JOINT INSTITUTE
FOR NUCLEAR RESEARCH
International Intergovernmental Organization

Fundamental Physics Challenges of the NICA Mission

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XV МЕЖДУНАРОДНЫЙ СЕМИНАР ПО ПРОБЛЕМАТИКЕ УСКОРИТЕЛЕЙ ЗАРЯЖЕННЫХ ЧАСТИЦ
памяти профессора В. П. Саранцева
16 сентября 2024 г.

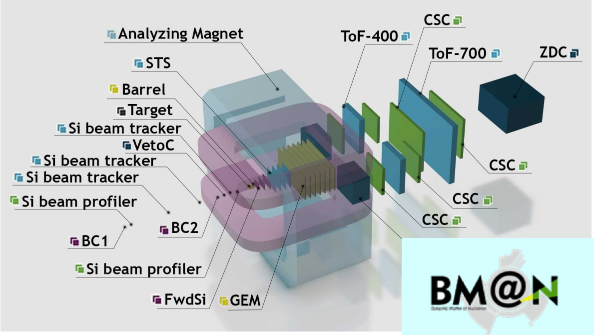
NICA

LHEP ЛФВЭ

Главные цели исследований NICA
Барионная материя экстремальной барионной плотности
Спиновая структура нуклона
Прикладные исследования

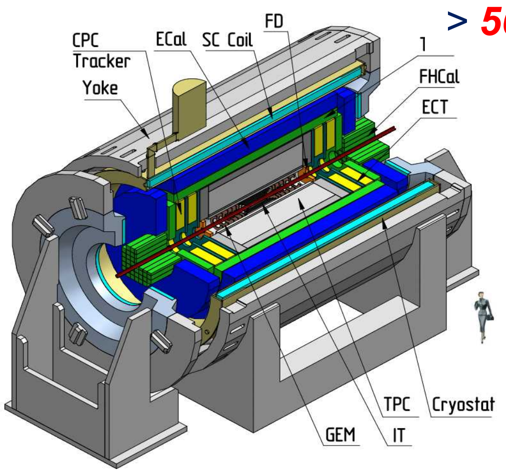
Baryonic **M**atter at **N**uclotron (**BM@N**) Collaboration:

*5 стран +**ОИЯИ**, **13** центров, >**220** участников*



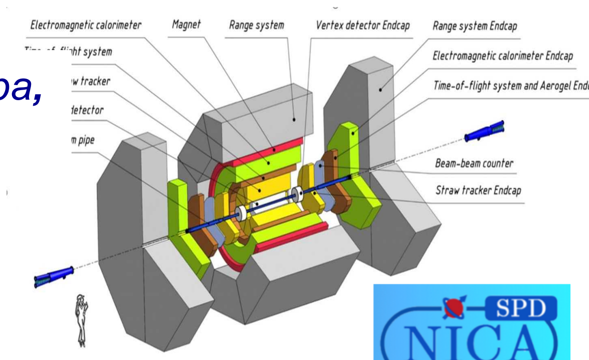
Multi **P**urpose **D**etector (**MPD**) Collaboration:

*11 стран + **ОИЯИ, 38** центров;*
*> **500** участников*



Spin **P**hysics **D**etector (**SPD**) Collaboration:

*14 стран +**ОИЯИ, 32** центра,*
*~ **300** участников*



Коллаборация **ARIADNA**

для прикладных и инновационных работ:
***20** центров, > **150** участников*

Nuclear matter

- **Normal nuclear matter density:**

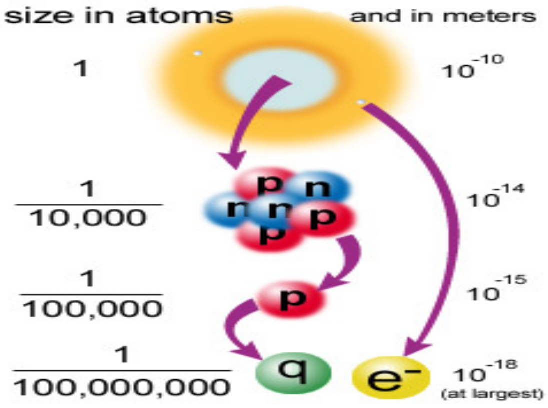
  $\rho = A / V_N \quad V_N = 4/3\, \pi\, R^3 \quad R = r_0 A^{1/3} \quad r_0 \sim 1.15$ fm

  $= 0.16$ nucleon/fm^3

  Normal nuclear matter energy density:

  $\varepsilon = A\, m_n / V_N \quad m_n = 0.94$ GeV

  $= 0.15$ GeV/fm^3



- **What does this mean in terms of compactness of the nucleus?**
- Fraction of the nuclear volume occupied by nucleons:

  $f = A\, v_n / V_N \quad v_n = 4/3\, \pi\, r_n^3 \quad r_n \sim 0.84$ fm (charge radius of the proton)

  ~ 0.38

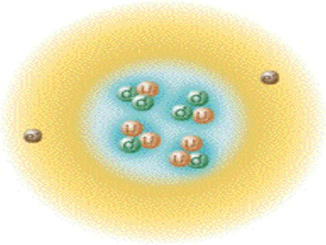
  → ~60% of the nuclear volume is empty!

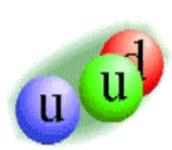
- Close packing condition $f = 1$:

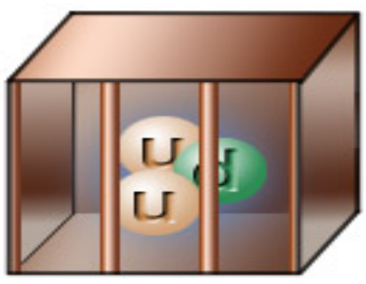
  $\rho \sim 0.4$ nucleon/fm^3

- QGP expected at a density ~10 times larger than the normal nuclear matter density:

  $\varepsilon \sim 2$ GeV/fm^3





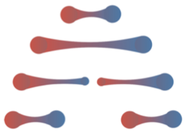


Deconfinement and Chiral Symmetry Restoration

QCD

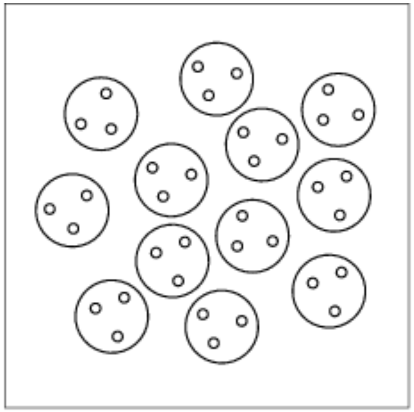
Color charges:

$V(r) = -\frac{\alpha}{r} + \sigma r$



$\approx \sigma r$ at large r

Long range → confinement
color insulator



QED

Electric charges:

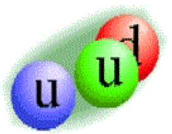
$$V(r) = \frac{e^2}{r}$$

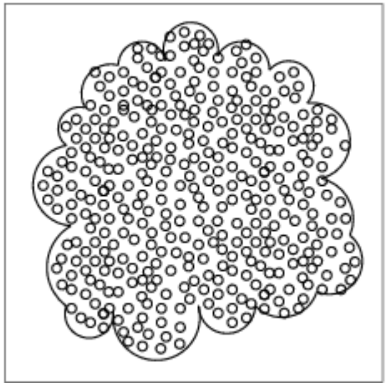
HIGH BARYON DENSITY

$V(r) \approx \sigma/\mu$ [1 - exp ($-\mu r$)]

Screening → Deconfinement
color conductor

Partons free to move over a volume >> hadron size.



