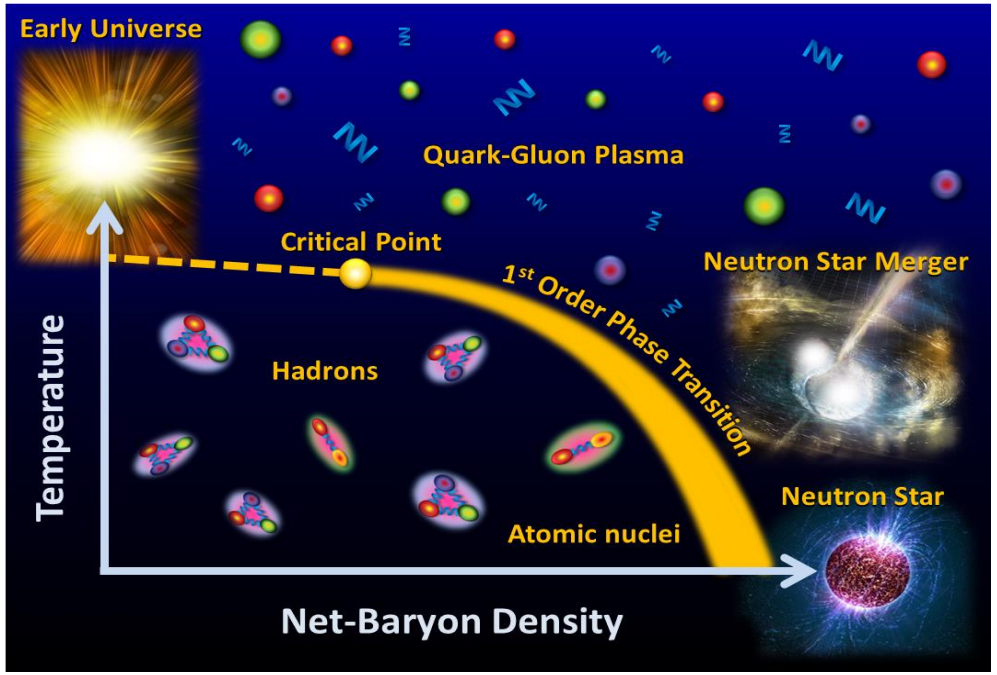
Эксперимент MPD (NICA)



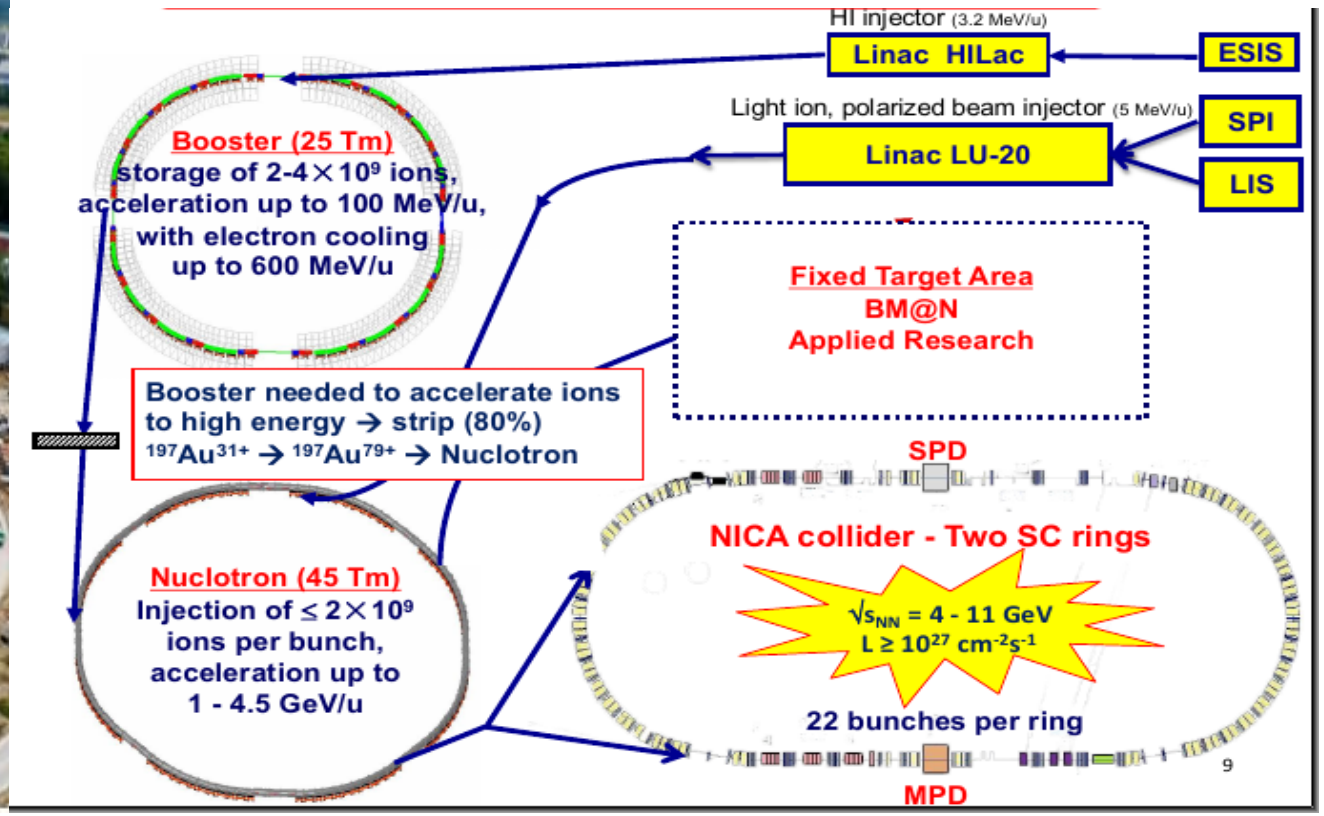


Аркадий Владимирович Тараненко (ataranenko@jinr.ru)

Весенняя школа по физике кварк-глюонной материи (КГМ-2026),
10 – 14 Апреля 2026 года, УНЦ ОИЯИ

Ускорительный комплекс NICA (ЛФВЭ, ОИЯИ, Дубна)

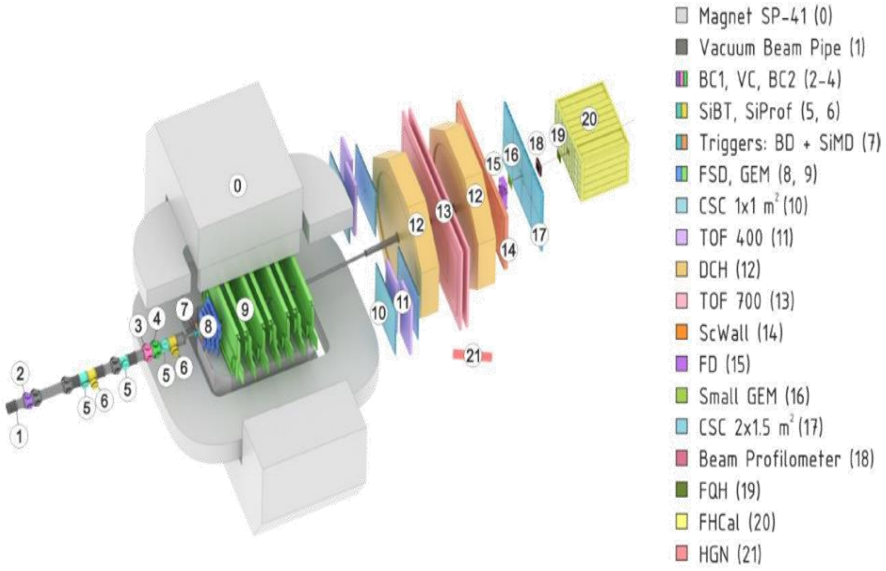




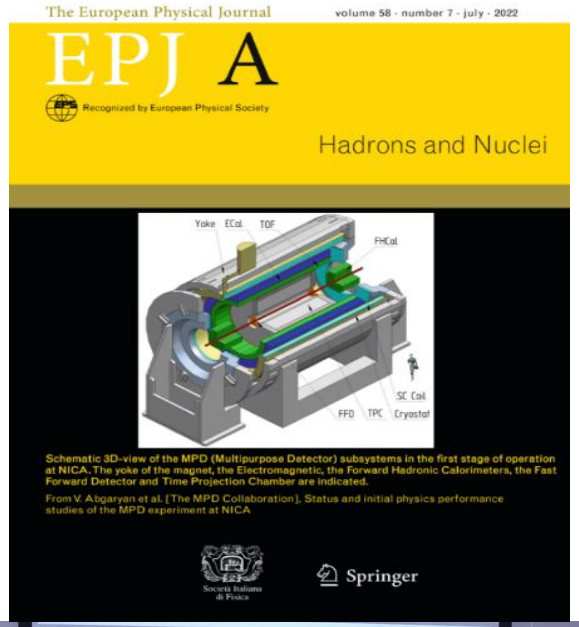
- Мегапроект NICA (Nuclotron based Ion Collider fAcility) - сверхпроводящий коллайдер протонов и тяжёлых ионов, строящийся на базе Лаборатории физики высоких энергий (ЛФВЭ, ОИЯИ), окончание строительства: 2026
  - BM@N (“Барионная материя на Нуклотроне “) – Nuclotron, с 2018 года (физика с 2023 года)
  - MPD (“Многоцелевой Детектор“) - коллайдер NICA, 2026 год
  - SPD (“Детектор Спиновой Физики“) - коллайдер NICA, 2030-2035 год?
  - ARIADNA – Инфраструктура для прикладных исследований с использованием пучков тяжелых ионов, Nuclotron, с 2022 года.

NICA: BM@N and MPD Collaborations

The BM@N spectrometer at the NICA accelerator complex
Nucl.Instrum.Meth.A 1965 (2024) 169352



Status and initial physics performance studies of the MPD experiment at NICA , Eur.Phys.J.A 58 (2022) 7, 140



BM@N: ~214 participants из 13 institutes, 5 countries



MPD: ~500 participants из 38 institutes, 12 countries



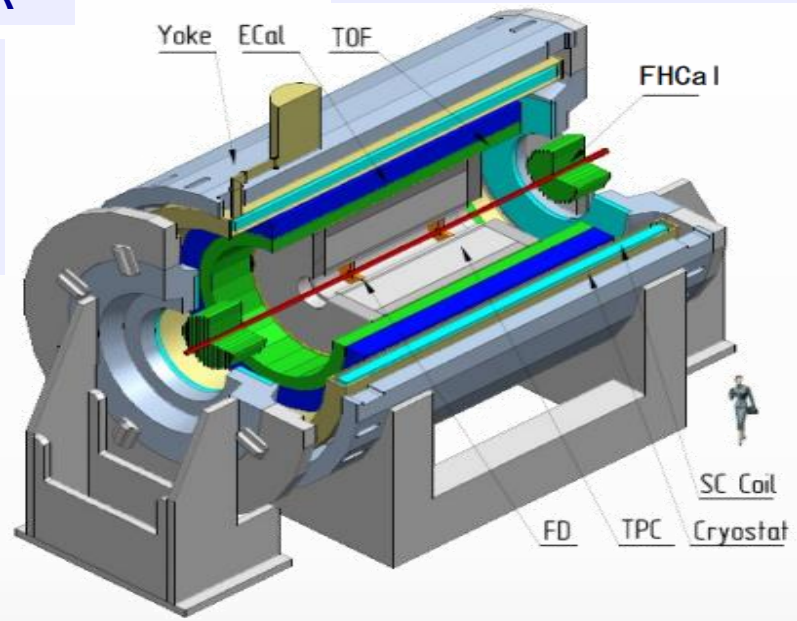
Multi-Purpose Detector (MPD) Collaboration

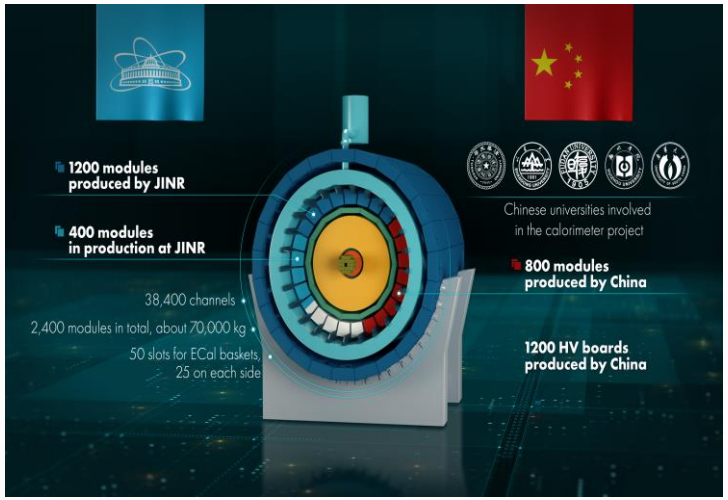
12** Countries, **>500** participants, **38** Institutions and **JINR

MPD** International Collaboration was established in **2018

Organization

Acting Spokesperson:	***Victor Riabov***
Deputy Spokespersons:	***Zebo Tang, Arkadiy Taranenko***
Institutional Board Chair:	***Alejandro Ayala***
Project Manager:	***Slava Golovatyuk***





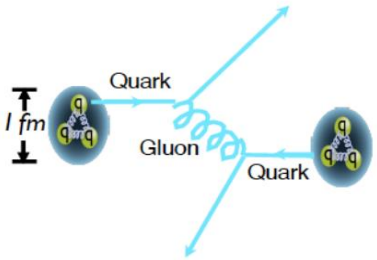
***Joint Institute for Nuclear Research**;*
*A.Alikhanyan National Lab of Armenia, Yerevan, **Armenia;***
*Institute for Nuclear Problems of Belarusian State University, **Belarus**;*
*Institute of Power Engineering of the NAS of Belarus, **Belarus**;*
*University of Plovdiv, **Bulgaria;***
*Tsinghua University, Beijing, **China**;*
*University of Science and Technology of China, Hefei, **China**;*
*Huzhou University, Huizhou, **China**;*
*Institute of Nuclear and Applied Physics, CAS, Shanghai, **China**;*
*Central China Normal University, **China**;*
*Shandong University, Shandong, **China**;*
*University of Chinese Academy of Sciences, Beijing, **China**;*
*University of South China, **China**;*
*Three Gorges University, **China**;*
*Institute of Modern Physics of CAS, Lanzhou, **China**;*
*Egyptian Center for Theoretical Physics, **Egypt**;*
*Tbilisi State University, Tbilisi, **Georgia**;*
*Institute of Physics and Technology, Almaty, **Kazakhstan**;*
*Instituto de Ciencias Nucleares, UNAM, **Mexico**;*
*Universidad Autónoma de Sinaloa, **Mexico**;*
*Universidad Autónoma Metropolitana, **Mexico**;*
*Universidad de Colima, **Mexico**;*
*Universidad Michoacana de San Nicolás de Hidalgo, **Mexico**;*
*Institute of Physics and Technology, **Mongolia**;*

