Accelerator Needs from Nuclear Physics for next 50 years

Boris Sharkov

Nuclear physics investigates :

how the fundamental building blocks from the big-bang plasma combine to make nucleons and complex nuclei ?,

how the chemical elements are formed in astrophysical processes ?,

and how their interactions power the sun and the stars ?.

1. Experiments on Nuclear Physics need **beams** of primary and secondary particles

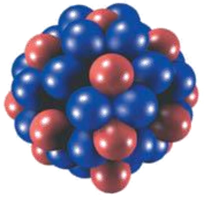
2. Nuclear scientists have pushed the boundaries of technologies with new accelerators, powerful computers and new detectors

3. Nuclear physics drives recent advances in accelerators:

- polarized and multi-charge state ion sources;
- beam cooling;
- superconducting radio-frequency acclererators for ions
- continuous wave (polarized) electron beams;
- superconducting cyclotrons;
- brilliant heavy-ion beams, up to maximum collision energies between heavy particles.

4 research frontiers of nuclear science :

1. Nuclear Structure and Nuclear Astrophysics



2. Compressed Barionic Matter

3. Hadron Physics (QCD)

4. Fundamental Symmetries and Neutrinos

…**having different needs**

1. Nuclear Structure and Nuclear Astrophysics

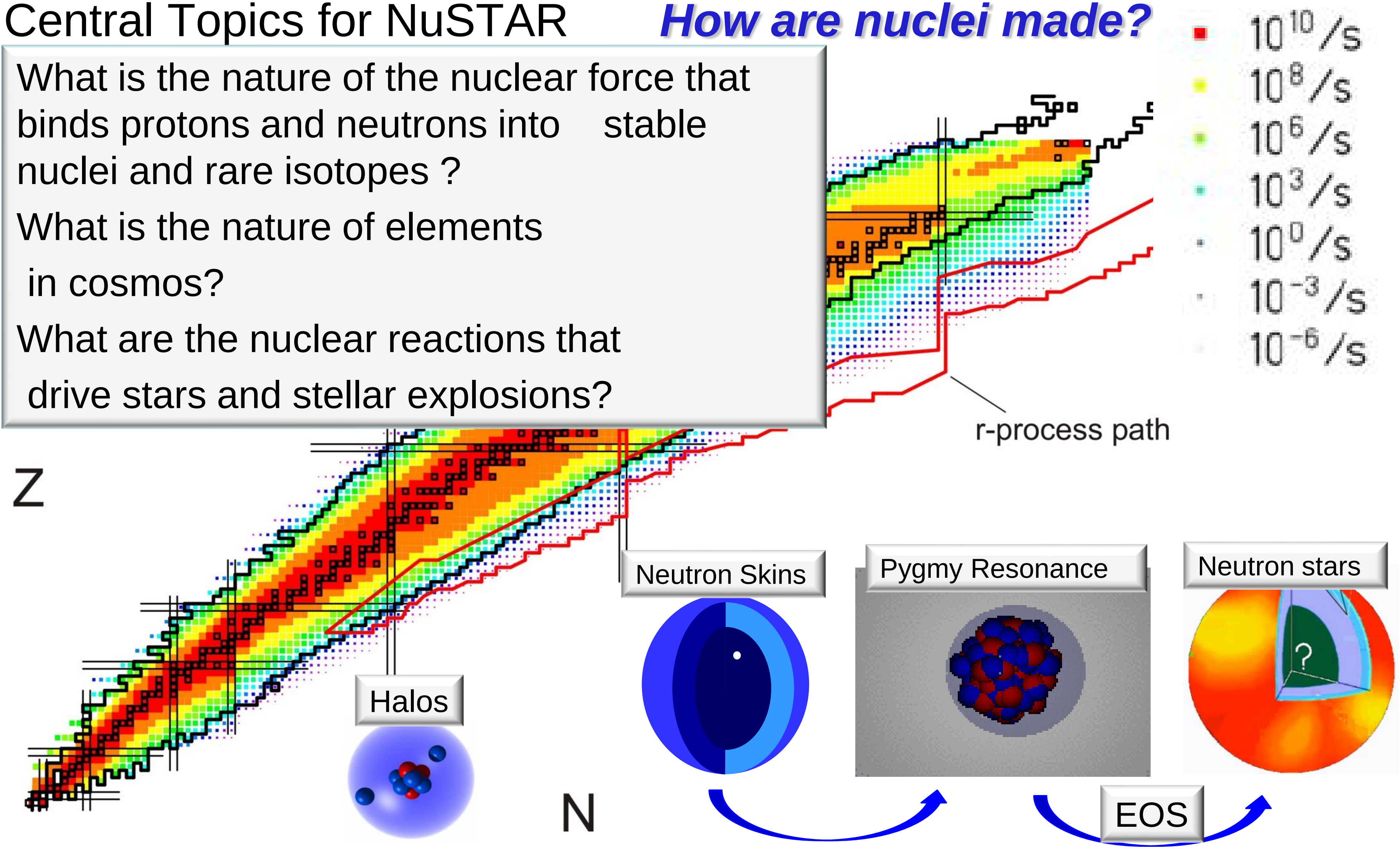
Central Topics for NuSTAR

How are nuclei made?

What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes ?

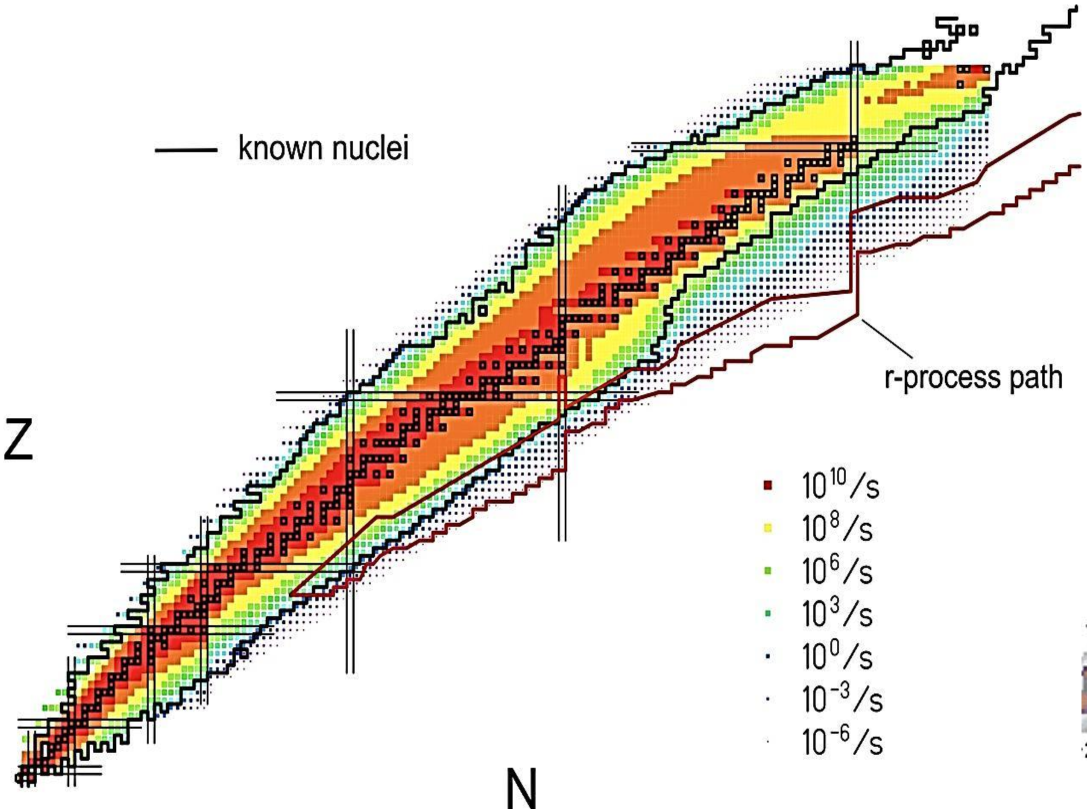
What is the nature of elements in cosmos?

What are the nuclear reactions that drive stars and stellar explosions?