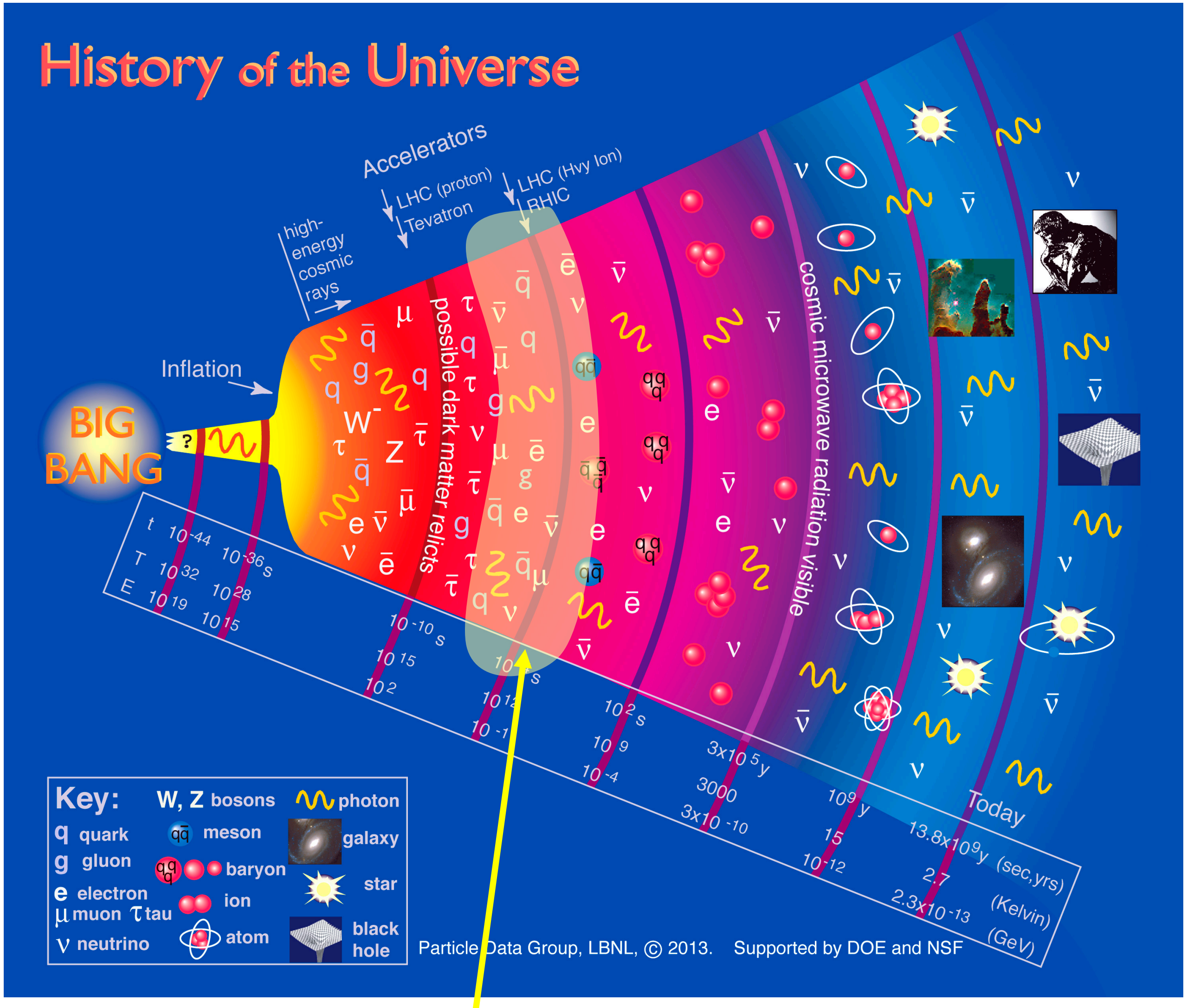


$$V(r) = \frac{e^2}{r}\exp(-\mu r)$$

$\mu = 1/ r_D$

r_D Debye screening radius

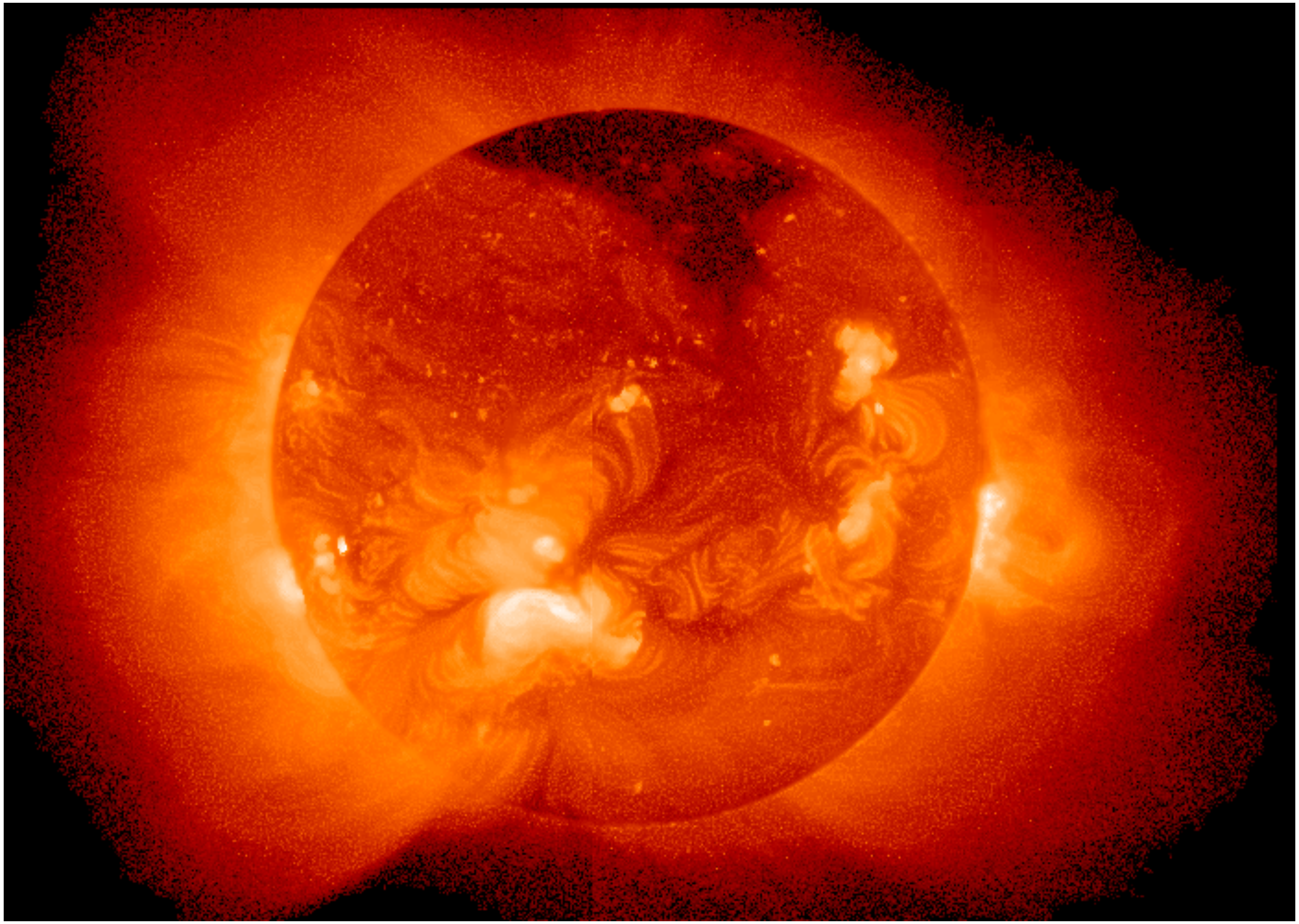
Primordial state of matter of the early Universe



Some ~10 μs after the Big Bang matter characterized by:

Temperature ~170 MeV (2.10^{12} K) and density ~1 GeV/fm^3 (10^{15} g/cm^3)

Temperature at the centre of the Sun ~ 15 000 000 K



A medium of 150-170 MeV is more than 100 000 times hotter !!!

Matter under extreme conditions

Main question : ***what are degrees of freedom in the state of Matter at exceedingly high density and temperature?***

solid → liquid → gas → plasma → nuclear matter (hadron gas) → QGP

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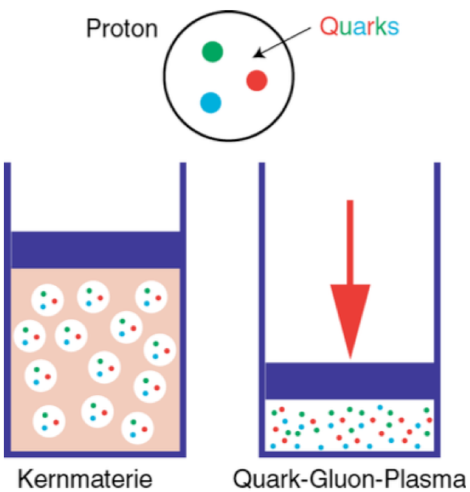
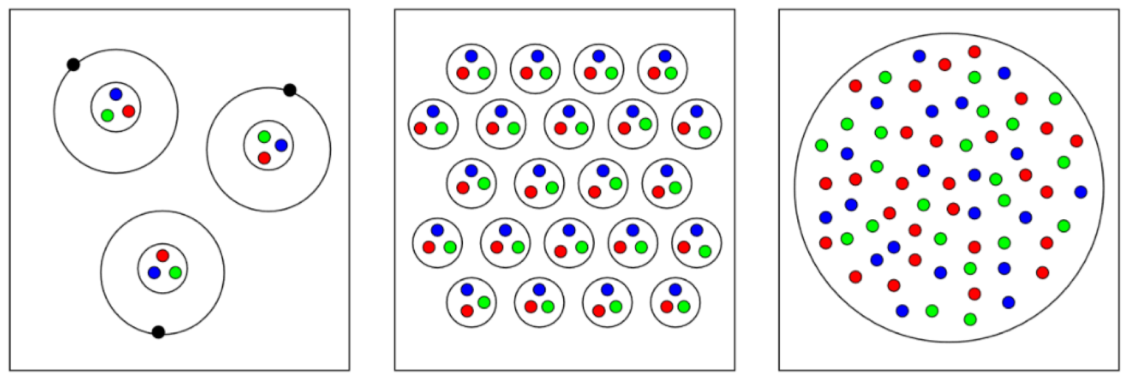
Can we "melt" hadrons by compression or/and increasing energy density?