*Belgorod National Research University, **Russia**;*
*High School of Economics University, Moscow, **Russia;***
*Institute for Nuclear Research of the RAS, Moscow, **Russia**;*
*National Research Nuclear University MEPhI , Moscow, **Russia**;*
*Moscow Institute of Science and Technology, **Russia**;*
*North Ossetian State University, **Russia**;*
*National Research Center "Kurchatov Institute", **Russia**;*
*National Research Tomsk Polytechnic University, **Russia**;*
*Peter the Great St. Petersburg Polytechnic University Saint Petersburg, **Russia**;*
*Plekhanov Russian University of Economics, Moscow, **Russia**;*
*St.Petersburg State University, **Russia**;*
*Skobeltsyn Institute of Nuclear Physics, Moscow, **Russia**;*
*Petersburg Nuclear Physics Institute, Gatchina, **Russia**;*
*Vinča Institute of Nuclear Sciences, **Serbia**;*
*Pavol Jozef Šafárik University, Košice, **Slovakia***

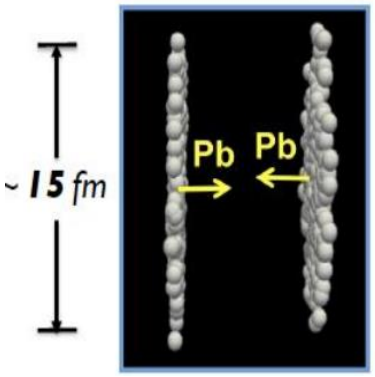


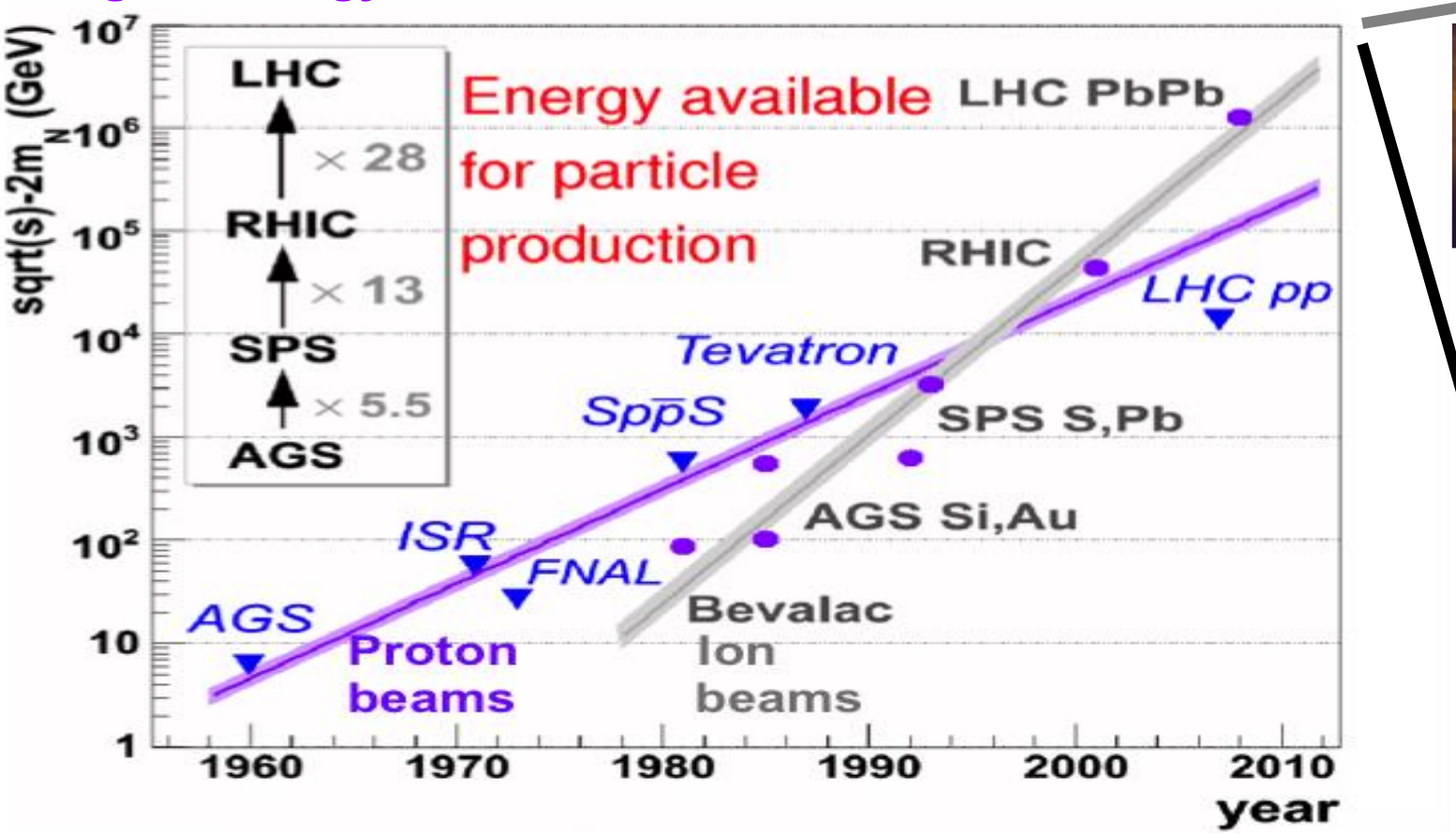
p+p and A+A collisions

HEP: concentrate higher energy in smaller and smaller volume.

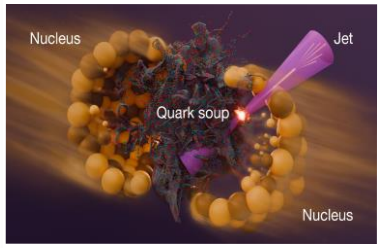


$V \gg 1\text{fm}^3$





LHC



Beam Energy Scan programs:

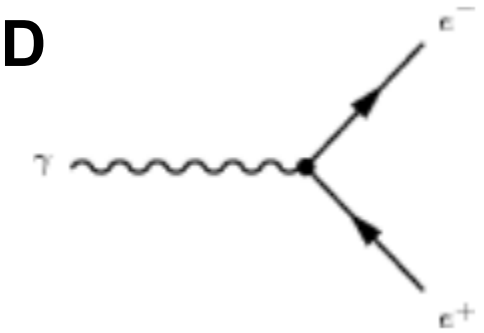
STAR (RHIC)
NA61 (SPS)
HADES (SIS18)

MPD (NICA)
BM@N (NICA)
CBM (FAIR)
CEE(HIAF)
NA60+(SPS)
JPARC-HI

RHIC: distribute high energy or high nucleon density over a relatively large volume

Condensed matter phenomena at extreme conditions: Physics of Complex Systems

QED

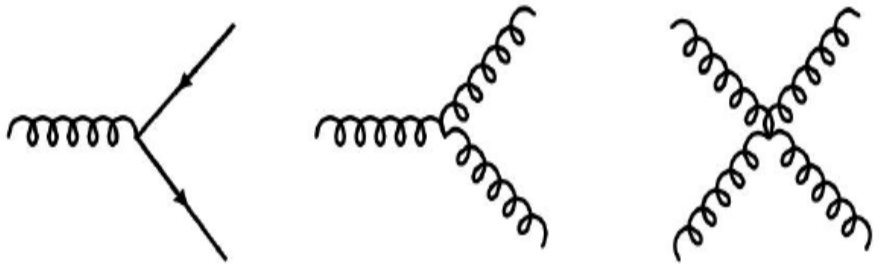


?

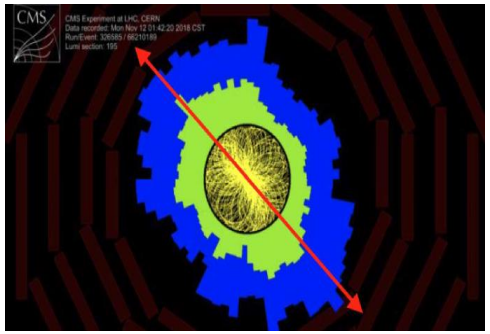


Superconductivity

QCD



?



Anisotropic flow
In HIC at LHC

- Given constituents and dynamics of elementary systems, what is the behaviour of complex systems?
-What are the possible states of matter and how can they be specified?
- How do transitions from one state of matter to another occur?
- Is there a general pattern of critical phenomena, independent of specific dynamics?

Helmut Satz (The Quark-Gluon Plasma, Four Lectures, 2011)

Even a fully unified fundamental theory does not solve the issue of complex systems, of the states of matter...

Normal Nuclear Matter / Units in this lecture

- **Heavy nuclei have an almost constant density.**
- **Normal nuclear matter density:**

  $\rho_0 = A / V_N \quad V_N = 4/3\ \pi R^3 \quad R = r_0 A^{1/3} \quad r_0 \sim 1.15$ 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:

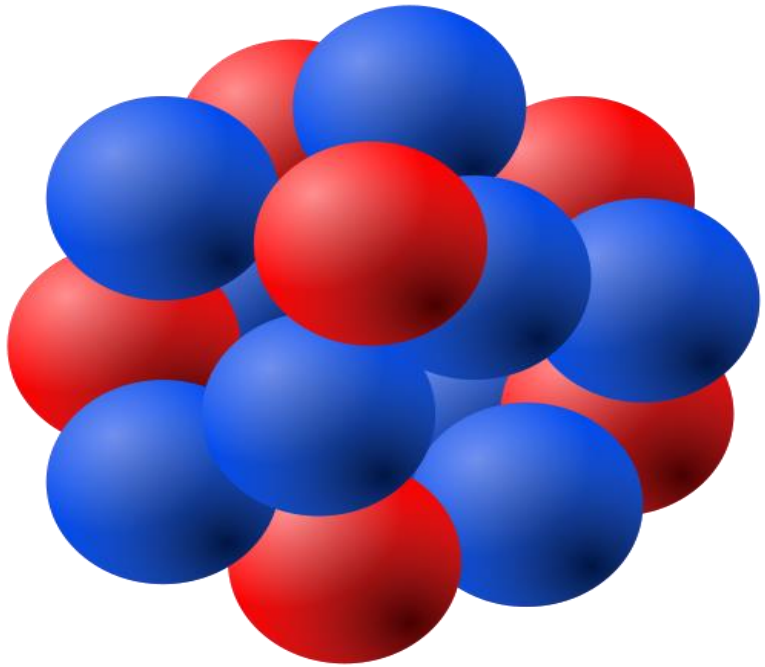
  $f = A v_n / V_N \quad v_n = 4/3\ \pi r_n^3$

  $r_n \sim 0.84$ fm (charge radius of the proton)

  ~ 0.38

  → **~60% of the nuclear volume is empty!**
- **When nuclei are compressed, eventually nucleons start to overlap**

  $\rho_c = 1/(4/3\ \pi r_n^3) \sim 3\ \rho_0$



Units:

Energy and momentum: GeV

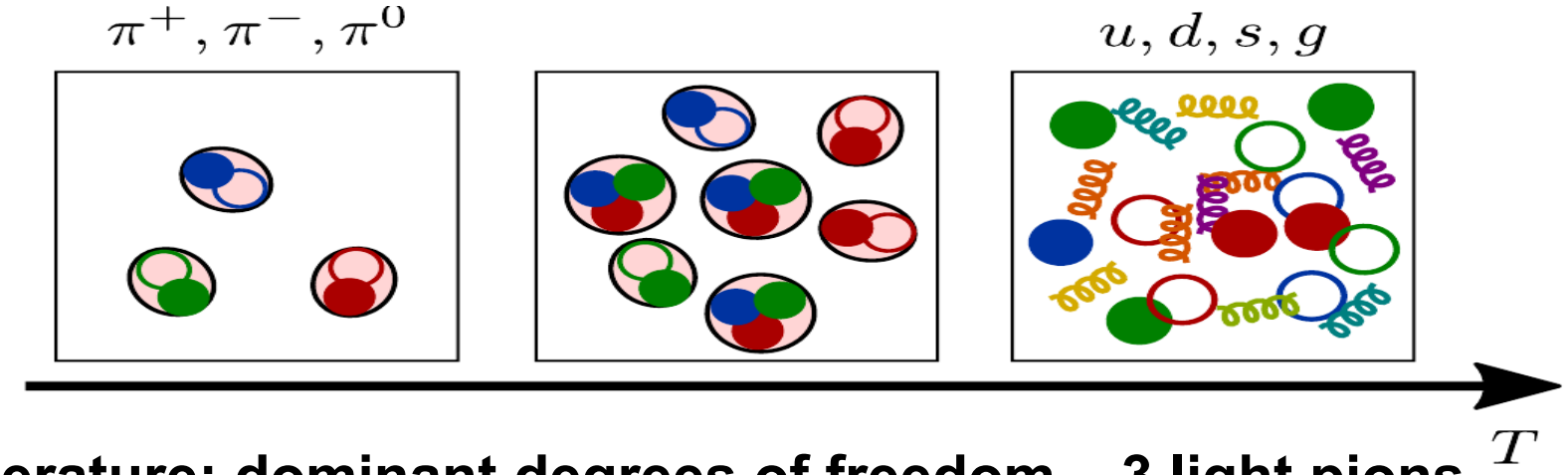
Length: fm ("Fermi") 1 fm = 10^{-15} m

Time: fm/c 1 fm/c = 0.33 10^{-23} s

Temperature: in energy units, i.e. $k_B T$ with $k_B = 8.617\ 10^{-5}$ eV/K

Equation of state of QCD matter at low and high temperatures

Consider baryon symmetric matter (baryon chemical potential μB = 0) at temperature T .
What is energy density *e* dependence on T ?