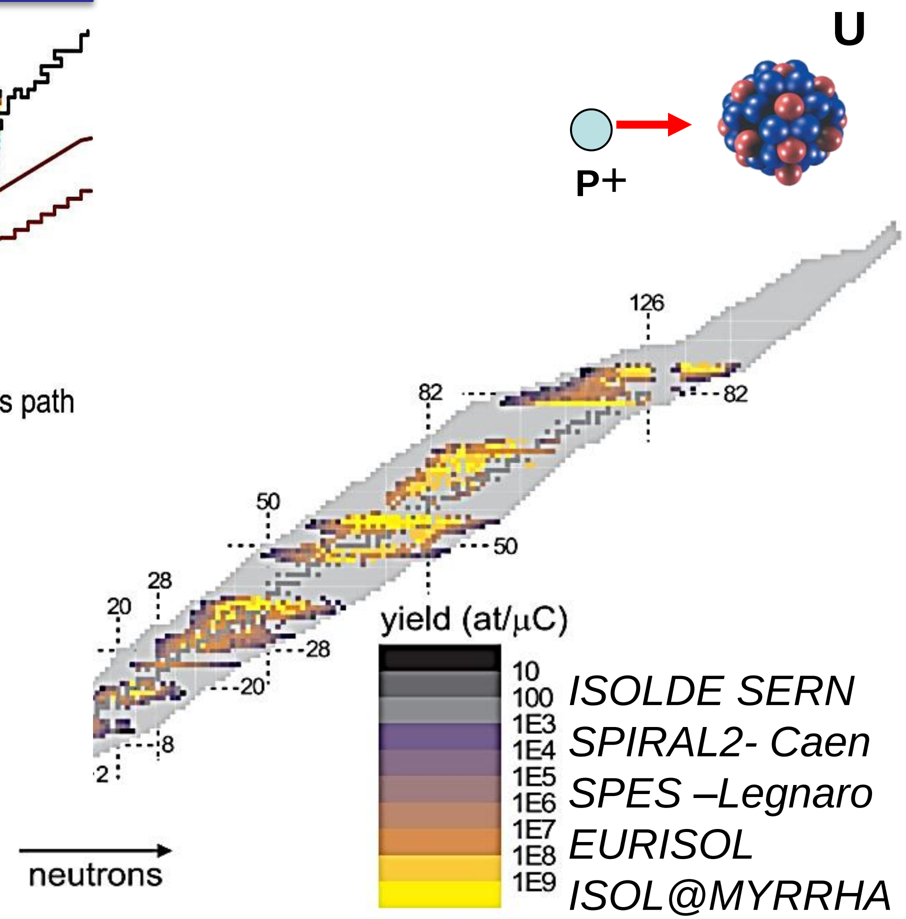


In-flight Fragmentation (separation) vs *ISOL* Facilities

NuSTAR @ FAIR



FRS GSI
BigRIPS RIKEN
Super-FRS FAIR
FRIB MSU

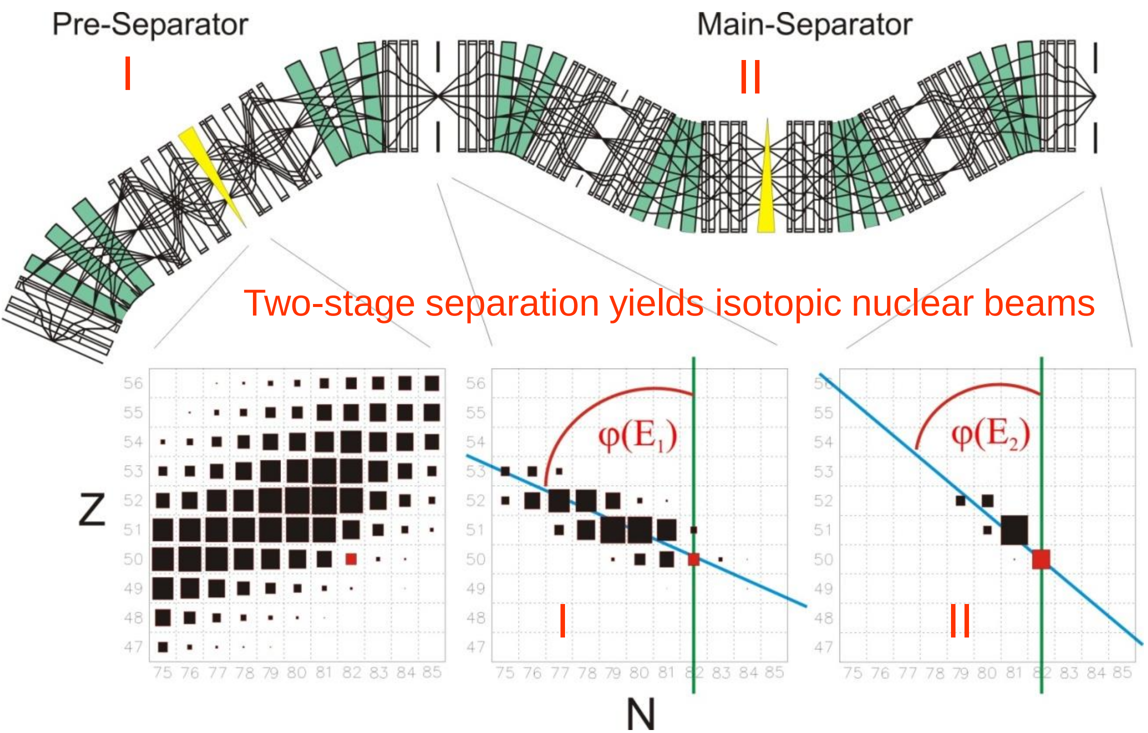


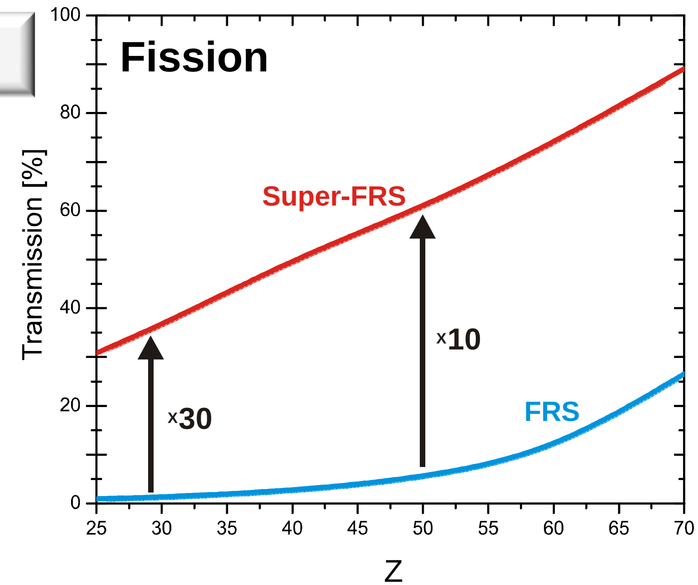
ISOLDE SERN
SPIRAL2- Caen
SPES –Legnaro
EURISOL
ISOL@MYRRHA

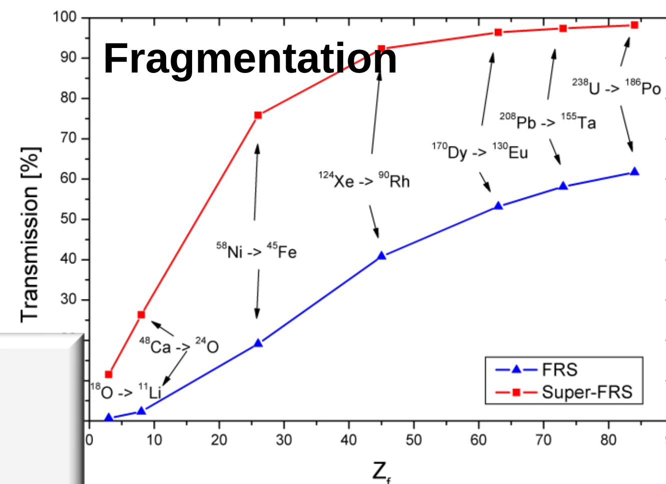
HIE-ISOLDE @ CERN   1.4 GeV p+

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 transmission gain relative to FRS**

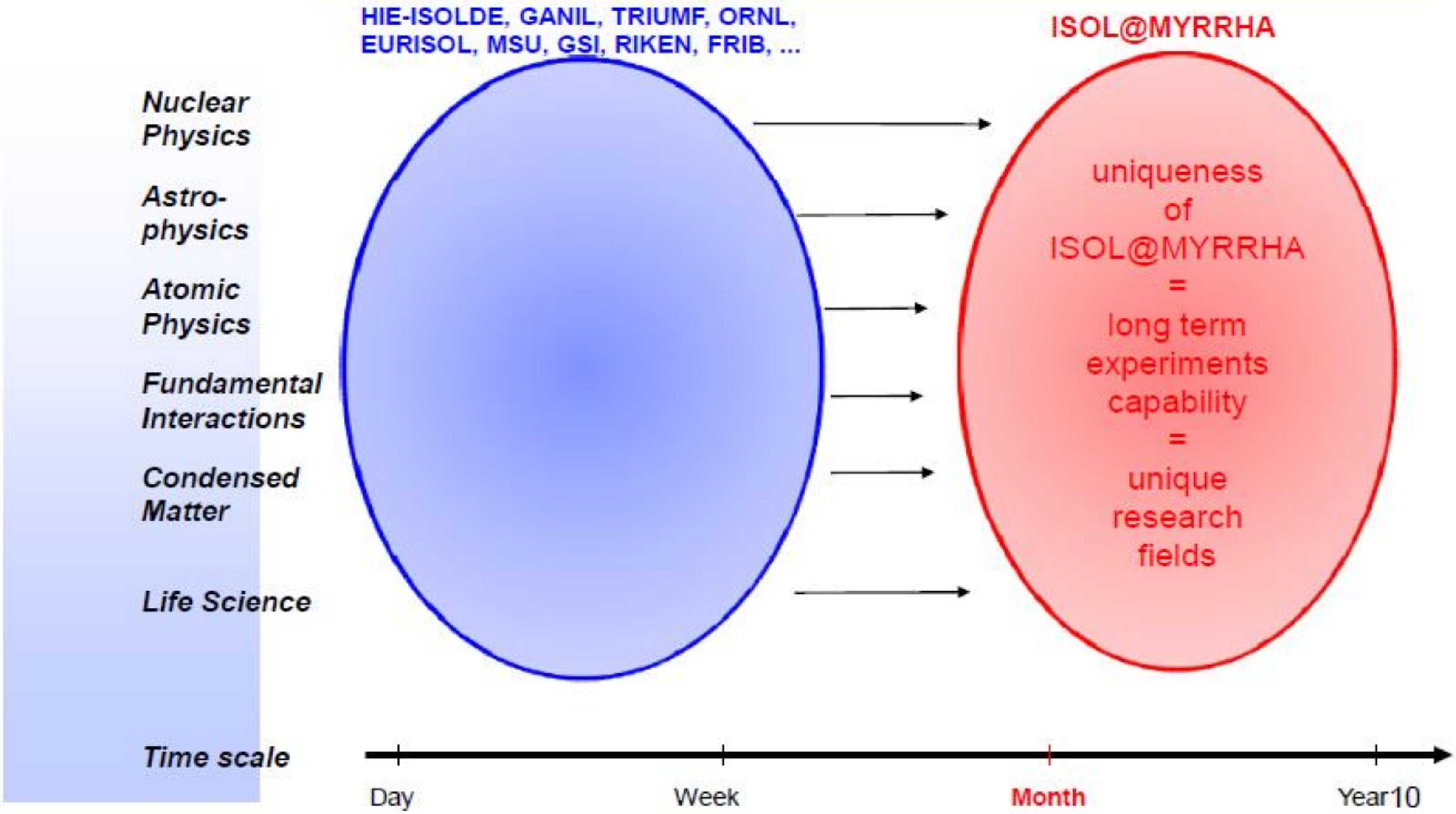
The field of high-intensity accelerators benefits strongly from synergies between

radioactive beam production, studies of ADS subcritical reactor systems, the International Fusion Materials Irradiation Facility - IFMIF, radiopharm isitope production and European Spallation Source - ESS project.