(a) (b) (c)

a) Ordinary matter (proton+electron=hydrogen); b) Nuclear natter – nucleus;
b) c) Quark-gluon matter

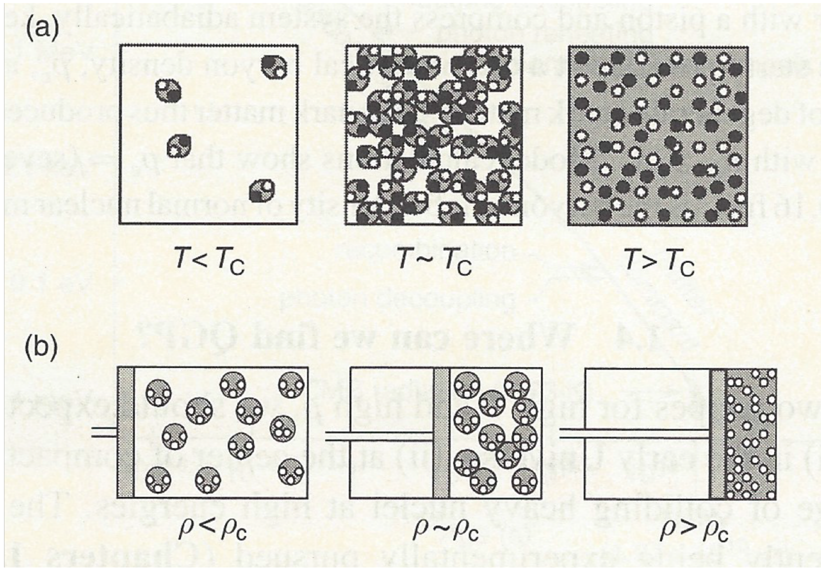
Bulk medium properties and its EOS are defined by interactions among degrees of freedom

Quark Matter formation

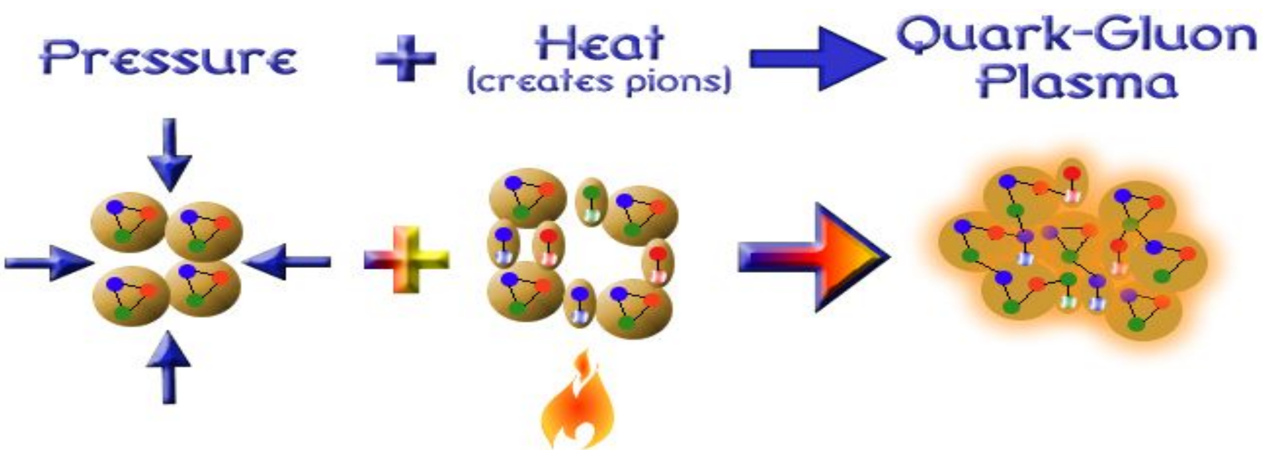
Two recipes:

(a) at high T - Early universe

(b) at high baryon density – Neutron stars



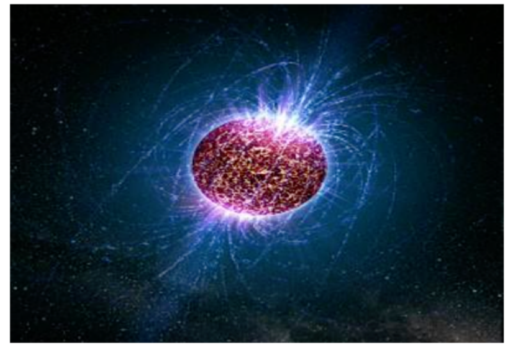
Relativistic heavy ion collisions - A combination of the two recipes



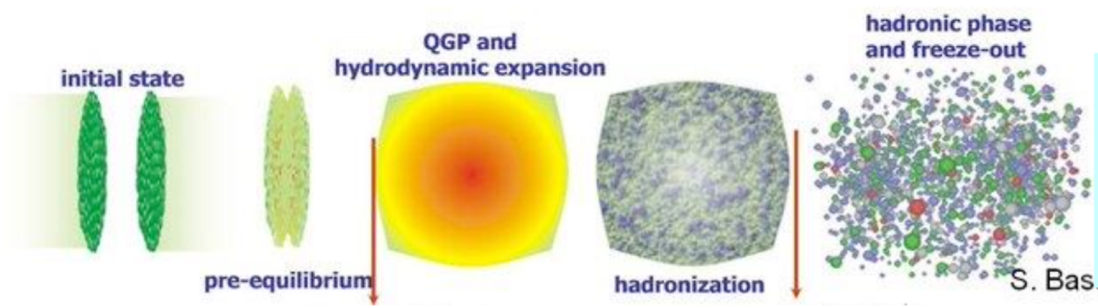
Where such extreme conditions of density and temperature can be achieved?

In the Early Universe

In Neutron Stars (NS)



In Heavy-Ion collisions (HIC)

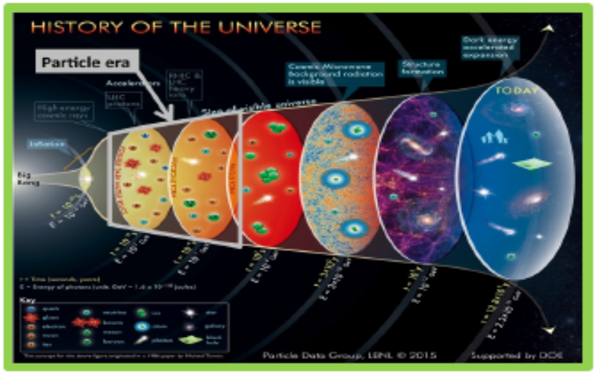


- *Huge amount of energy in a small volume!*
- *HIC not only address fundamental properties of Nature, but also has become a bridge between nuclear physics and astrophysics*

Relativistic Heavy-Ion Collisions and Quark Gluon Plasma (QGP)

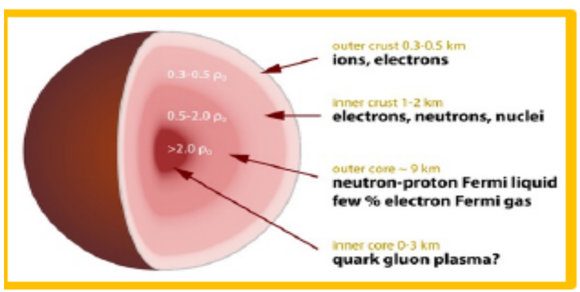
HADRON → **QGP**

Bevalac ~1 GeV → **AGS** ~5 GeV → **SPS** ~20 GeV → **RHIC** ~100 GeV → **LHC** ~5000 GeV