Low temperature: dominant degrees of freedom – 3 light pions

$$\text{energy density} \quad e = \nu_\pi \int \frac{d^3p}{(2\pi)^3} \frac{p}{e^{p/T} - 1} = \frac{\pi^2}{30}(3)T^4 \approx T^4.$$

High temperature: free gas of 3 massless quarks (up, down, strange) and gluons

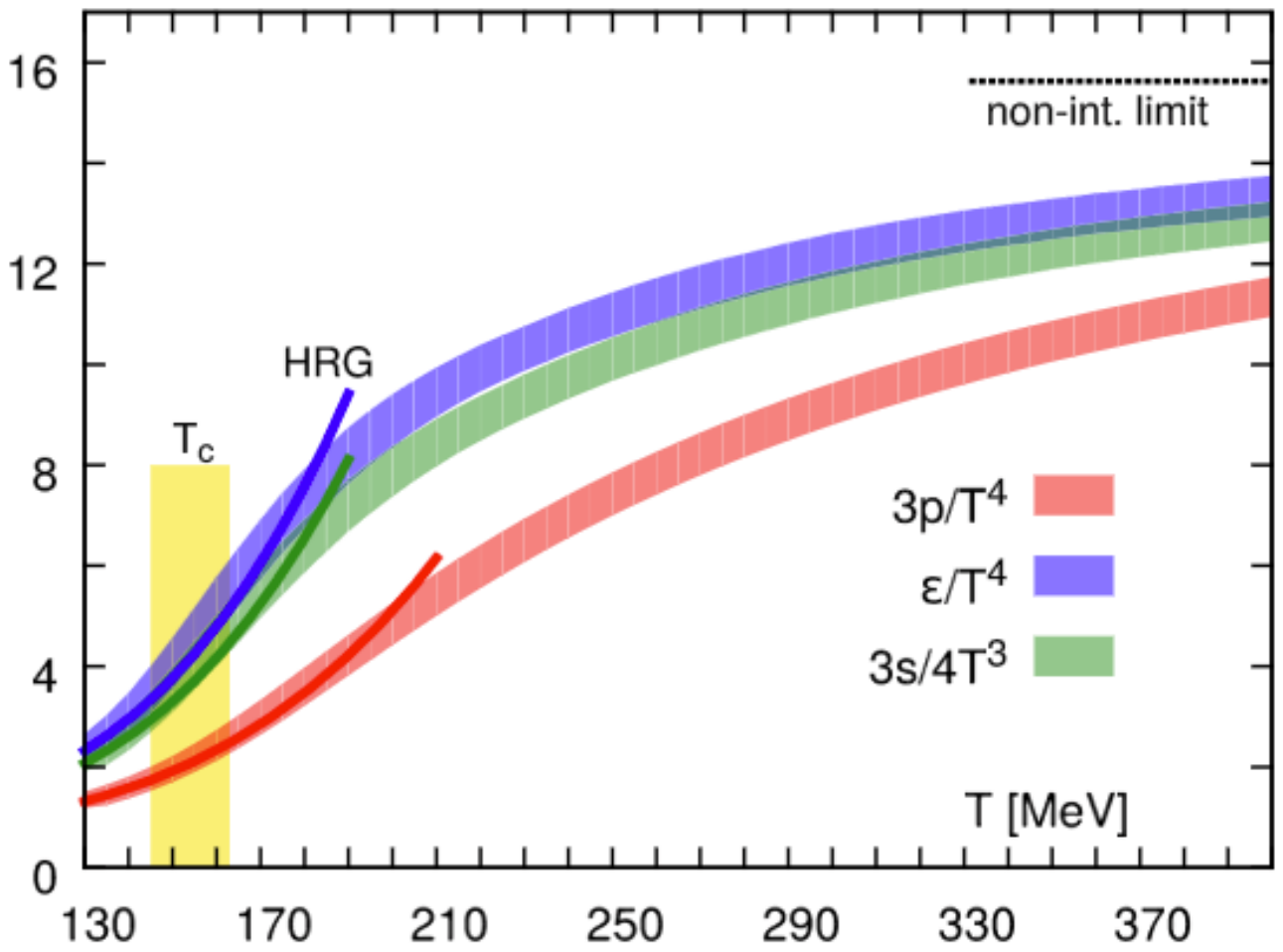
$$e = \frac{\pi^2}{30}\Big(\underbrace{2}_{\text{polarization}} \times \underbrace{8}_{\text{colour}} + \underbrace{2}_{\text{anti-/particle}} \times \underbrace{2}_{\text{spin}} \times \underbrace{3}_{\text{colour}} \times \underbrace{3}_{\text{flavour}} \frac{7}{8}\Big) T^4 \approx 16T^4.$$

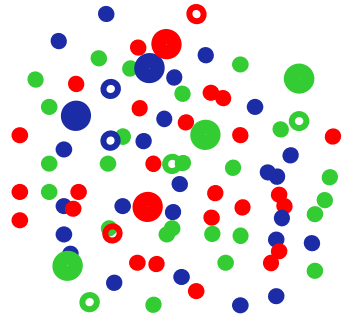
Phase transition in Lattice QCD

Energy density ε
Pressure p
Entropy density s

Critical temperature
$T_c \approx 156$ +/- 9 MeV

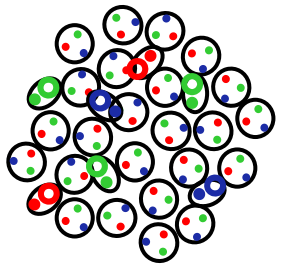
[PRD 90 094503 (2014)]





deconfined:
many d.o.f

confined:
few d.o.f.



$\varepsilon_c = 0.42 \pm 0.06$ GeV/fm^3

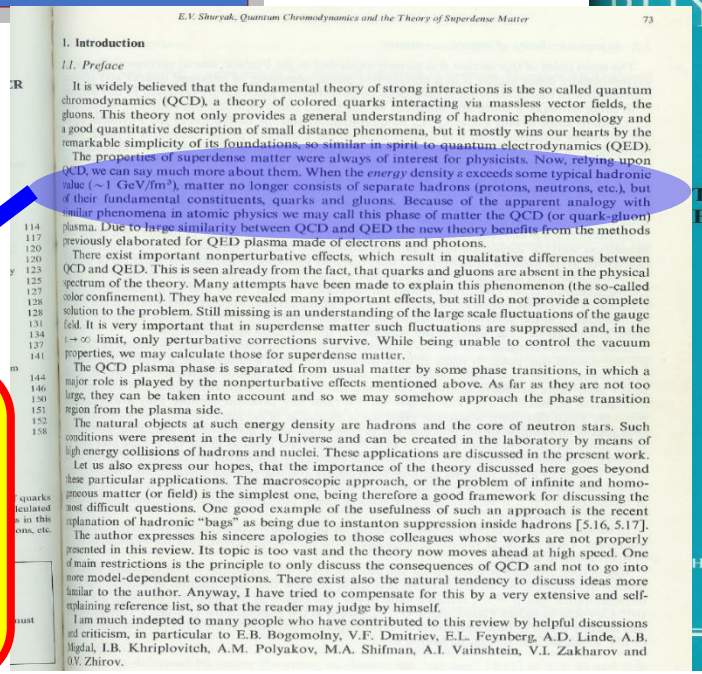
Crossover transition at $T_c \approx 156$ MeV $\approx 2 \cdot 10^{12}$ K $\approx 130{,}000 \cdot T$ [Sun's core]

Quark Gluon Plasma – coining of a name

E.V. SHURYAK

Institute of Nuclear Physics, Novosibirsk, USSR

First review on QCD at extreme density conditions, Physics Reports 1980



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.

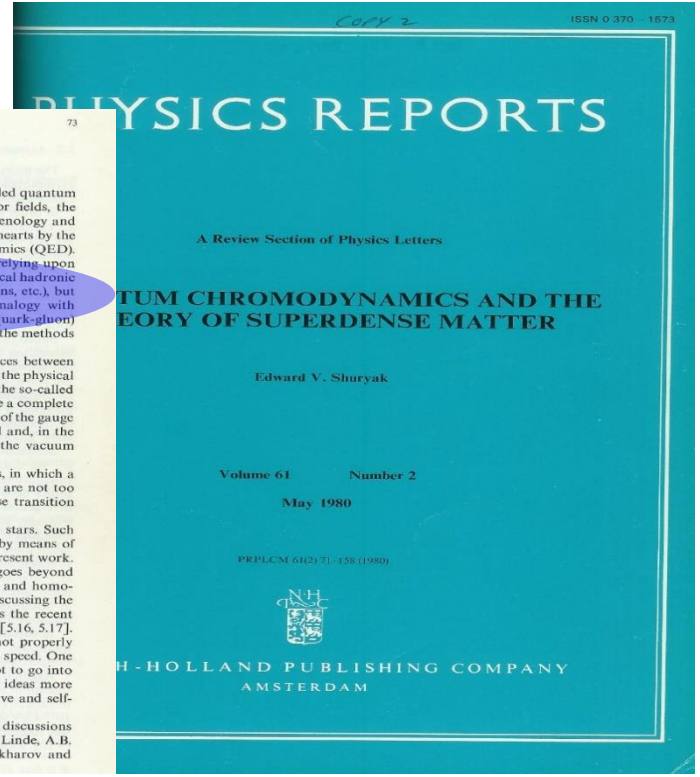
The QCD plasma phase is separated from usual matter by some phase transitions, in which a major role is played by the nonperturbative effects mentioned above. As far as they are not too large, they can be taken into account and so we may somehow approach the phase transition region from the plasma side.

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 familar 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.



ISSN 0370-1573

PHYSICS REPORTS

A Review Section of Physics Letters

TUM CHROMODYNAMICS AND THE EORY OF SUPERDENSE MATTER

Edward V. Shuryak

Volume 61 Number 2

May 1980

PRPLCM 61(2) 71–158 (1980)

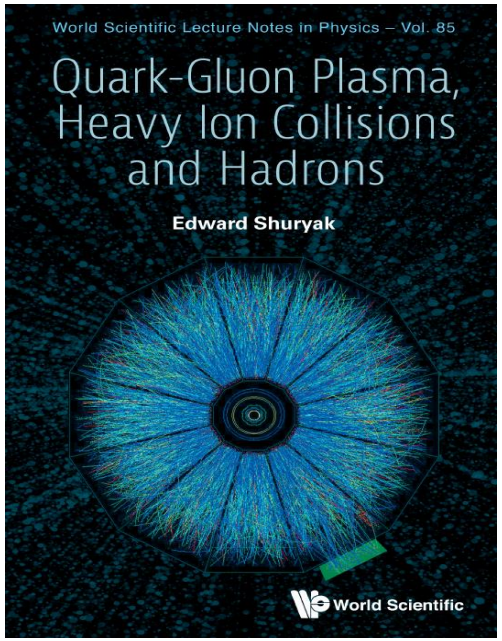
H-HOLLAND PUBLISHING COMPANY

AMSTERDAM

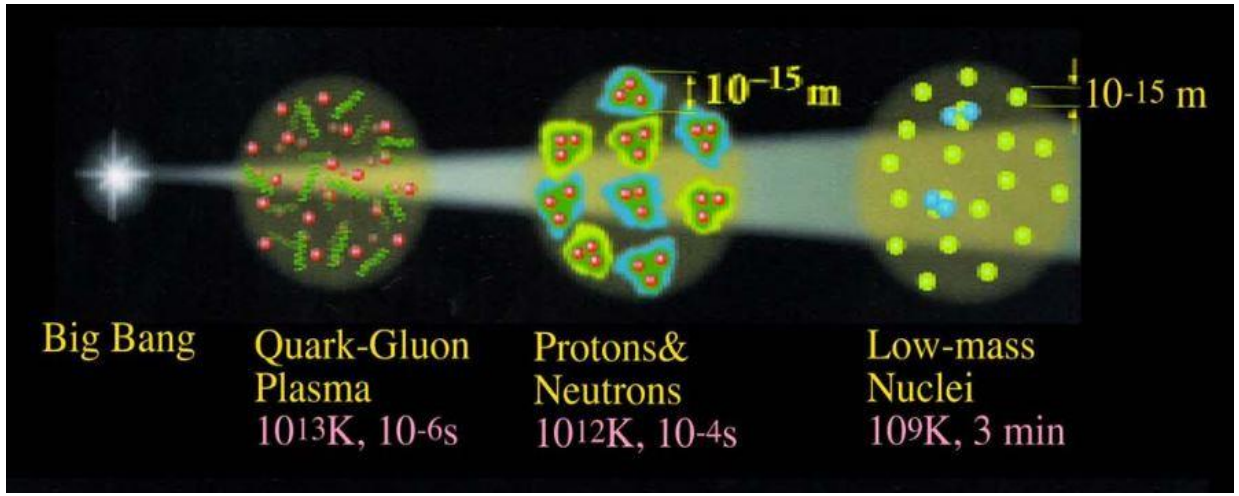
"Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the QCD

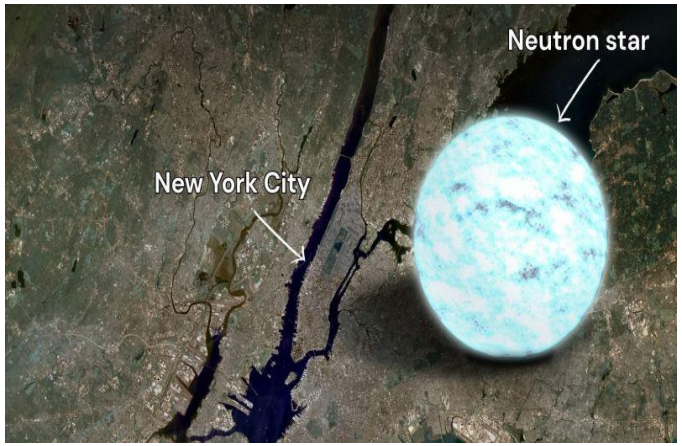
(or quark-gluon) plasma."





