Heavy Ion Physics and NICA's Mission

NICA Days, Almaty
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Outline

- **Introduction to HI physics**
  - Why?
  - QCD phase diagram
  - Deconfinement and Chiral symmetry Restoration
  - When and where?

- **The NICA Facility**
  - Accelerator complex
  - BM@N and MPD experiments

- **NICA's scientific mission**
  - Critical Point and first order phase transition
  - Onset of deconfinement and chiral symmetry restoration

- **Summary**

Introduction

Relativistic Heavy-Ion Collisisons: Why?

- Simple argument: confinement of quarks inside hadrons cannot survive when the density of hadrons is large compared to that inside ordinary hadrons.

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:
  $\varepsilon = Am_n / V_N \quad m_n = 0.94$ 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:
  $f = Av_n/V_N \quad v_n = 4/3\ \pi\ r_n^3 \quad r_n \sim 0.84$ fm (charge radius of the proton)
  ~ 0.38
  → ~60% of the nuclear volume is empty!

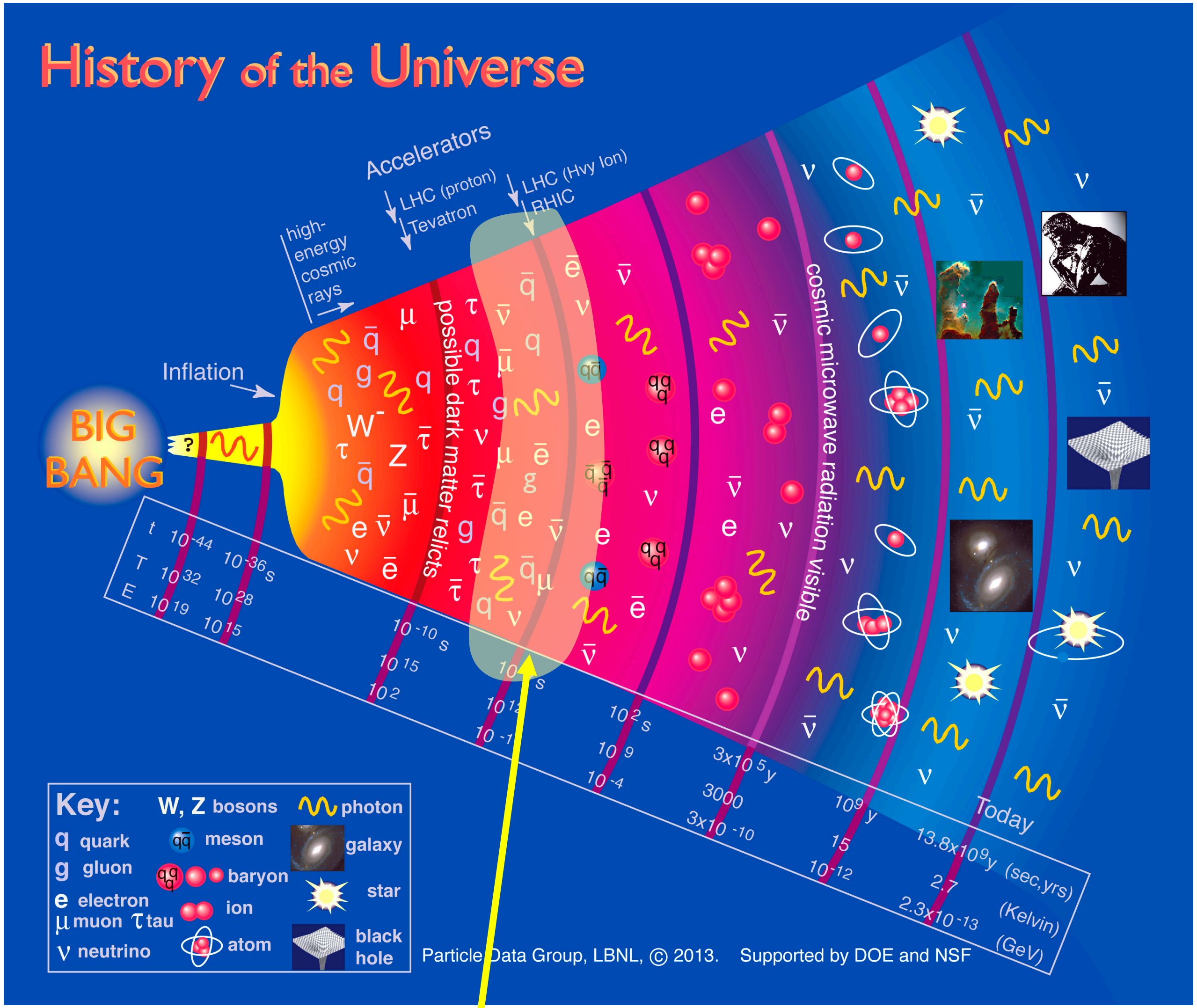
- Close packing condition f =1:
  $\rho \sim 0.4$ nucleon/fm^3

- QGP expected at a density ~10 times larger than the normal nuclear matter density:
  $\varepsilon \sim 2$ GeV/fm^3

Relativistic Heavy-Ion Collisisons: Why?

- Simple argument: confinement of quarks inside hadrons cannot survive when the density of hadrons is large compared to that inside ordinary hadrons.
- QGP: Primordial state of matter, existed in the early universe some ten microseconds after the big bang.

History of the Universe



QGP: 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)

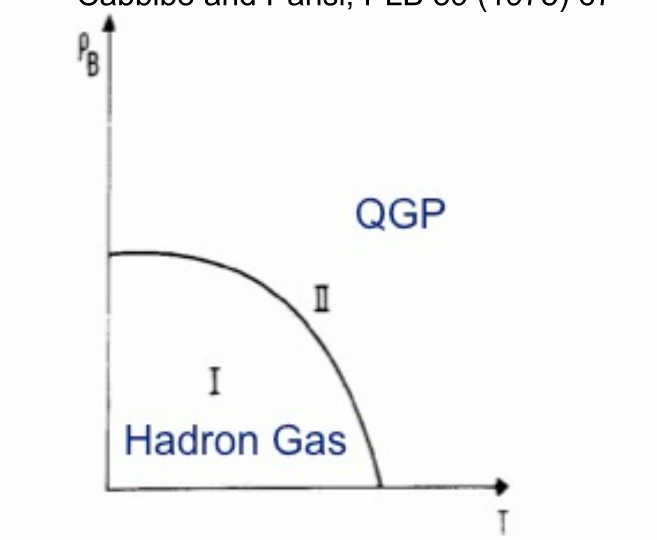
Relativistic Heavy-Ion Collisisons: Why?

- Simple argument: confinement of quarks inside hadrons cannot survive when the density of hadrons is large compared to that inside ordinary hadrons.
- QGP: Primordial state of matter, existed in the early universe some ten microseconds after the big bang.
- Study QCD under extreme conditions of temperature and density → Explore the QCD phase diagram, search for the QGP and study its properties.

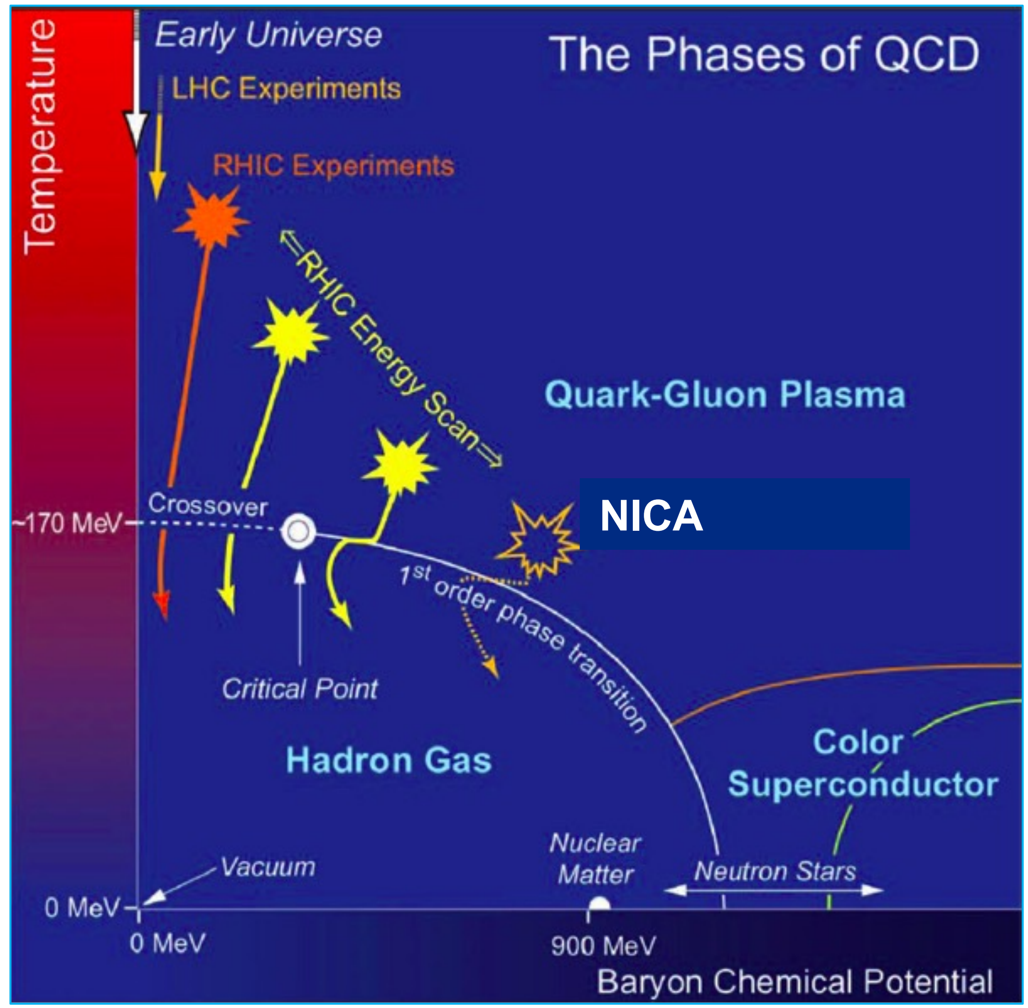
QCD Phase Diagram then and now

First schematic QCD phase diagram

Cabbibo and Parisi, PLB 59 (1975) 67



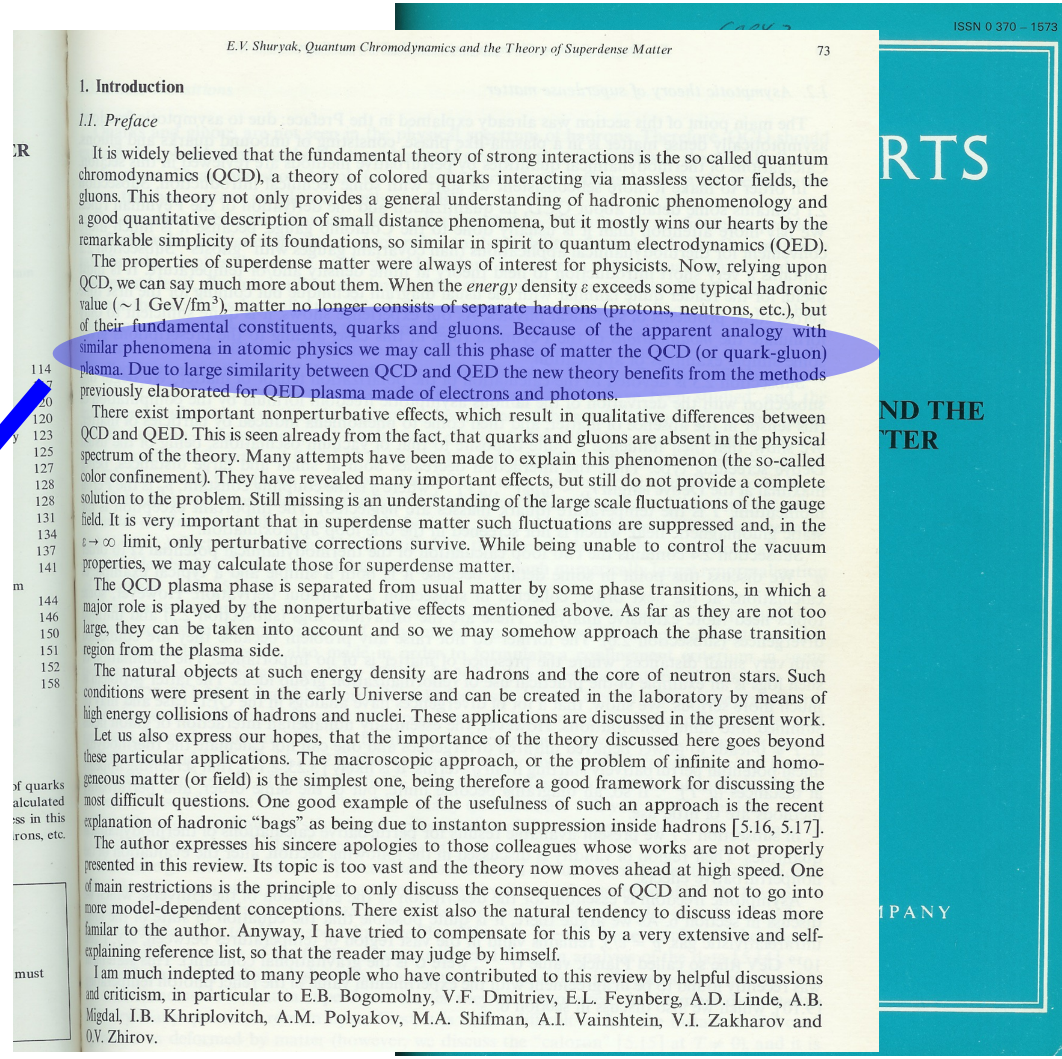
g. 1. Schematic phase diagram of hadronic matter. ρ_B is the nsity of baryonic number. Quarks are confined in phase I d unconfined in phase II.