High temperature:
Early Universe evolution

High baryon density:
Inner structure of
compact stars



1. *It is the primordial form of QCD matter at high temperature and/or baryon density.*

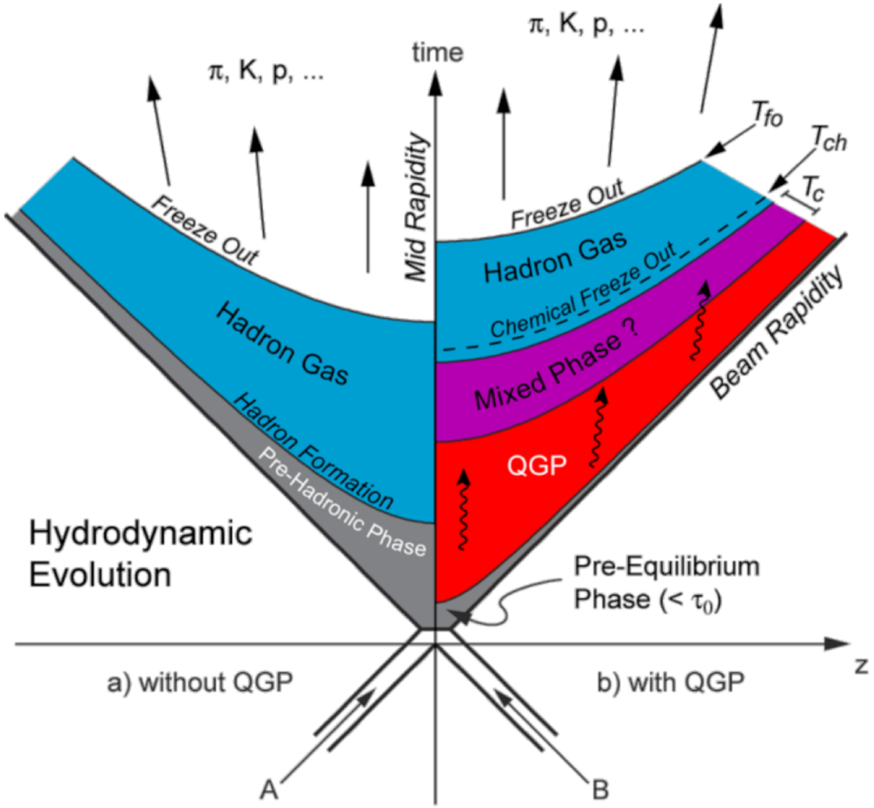
2. *It was present during the first few microseconds of the Big Bang.*

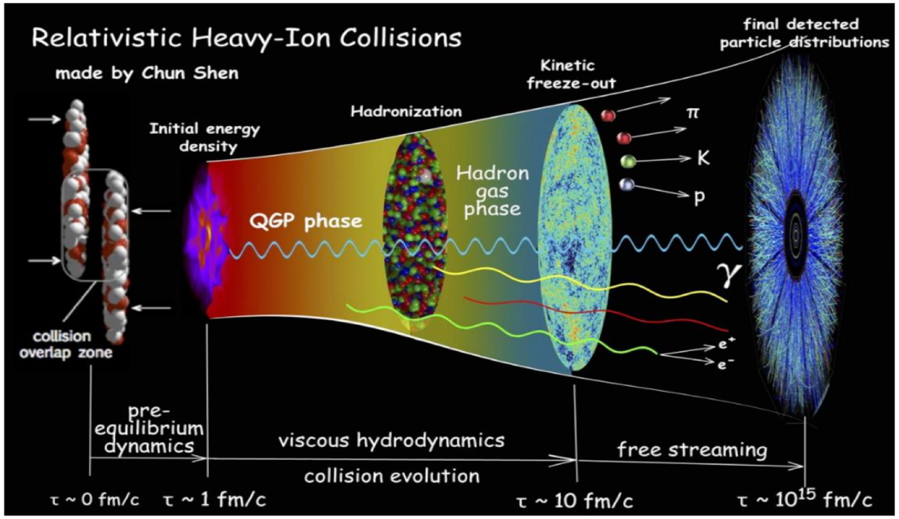
3. *It provides an example of phase transitions which may occur at a variety of higher temperature scales in the early universe.*

4. *It can provide important insights on the origin of mass for matter, and how quarks are confined into hadrons.*

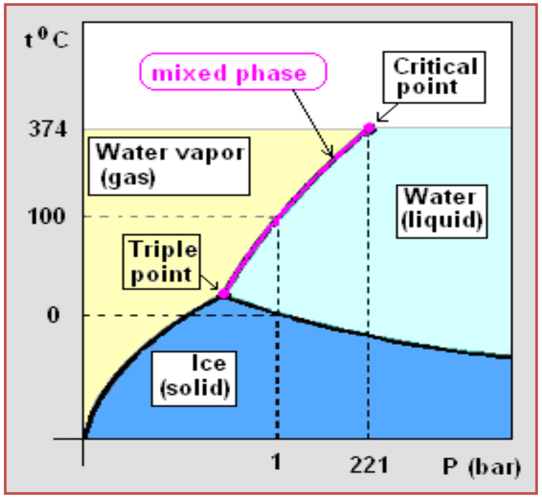
Study matter under extreme temperature and baryon density → Explore its phase diagram, search for its new states and study their properties.