Big Bang vs Little Bang / QGM in Neutron Stars

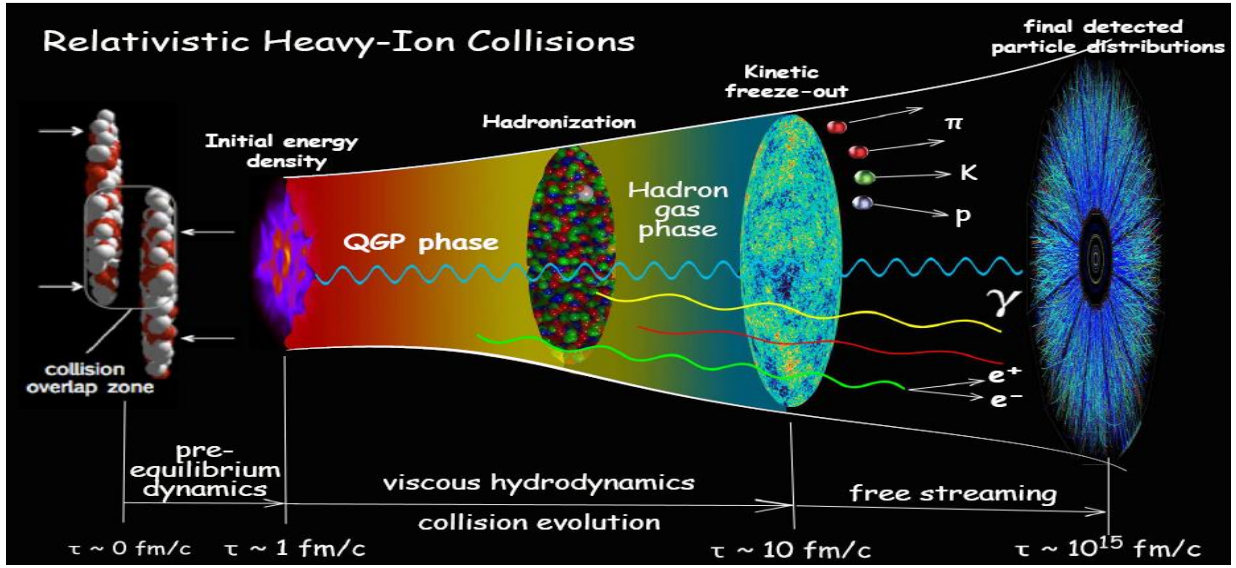


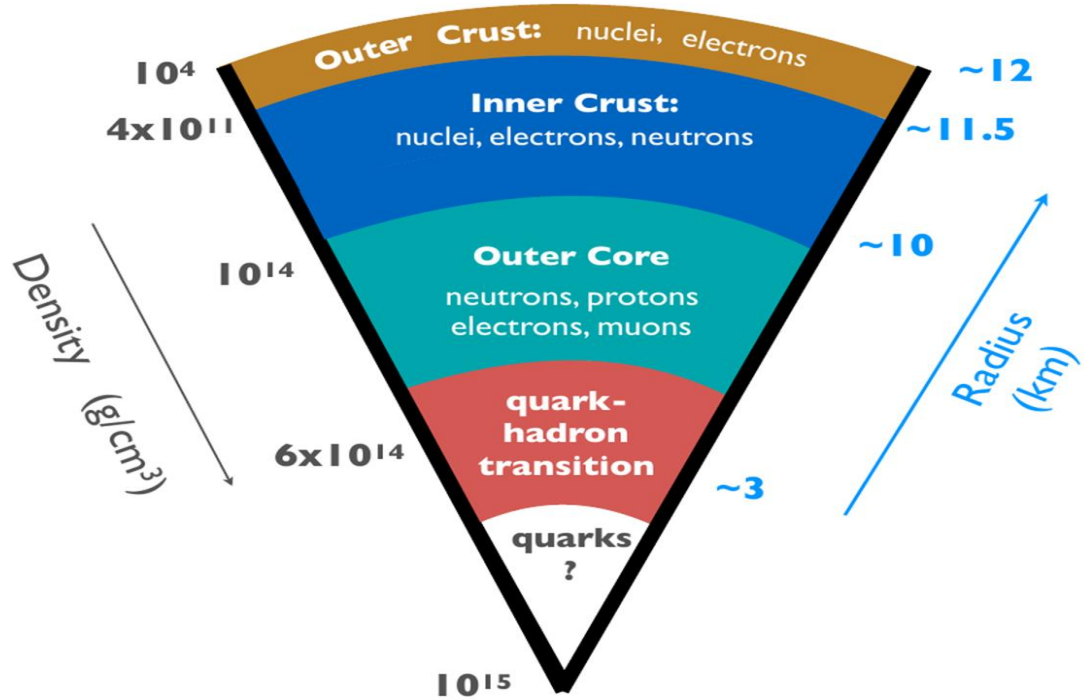


1 Event, slow expansion, long-lived

Time

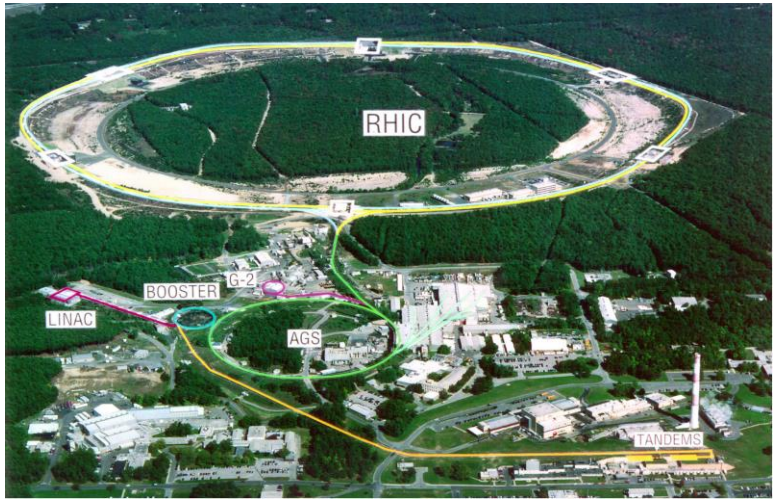
Millions of events, rapid expansion, short-lived



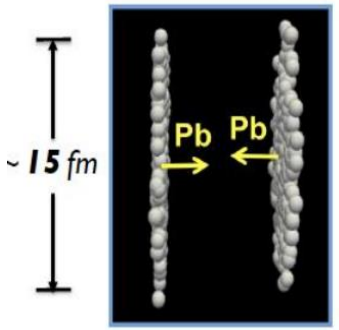


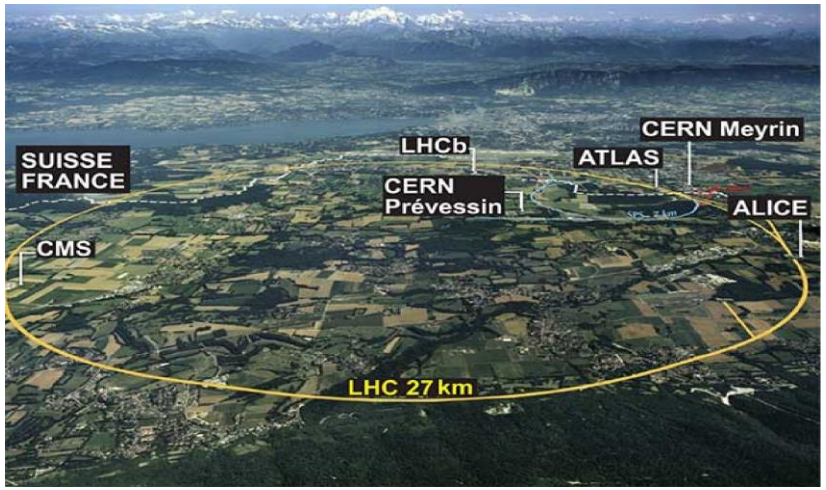
Extreme densities up to $5\text{-}10\rho_0$

Heavy Ions Colliders for QCD laboratories



RHIC@BNL (2000-2025), 3-200 GeV, **Au+Au**
Au (197 = 79 protons + 118 neutrons)

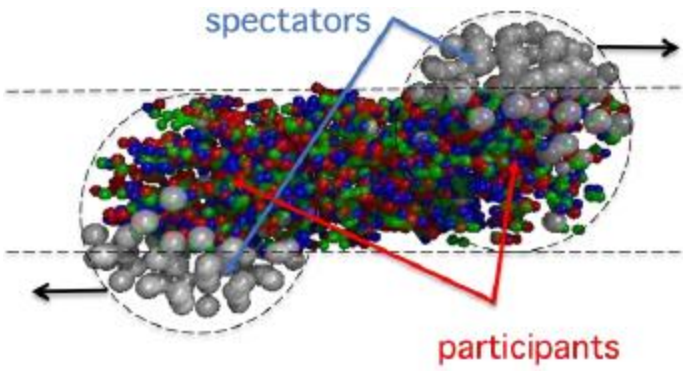


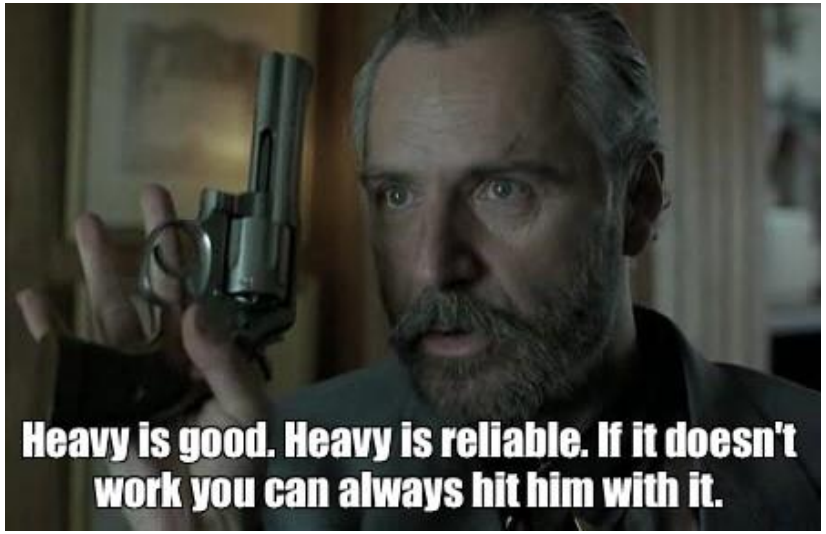


LHC@CERN (2010-...), 3-200 GeV, **Pb+Pb**
Pb (208= 82 protons + 126 neutrons)

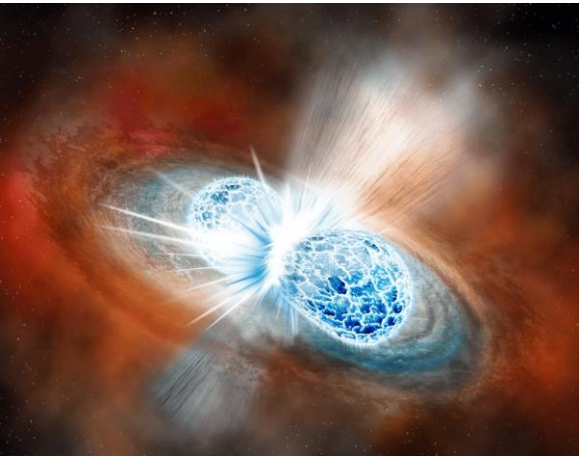


NICA@JINR (2026-), 4-11 GeV, **Bi+Bi**
Bi (209=83 protons+126 neutrons)

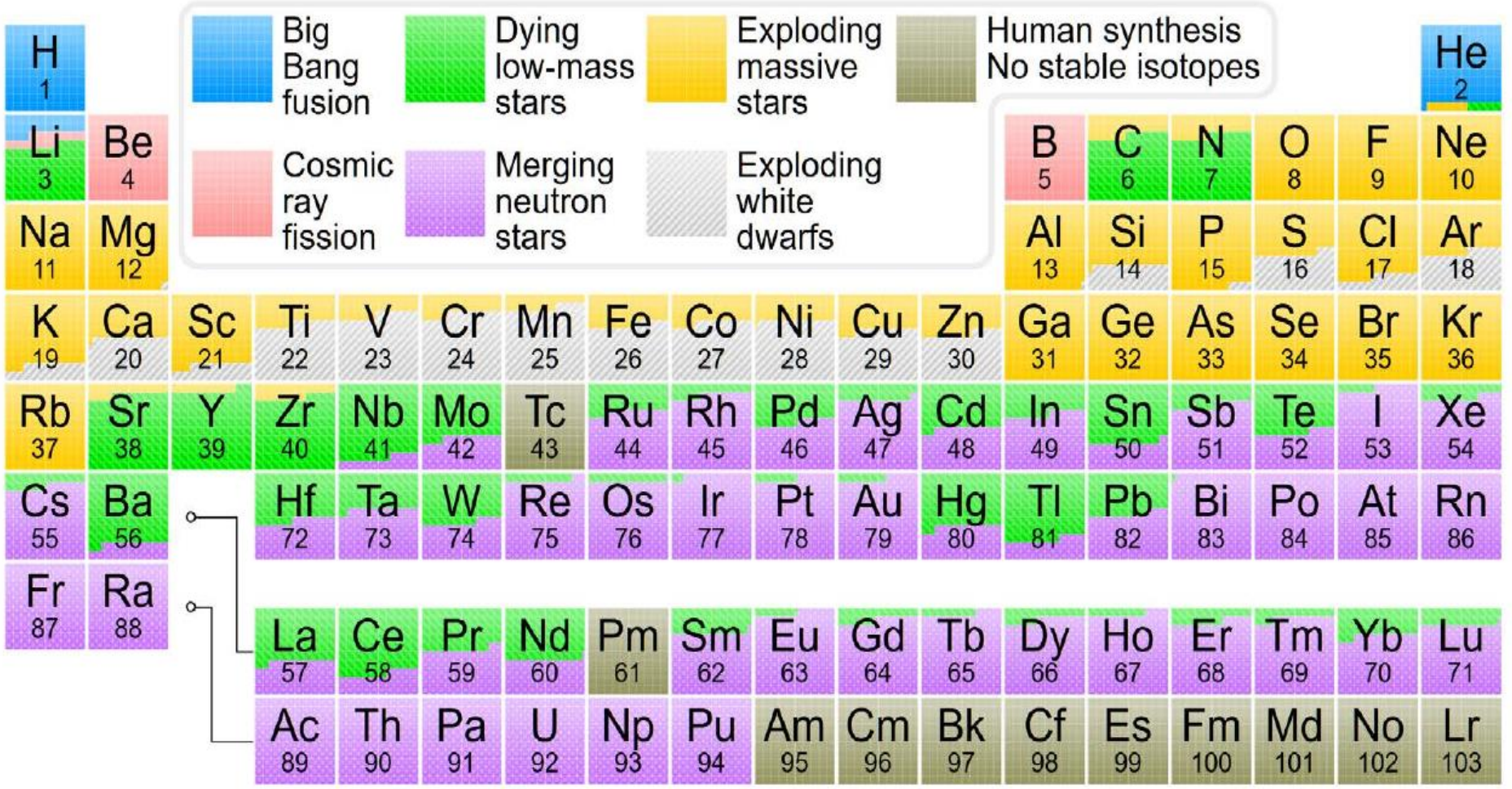




Nuclear EoS is important also for the r-process nuclear synthesis in neutron star merger

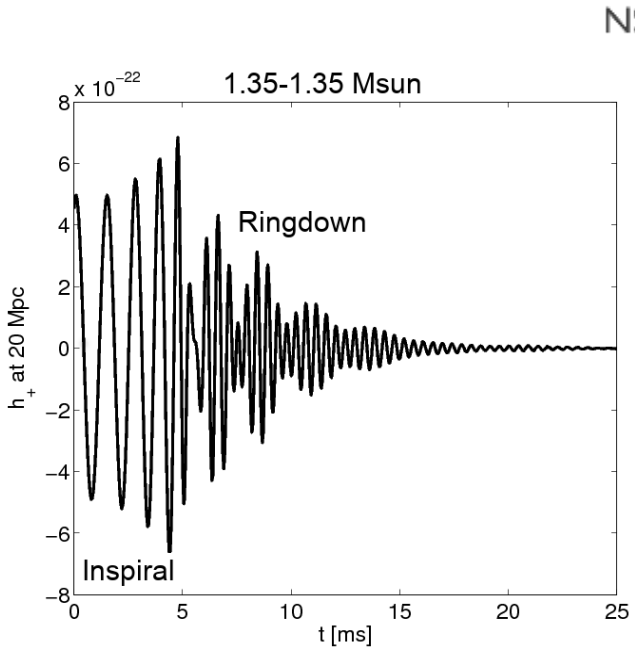






r-process - source of heavy elements including gold, platinum, and uranium.