	particles	Peak power	Avarage power
Heavy Ion Fusion	Bi^{1+}	4000 MW (ms in linac)	50 MW
SNS (Oakridge) **ESS (Lund)**	P^{+}	30 MW (ms)	1.5 MW 5 MW
IFMIF	D^{+}	cw	5 kW
ADS **MYRRHA**	P^{+}	cw cw	10-40 MW 2.4 MW

SCK•CEN
STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

Unique Radioactive Ion Beam applications at ISOL@MYRRHA



ISOL @ MYRRHA

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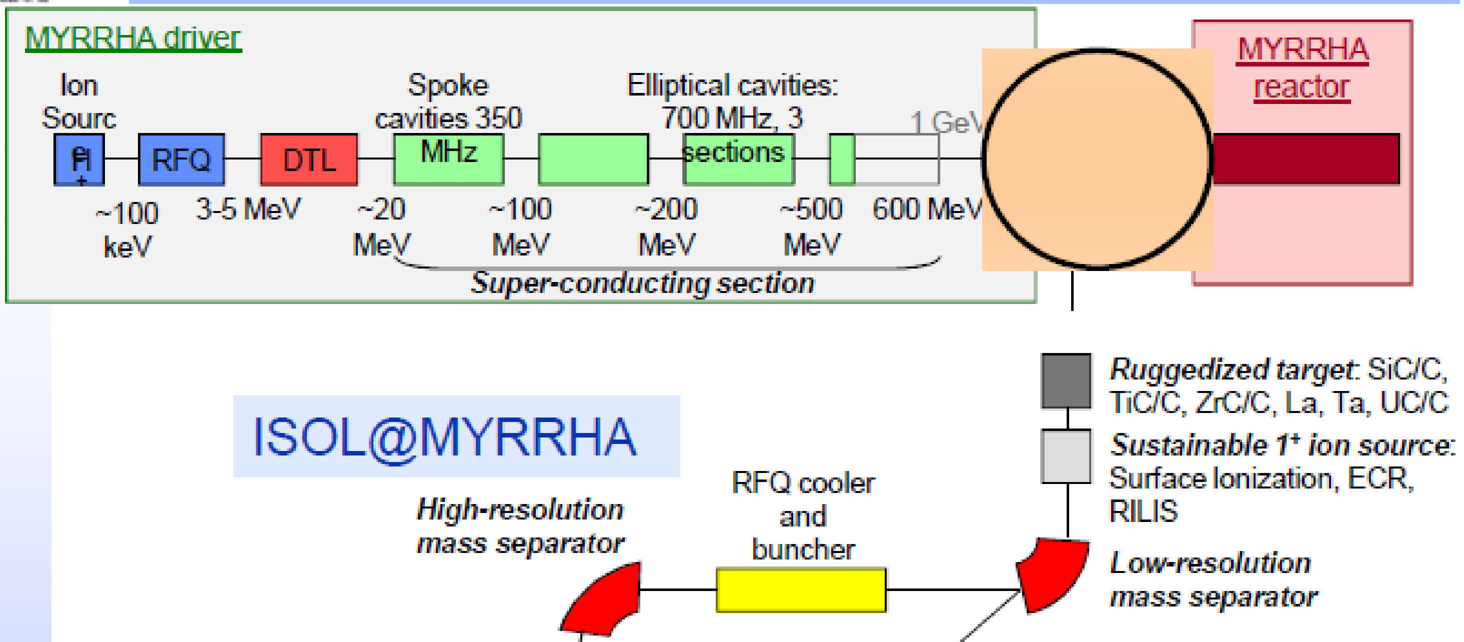
Serving the needs of accelerator-based scientific communities



experiments:

- nuclear physics
- condensed matter
- atomic physics
- fundamental Interactions
- life science (production of radioisotopes alpha emitters)

The major accelerator challenges for rare isotope beam facilities include:

1. high-intensity ion sourc

2. high-power supercondu
   accelerators for the inte

Primary HI Beams:

- $^{40}Ar^{18+}$ $2x10^{12}$/s @ 1 – 2 GeV/u
- $^{238}U^{28+}$: $5x10^{11}$/s @ 1 – 2 GeV/u

- $^{40}Ar^{18+}$ $2x10^{10}$/s @ 1 – 45 GeV/u
- $^{238}U^{92+}$: $1x10^{10}$/s @ 1 – 35 GeV/u

100 x 1000 times current intensity

3. high-power charge-state strippers target set-ups

   (*Targets and stripper systems that can withstand MW-levels of beam power are key for producing rare isotope beams,*

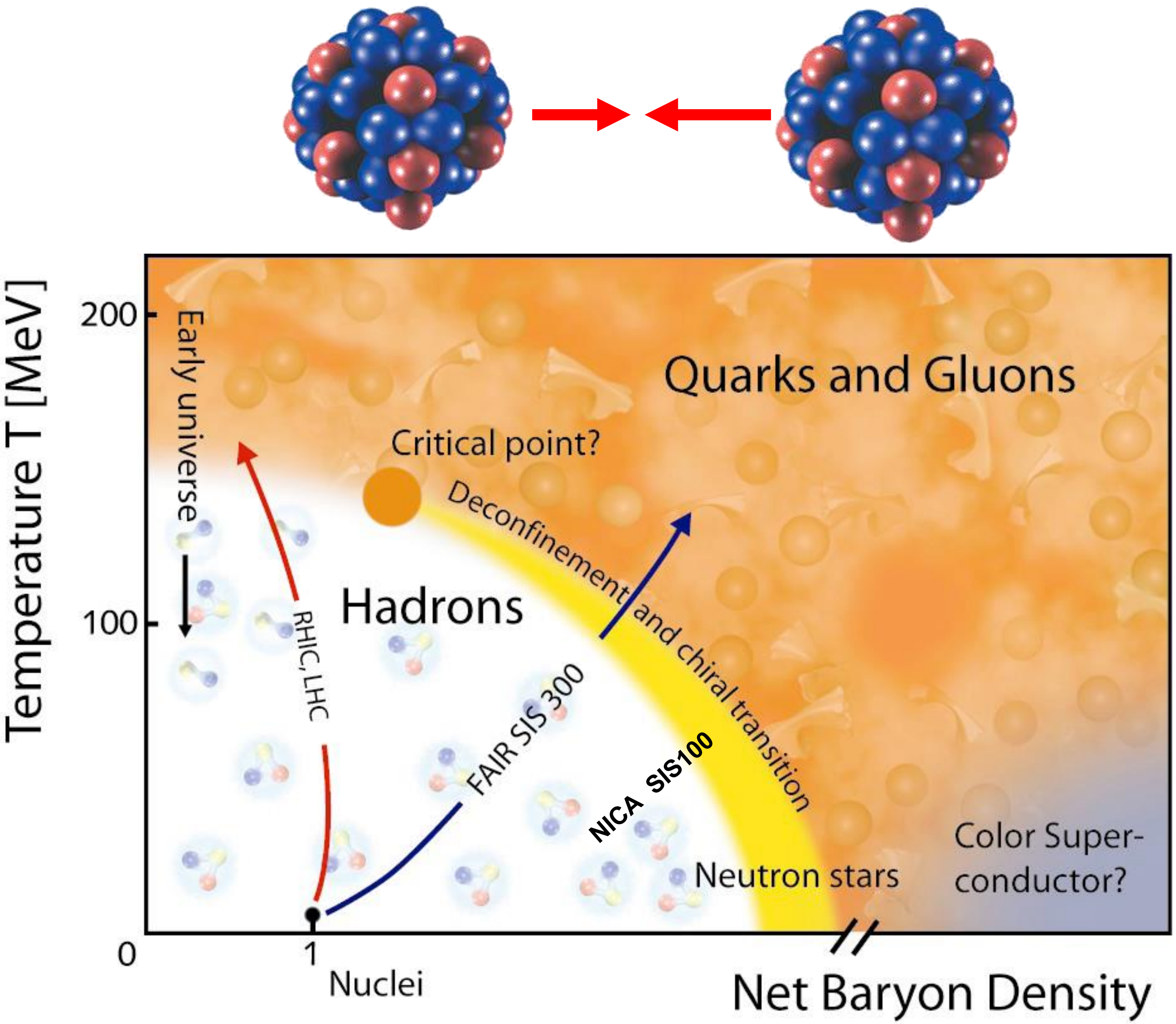
   (*generating intense neutron fluxes and beams of kaons, muons and neutrinos).*

   Technical challenges include thermal management, radiation and thermal shock of solid or liquid materials).