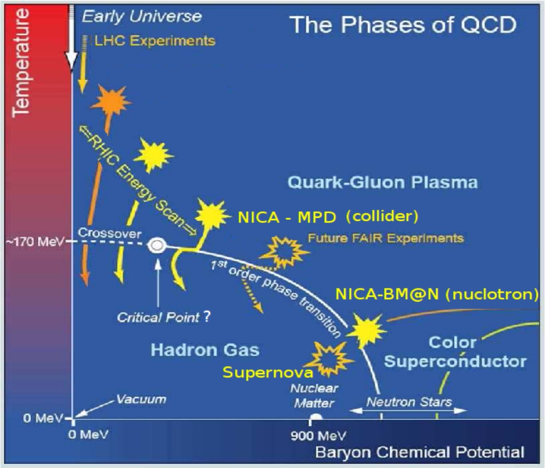
Time evolution of an A+A collision

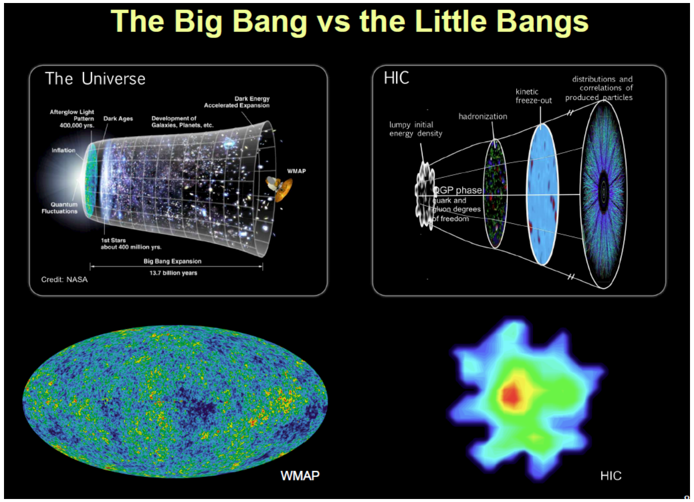


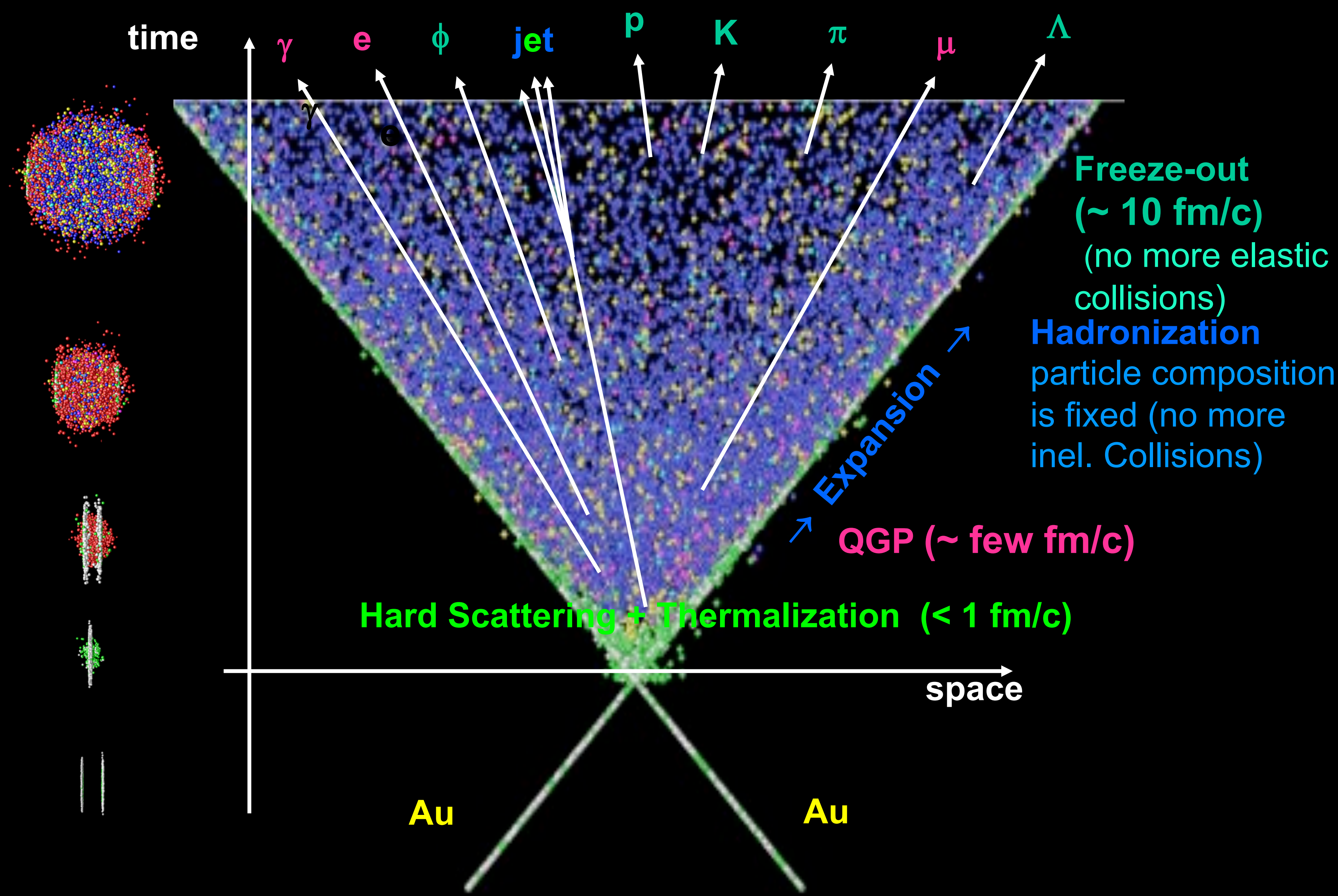


- A moment when particle abundances are fixed - ***chemical freezeout*** **(CFO)**
- A moment when particle's momentum distributions are fixed - ***kinetic freezeout t (FO)***