Coining of a name

Ed Shuryak - Physics Reports 1980

First review on QCD at extreme density conditions



E.V. Shuryak, *Quantum Chromodynamics and the Theory of Superdense Matter* 73

1. Introduction

1.1. Preface

It is widely believed that the fundamental theory of strong interactions is the so called quantum chromodynamics (QCD), a theory of colored quarks interacting via massless vector fields, the gluons. This theory not only provides a general understanding of hadronic phenomenology and a good quantitative description of small distance phenomena, but it mostly wins our hearts by the remarkable simplicity of its foundations, so similar in spirit to quantum electrodynamics (QED).

The properties of superdense matter were always of interest for physicists. Now, relying upon QCD, we can say much more about them. When the *energy* density ε exceeds some typical hadronic value (~ 1 GeV/fm^3), matter no longer consists of separate hadrons (protons, neutrons, etc.), but of their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or quark-gluon) plasma. Due to large similarity between QCD and QED the new theory benefits from the methods previously elaborated for QED plasma made of electrons and photons.

There exist important nonperturbative effects, which result in qualitative differences between QCD and QED. This is seen already from the fact, that quarks and gluons are absent in the physical spectrum of the theory. Many attempts have been made to explain this phenomenon (the so-called color confinement). They have revealed many important effects, but still do not provide a complete solution to the problem. Still missing is an understanding of the large scale fluctuations of the gauge field. It is very important that in superdense matter such fluctuations are suppressed and, in the $\varepsilon \to \infty$ limit, only perturbative corrections survive. While being unable to control the vacuum properties, we may calculate those for superdense matter.

The QCD plasma phase is separated from usual matter by some phase transitions, in which a major role is played by the nonperturbative effects mentioned above. As far as they are not too large, they can be taken into account and so we may somehow approach the phase transition region from the plasma side.

The natural objects at such energy density are hadrons and the core of neutron stars. Such conditions were present in the early Universe and can be created in the laboratory by means of high energy collisions of hadrons and nuclei. These applications are discussed in the present work.

Let us also express our hopes, that the importance of the theory discussed here goes beyond these particular applications. The macroscopic approach, or the problem of infinite and homogeneous matter (or field) is the simplest one, being therefore a good framework for discussing the most difficult questions. One good example of the usefulness of such an approach is the recent explanation of hadronic "bags" as being due to instanton suppression inside hadrons [5.16, 5.17].

The author expresses his sincere apologies to those colleagues whose works are not properly presented in this review. Its topic is too vast and the theory now moves ahead at high speed. One of main restrictions is the principle to only discuss the consequences of QCD and not to go into more model-dependent conceptions. There exist also the natural tendency to discuss ideas more familiar to the author. Anyway, I have tried to compensate for this by a very extensive and self-explaining reference list, so that the reader may judge by himself.

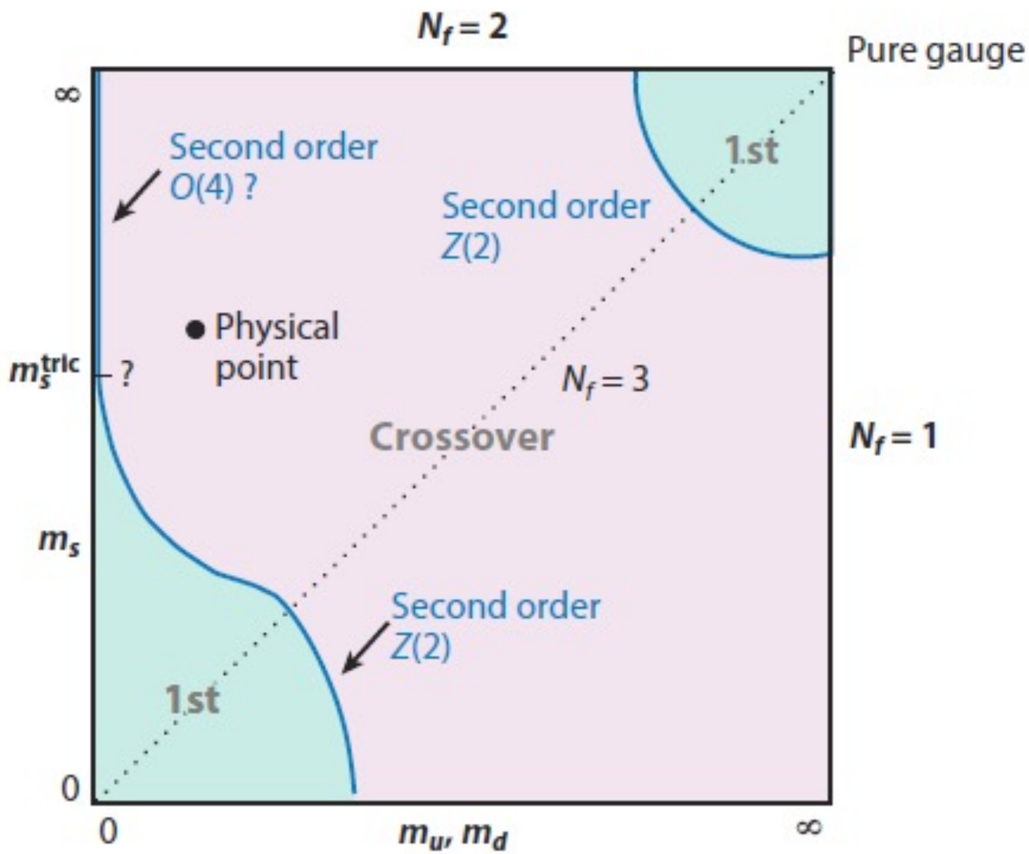
I am much indepted to many people who have contributed to this review by helpful discussions and criticism, in particular to E.B. Bogomolny, V.F. Dmitriev, E.L. Feynberg, A.D. Linde, A.B. Migdal, I.B. Khriplovitch, A.M. Polyakov, M.A. Shifman, A.I. Vainshtein, V.I. Zakharov and O.V. Zhirov.

"Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the QCD (or quark-gluon) plasma."

Relativistic Heavy-Ion Collisisons: Why?

- ❖ Simple argument: confinement of quarks inside hadrons cannot survive when the density of hadrons is large compared to that inside ordinary hadrons.
- ❖ Primordial state of matter: existed in the early universe some ten of microseconds after the big bang.
- ❖ Study QCD under extreme conditions of temperature and density → Explore the QCD phase diagram, search for the QGP and study its properties.
- ❖ QGP predicted by numerical lattice QCD calculations.

Order of the transition?



LQCD results in net baryon-free matter ($\mu_B = 0$):

❖ Pure gauge ($m_q \rightarrow \infty$): 1st order phase transition

❖ Chiral limit ($m_q \rightarrow 0$): 1st order phase transition

❖ For realistic quark masses, LQCD results indicate a smooth cross-over transition
Y. Aoki et al, Nature 443, 675 (2006)

Relativistic Heavy-Ion Collisisons: Why?

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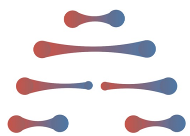
- Study QCD under extreme conditions of temperature and density → Explore the QCD phase diagram, search for the QGP and study its properties.
- QGP predicted by numerical lattice QCD calculations.
- Fundamental characteristics of the QGP:
  - Deconfinement
  - Chiral symmetry restoration

Deconfinement and Chiral Symmetry Restoration

QCD

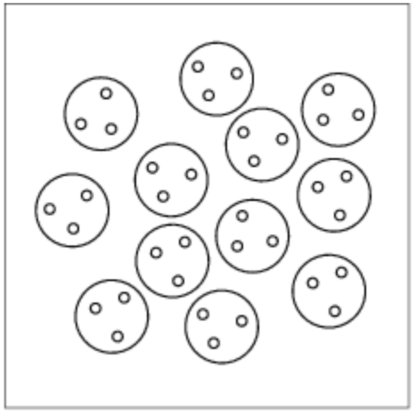
Color charges:

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



≈ σr at large r

Long range → confinement
color insulator



QED

Electric charges:

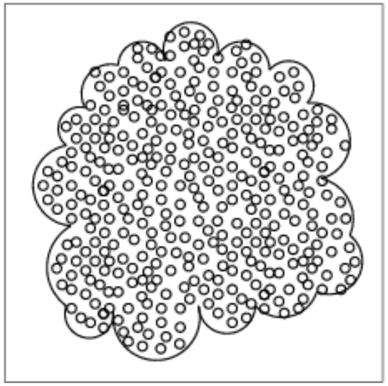
$$V(r) = \frac{e^2}{r}$$

HIGH DENSITY

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

Screening → Deconfinement
color conductor

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

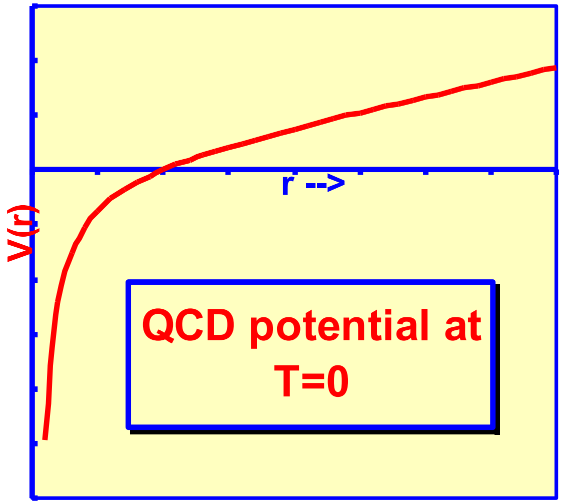


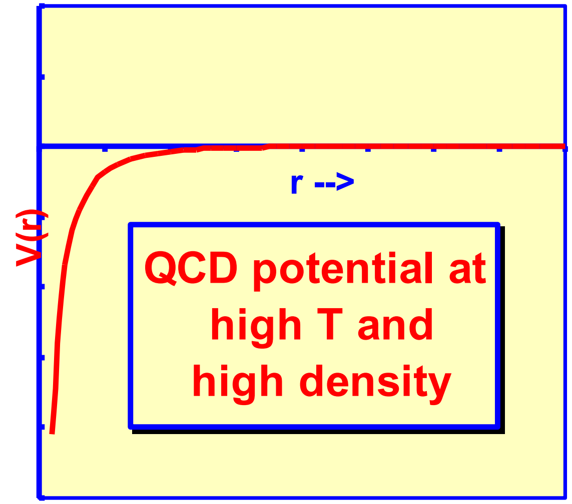
$$V(r) = \frac{e^2}{r}\exp(-\mu r)$$

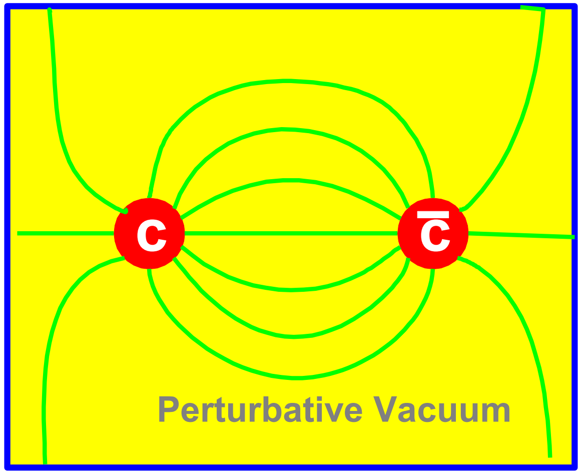
$\mu = 1/\ r_D$

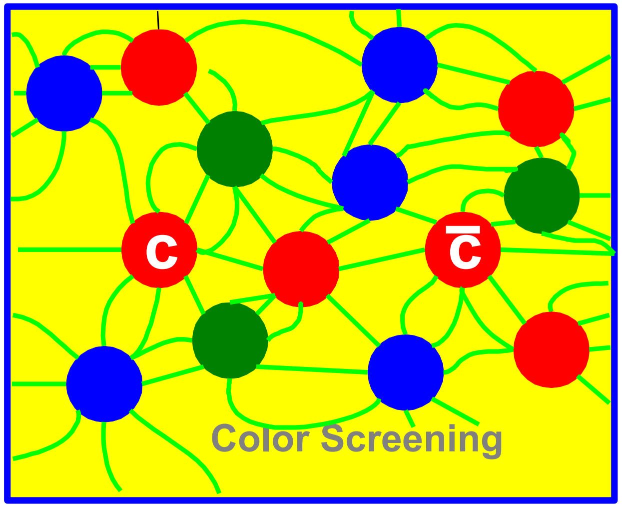
r_D Debye screening radius

Screening in the QGP









Deconfinement and Chiral Symmetry Restoration

QCD

Color charges:

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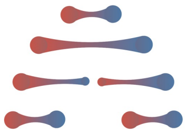
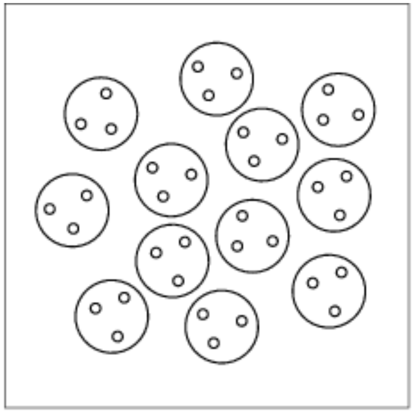


≈ σr at large r

Long range → confinement
color insulator



QED

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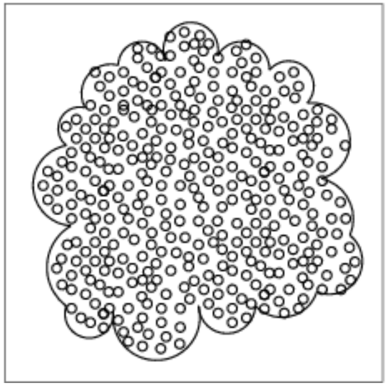
HIGH DENSITY

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

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

Constituent mass $M_q \sim 300$ MeV

Current mass $m_q \sim 5\text{-}10$ MeV

$m_e \rightarrow m_{eff}$

Chiral Symmetry (app.) restored

Relativistic Heavy Ion Collisions: When and Where

When and where

Short heavy-ion physics history

❖ **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

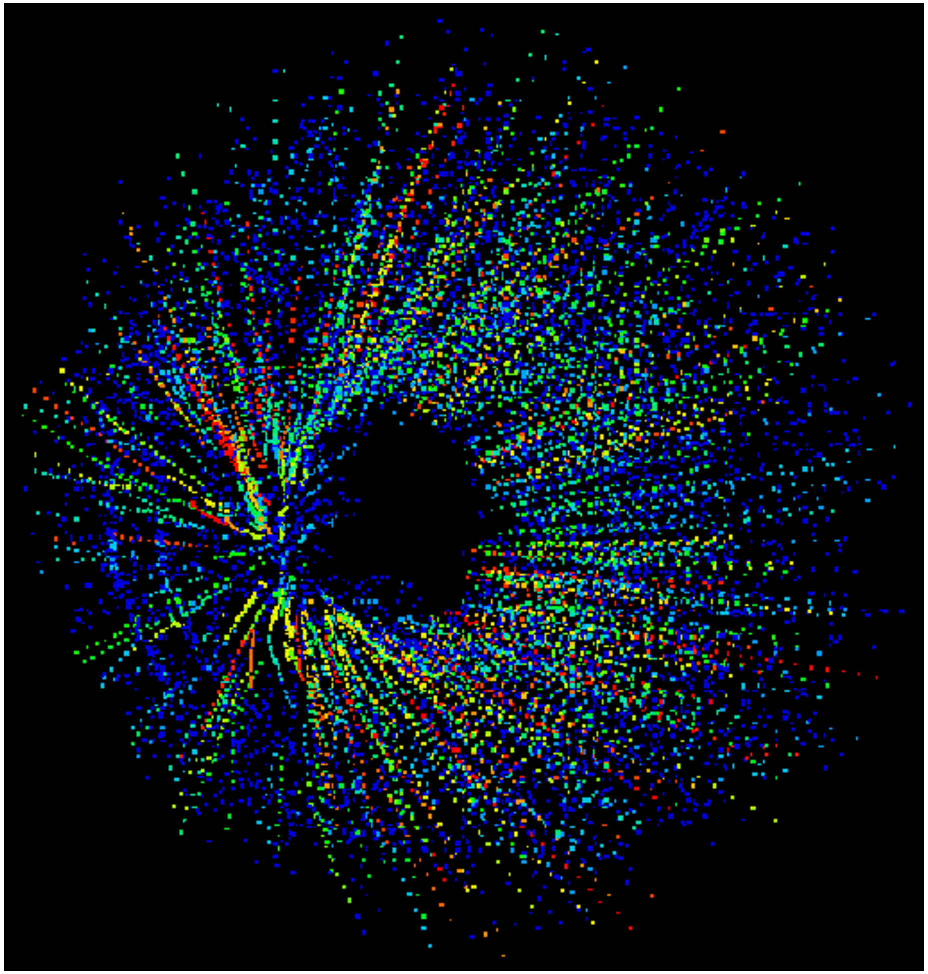
❖ NICA – JINR 2025 $\sqrt{s_{NN}}$ = 11 GeV	MPD, BM@N	Collider & Fixed target
❖ SIS100 – FAIR 2028? $\sqrt{s_{NN}}$ = 5 GeV	CBM, HADES	Fixed target

Spectacular events

Fixed target

CERES @ SPS

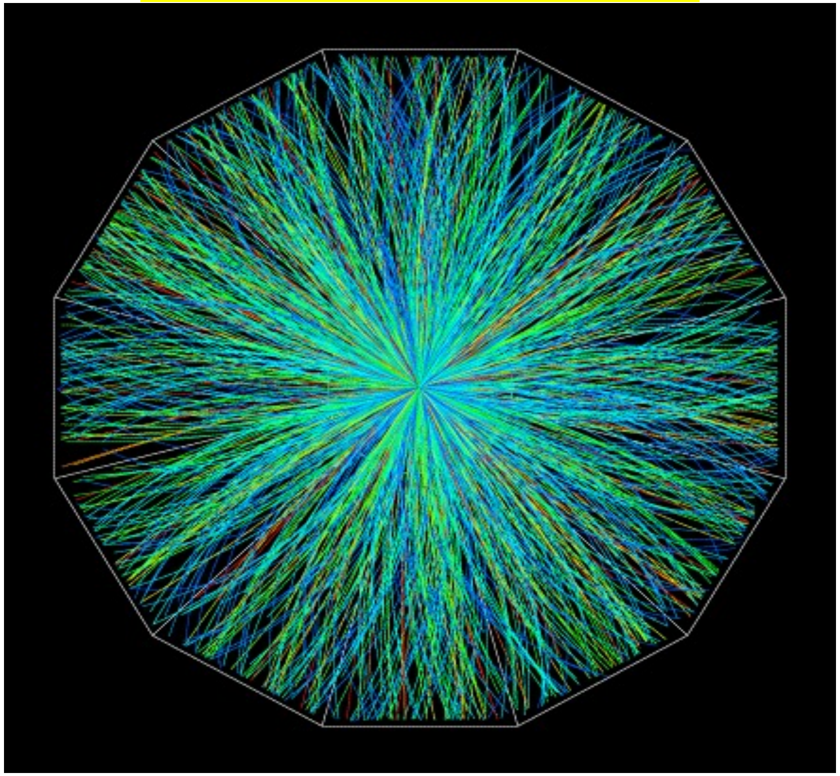
Pb – Au $\sqrt{s_{NN}}$ = 17 GeV/c



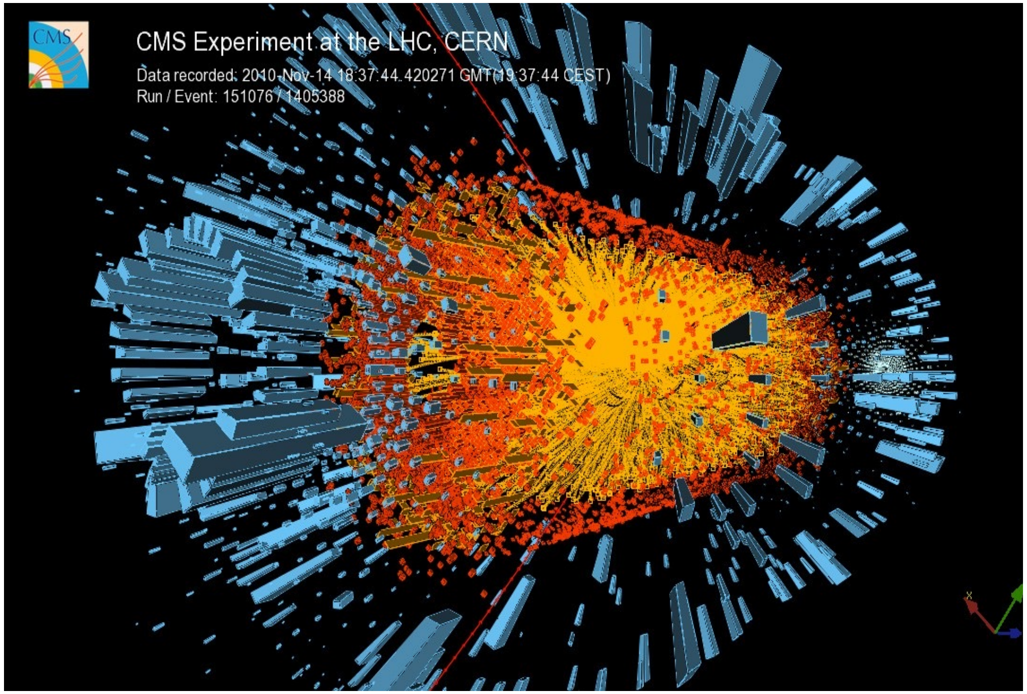
Spectacular events

Collider

STAR @ RHIC
Au+Au $\sqrt{s_{NN}}$ = 200 GeV/c



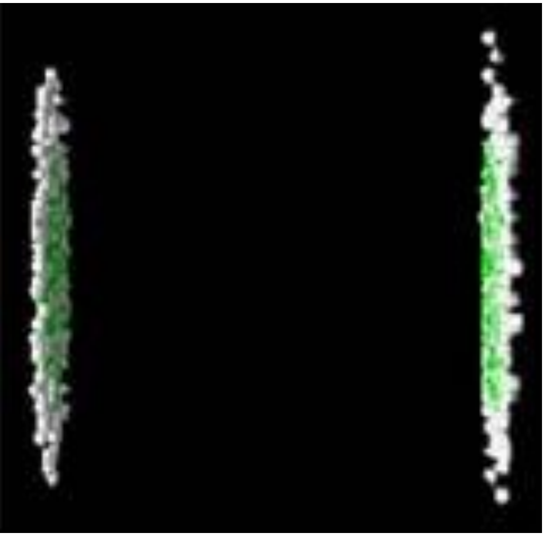
CMS @ LHC
Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV/c