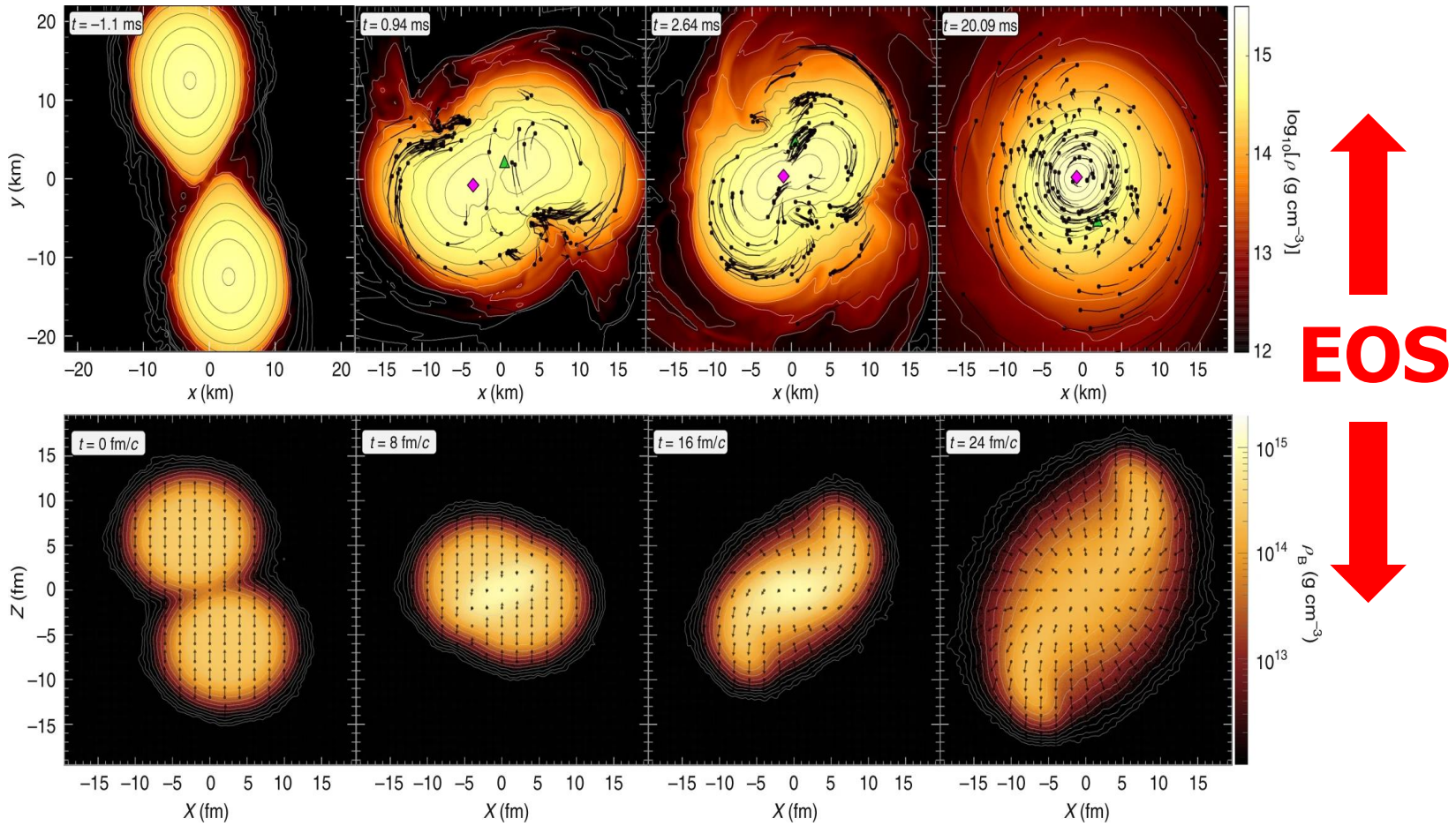
Neutron star mergers and heavy-ion collisions



Gravitational Wave Signal

LIGO and Virgo Collaborations, Phys. Rev. Lett. 119 (2017) 16, 161101

Nature Phys. 15 (2019) 10, 1040-1045

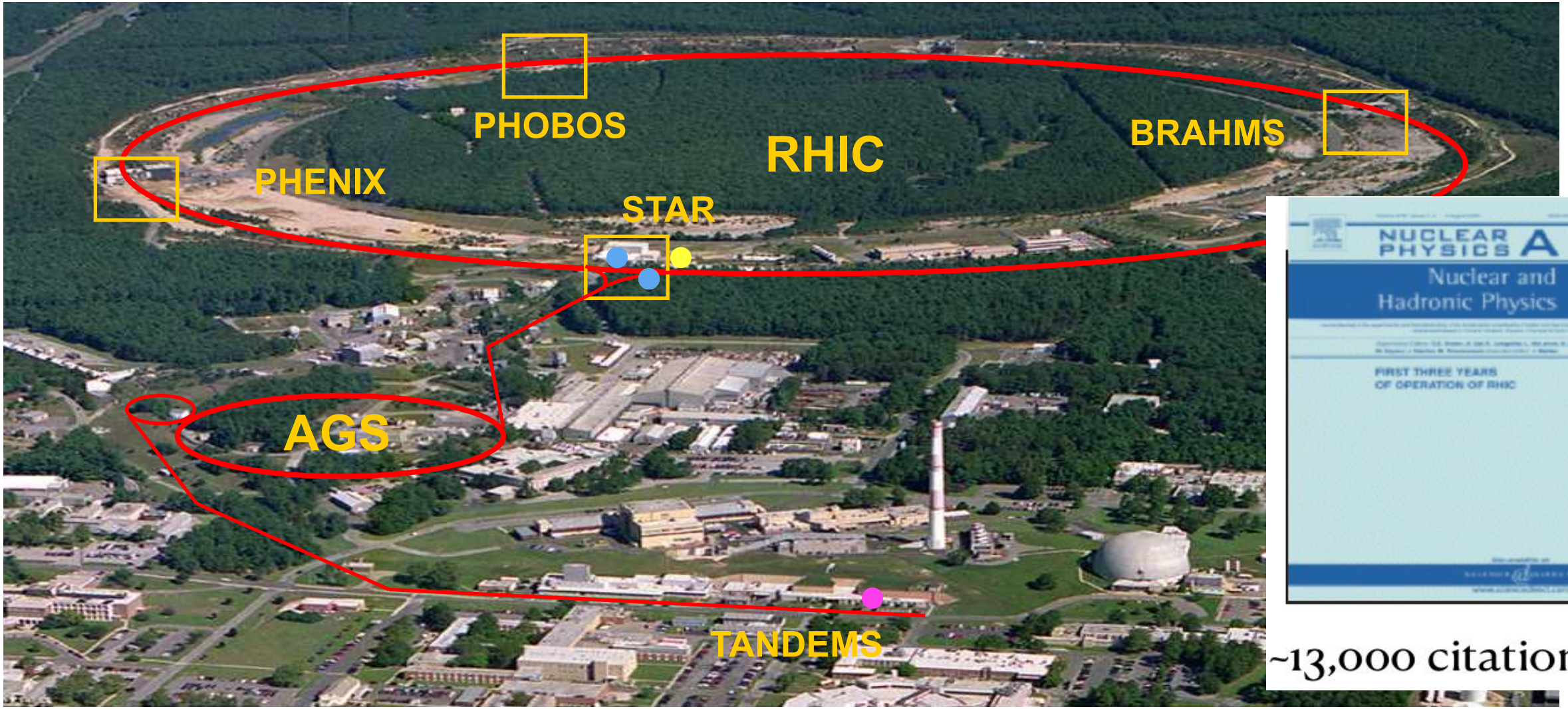


Au+Au 1.25A GeV

- Confirmation by astronomical observations after gravitational
- wave detection from GW170817 (August 2017).
- Source of heavy elements including gold, platinum, and uranium.

- T<70 MeV, $\rho \cong 3\rho_0$ for both
- Probe NS merger matter in the laboratory

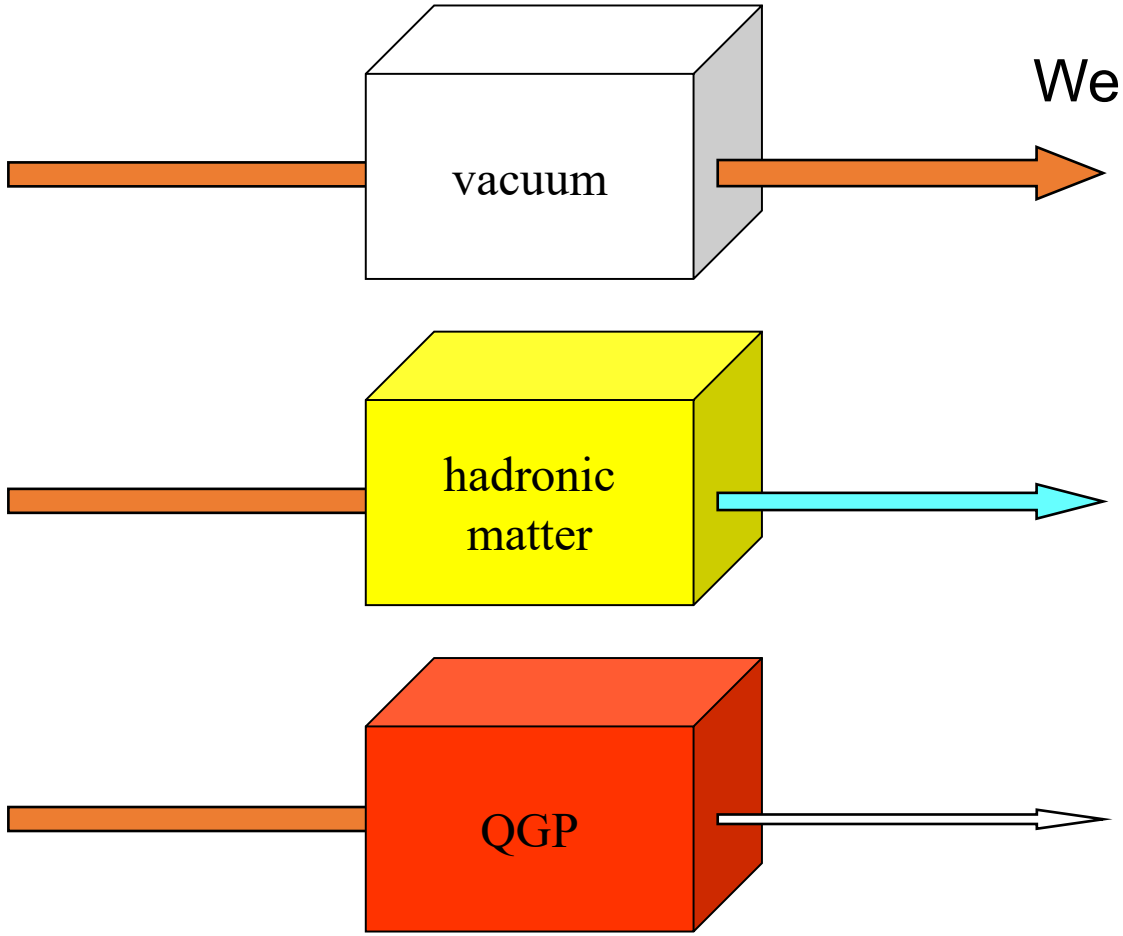
Relativistic Heavy Ion Collider (RHIC): 2000-2026



~13,000 citations!

2005: Quark-Gluon Matter (Plasma) is a "perfect liquid"

The good QCD matter probes should be:



Well understood in “p+p collisions”

Affected by hadronic matter,
in a well understood way,
which can be accounted for

Strongly affected by the dense and *deconfined* QCD medium...

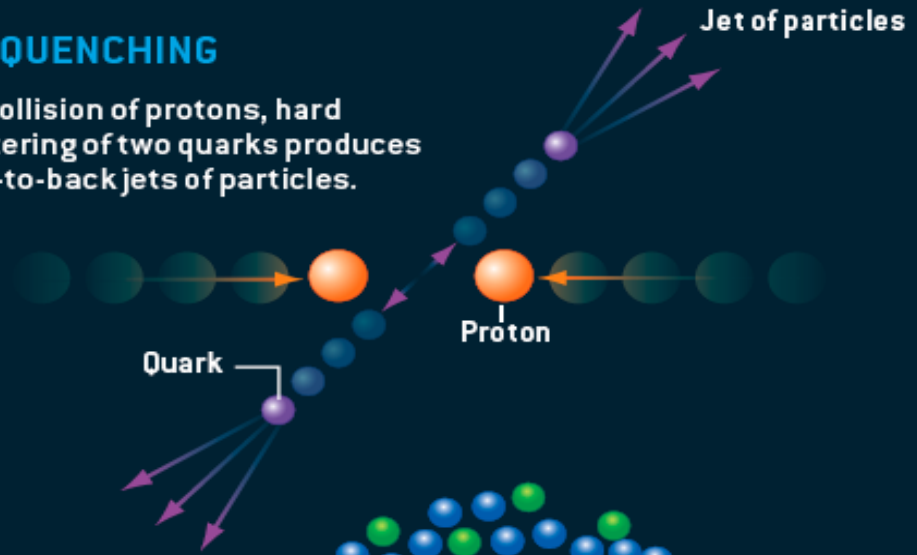
Perfect Liquid Discovered at RHIC: 2005

EVIDENCE FOR A DENSE LIQUID

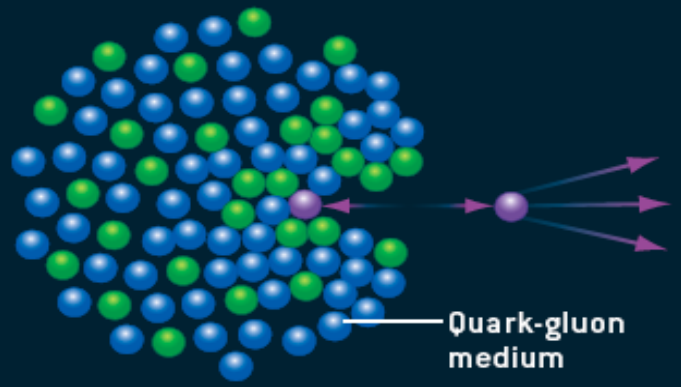
Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

In a collision of protons, hard scattering of two quarks produces back-to-back jets of particles.