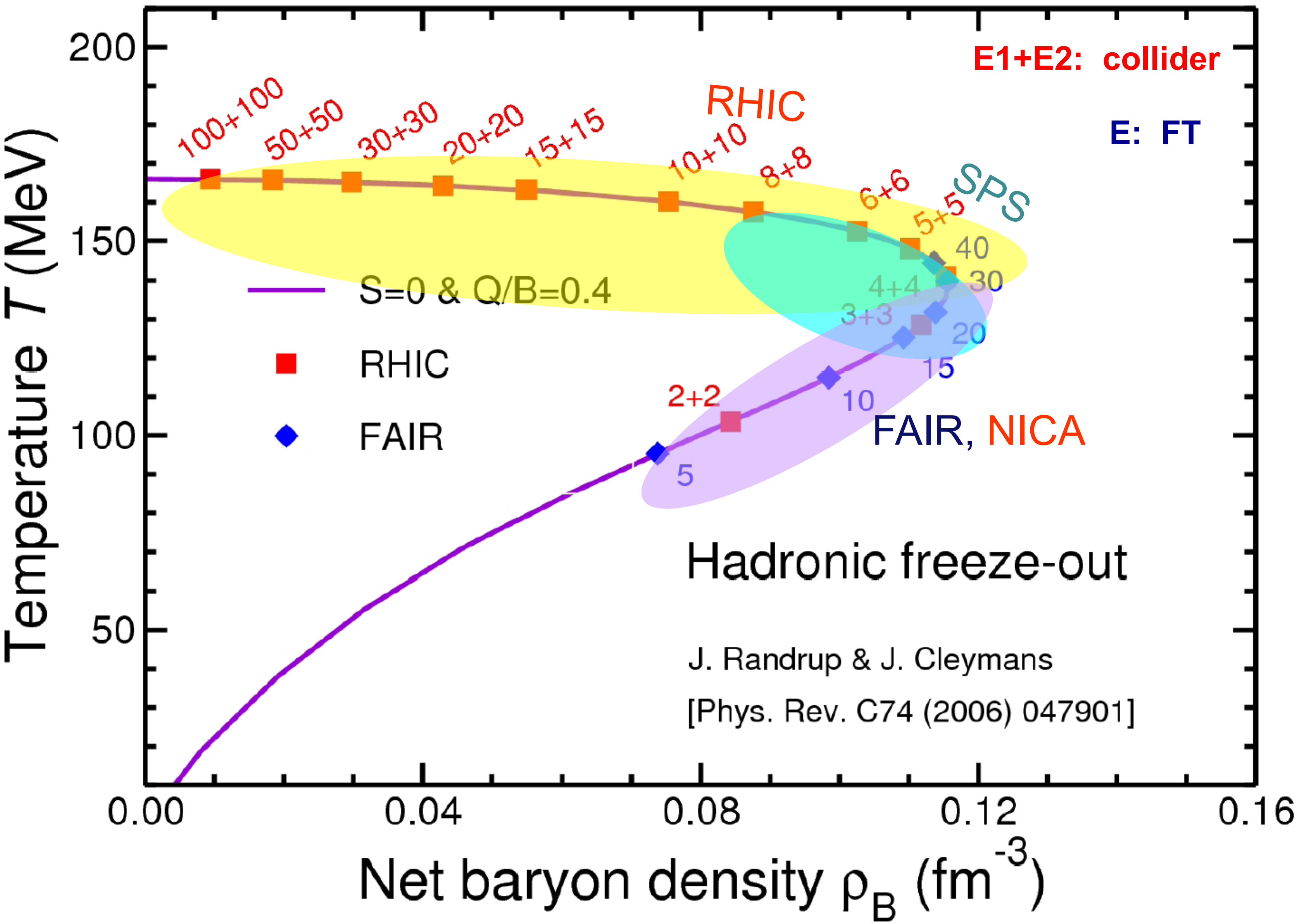


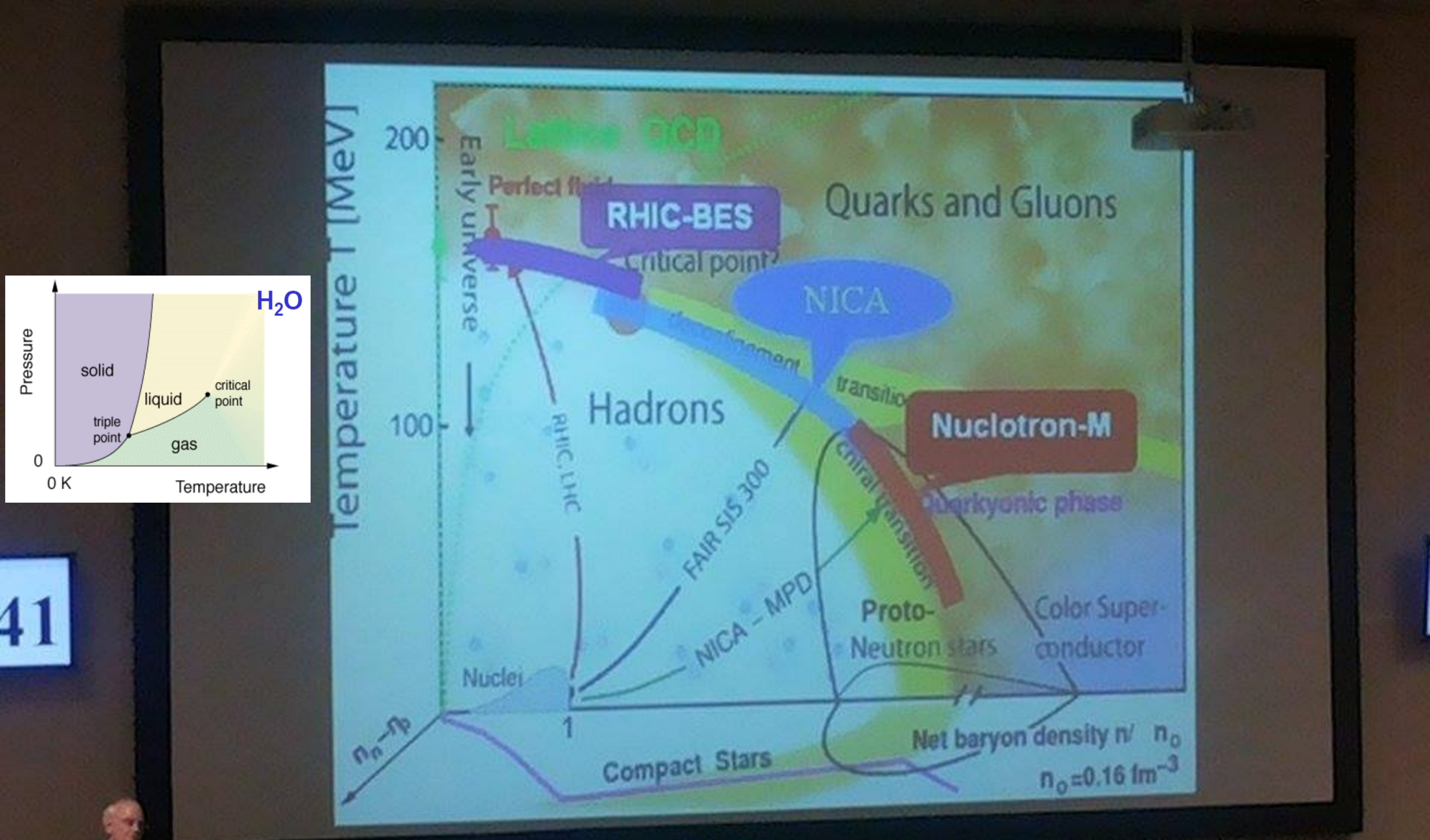





time
γ
e
φ
jet
p
K
π
μ
Λ
γ
e
Freeze-out
(~ 10 fm/c)
(no more elastic
collisions)
Hadronization
particle composition
is fixed (no more
inel. Collisions)
Expansion
QGP (~ few fm/c)
Hard Scattering + Thermalization (< 1 fm/c)
space
Au
Au

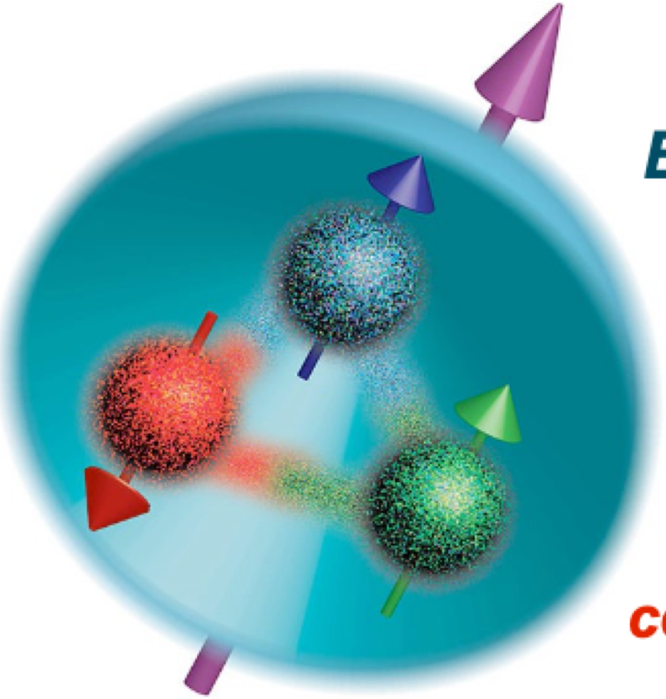
Freeze-out conditions



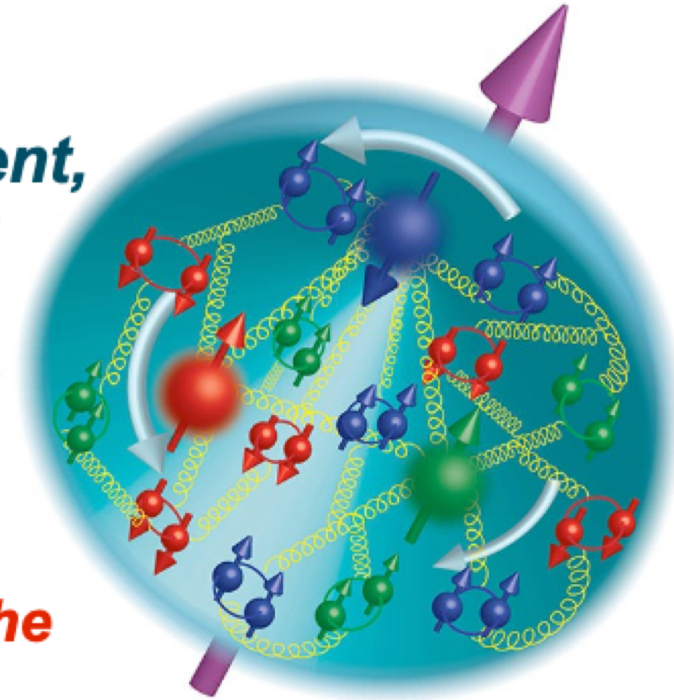


- Study of the phase transition from hadronic to quark-gluon matter
- Search for the critical point
- Study of in-medium properties of hadrons at high baryon density and temperature

Spin crisis



EMC experiment, CERN 1988



Quark contribution to the proton spin is below 30%!