4. Secondary Beams:

- ➢ Broad range of radioactive ion beams up **to 2 GeV/u**
- ➢ **RI- Intensities up to 10 000 over present > 10E10 ions/s.**

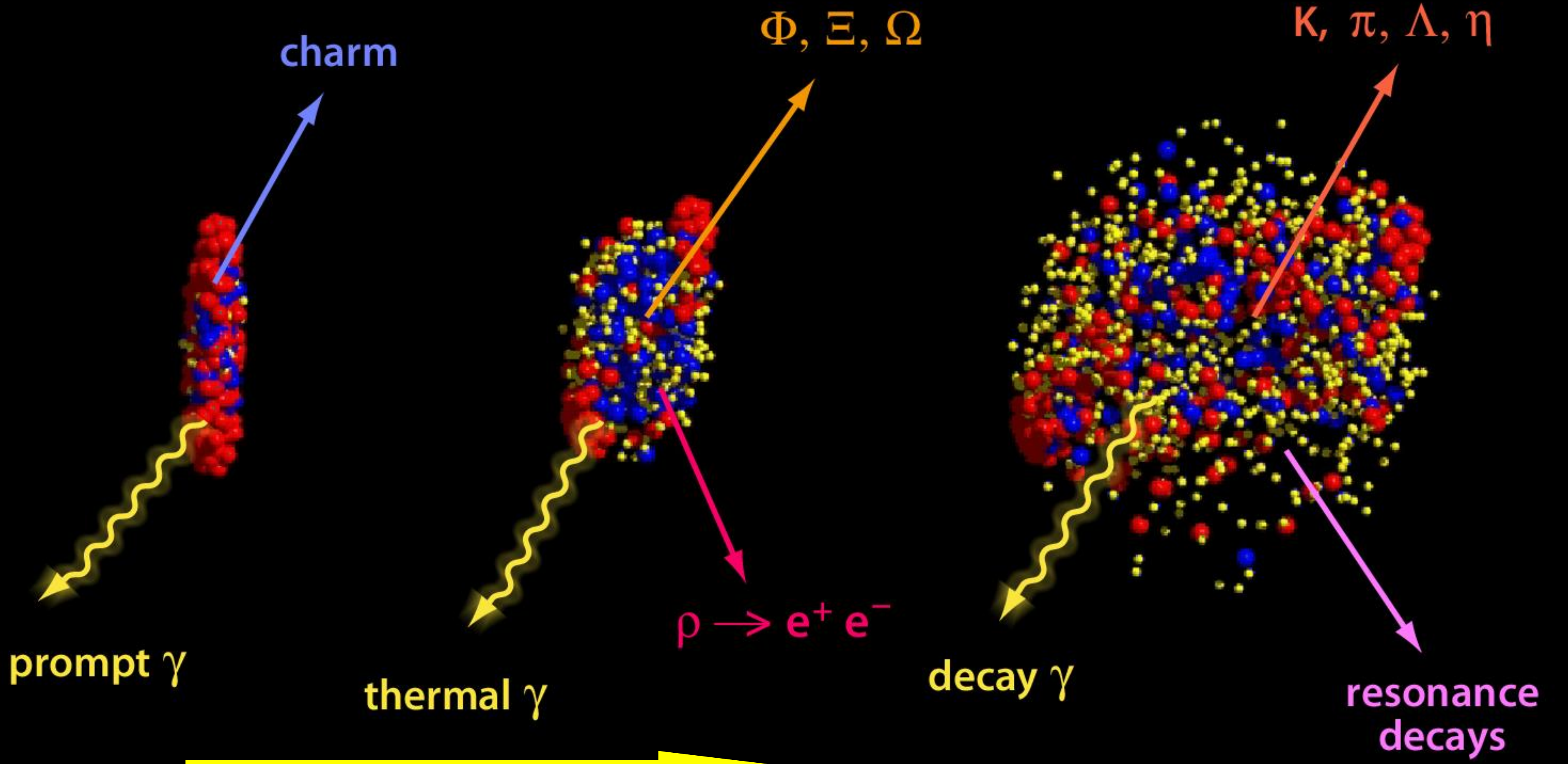
2. Compressed Barionic Matter



STAR@RHIC BNL
ALICE CERN
CBM @ FAIR
NPD NICA Dubna

Exploring phase diagram of nuclear matter

Probes of Dense Phase



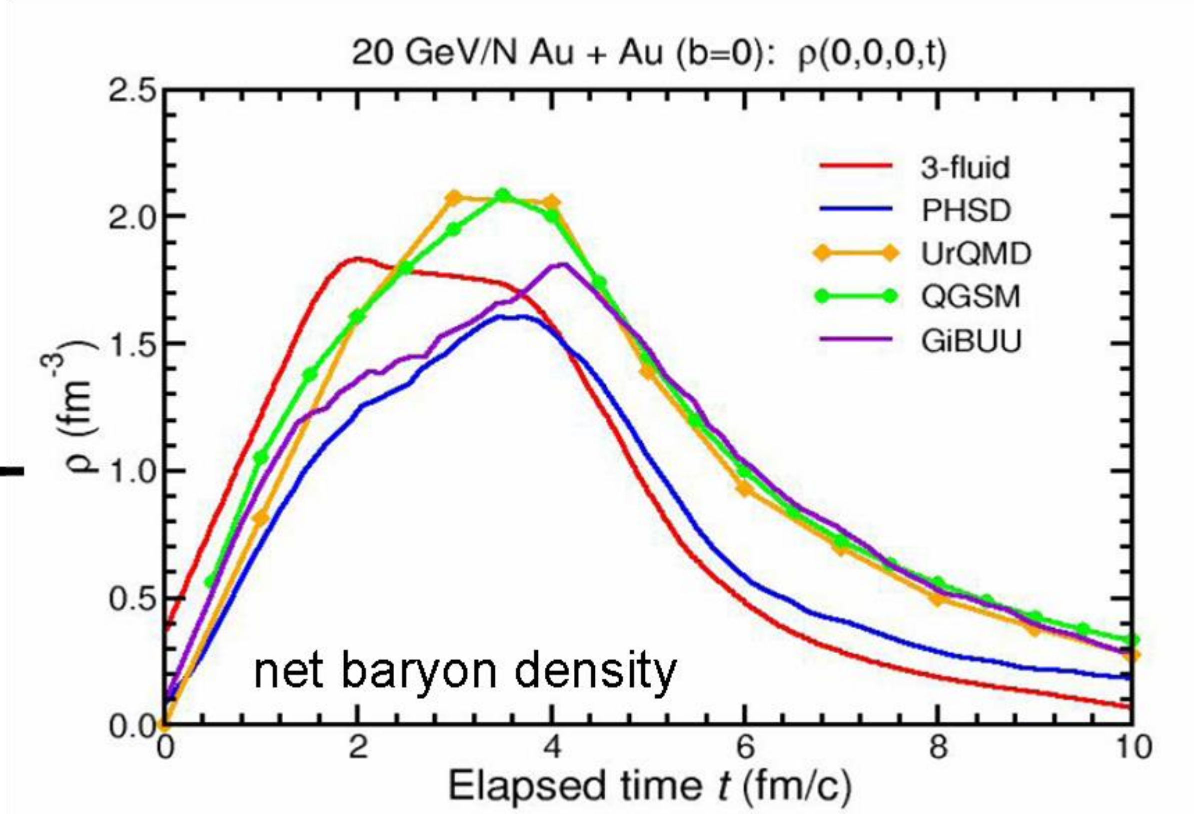
No data so far → FAIR Range

High Baryon Density @ **CBM**

- high baryon and energy densities created in central Au+Au collisions
- max. net baryon densities from 5 - 40 AGeV ~ 1 - 2 fm^{-3} ~ (6 – 12) ρ_0