Collision Modeling

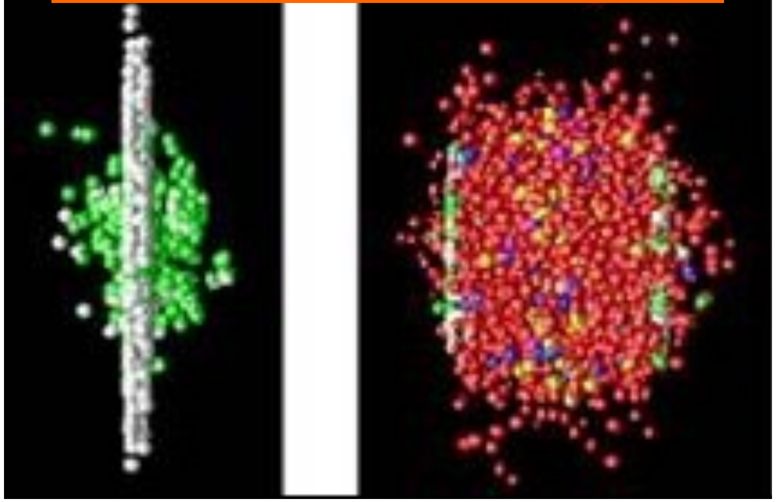
❖ Three stages:

Approach Phase



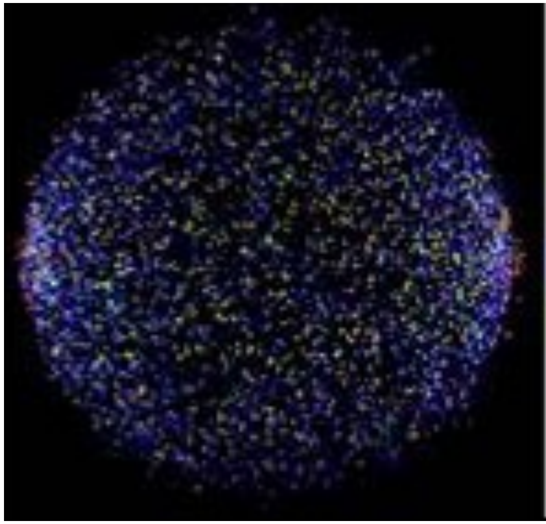
The ions are flat (instead of their usual spherical shape) due to Lorentz contraction.

Collision
Passing through



The ions smash into one another and pass through each other. A large fraction of their initial energy is transformed into heat and new particles, forming eventually a QGP

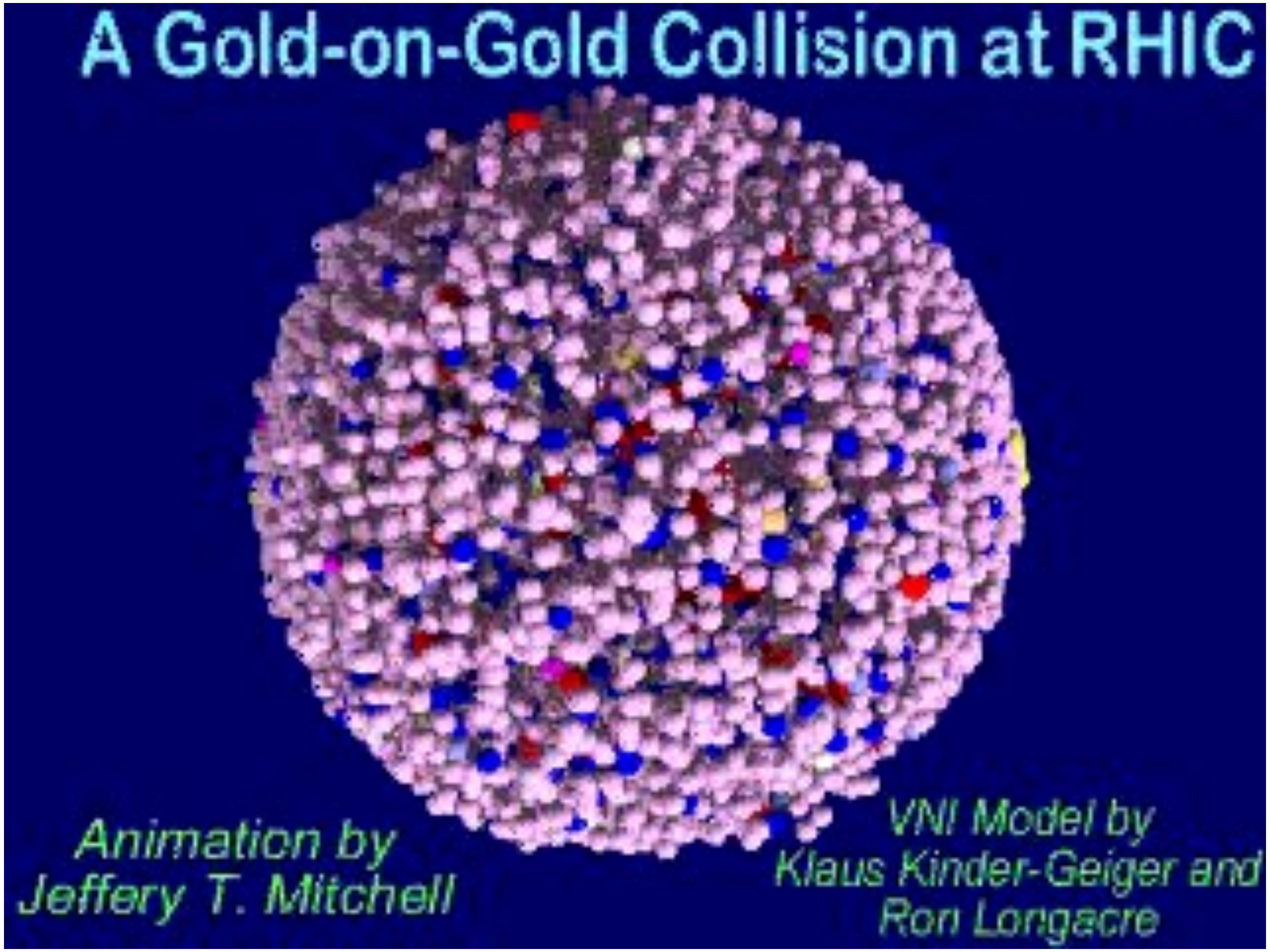
After the collision



Thousands of particles form as the area cools off. They are the clue to what happened inside the collision zone.

❖ Models are developed to describe each of these stages.

Collision simulation (II)



NICA Facility

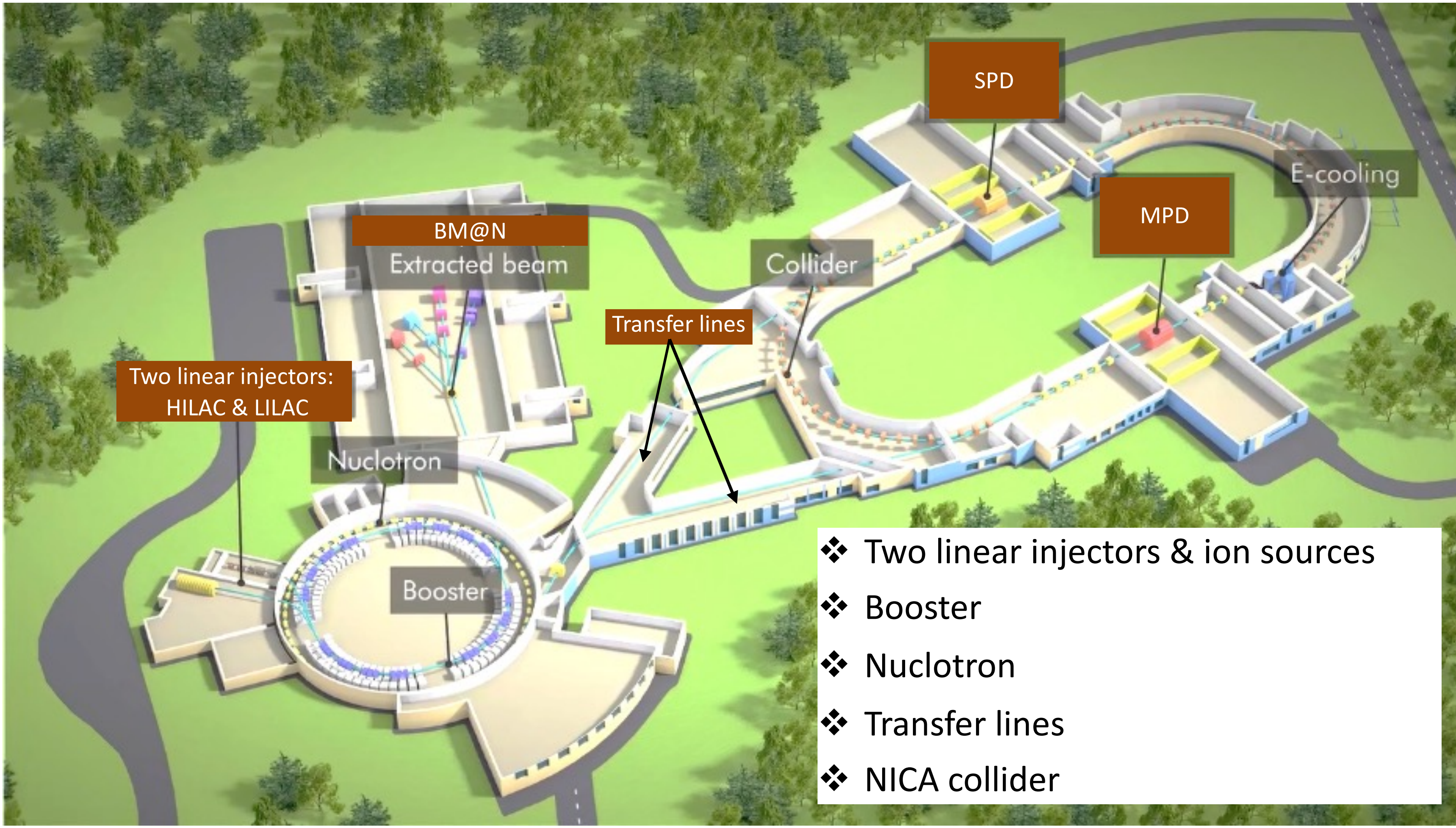
(Nuclotron based Ion Collider fAcility)

- Accelerator complex under construction at JINR, Dubna
- Shall provide high intensity beams :