Naive quark model

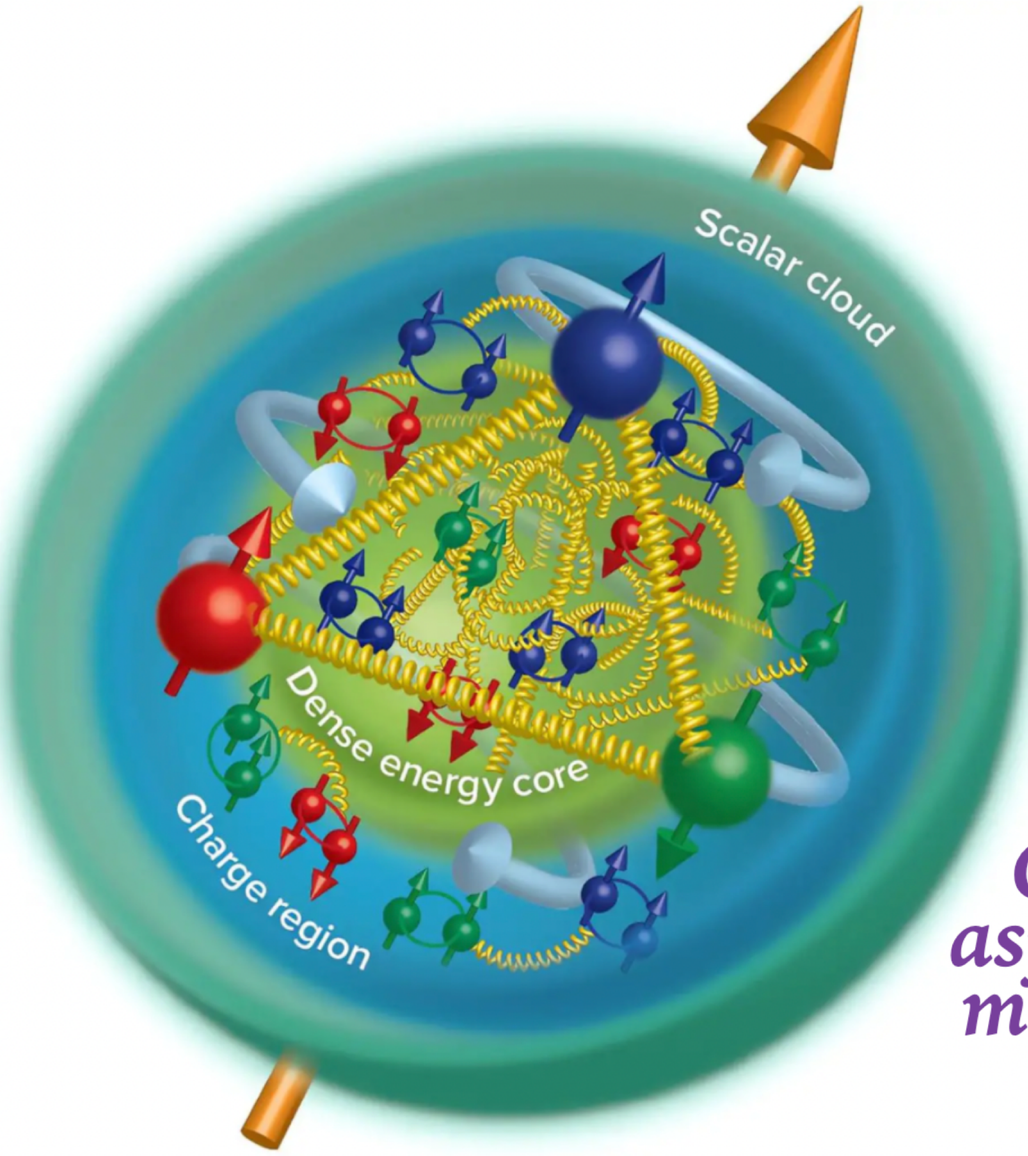
Real situation

$$\frac{1}{2} = \sum_{q=u,u,d} (\frac{\vec{1}}{2})$$

L - orbital moments of quarks and gluons

$$S_N = ½ = ½\ \Delta\Sigma + \Delta G + L$$

Spin Physics @ NICA



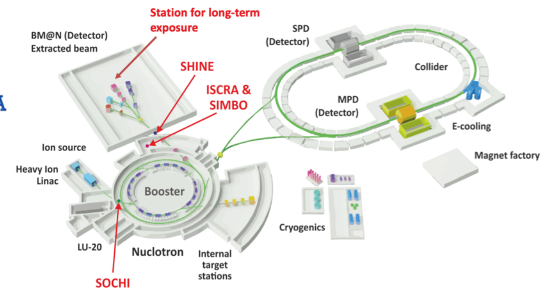
we plan to study how the proton and deuteron spin!

especially their gluon component!

Gluon TMD PDFs via asymmetries and angular modulations in the cross sections

Applied Research and Innovations @ NICA

The Applied Research Infrastructure for Advanced Developments at NICA fAcility (ARIADNA)



Applied Research and Innovations @ NICA

The Applied Research Infrastructure for Advanced Developments at NICA fAcility (ARIADNA) will include:

(1) Beamlines with magnetic optics, power supplies, beam diagnostics systems, cooling systems, etc.

(2) Experimental zones equipped with target stations for users (detectors, sample holders, irradiation control and monitoring system, etc.)

(3) Supporting user infrastructure (areas for deployment of user's equipment, for sample preparation and post-irradiation express analyses, etc.)

Low-energy ion beams available at HILAC 3.2 MeV/nucleon	Intermediate-energy ion beams available at Nuclotron 150-1000 MeV/nucleon	High-energy ion beams available at Nuclotron up to 4.5 GeV/nucleon
Life sciences, Radiation damage to microelectronics, Materials science, Novel relativistic nuclear technology		

Protons and ions with Z = 2 to 92

Irradiation of decapsulated microcircuits and solid materials with 3.2 MeV/nucleon ions.

Ions: $^{12}C^{6+}$, $^{40}Ar^{18+}$, $^{56}Fe^{26+}$, $^{84}Kr^{36+}$, $^{131}Xe^{54+}$, $^{197}Au^{79}$

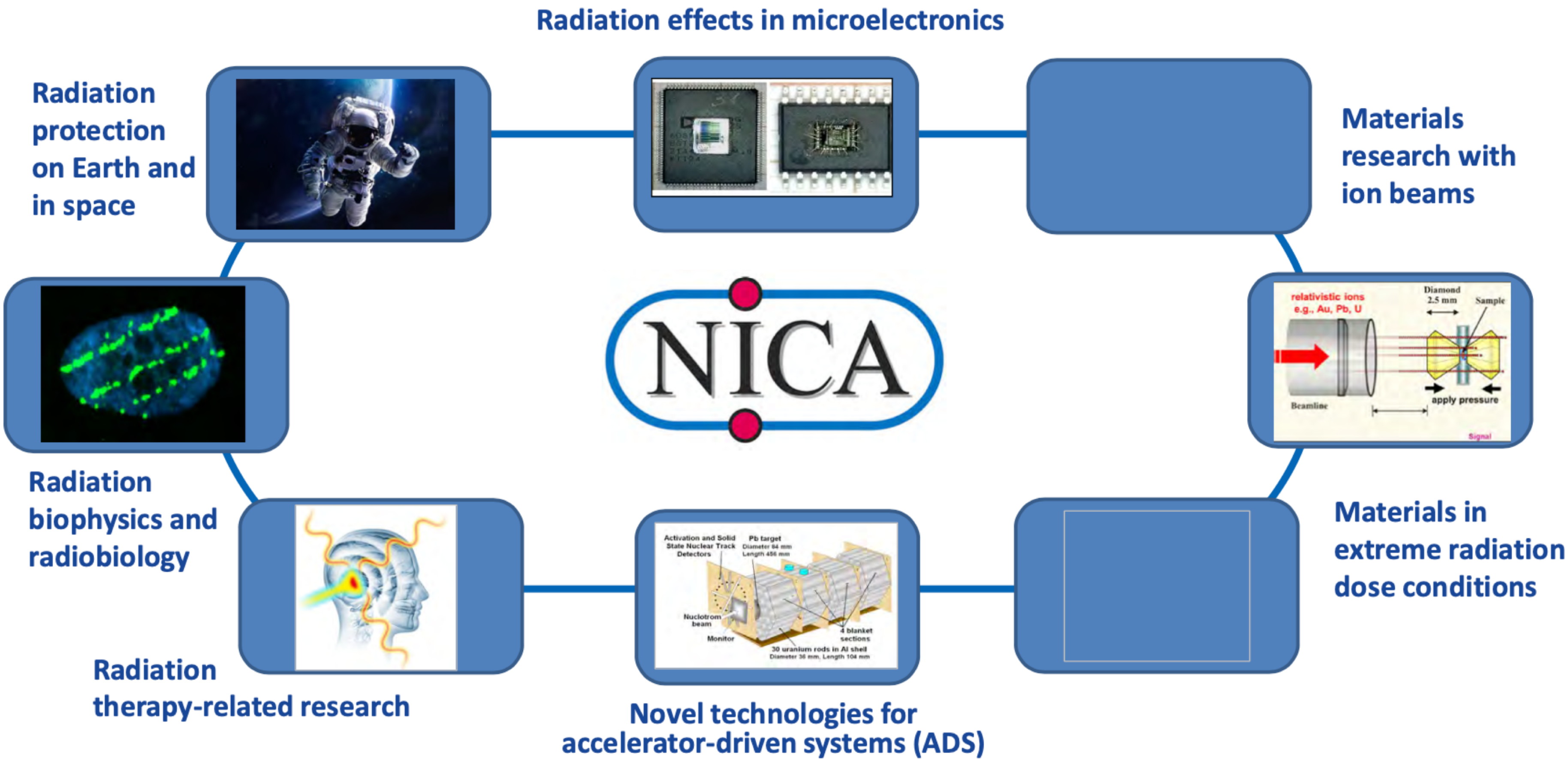
Irradiation of capsulated microcircuits with 150-350 MeV/nucleon ions. Ions like $^{197}Au^{79+}$ are decelerated in the capsule to 5-10 MeV/nucleon.

500-1000 MeV/nucleon ions be available at the target station for biological sample irradiation.

Ions: $^{1}H^{1+}$, $^{2}D^{1+}$, $^{12}C^{6+}$, $^{40}Ar^{18+}$, $^{7}Li^{3+}$

Target station will be equipped with targets from C to Pb and with the systems of beam and target diagnostics, positioning, thermometry, synchronization, radiation control, and data acquisition.