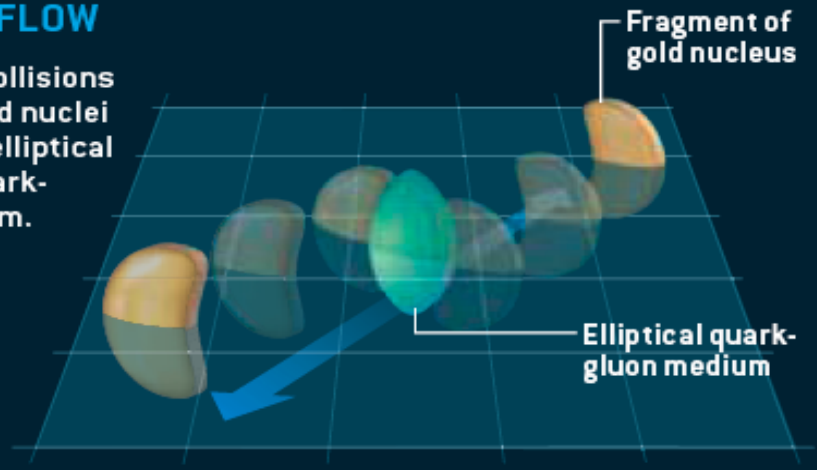


In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

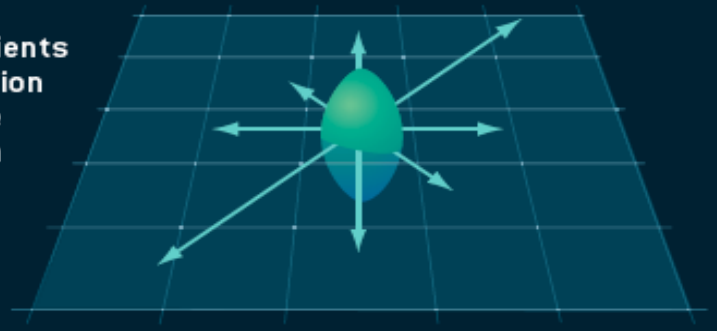


ELLIPTIC FLOW

Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium.

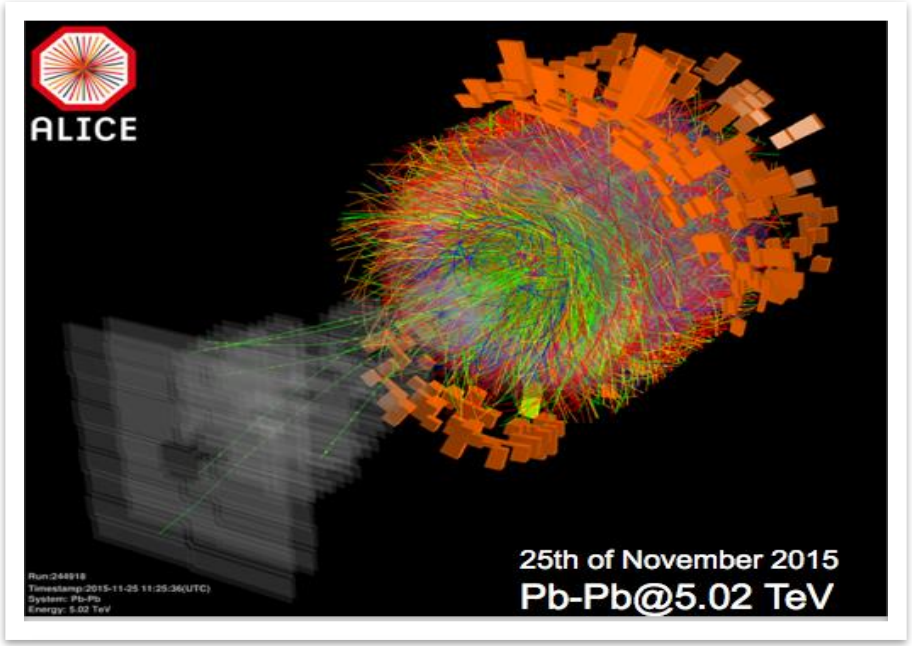


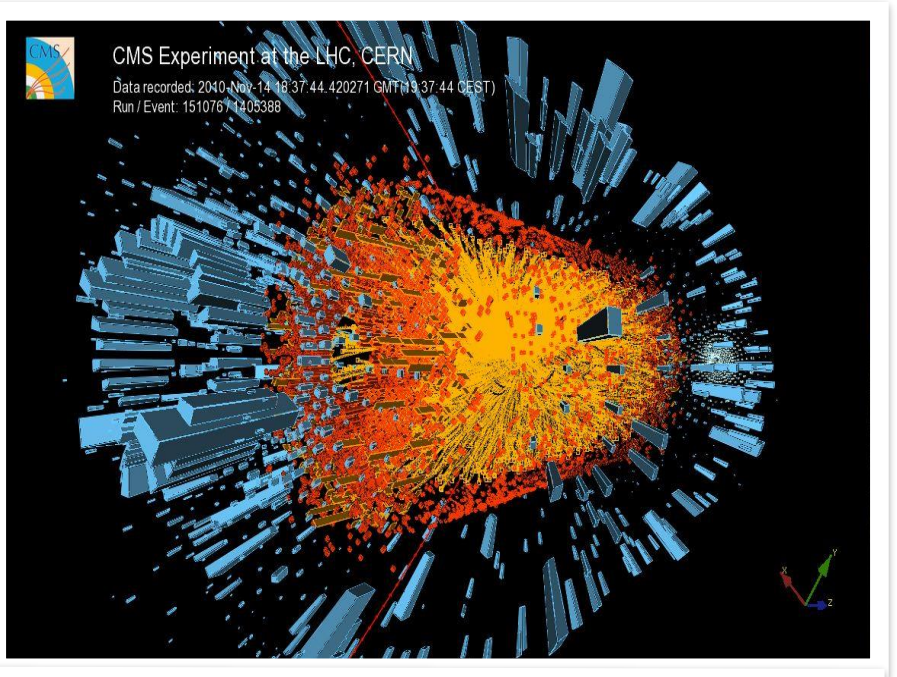
The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (*arrows*).

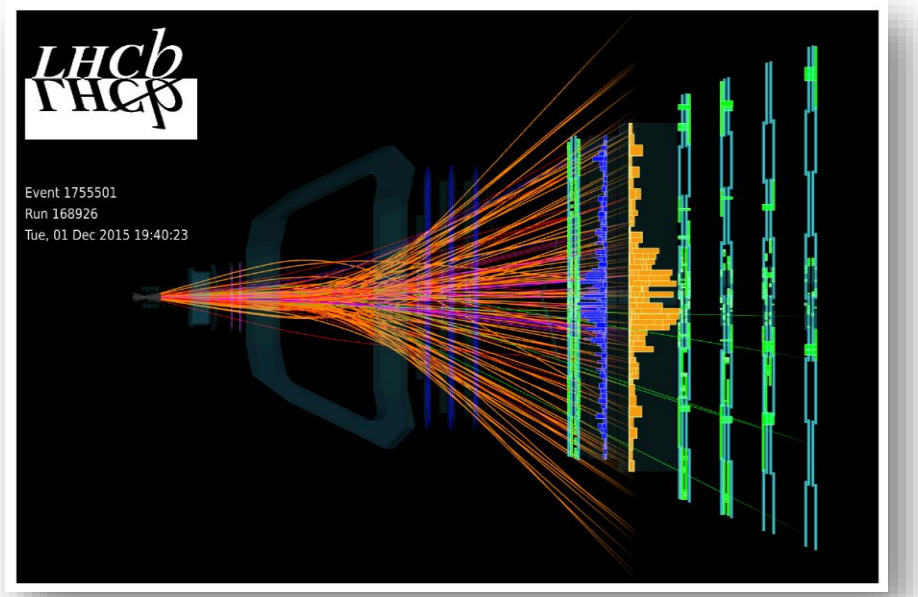


M. Roirdan and W. Zajc, Scientific American, May 2006

Ultra-Relativistic Heavy-Ion Collisions at LHC 2010-……



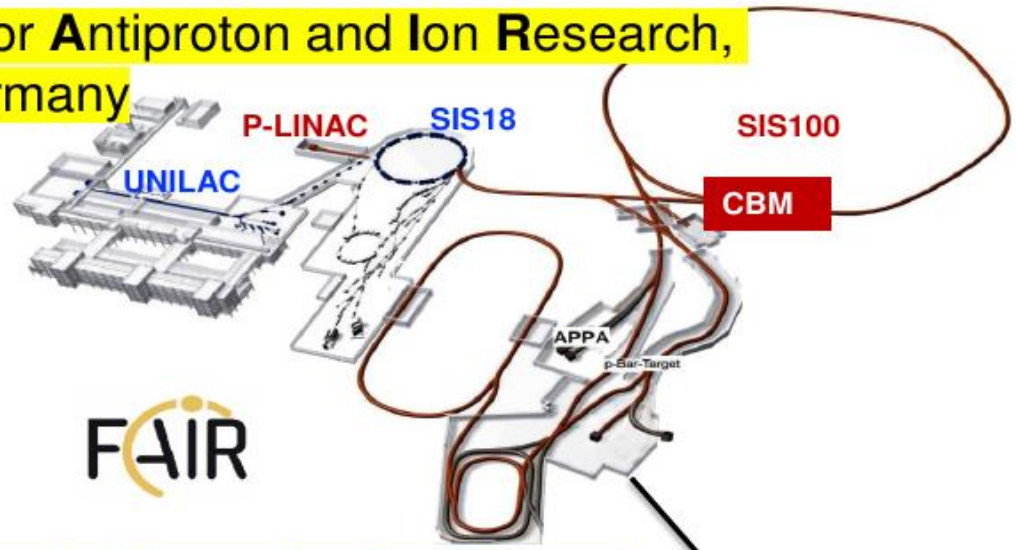




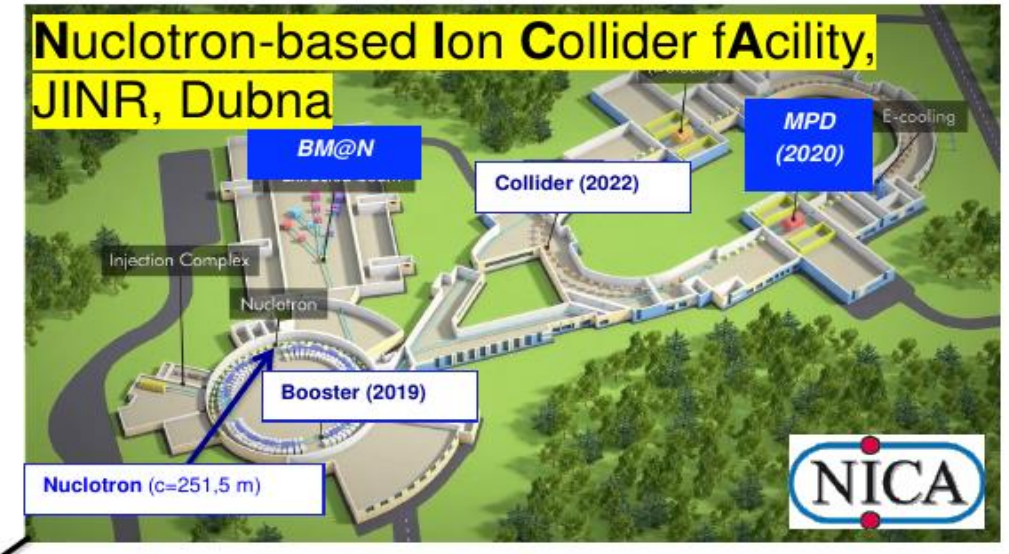


Relativistic Heavy-Ion Collisions: Beam energy Scan programs

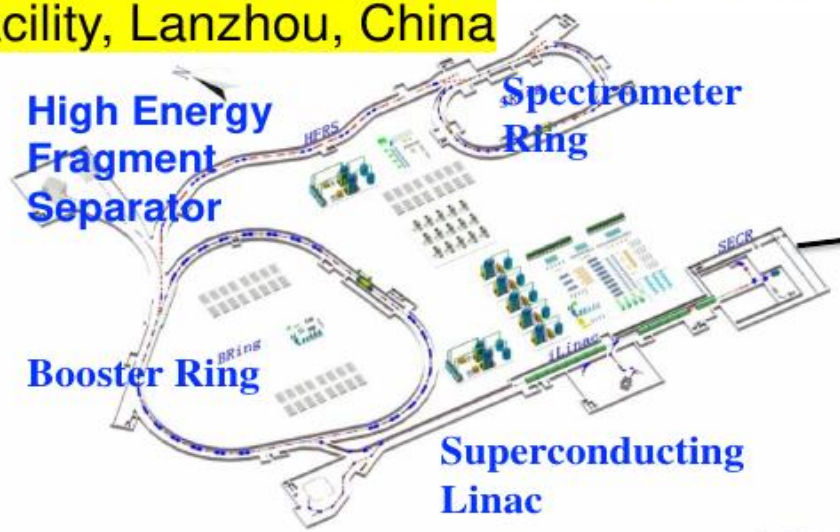
Facility for **A**ntiproton and **I**on **R**esearch, GSI, Germany