ρ = 1 fm^{-3}

~ 6 times normal nuclear matter density

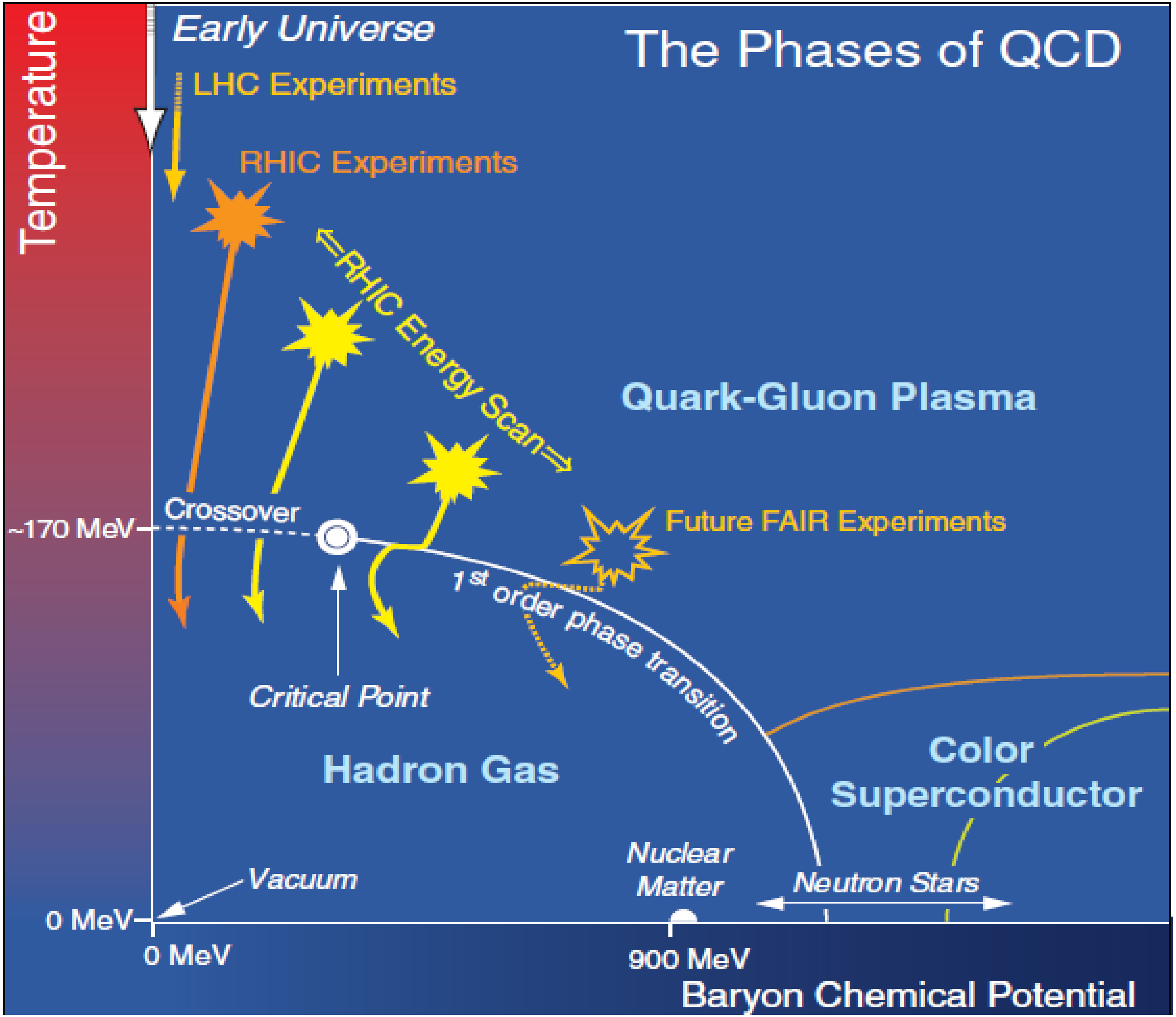


B. Sharkov 26 June 2012

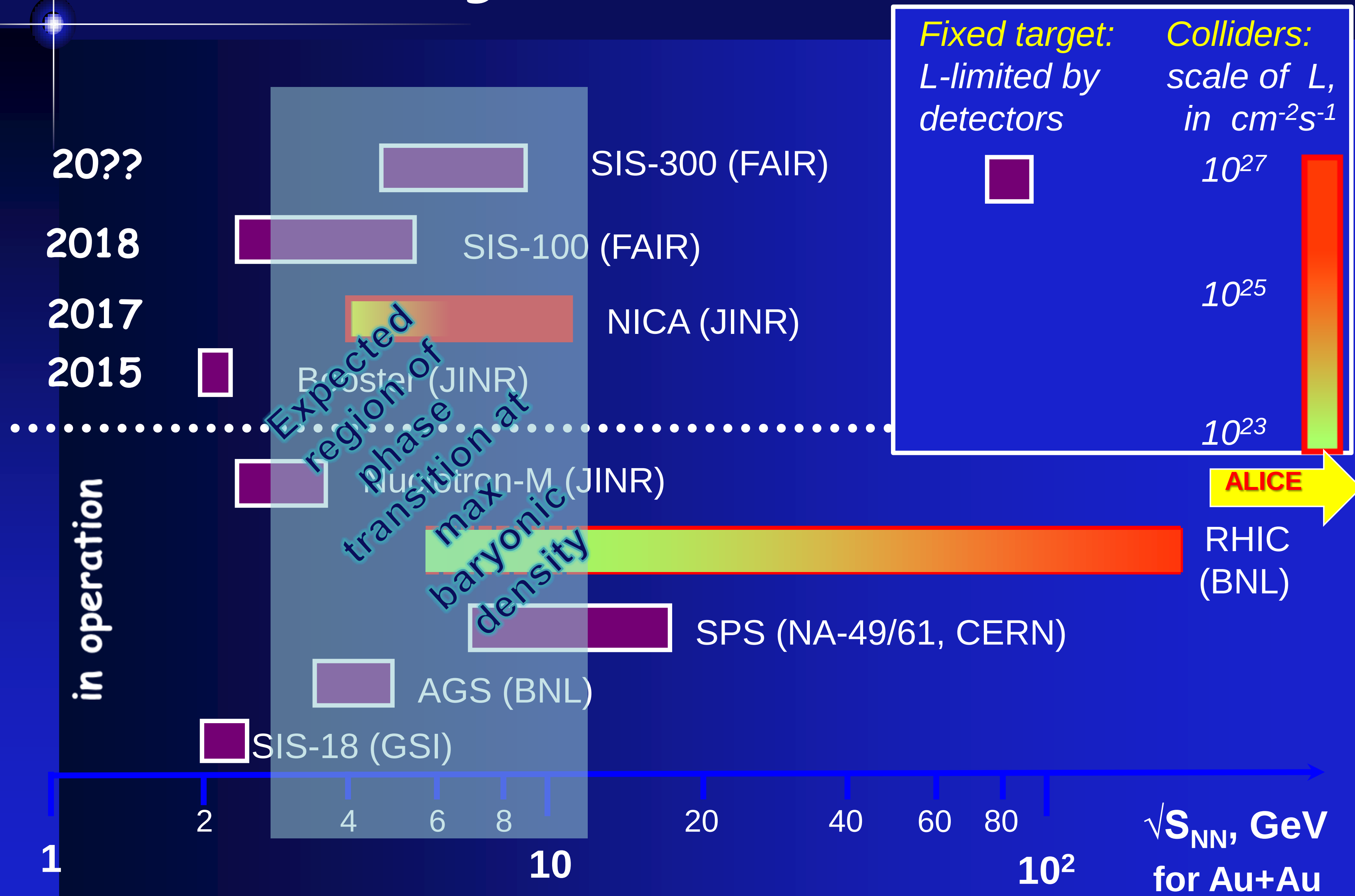
Experiments on superdense nuclear matter

Experiment	Energy range (Au/Pb)	Reaction rates (Hz)
STAR@RHIC (BNL)	$\sqrt{s_{NN}}$ = 7 – 200 GeV	1 – 800
NA61@SPS (CERN)	$\sqrt{s_{NN}}$= 6.4 – 17.4 GeV	80
MPD@NICA	$\sqrt{s_{NN}}$= 4.0 – 11.0 GeV	~6000
BM@Nuclotron	E_{kin}= 2.0 – 4.5 A GeV	10^5
CBM@FAIR	$\sqrt{s_{NN}}$= 2.7 – 8.3 GeV E_{kin}= 2.0 – 35 A GeV	$10^5 – 10^7$ 2 10E5 ALICE

Experiment	Observables (Au+Au at $\sqrt{s_{NN}}$ = 8 GeV)
STAR@RHIC (BNL)	Pions, kaons, protons, hyperons
NA61@SPS (CERN)	Pions, kaons, protons, hyperons
MPD@NICA	Pions, kaons, protons, gammas, (multi-strange) hyperons, electron pairs ?
CBM@FAIR	Pions, kaons, protons, gammas, (multi-strange) hyperons, electron pairs, open charm, charmonium

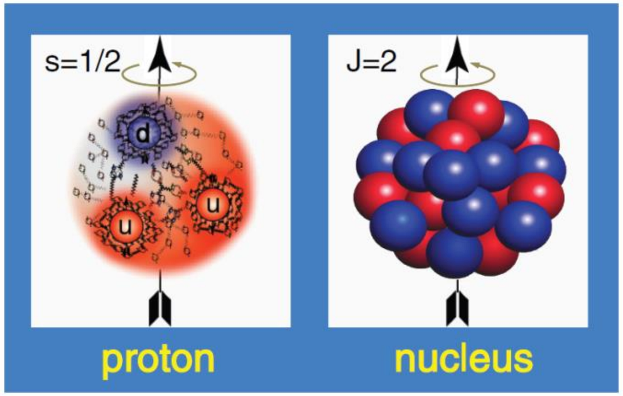

The Phases of QCD
Temperature
Early Universe
LHC Experiments
RHIC Experiments
⇐RHIC Energy Scan⇒
Quark-Gluon Plasma
Crossover
~170 MeV
Future FAIR Experiments
1 st order phase transition
Critical Point
Hadron Gas
Color
Superconductor
Nuclear
Matter
Neutron Stars
Vacuum
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

Existing and future facilities



3. Hadron Physics

1. explores the theory of the strong nuclear interaction, quantum chromodynamics, called QCD;
2. its implications and predictions for the matter in the early Universe;
3. quark confinement (the absence of free quarks);
4. the role of gluons;
5. the structure of the proton and neutron.

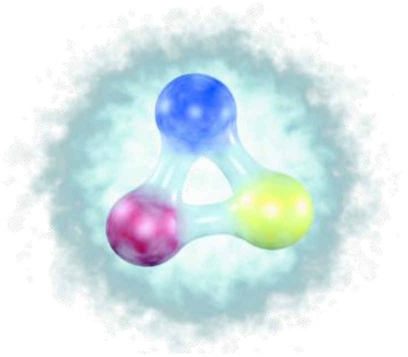


The role of the gluons, the carriers of the strong force, in determining the properties and structure of strongly interacting matter is the major focus for future research ***beyond*** TJNAF, RHIC, FAIR in nuclear physics.