  heavy ions: Au^{79+} $\sqrt{s_{NN}}$ = 4 - 11 GeV, L ~ 10^{27} cm^{-2} s^{-1}

  polarized p and d: $\sqrt{s}$ up to 27 GeV, L ~ 10^{32} cm^{-2} s^{-1}

The NICA Facility

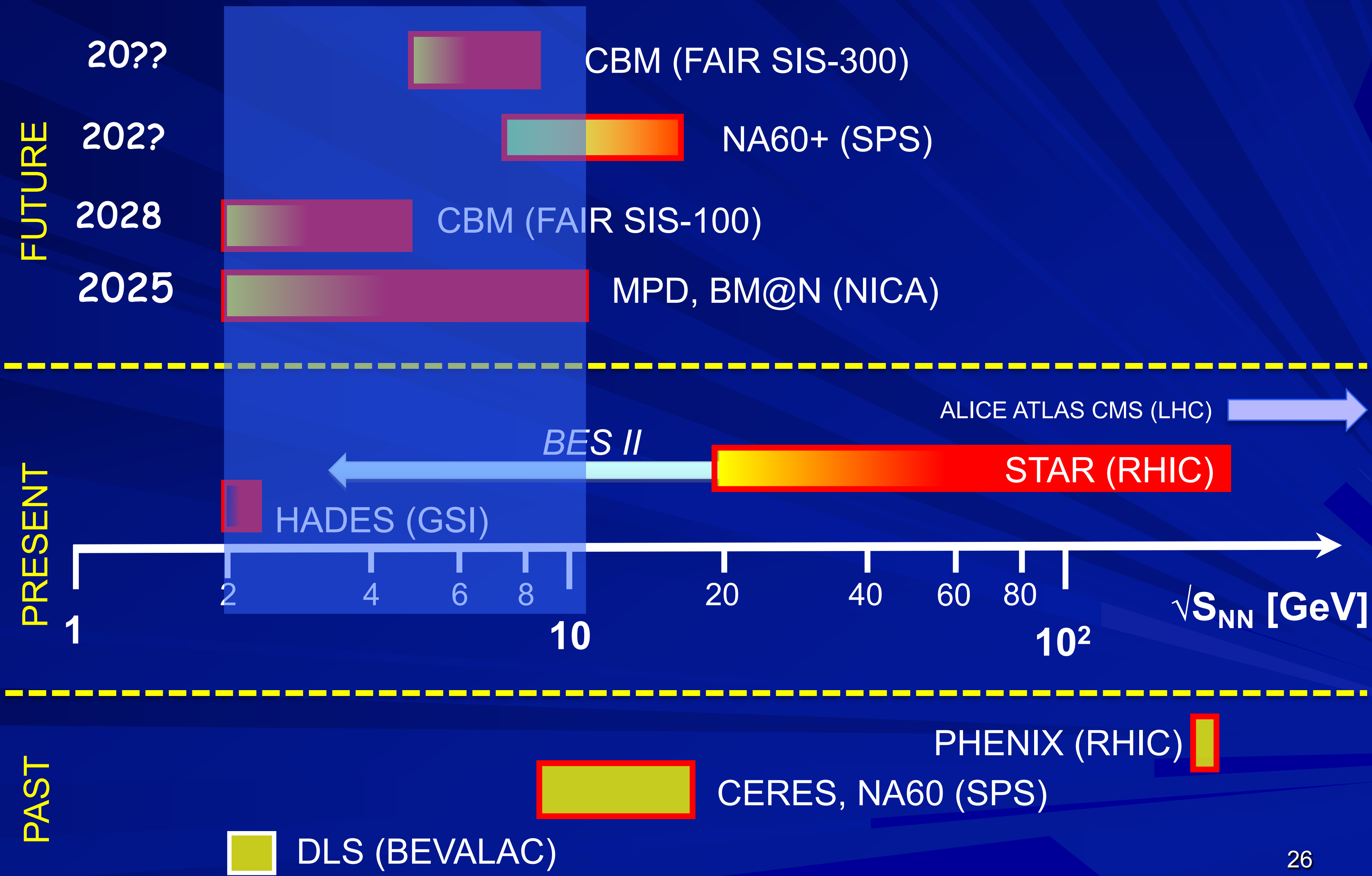


- Two linear injectors & ion sources
- Booster
- Nuclotron
- Transfer lines
- NICA collider

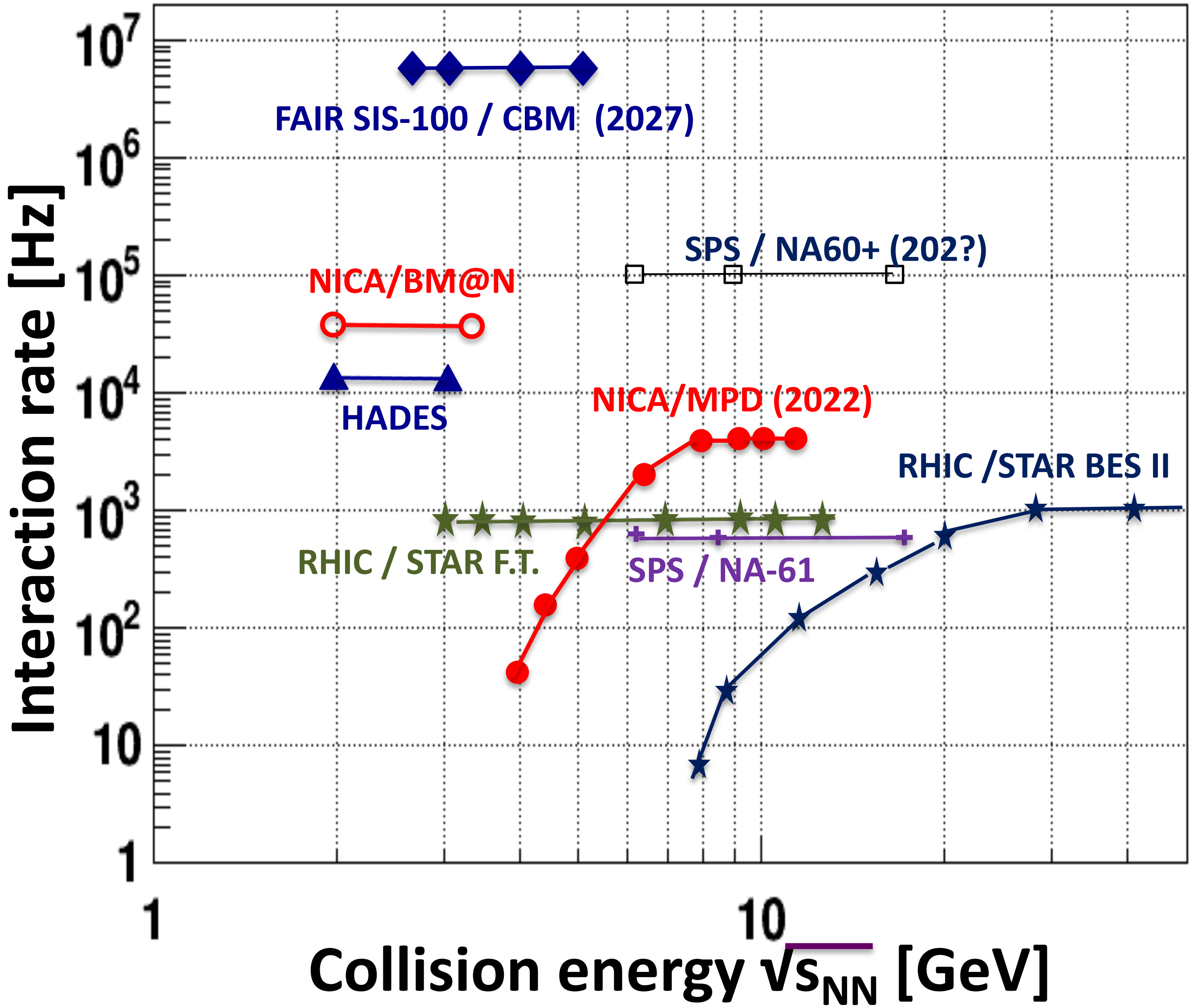
The NICA Facility

Technical run – end of 2024
First Cillisions - Spring 2025

Low energy HI experiments

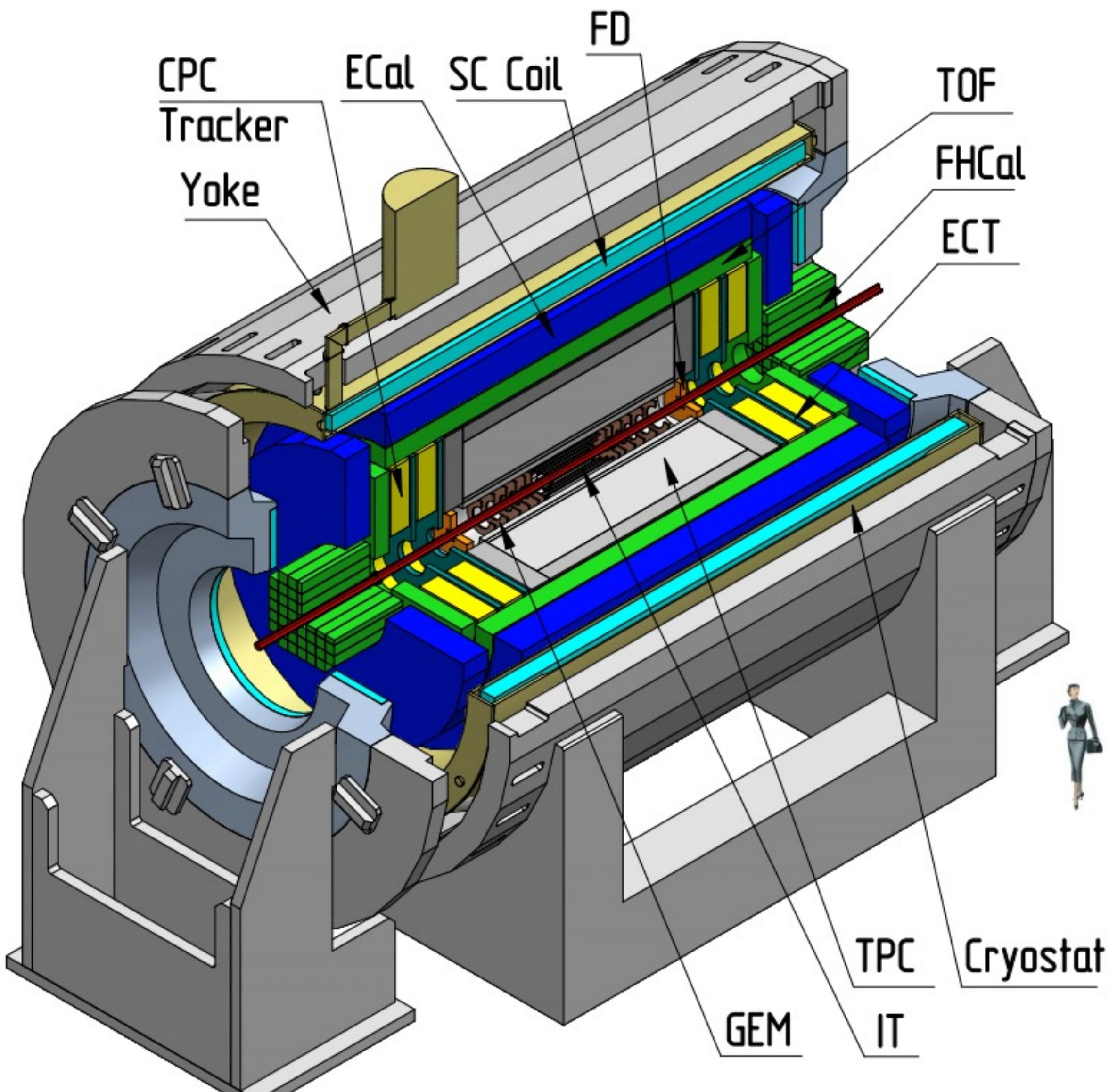


Interaction rate at various facilities



MPD at NICA

$\sqrt{s_{NN}}$ = 4 - 11 GeV Ready for first collisions in 2025



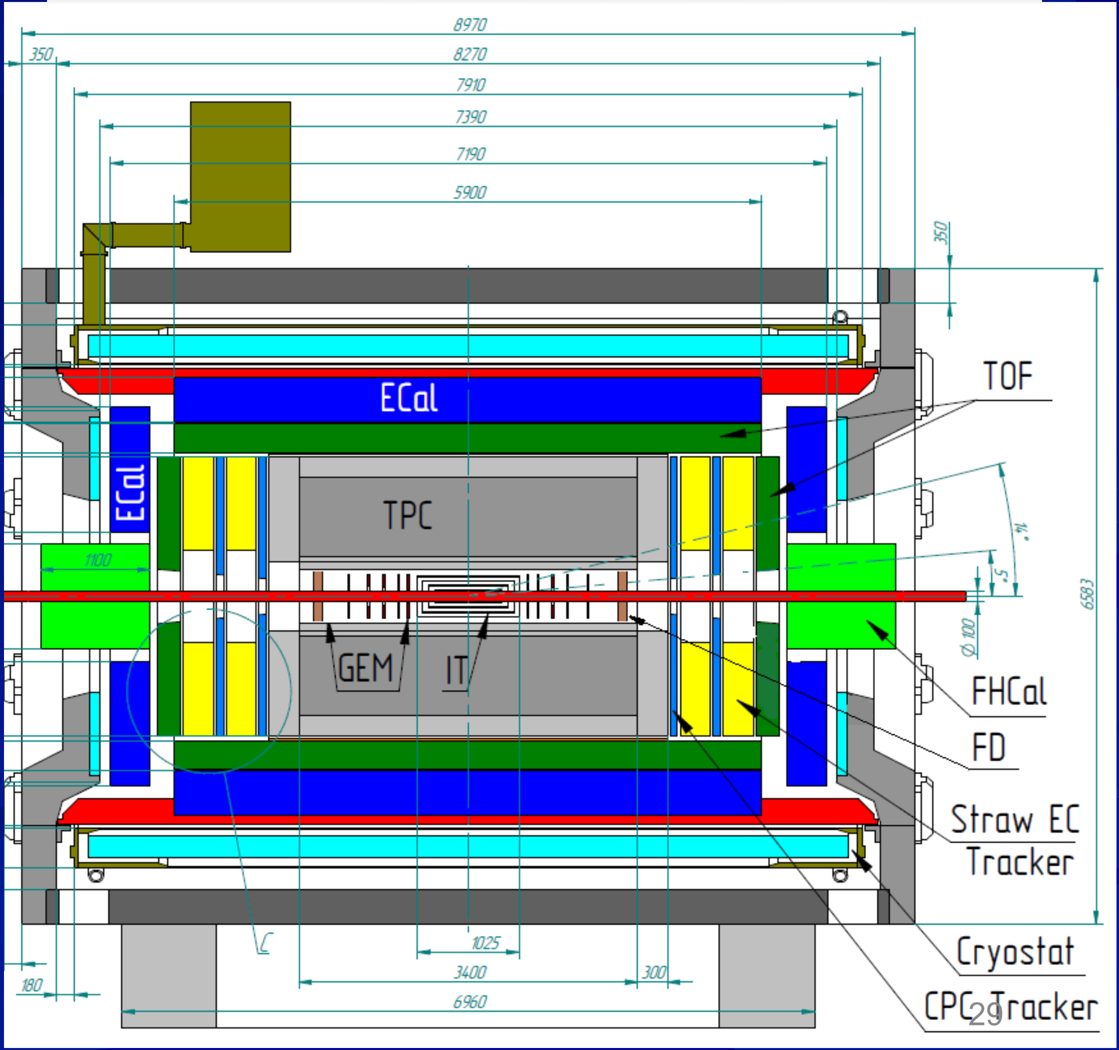
MPD (Multi-Purpose Detector)

