- 12 countries

SPARC

- 284 scientists
- 83 institutions
- 26 countries

FLAIR

- 144 scientists
- 49 institutions
- 15 countries

Plasma Physics

- Interior of massive planets like Jupiter

..do we understand the interior of planets?

- Warm and dense plasmas

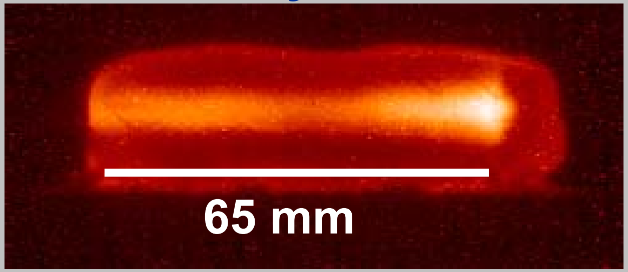
...Equation of State, transport properties, etc.,

• Energy production through Inertial Confinement Fusion:

..do we understand the basic physics problems?

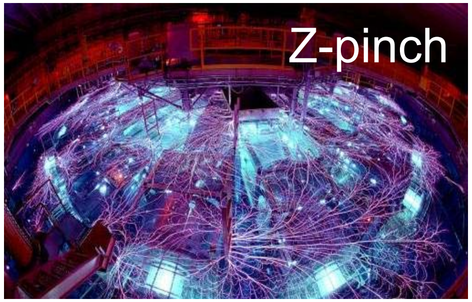
The uniqueness of heavy ion beams compared to other techniques (Laser, Z-pinch)

intense, energetic beams of heavy ions



Ne^{10+} 300 MeV/u; Kr crystal

- large volume of sample (mm^3)
- fairly uniform physical conditions
- thermodynamic equilibrium
- any material

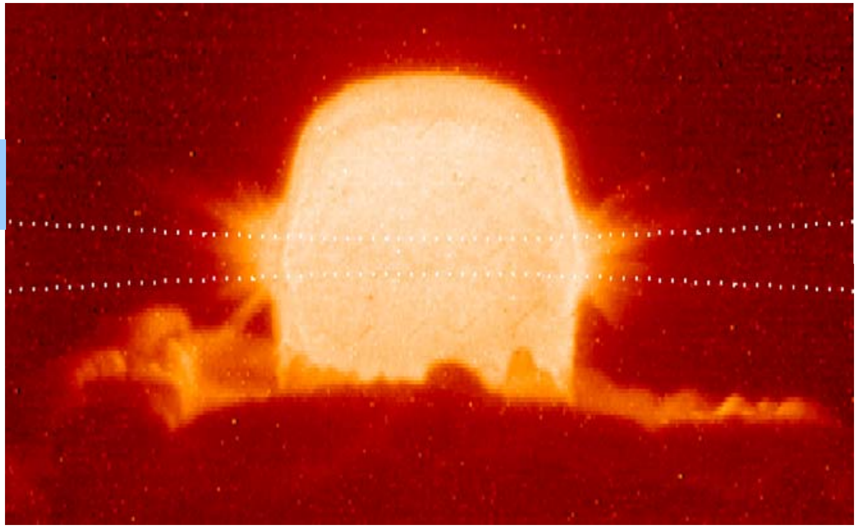


Already within module 1: Compared to GSI, FAIR will provide an ***intensity and energy density increase by a factor of 100.***

WDM-parameters: **T:** up to 10 eV **ρ:** ~ solid **P:** up **to 1** Mbar

Intense beams of energetic heavy ions are an excellent tool to create and investigate extreme states of matter in reproducible experimental conditions

$$E_s = (1.6 \cdot 10^{-19}) \cdot \frac{dE/\rho dx}{\pi \cdot r^2} \cdot N \, [J/g]$$



$$dE/dx \sim -\rho \frac{Z_{эф}^2}{E_i} \ln \Lambda$$

Intense Heavy Ion Beams

large volume of sample (N mm3)
fairly uniform physical conditions
high entropy @ high densities
extended life time

HI : high entropy states of matter - without shocks !

Intense particle beams are a novel, very efficient tool to study HEDP and WDM:

[N.A. Tahir et al. PRE 60 *(1999) 4715;*
PRE 61 *(2000) 1975; PRE* 62 *(2000) 1224; PRE* 63 *(2001) 016402;*
PRE 63 *(2001) 036407; PRB* 67 *(2003) 184101].*

Main Advantages of Ion Beams are:

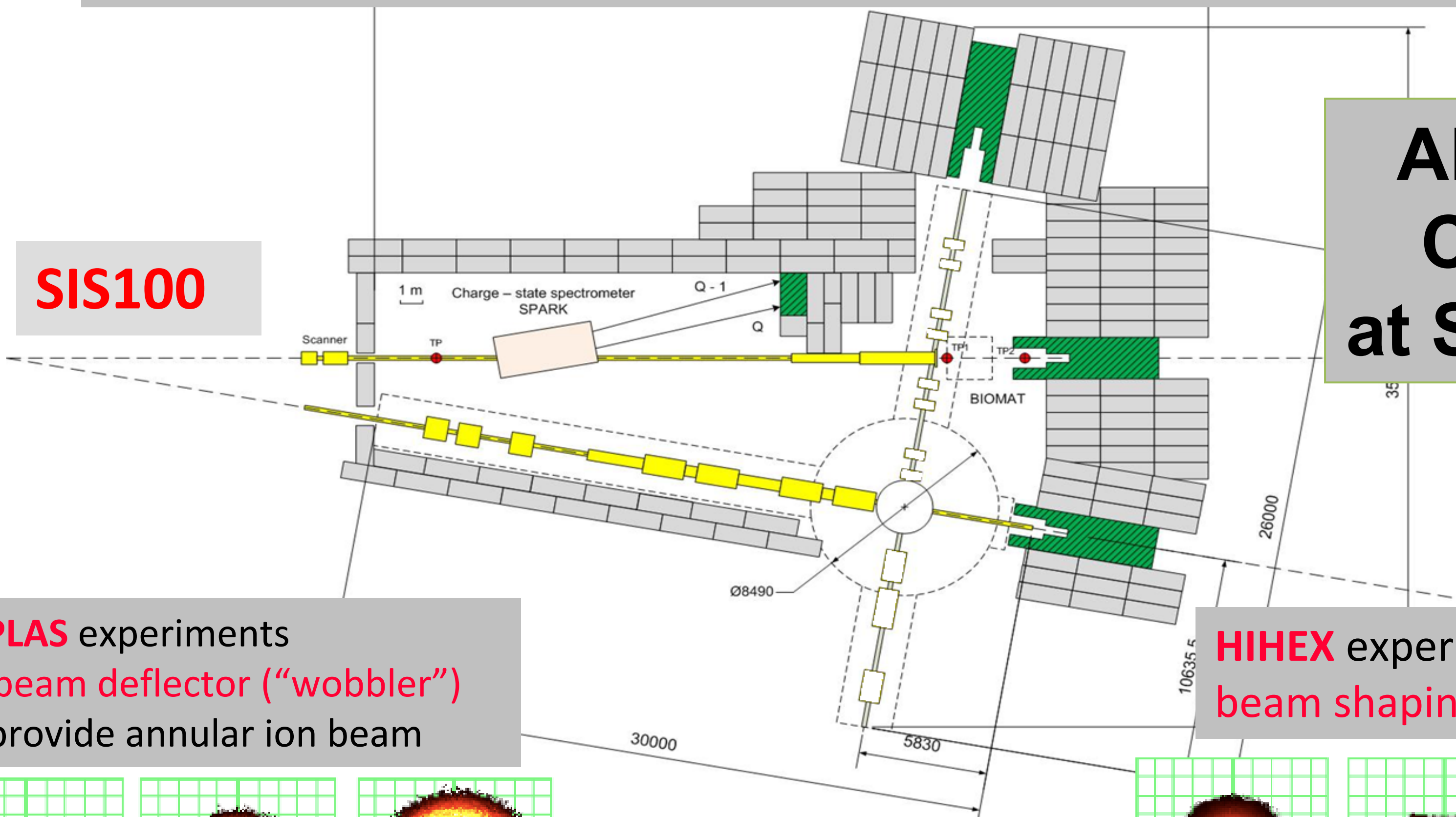
- High repetition rate, high coupling efficiency
- Large sample size [mm^3 cm^3]
- Fairly uniform physical conditions (no sharp gradients)
- Precise knowledge of energy deposition in the sample
- Long life times
- Any target material can be used
- Unrivaled flexibility (Generate HED matter by isochoric heating as well as by shock compression)

Plasma Physics beam line at SIS100

SIS-100: One beam line with replaceable elements:

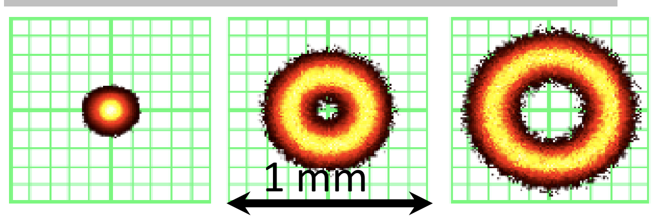
SIS100

APPA Cave at SIS100

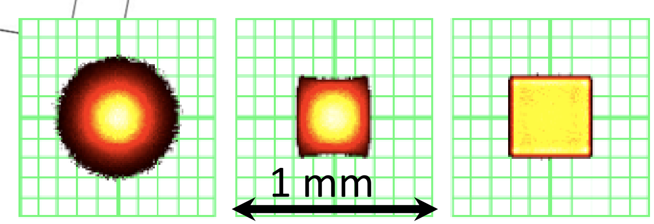


LAPLAS experiments
RF beam deflector ("wobbler")
to provide annular ion beam

HIHEX experiments
beam shaping system



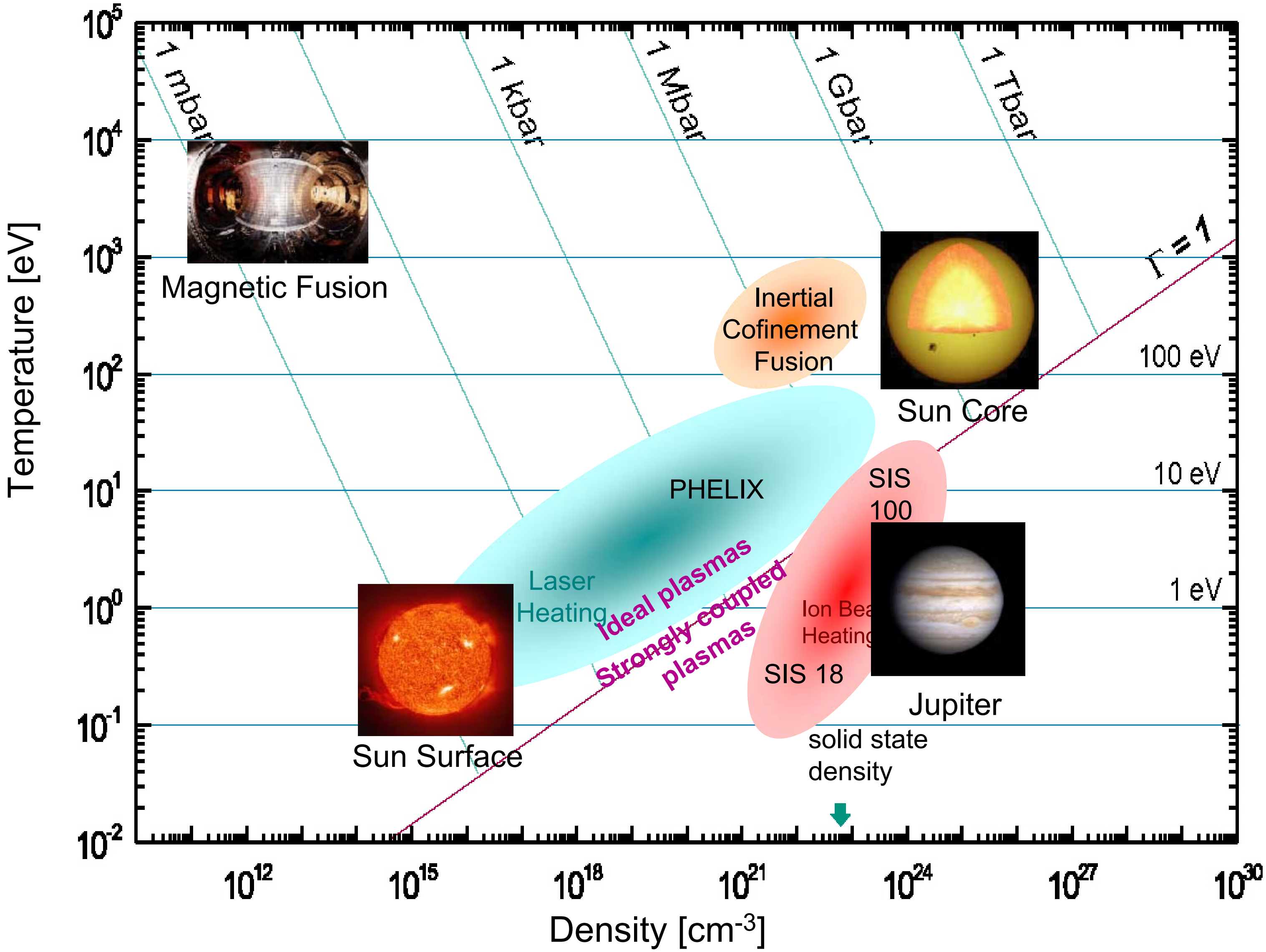
Transverse distributions of beam intensity at focal plane for LAPLAS



Transverse distributions of beam intensity at focal plane for HIHEX

Plasma Physics with highly Bunched Beams

Bulk matter at very high pressures, densities, and temperatures



Perspectives of HED-experiments at FAIR

Up to **200 times** the beam power and **100 times** higher energy density in the target will be available at FAIR

Ion beam U^{28+}	SIS-18	SIS-100	
Energy/ion	400MeV/u	0.4-27 GeV/u	
Number of ions	4.10^{9} ions	5.10^{11} ions	X100
Full energy	0.06 kJ	6 kJ	
Beam duration	130 ns	50 ns	
Beam power	0.5 GW	0.1TW	X200

Lead Target

Specific energy	1 kJ/g	100 kJ/g	X100
Specific power	5 GW/g	1 TW/g	X200
WDM temperature	~ 1 eV	10-20 eV	

only available at FAIR

Plasma Physics

- Interior of massive planets like Jupiter

  ..do we understand the interior of planets?