3. Hadron Physics

Accelerators are used to probe the Hadrons with

P+	(COSY,HESR@FAIR)
P-	(HESR @ FAIR, J-parc)
π , K	(DAΦNE, J-parc)
γ	(ELI–NP)
e-	(CEBAF, HERMES, MAMI,
e+	DAΦNE, COMPASS, ELSA
μ	BELLE)



From such experiments one can obtain "snapshots" of the internal structure. Depending on energy of the projectile, such snapshots provide position or momentum distributions of the quarks inside hadron.

Hadron Physics community is discussing the need for a high-energy electron-ion collider as a gluon microscope.

Physics drives technical challenges rising complex requirements

1. For increased luminosity (L ~10E34 cm-2 s-1) techniques to cool high-energy hadrons (up to 40 GeV/u) are needed. (*coherent electron cooling and optical stochastic cooling are promising techniques* (BNL, FAIR).
2. Intense (> 50 mA, cw) sources of **polarized** electrons (~80%) and ions (~70%, p+, D+ 10E11/10μs) BNL, IHEP, JINR.

   (*Access to the spin degrees of freedom is essential for unraveling the underlying forces between colliding particles. These experiments require high brightness intense polarized electron, proton and light-ion sources*.)

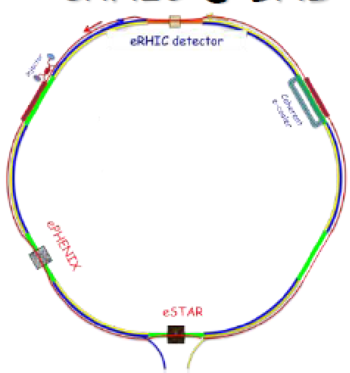
3. Development of high-intensity, high-brightness, multi-pass energy recovery linacs are of critical importance for the advancement of hadron and lepton-hadron colliders (*Energy recovery linacs would also provide the beams for the linac-ring option of high-luminosity electron-hadron colliders*)

Lepton/Nucleon colliders are considered as a decisive tool for hadron structure physics experiments, providing three-dimensional picture of the nucleon -

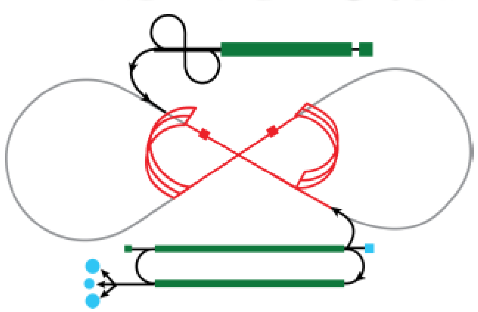
- a “gluon microscope” - **LHeC** highest resolution of hadron structure

EIC - staging at BNL and JLab

eRHIC @ BNL



MEIC / EIC @ JLab



	Stage I	Stage II
eRHIC @ BNL	$\sqrt{s}$ = 34 – 71 GeV E_e = 3 – 5 (10 ?) GeV E_p = 100 – 255 GeV E_{Pb} = up to 100 GeV/A	$\sqrt{s}$ = up to ~180 GeV E_e = up to ~30 GeV E_p = up to 275 GeV E_{Pb} = up to 110 GeV/A
MEIC / EIC @ JLab	$\sqrt{s}$ = 13 – 70 GeV E_e = 3 – 12 GeV E_p = 15 – 100 GeV E_{Pb} = up to 40 GeV/A	$\sqrt{s}$ = up to ~140 GeV E_e = up to 20 GeV E_p = up to at least 250 GeV E_{Pb} = up to at least 100 GeV/A
	(MEIC)	(EIC)

eRHIC is designed to collide electron beams with energies from 5- to 30-GeV[1] with hadrons, viz., either with heavy ions with energies from 50- to 130-GeV per nucleon, or with polarized protons with energies between 100- and 325-GeV. Accordingly, eRHIC will cover the C.M. energy range from 44.7- to 197.5-GeV for polarized e-p, and from 31.6- to 125-GeV for electron heavy-ion-collisions.

1. Bunch-intensity limits:
   a. For protons: $2\ 10^{11}$
   b. For Au ions: $1.2\ 10^{9}$
2. Electron-current limits:
   a. Polarized current: 50 mA
   b. Un-polarized current: 250 mA
3. Minimum $\beta^* = 5$ cm for all species
4. Space-charge tune shift for hadrons: $\leq$0.035
5. Proton (ion) beam-beam parameter: $\leq$0.015
6. Bunch length (with coherent electron-cooling):
   a. Protons: 8.3 cm at energies below 250 GeV, 4.9 cm at 325 GeV
   b. Au ions: 8.3 cm in all energy ranges
7. Synchrotron radiation intensity limit is defined as that of a 50 mA beam at 20 GeV
8. Collision rep-rate $\leq$ 50 MHz.

eRHIC, Phase I Luminosity

	e	p	$^{2}He^{3}$	$^{79}Au^{197}$	$^{92}U^{238}$
Energy, GeV	10	250	167	100	100
CM energy, GeV		100	82	63	63
Number of bunches/distance between bunches	107 nsec	111	111	111	111
Bunch intensity (nucleons) ,10^{11}	0.36	4	6	6	6
Bunch charge, nC	5.8	64	60	39	40
Beam current, mA	50	556	556	335	338
Normalized emittance of hadrons , 95% , mm mrad		1.2	1.2	1.2	1.2
Normalized emittance of electrons, rms, mm mrad		16	24	40	40
Polarization, %	80	70	70	none	none
rms bunch length, cm	0.2	5	5	5	5
β*, cm	5	5	5	5	5
Luminosity per nucleon, × 10^{34} $cm^{-2}s^{-1}$		2.7	2.7	1.6	1.7

Hourglass the pinch effects are included. Space charge effects are compensated.
Energy of electrons can be selected at any desirable value at or below 10 GeV
The luminosity does not depend on the electron beam energy.
The luminosity is proportional to the hadron beam energy: $L \sim E_h/E_{top}$