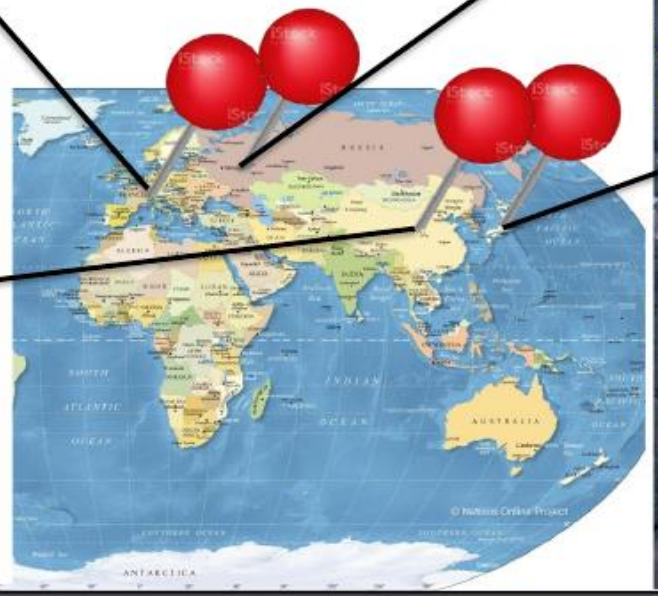


Nuclotron-based **I**on **C**ollider f**A**cility, JINR, Dubna

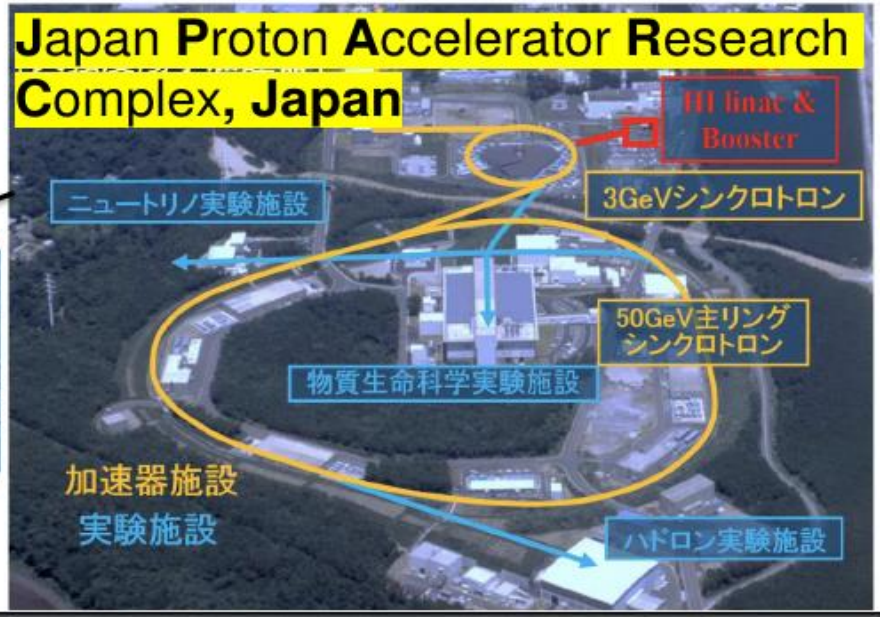


High-**I**ntensity Heavy Ion **A**ccelerator **F**acility, Lanzhou, China

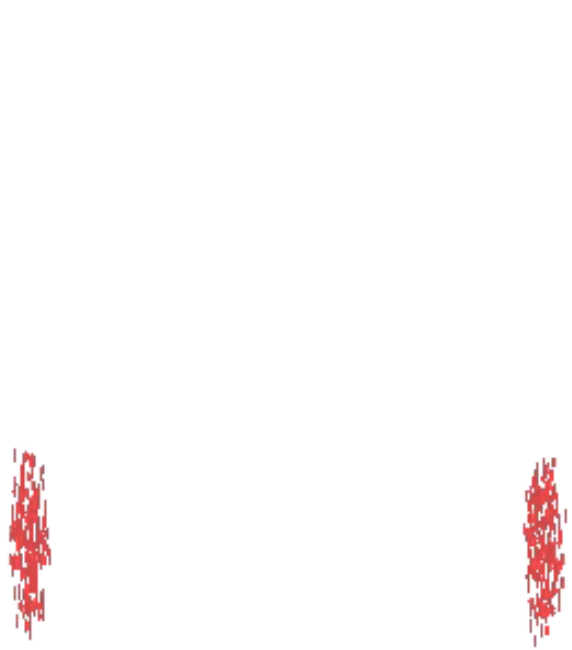




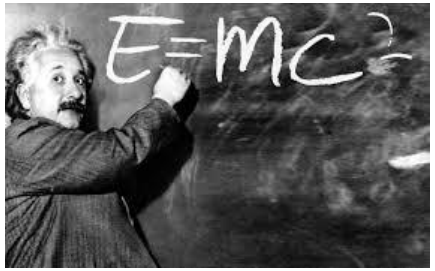
Japan **P**roton **A**ccelerator **R**esearch **C**omplex, **J**apan



Relativistic heavy-ion collisions



UrQMD model simulation



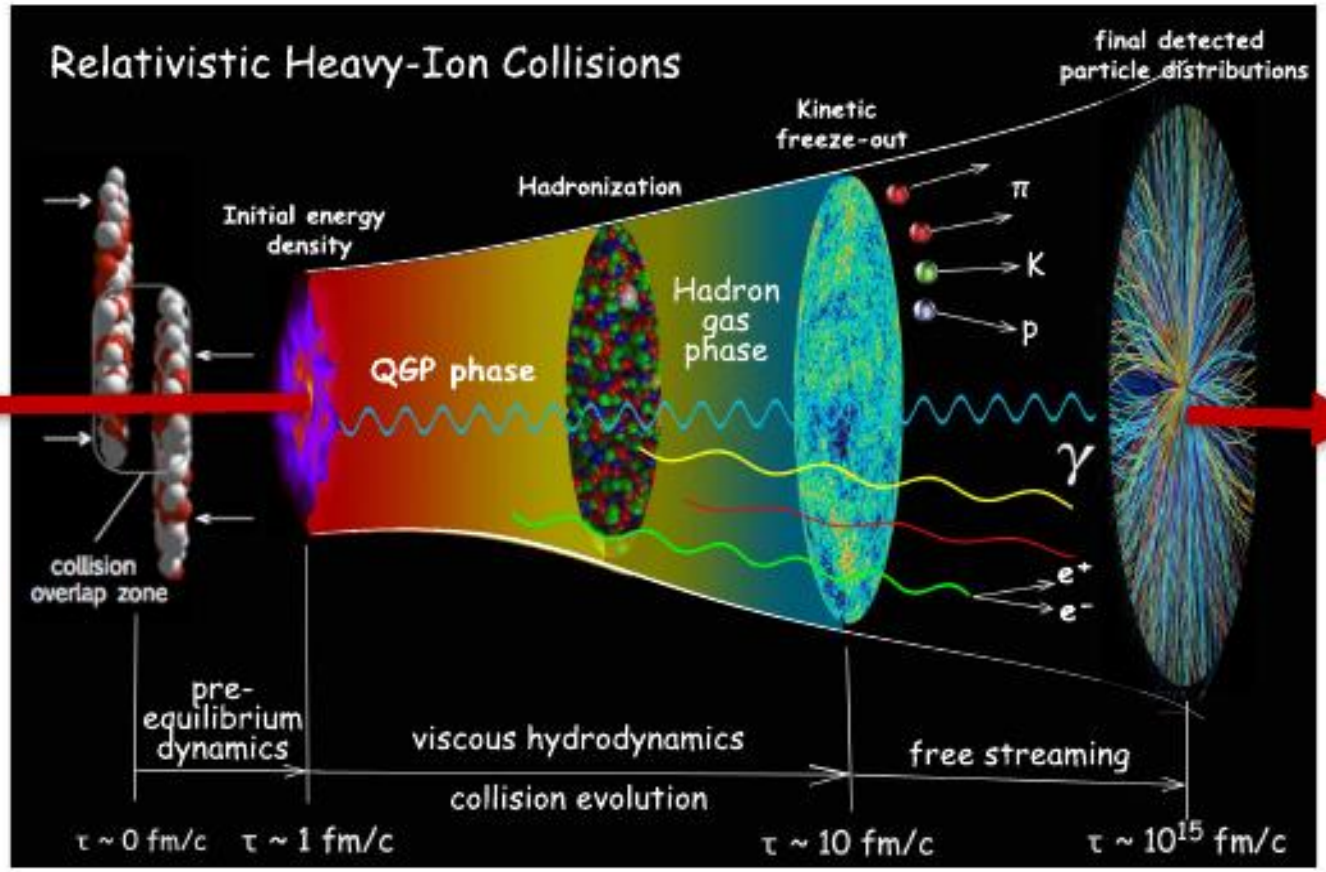
Relativistic collision energy leads to particle production

Length: 10^{-15} m

Time: 10^{-22} s

Temperature: 10^{12} K





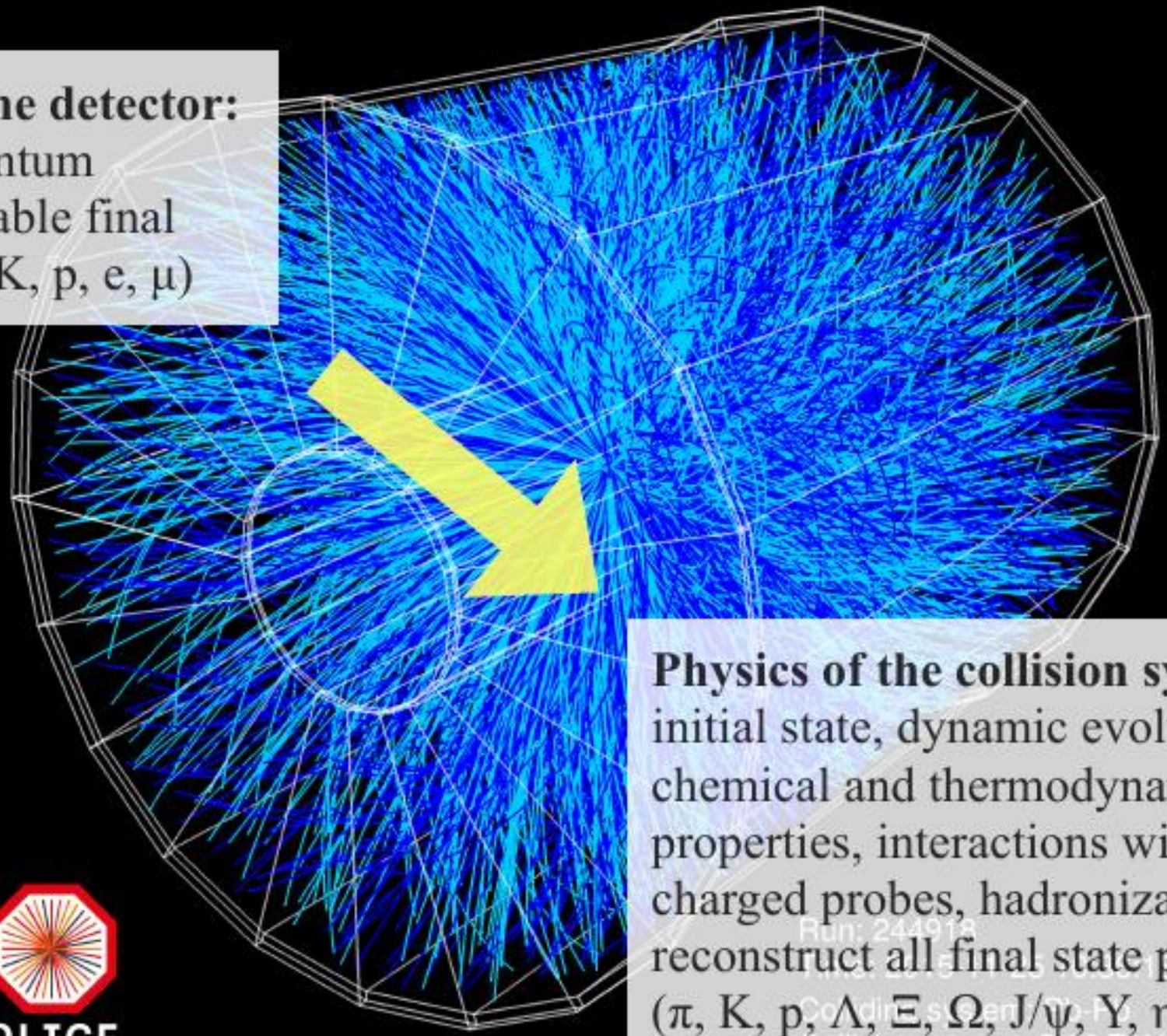


"Psychoanalysis" of Matter

~200+200 nucleons in 10^{-22} seconds = 1000-30000 hadrons

- The measurements are used to infer properties of the early state of relativistic heavy-ion collisions
- Only final state particles are measured in the detector: γ, $e^{\pm}$, $\mu^{\pm}$, π^0, $\pi^{\pm}$, K^0, $K^{\pm}$, η, ω, p, $\bar{p}$, ϕ, Λ, Σ, Ξ, etc.

Observables in the detector:
spatial and momentum distributions of stable final state particles (π, K, p, e, μ)



Physics of the collision system:
initial state, dynamic evolution, chemical and thermodynamic properties, interactions with charged probes, hadronization, reconstruct all final state particles (π, K, p, Λ, Ξ, Ω, J/ψ, Υ, η, ρ, γ, e, μ,…)

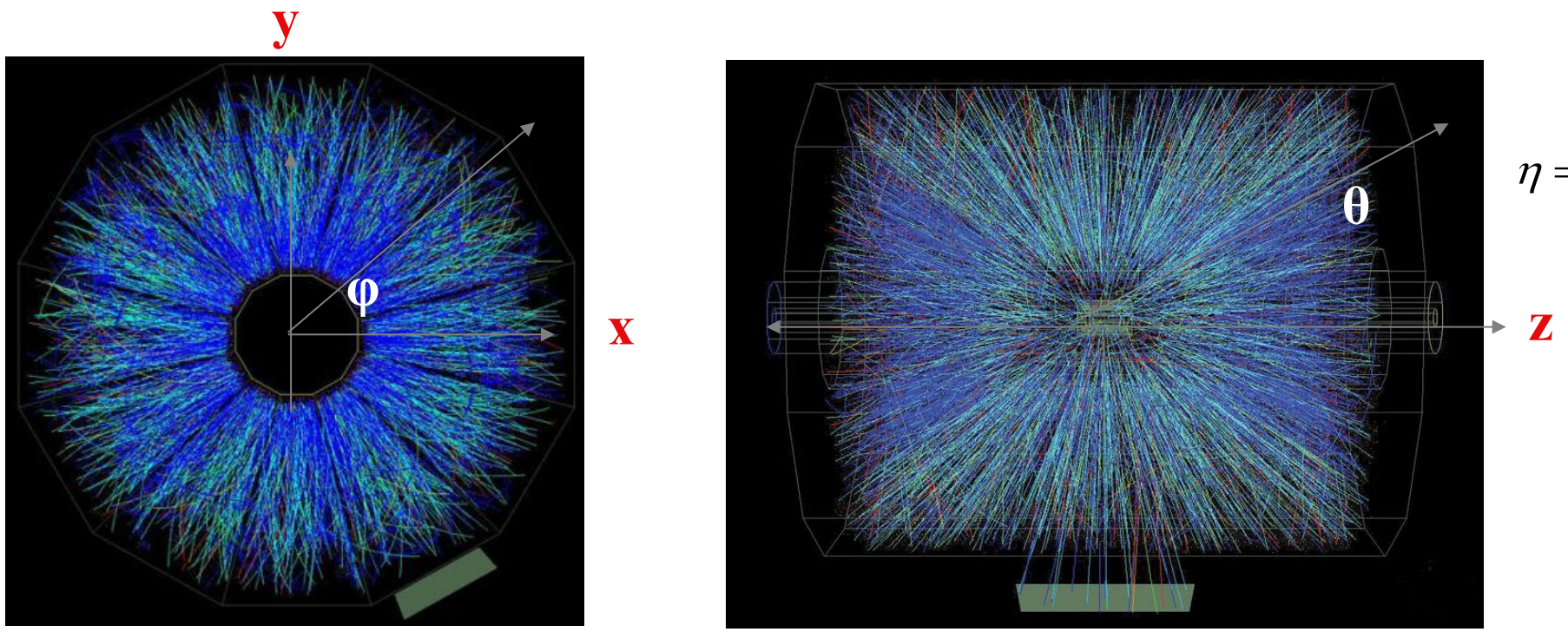
ALICE

Кинематические переменные

кинематические распределения образовавшихся частиц обычно выражаются как функции
y – быстроты частицы (rapidity) и p_T – поперечного импульса (transverse momentum)

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right) \qquad p_T = \sqrt{p_x^2 + p_y^2} \qquad m_T = \sqrt{m^2 + p_T^2}$$