Stage 1: TPC, TOF, ECAL, FHCAL, FD

Stage 2: IT + Endcaps (tracker, TOF, ECAL)

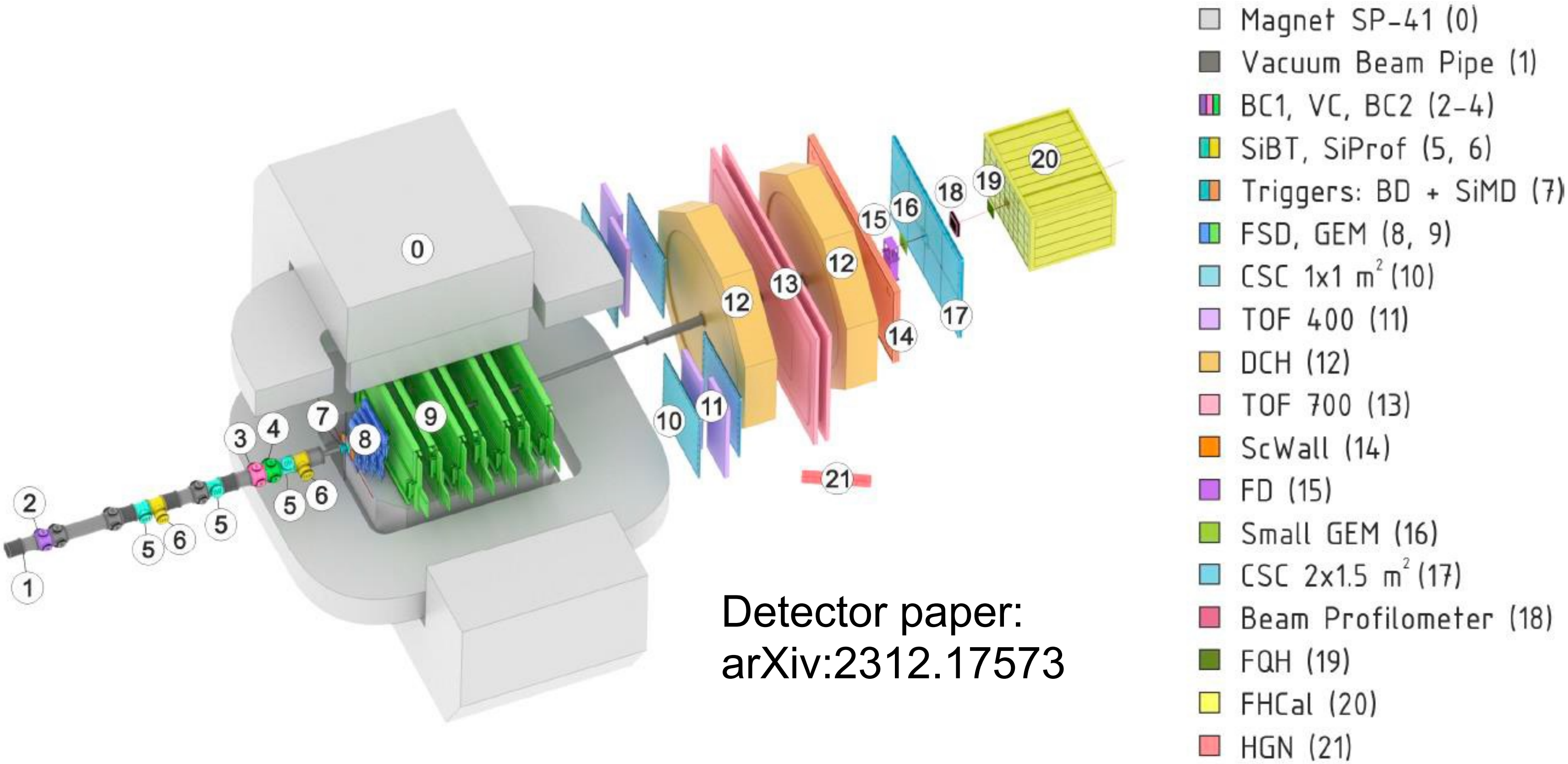
- 9 m long, 6m diameter
- Low material budget
- Good tracking and powerful pid

- Tracking (TPC):
  up to |η|<1.5, 2π in azimuth
- PID (TOF, TPC, ECAL):
  hadrons, e, γ
- Event characterization (FHCAL):
  centrality & event plane



BM@N

Baryonic matter at he Nuclotron - Fixed target experiment

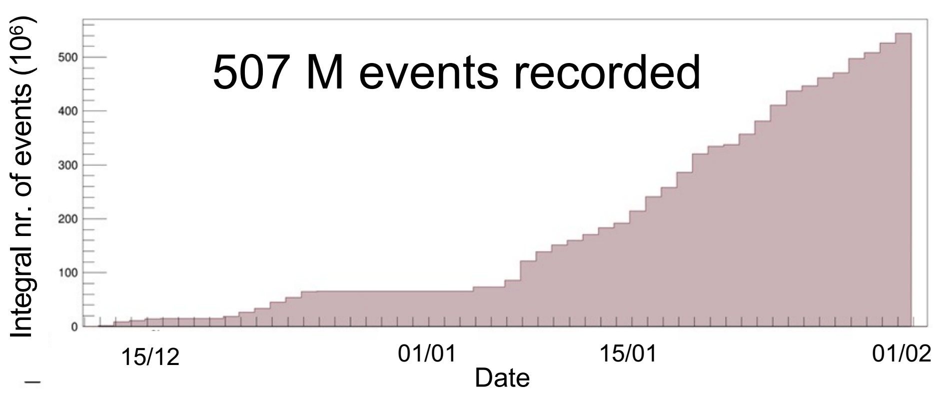


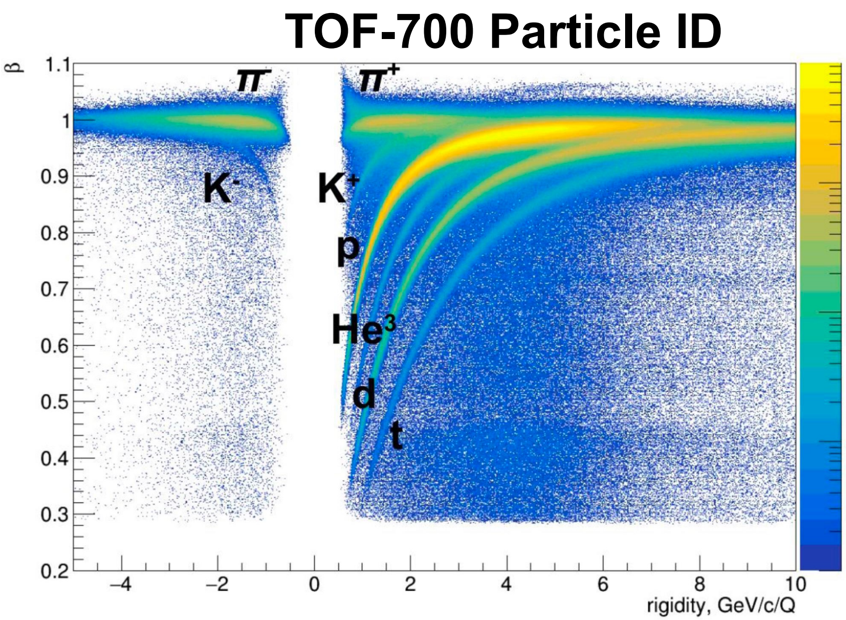
Detector paper:
arXiv:2312.17573

BM@N

Baryonic matter at the Nuclotron - Fixed target experiment

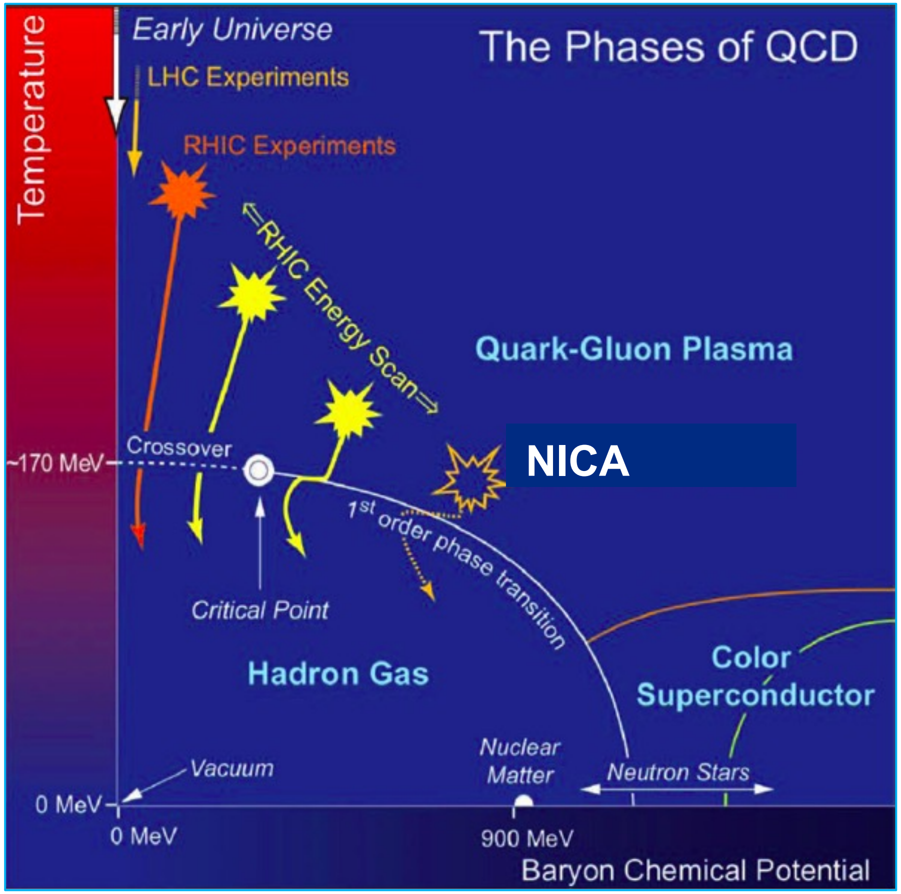
- Fully operational
- First HI physics run with limited configuration using a 3.2 AGeV Ar beam on C, Al, Cu, Sn and Pb targets in 2018.
- First physics run with a 3.6 AGeV Xe beam on a CsI target Nov. 22 – Jan 23. Collected a total of 507 M events
- Smooth operation of Booster + Nuclotron over weeks.
- Ar and Xe Data analysis in progress