- Warm and dense plasmas

  ...Equation of State, transport properties, etc.,

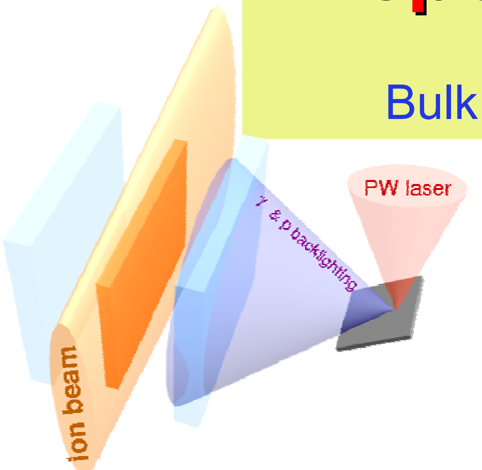
- Energy production through Inertial Confinement Fusion:

  ..do we understand the basic physics problems?

Proposed experiments on Plasma Physics

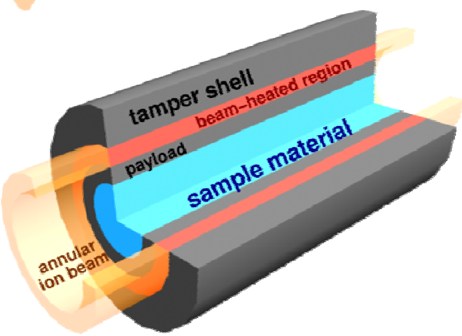
with highly Bunched Beams

Bulk matter at very high pressures, densities, and temperatures



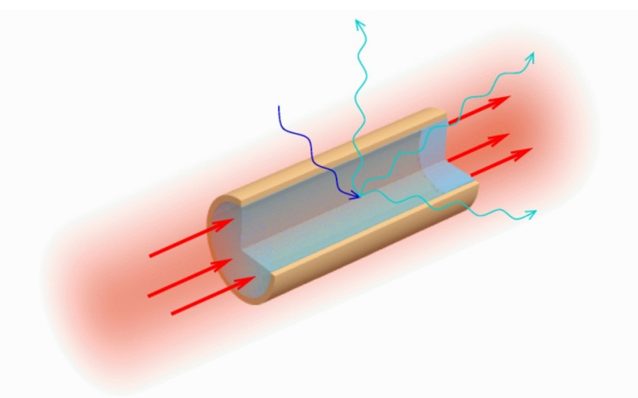
HIHEX: Heavy Ion Heating and Expansion

(HEDgeHOB)



LAPLAS: Laboratory Planetary Sciences

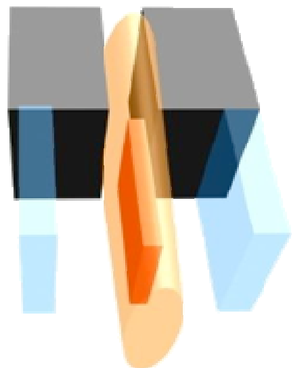
(HEDgeHOB)



WDM: Warm Dense Matter

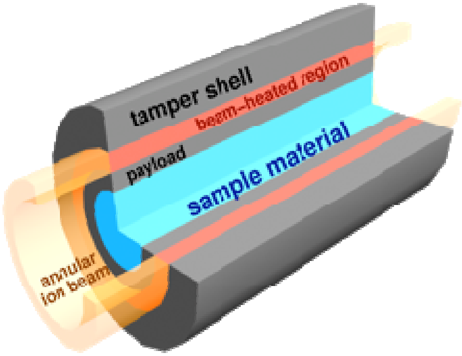
High Energy Density experiments of HEDgeHOB collaboration

HIHEX
Heavy Ion Heating and Expansion



- uniform quasi-isochoric heating of a large-volume dense target, isentropic expansion in 1D plane or cylindrical geometry

LAPLAS
Laboratory Planetary Sciences



- hollow (ring-shaped) beam heats a heavy tamper shell cylindrical implosion and low-entropy compression

Numerous high-entropy HED states:
EOS and transport properties of e.g., non-ideal plasmas, WDM and critical point regions for various materials

Mbar pressures @ moderate temperatures:
high-density HED states, e.g. hydrogen metallization problem, interior of Jupiter and Saturn