PILLARS OF APPLIED RESEARCH PROGRAMME WITH NICA BEAMS



When and where

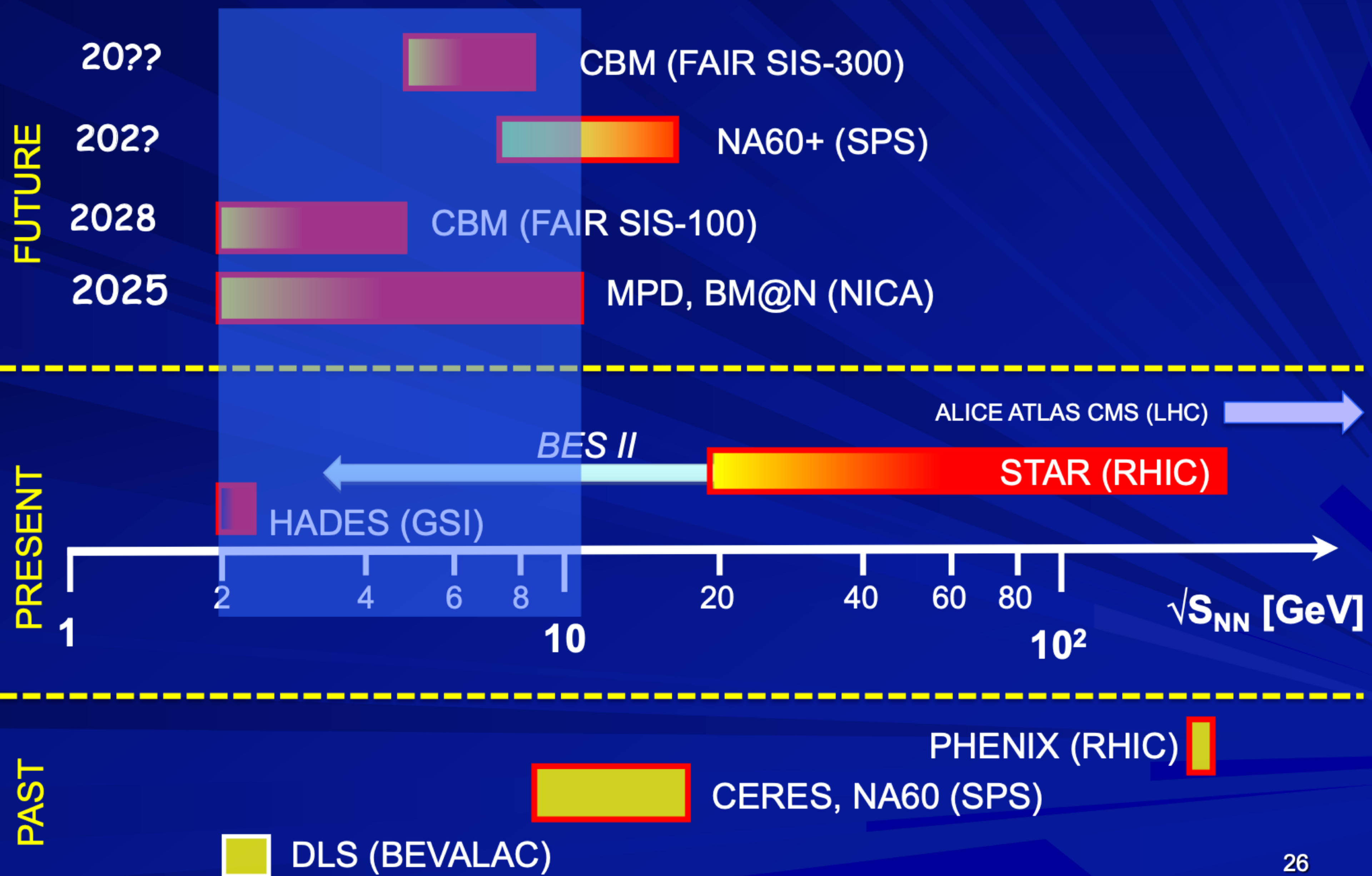
Short heavy-ion physics history

Accelerator	Years	Energy	Experiments	Type
BEVALAC – LBNL	1972-1984	max. $\sqrt{s_{NN}}$ = 2.2 GeV		Fixed target
SPS – CERN	1986-2000	$\sqrt{s_{NN}}$ = 17.3 GeV	NA35/49, NA44, NA38/50/51, NA45, NA52, NA57, NA60, WA80/98, WA97 …	Fixed target
AGS – BNL	1988-1996	$\sqrt{s_{NN}}$ = 4.8 GeV	E864/941, E802/859/866/917, E814/877, E858/878, E810/891, E896, E910 …	Fixed target
SIS18 – GSI	1990 →	$\sqrt{s_{NN}}$ = 2.4 GeV		Fixed target
RHIC – BNL	2000-2025	$\sqrt{s_{NN}}$ = 200 GeV	BRAHMS, PHENIX, PHOBOS, STAR	Collider
LHC – CERN	2010 →	$\sqrt{s_{NN}}$ = 5.02 TeV	ALICE, ATLAS, CMS, LHCb	Collider

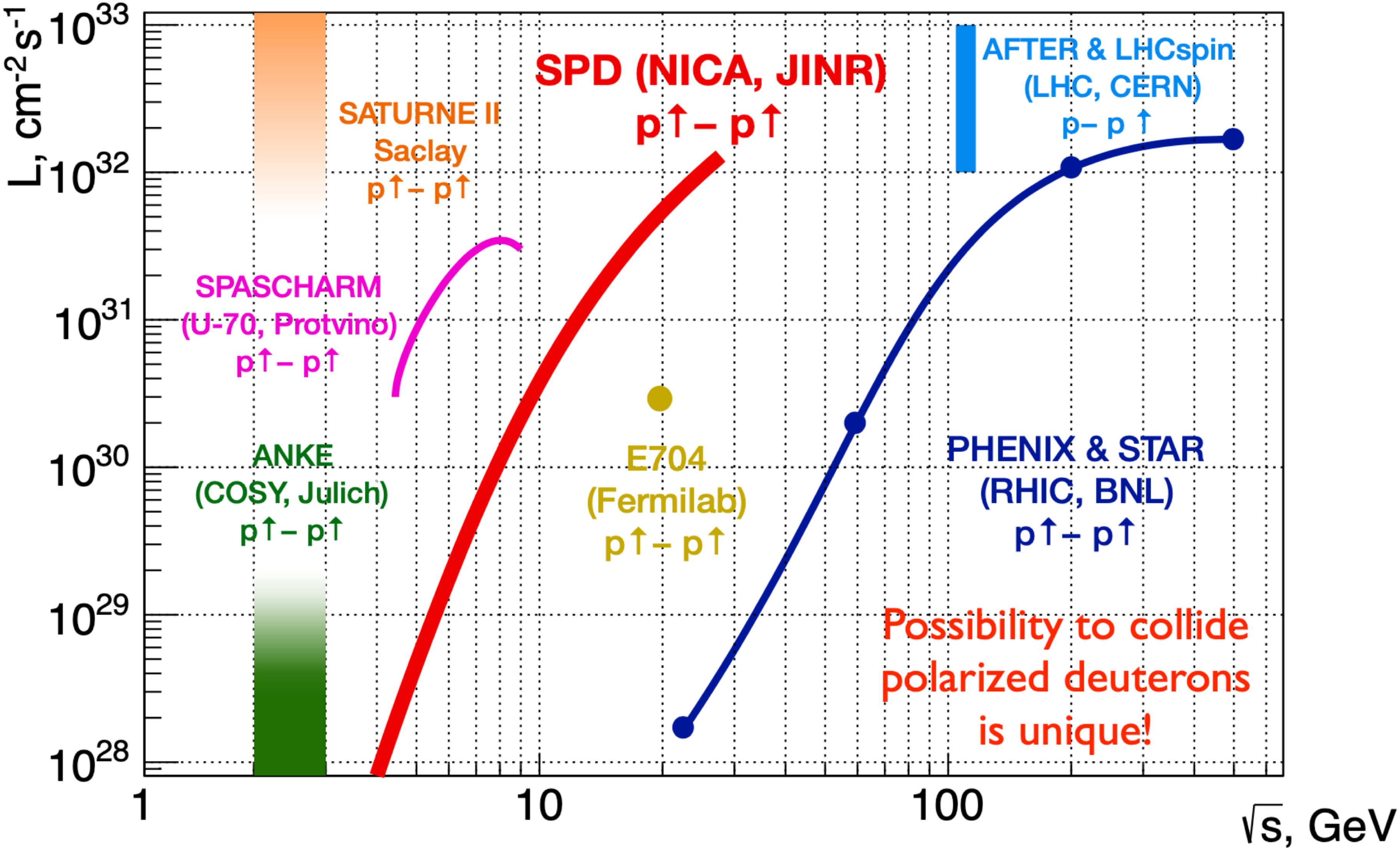
Near future

Accelerator	Years	Energy	Experiments	Type
NICA – JINR	2025	$\sqrt{s_{NN}}$ = 11 GeV	MPD, BM@N, SPD	Collider & Fixed target
SIS100 – FAIR	2028?	$\sqrt{s_{NN}}$ = 5 GeV	CBM, HADES	Fixed target

Low energy HI experiments



SPD and others



"Hilbert Problems" of Dense Matter Physics for NICA

- Which phases of QCD matter?
- Which degrees of freedom?
- Nature of the (spin) nucleon?
- How hadronization proceeds?
- ...

Challenging questions:

- Character of phase transitions (if any)?
- Signals for 1st order phase transition?
- Critical Point?
- When does the perfect fluid turn on?
- Duality of dynamical and thermal descriptions?
- Global polarization in HIC?
- …