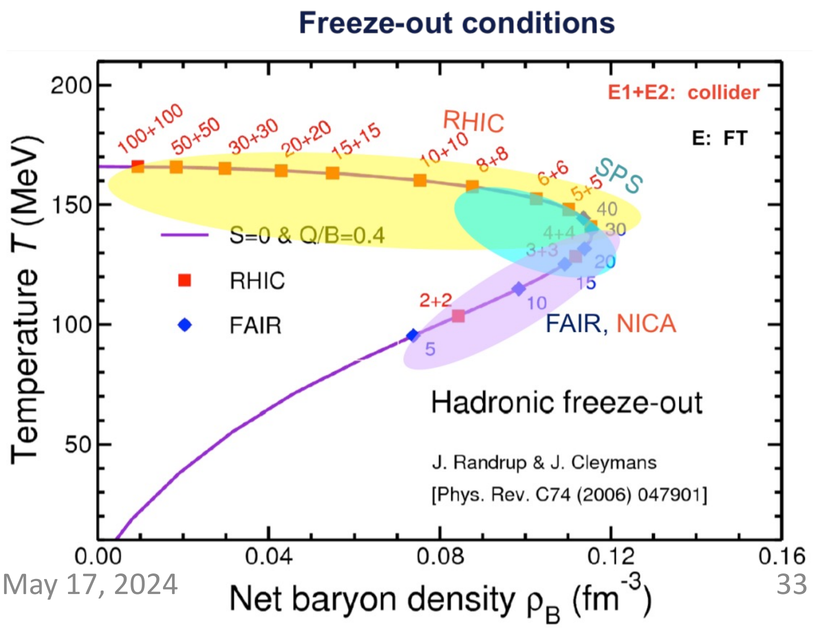
NICA's scientific mission

QCD phase diagram



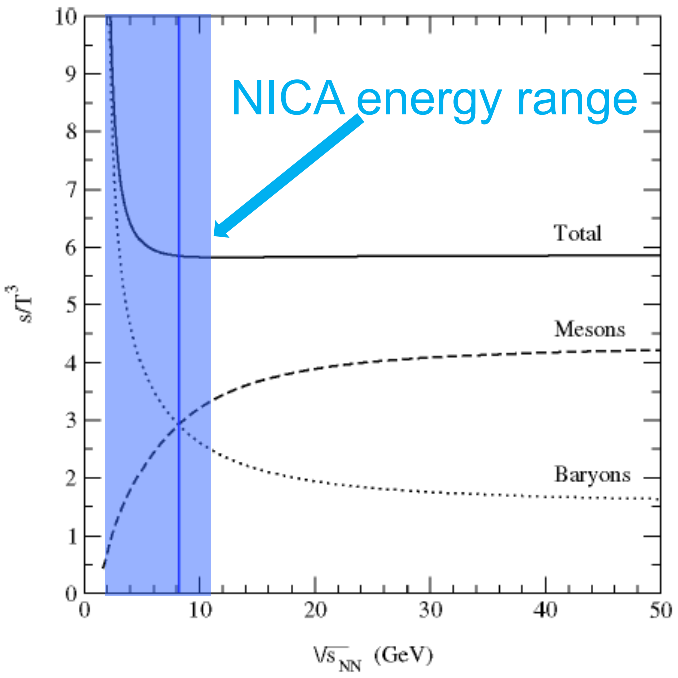
- Explore the QCD phase diagram in the region of high net baryon density or equivalently high baryon chemical potential μ_B.

- Search for the conjectured critical point and first order phase transition

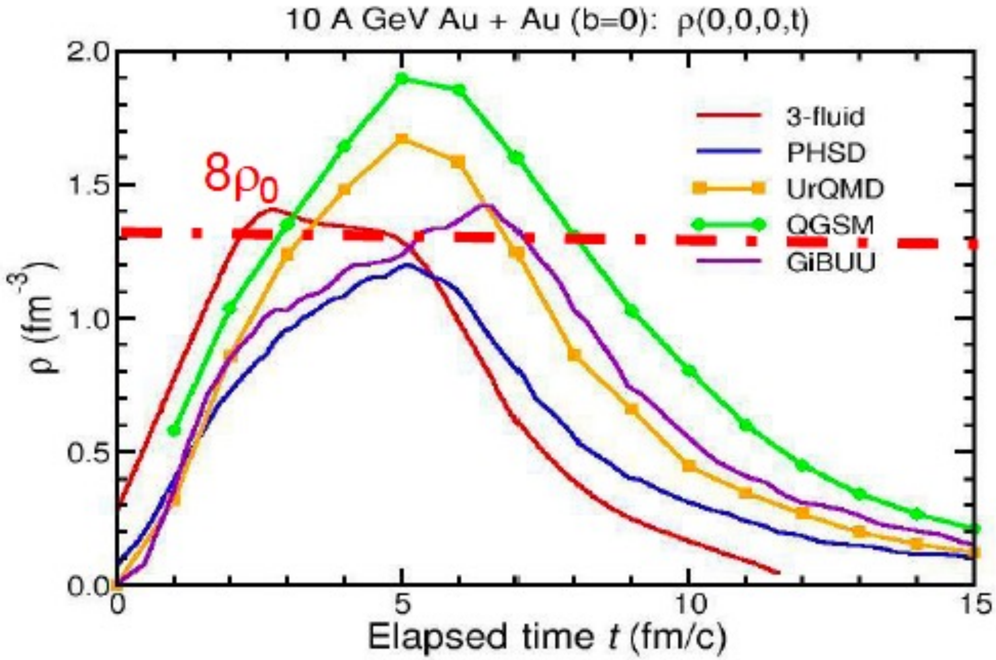


QCD matter at NICA energies

J. Cleymans et al., PLB 615, 50 (2005)



PRC 75, 034902 (2007)



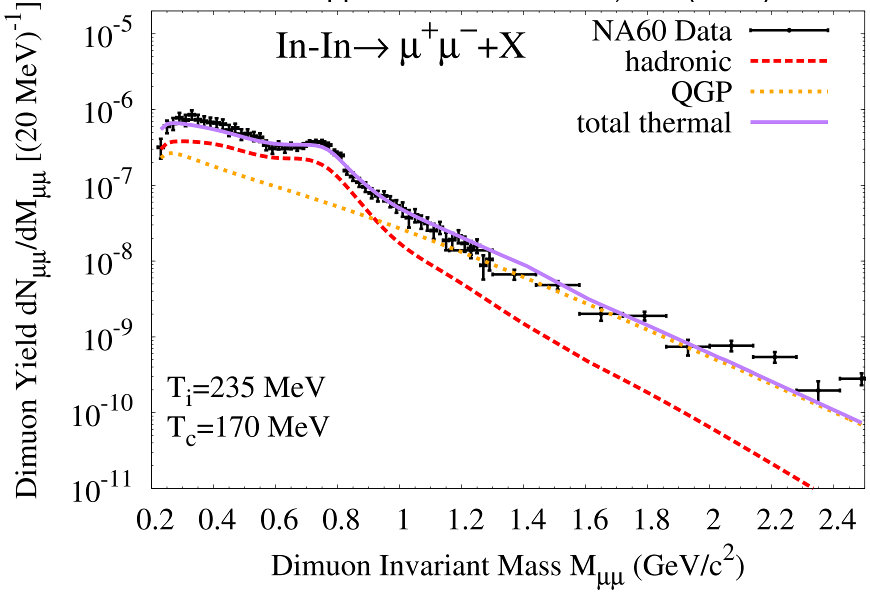
- ❑ NICA energy range brackets the transition from baryon to meson dominated matter

- ❑ Sizable densities up to O($10\rho_0$)
- ❑ Long lifetime

Dileptons (I)

- All HI systems at all energies studied show an excess of dileptons wrt to hadronic sources

NA60 data: Eur. Phys. J. C61, 711 (2009)
Curves: Rapp and Hees PLB 753, 586 (2016)

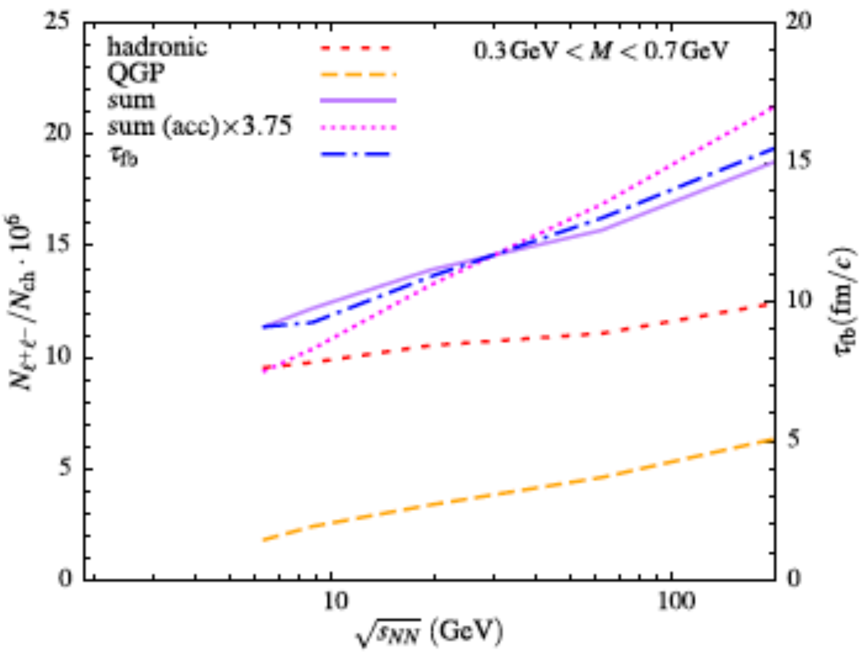


- LMR: Thermal radiation from HG - $\pi^+\pi^- \to \rho \to \mu^+\mu^-$ – linked to CSR
- IMR: Thermal radiation from QGP - $\bar{q}q \to \mu^+\mu^-$ – evidence of deconfinement
- Onset of deconfinement? Onset of CSR? Energy scan of dilepton excess

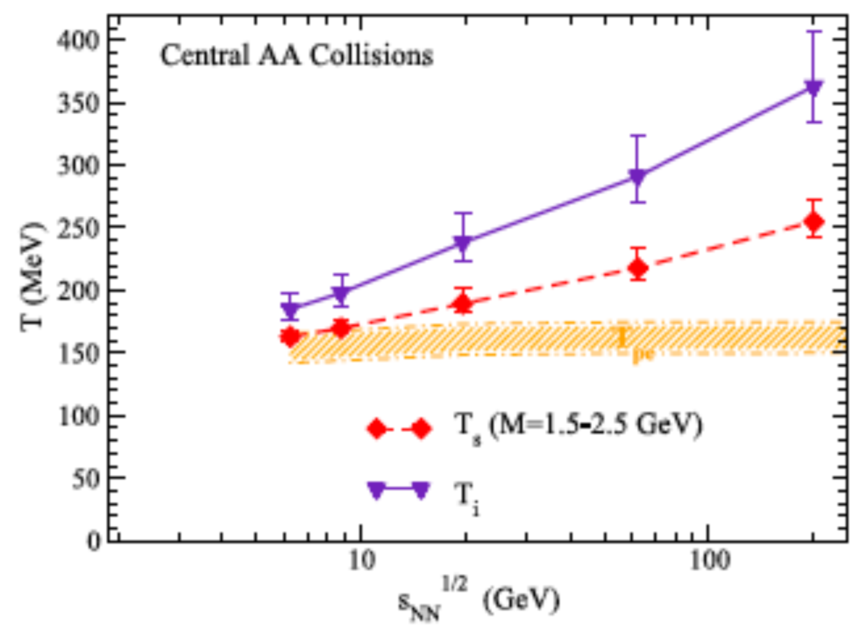
Dileptons - Onset of deconfinement and chiral symmetry restoration (II)

- ❑ Onset of deconfinement? Onset of CSR? Energy scan of dilepton excess
  - Integrated yield in the LMR tracks the fireball lifetime
  - Inverse slope of the mass spectrum in the IMR provides a measurement of <T> First order phase transition?
  - Thermal radiation down to $\sqrt{s_{NN}}$ – 6 GeV ?