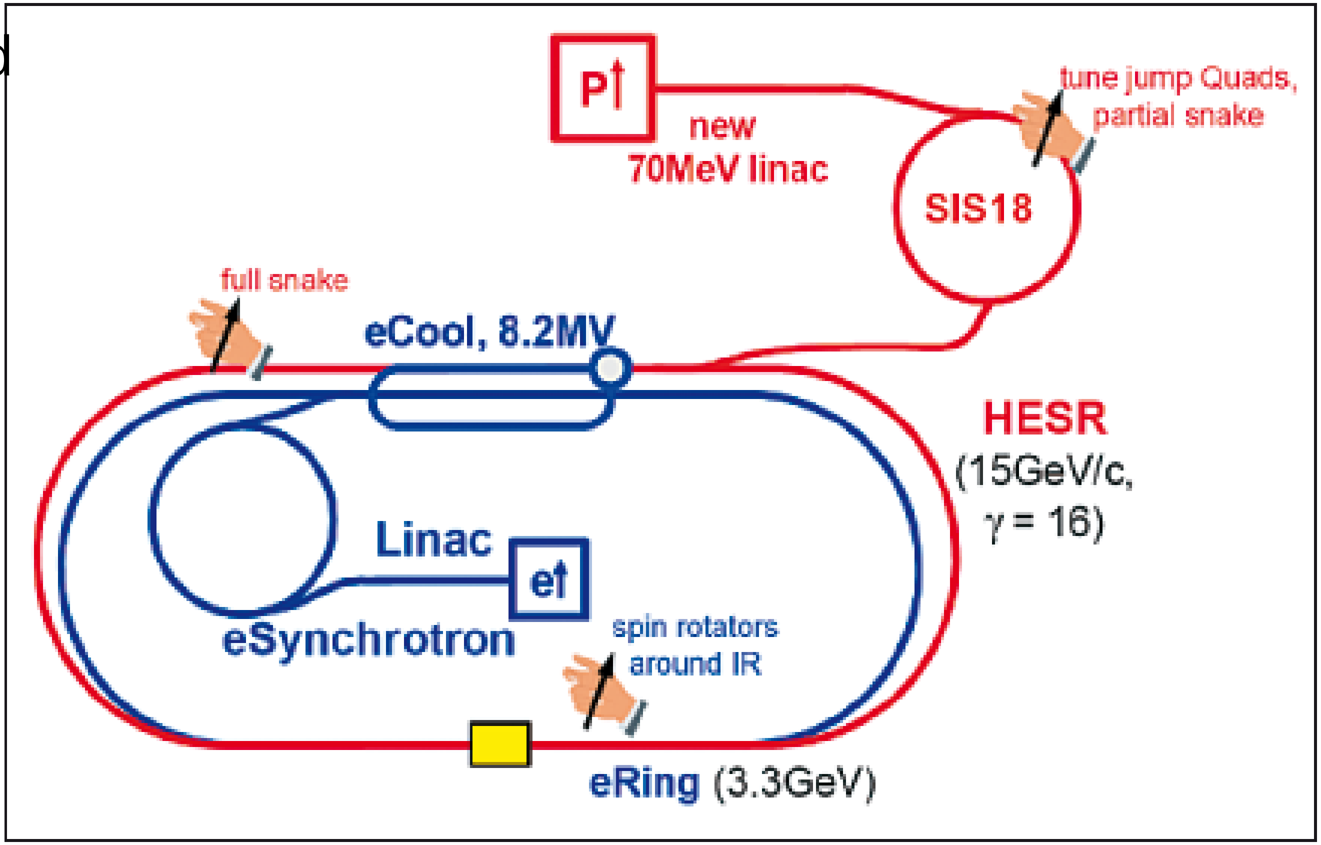
ENC at FAIR, Darmstadt

e-, P and D, polarized

up to 80% ↑

CM E = 14GeV

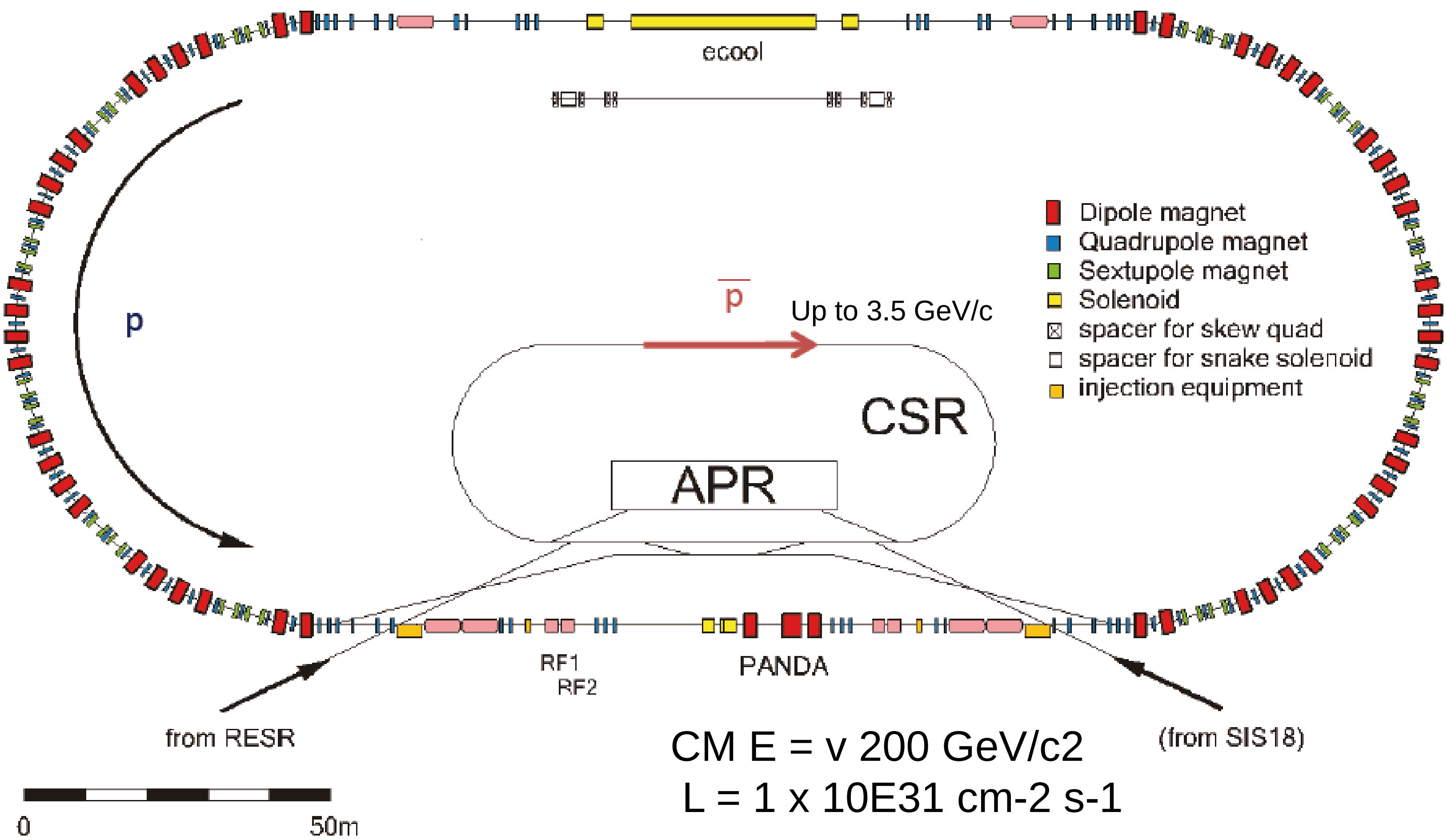
L = 10E32 cm-2 s-1



Layout of ENC@FAIR.

PAX at FAIR, (FZJ)

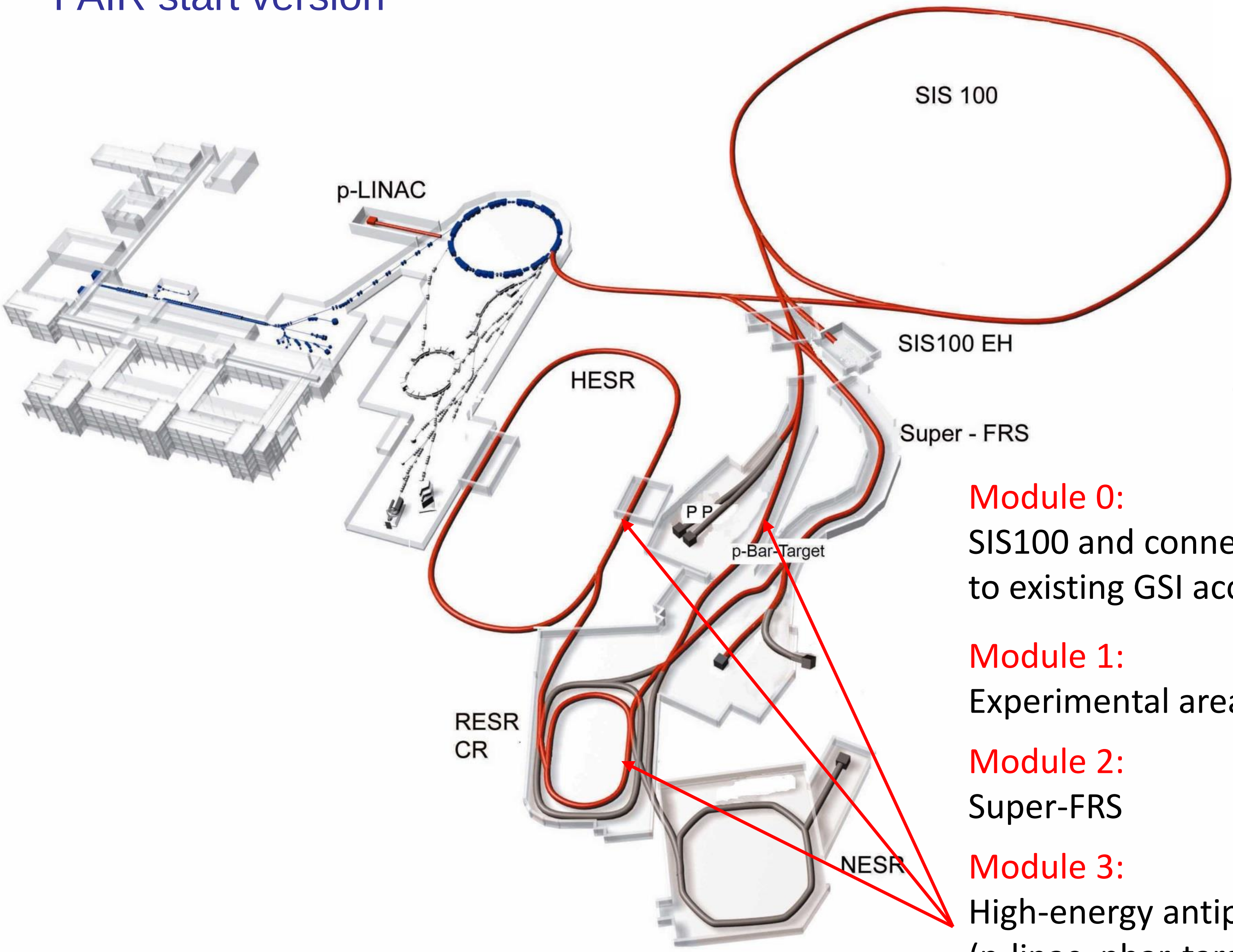
Proposed accelerator layout to convert the HESR into a double-polarised proton-antiproton collider. Polarised antiprotons are produced in the Antiproton Polariser Ring (APR) and then injected in the (COSY-like) Cooler Synchrotron Ring (CSR). Polarised protons will circulate in the HESR.



CM E = v 200 GeV/c2

L = 1 x 10E31 cm-2 s-1

FAIR start version



Module 0:
SIS100 and connection to existing GSI accel.