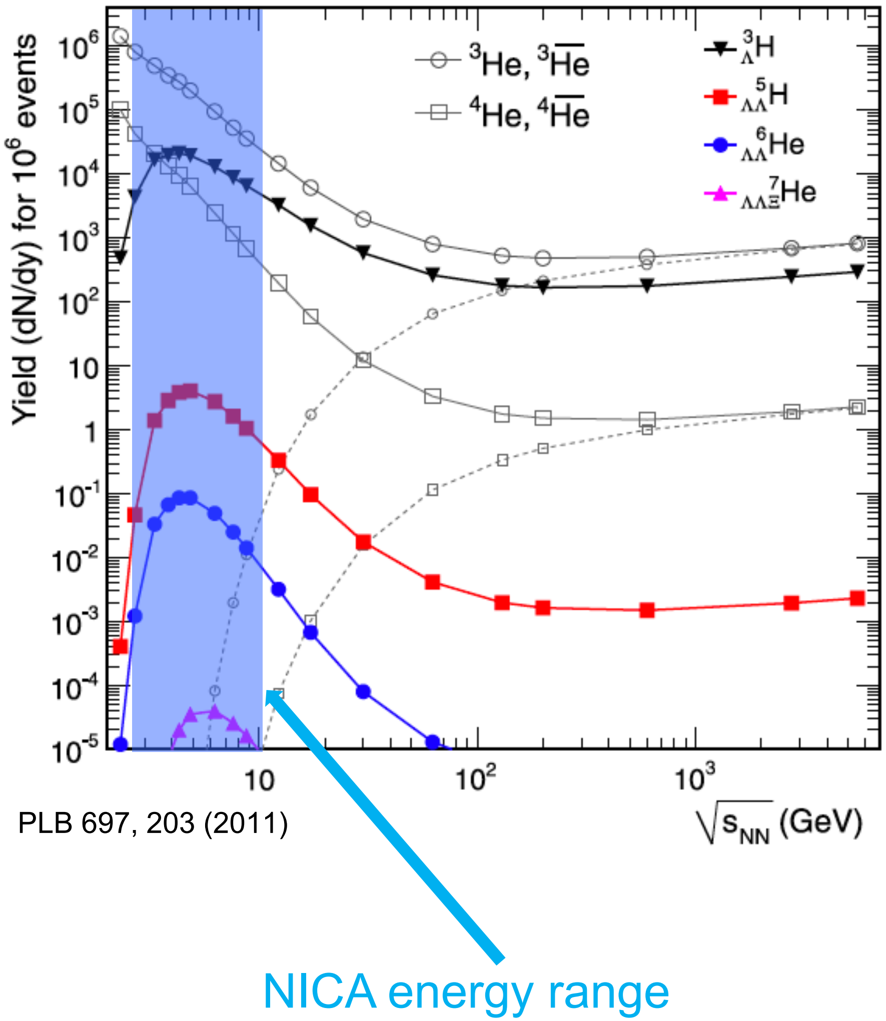
LMR as chronometer



IMR as thermometer



Hyperons and Hypernuclei

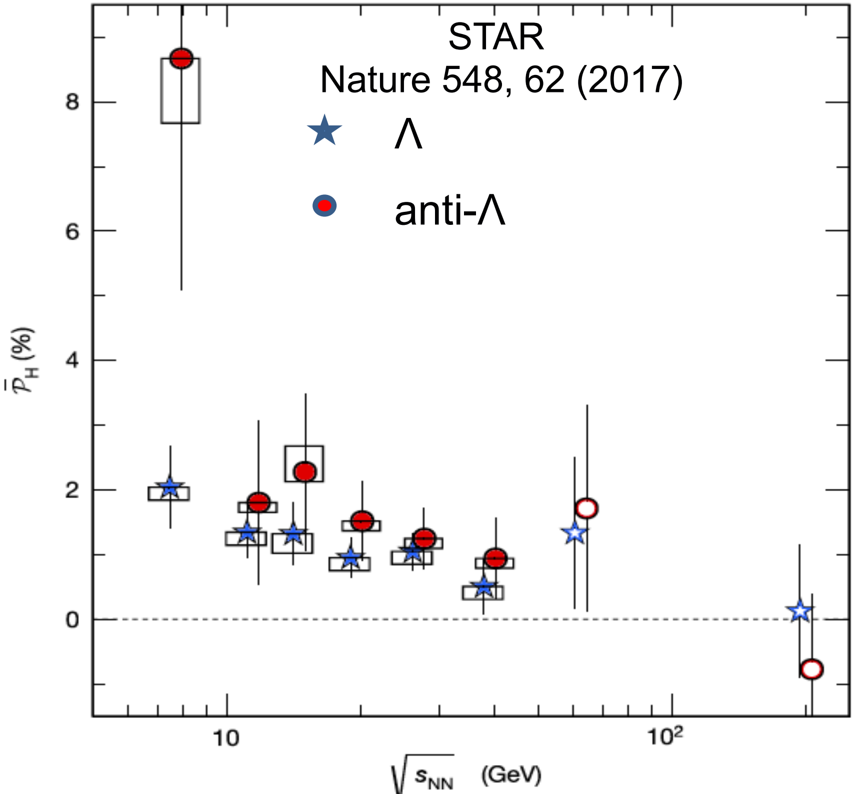


PLB 697, 203 (2011)

- Maximum production of hypernuclei in the NICA energy range.
- Access the hyperon-nucleon and hyperon-hyperon interactions at high baryon density.
- Valuable insight into the particle interactions that may take place in the inner cores of neutron stars.
- Sub-threshold production of multistrange (anti-)hyperons via sequential collisions.

Global Polarization

- Non-central collisions have angular momentum of the order of 1000 hbar.
- Spin-orbit coupling can lead to preferential orientation of particle spins along the global angular momentum.



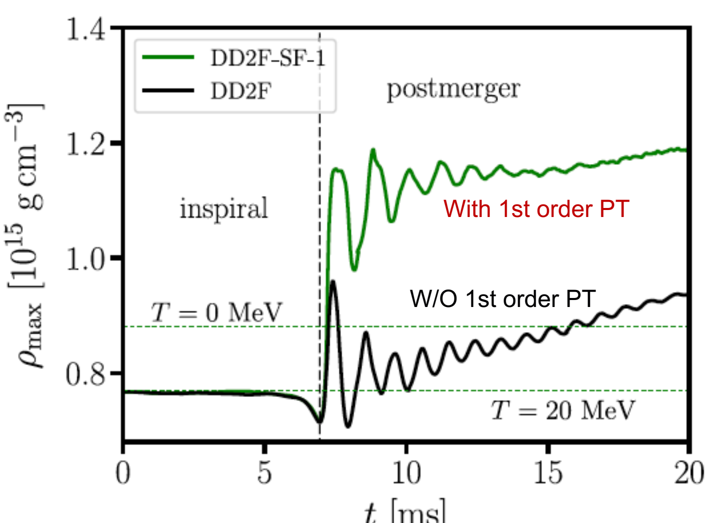
- Global polarization of Λ and anti-Λ
  - ➢ First experimental evidence of vorticity in heavy-ion collisions
  - ➢ Insights into initial conditions and dynamics of the fluid formed in these collisions
  - ➢ Expected to be high at the NICA energies

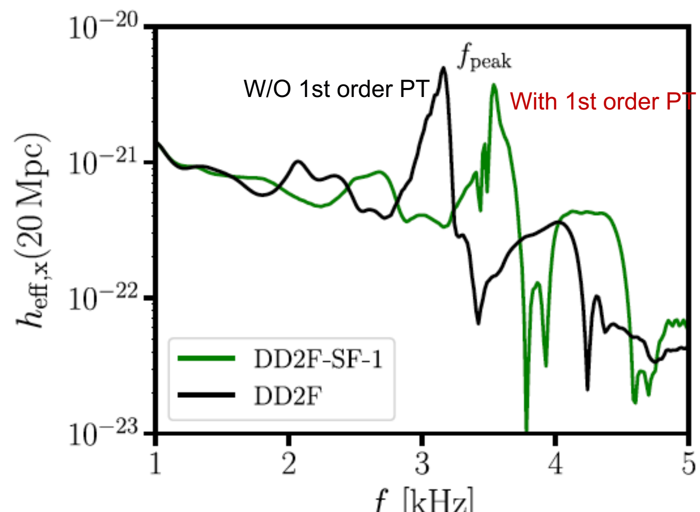
Synergy with Multi-Messanger Astronomy

- Model calculations show that in heavy-ion collisions in the NICA energy range, nuclear matter reaches densities and temperatures similar to those occurring in a neutron star merger .
- Heavy-ion collisions at NICA and neutron star mergers probe similar regions of the QCD phase diagram.

- Simulations show that the GW signal could provide clear signature of a first order quark-hadron phase transition. Such finding would necessarily imply the existence of a CP in the QCD phase diagram.

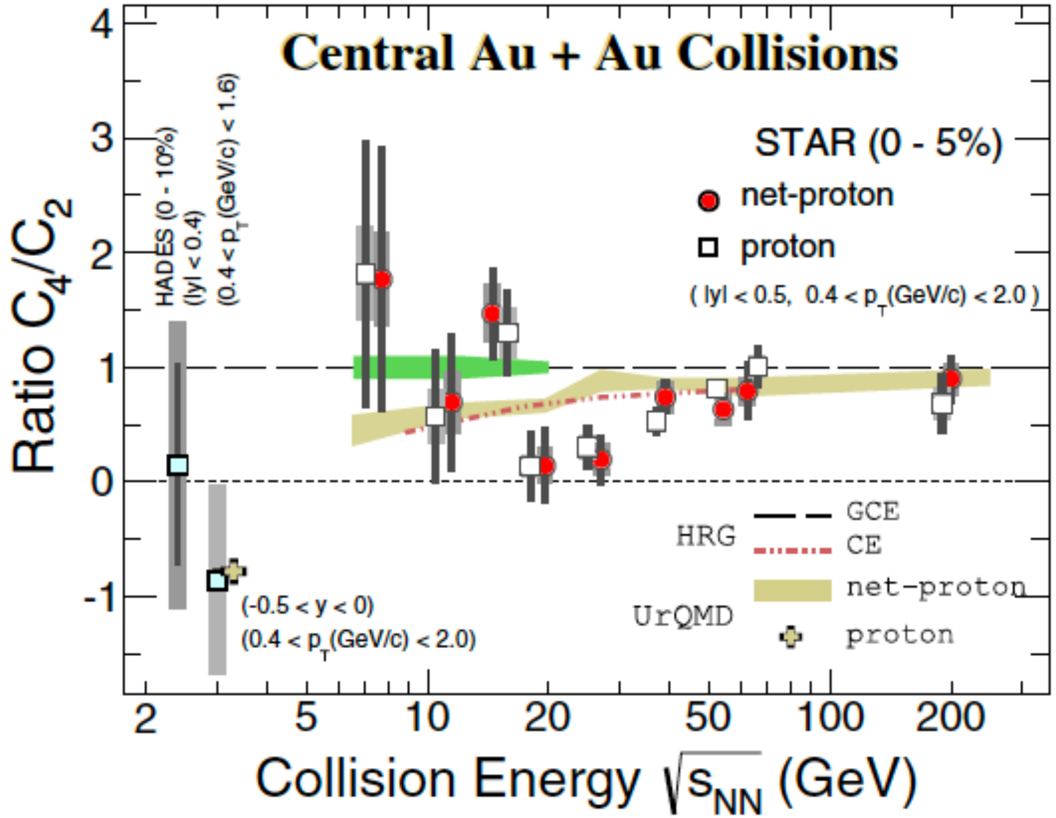
PRL, 122, 061102 (2019)





Net proton fluctuations

PRL 128, 202303 (2022)



- Intriguing non-monotonic behavior of the fourth-order net-proton cumulant observed by STAR in the RHIC BES.
- Not reproduced by non-critical models.
- High precision data needed

MPD Physics programme

Organized and developed in 5 Physics Working Groups

Global observables

- Total event multiplicity
- Total event energy
- Centrality determination
- Total cross-section
- Event plane measurement at all rapidities
- Spectator measurement

Spectra of light flavor and hypernuclei

- Light flavor spectra
- Hyperons and hypernuclei
- Particle yields and yield ratios
- Kinematic and chemical freeze-out
- QCD Phase Diagram

Correlations and Fluctuations

- Collective flow
- Vorticity, Λ polarization
- E-by-E fluctuation of multiplicity, momentum and conserved quantities
- Femtoscopy
- Forward-Backward corr.

Electromagnetic probes

- Dilepton spectra in low and intermediate mass regions:
  - * In-medium modification of resonances
  - * Onset of deconfinement
  - * Onset of Chiral Symmetry restoration
- Photons in ECAL and central barrel

Heavy flavor

- Open charm production
- Charmonium with ECAL and central barrel
- Charmed meson through secondary vertices in ITS and HF electrons
- Threshold charm production

Summary

- ❖ NICA's energy range allows the systematic study of the QCD phase diagram in the high net baryon density region.

- ❖ Many interesting questions with discovery potential:
  - ➢ critical point, first order ohase transition?
  - ➢ onset of deconfinement and chiral symmetry restoration
  - ➢ hyperons and hypernuclei
  - ➢ global polarization
  - ➢ synergy with multi-messanger astronomy
  - ➢ Fluctuations

  ….

- ❖ First collisions expected in less than one year

- ❖ Excellent time to join the experimental program

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Thank you!