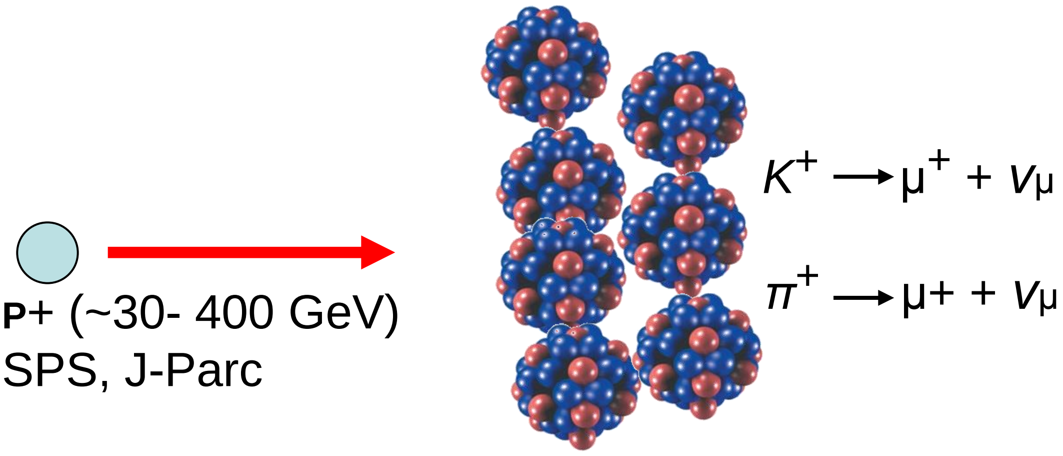
Module 1:
Experimental areas

Module 2:
Super-FRS

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

4. Fundamental Symmetries and Neutrinos

- What is the nature of Neutrinos, what are their masses?
- How neutrinos shaped the evolution of the Universe?
- Why is there now more visible matter than ani-matter in the Universe ?
- Nucleus as a target is used for generation of neutrinos

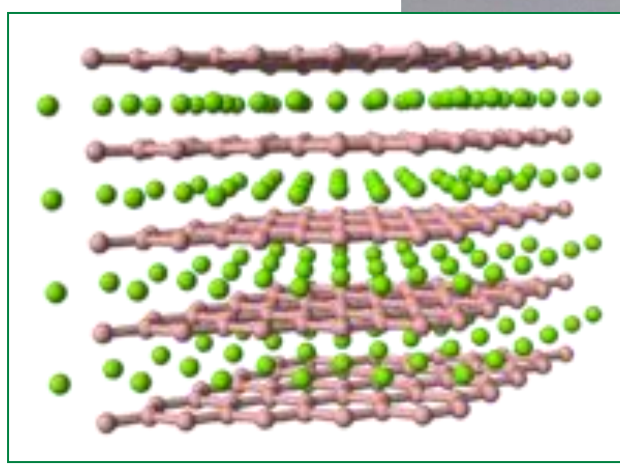


Summary : Nuclear Physics needs

Development of high-intensity, high-power, low-beam-loss, energy efficient SRF accelerators is a common thread for accelerators in nuclear science.

1. **high-intensity heavy ion sources** (ESR, KRION-M (JINR), LIS (ITEP));
2. **Intense (> 50 mA, cw) sources of polarized electrons (~80%) and ions (~70%, p+, D+ 10E11/10μs)** BNL, JINR, IHEP**. ERL!**
3. **high-power superconducting radio-frequency (SRF) accelerators for the intense primary production beams**;
4. **For increased luminosity (L ~10E34 cm-2 s-1) techniques to cool high-energy hadrons (up to 40 GeV/u) are needed (stohastic, e-, CeC) .**
5. **Targets and stripper systems** *(that can withstand megawatt-levels of beam power are key for producing rare isotope beams, generating intense neutron fluxes, secondary beams of kaons, muons and neutrinos).*

High Temperature Superconductivity
Transmit Electricity without losses

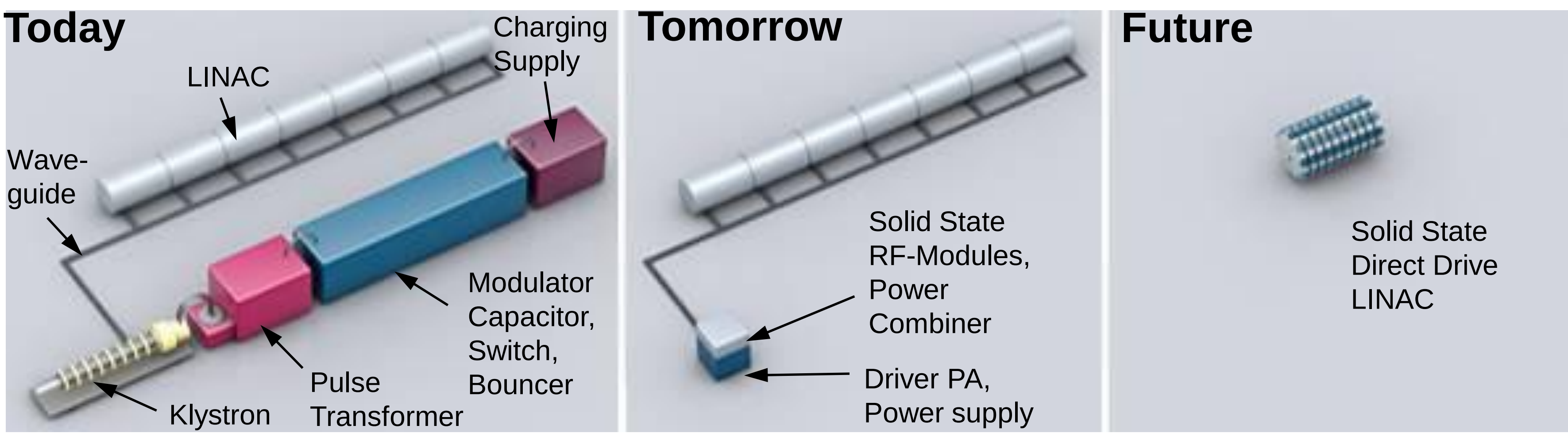


Magnesium boride

Solid State RF modules

SIEMENS
RESEARCH CENTER

- Electromagnetically coupled resonating cavities of traditional LINACs are driven by a single (or few) external RF power source connected via a waveguide and power couplers.
- **Traditional RF power sources (eg. Klystrons) can be replaced by high power SiC solid state RF-modules to enable compact system designs (70-700 MHz).**



O. Heid et al, Compact solid state direct drive RF linac, THPD002, IPAC'10, Kyoto, Japan

Back up slides

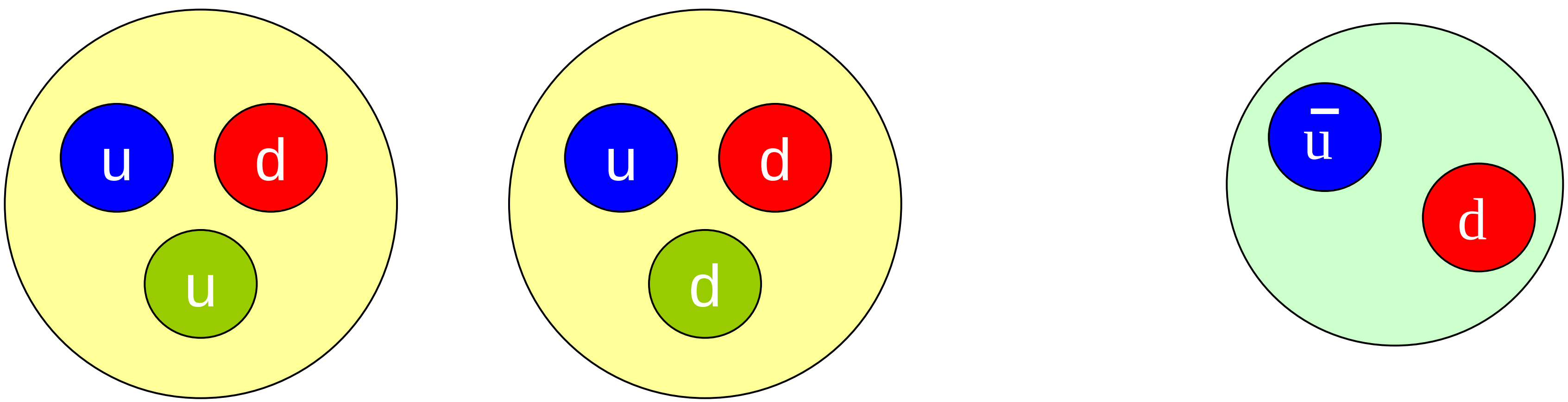
3. Hadron Physics

Brain Twister I : No free quarks observed. They are **confined** in pairs or triplets in strongly interacting particles (hadrons).

Proton (p)
938 MeV/c^2

Neutron (n)
939 MeV/c^2

π^-
140 MeV/c^2

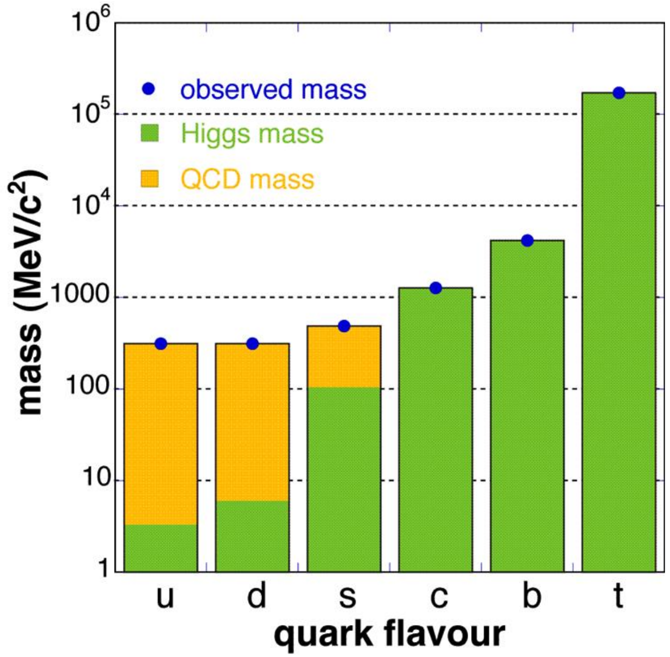


Baryons

Mesons

3. Hadron Physics

Brain Twister II : Normal (heavy) matter consists of pointlike, nearly massless quarks.



➢99% of the mass of the visible universe is, strictly speaking, **energy**!