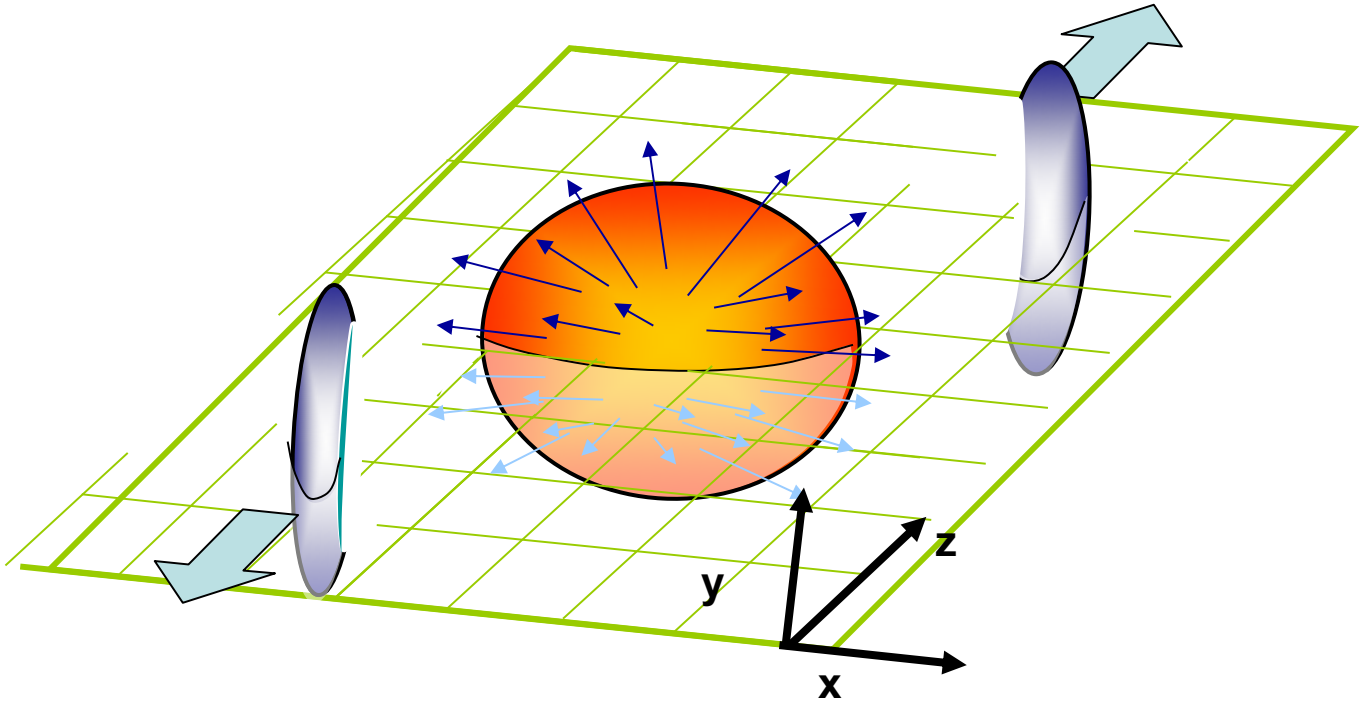
- p_T: Лоренц-инвариантный по отношению к ускорению в направлении пучка
- p_T генерируется при столкновении (p_z = присутствует «до столкновения»)
- y: не лоренц-инвариант, а аддитивный закон преобразования → y'=y-y_β (y_β быстрота реф. системы)

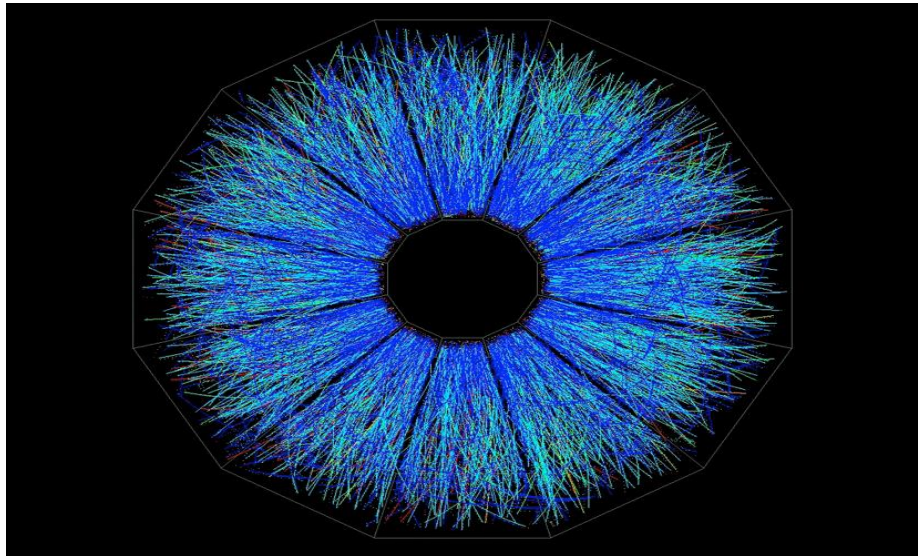


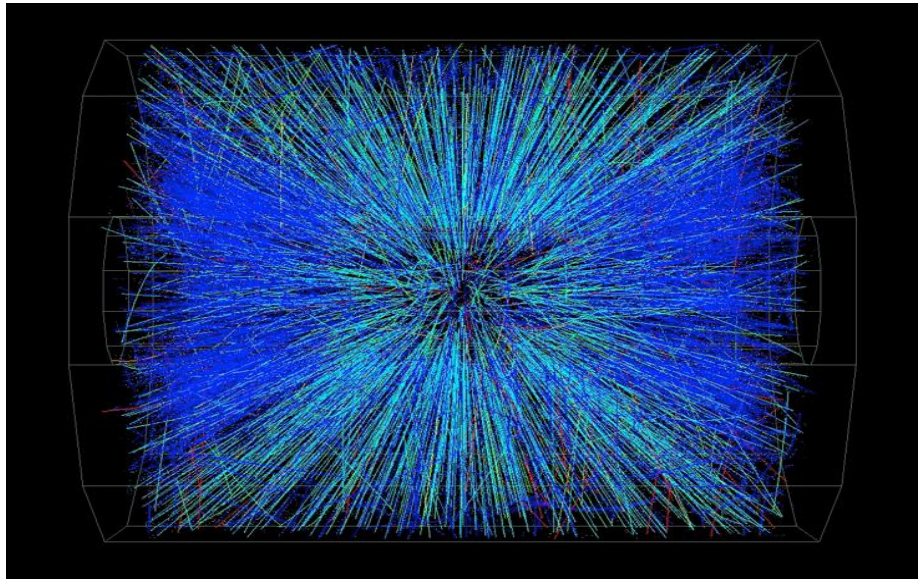
$$\eta = \frac{1}{2}\log\left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z}\right) = -\log\left[\tan\left(\frac{\theta}{2}\right)\right]$$

y~η for relativistic particles

HIC: Central Collision

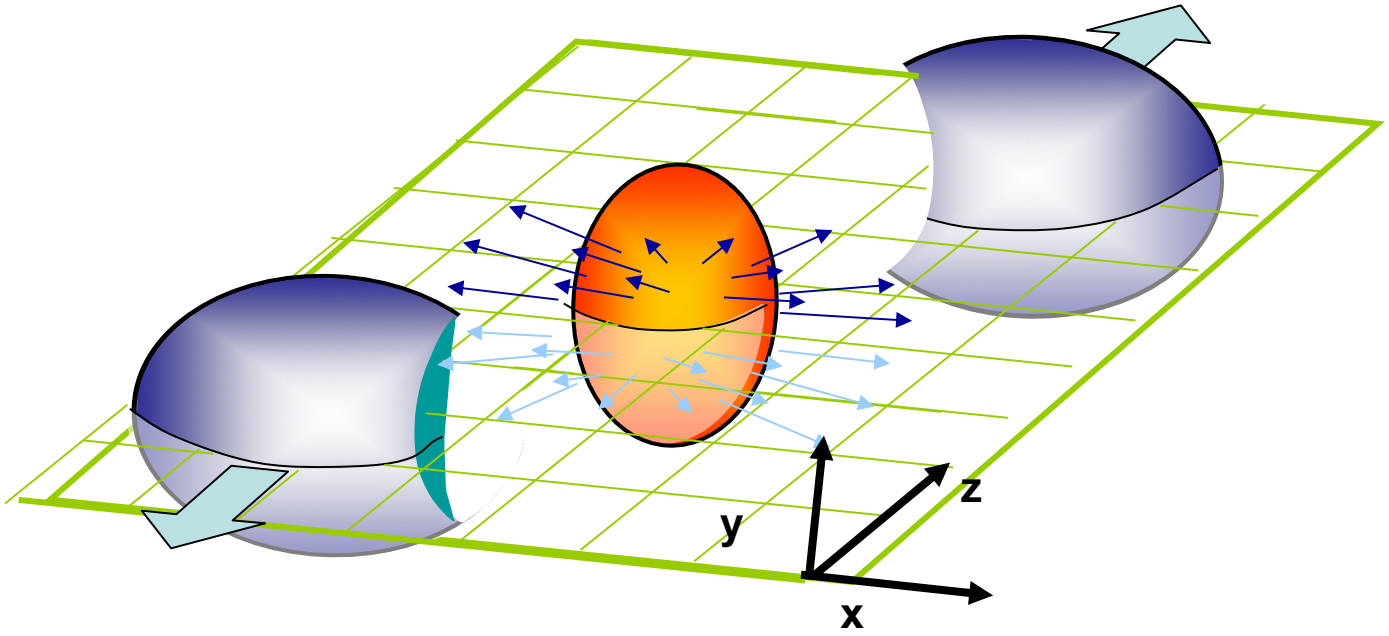


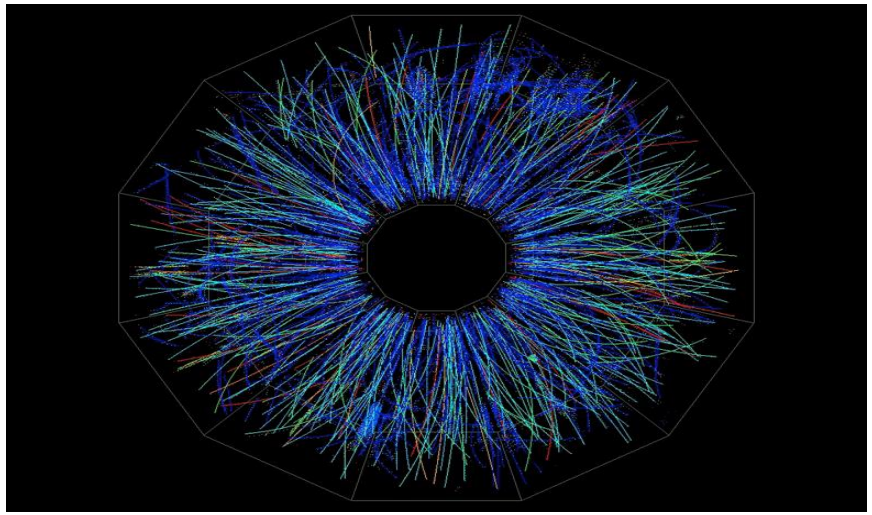


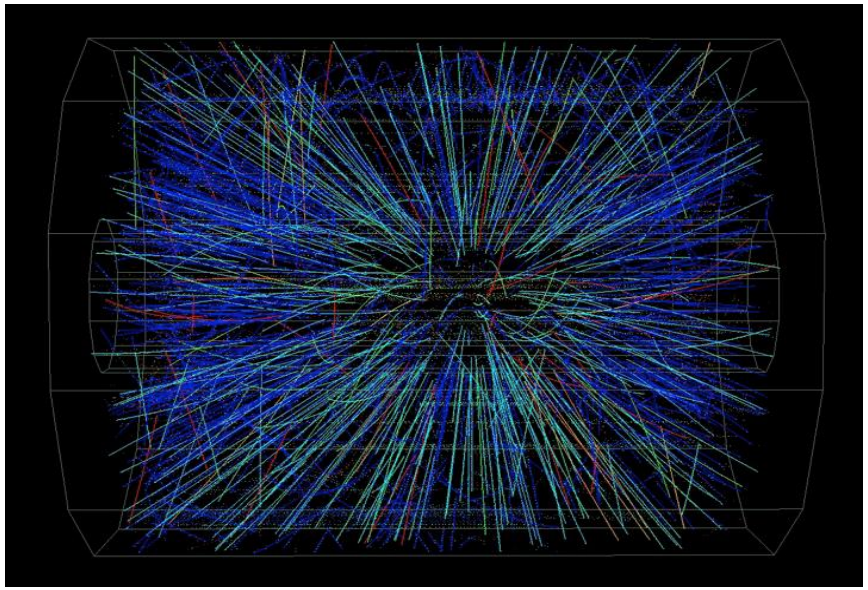


- Small impact parameter **b**
- Overlap region is close to be symmetric in the x-y plane
- Few spectators
- Many produced particles

HIC: Peripheral Collision

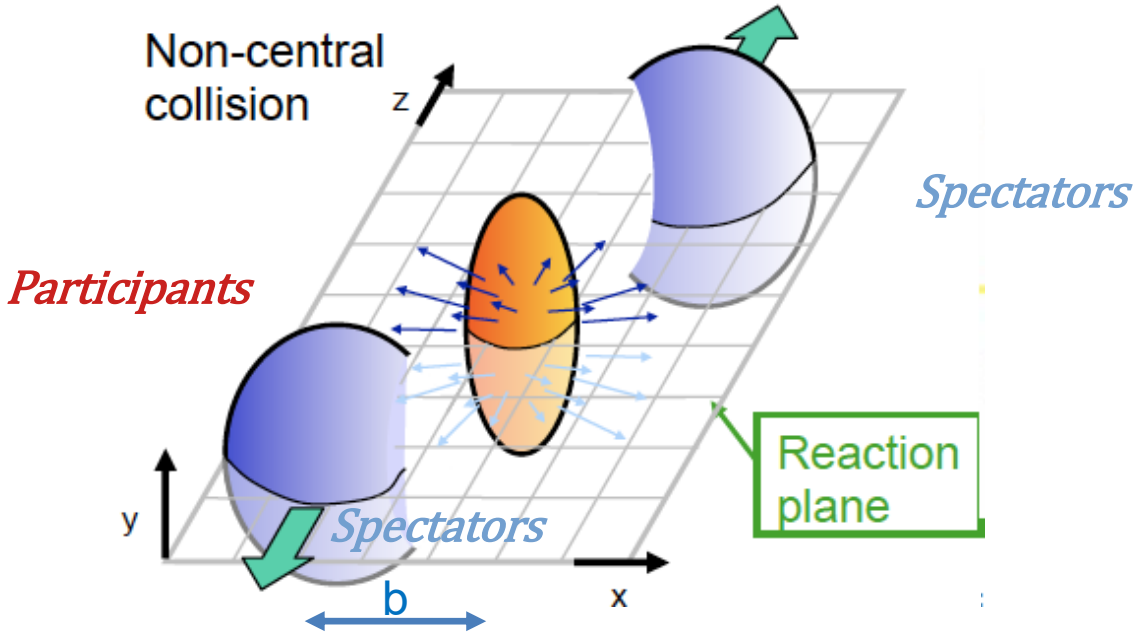


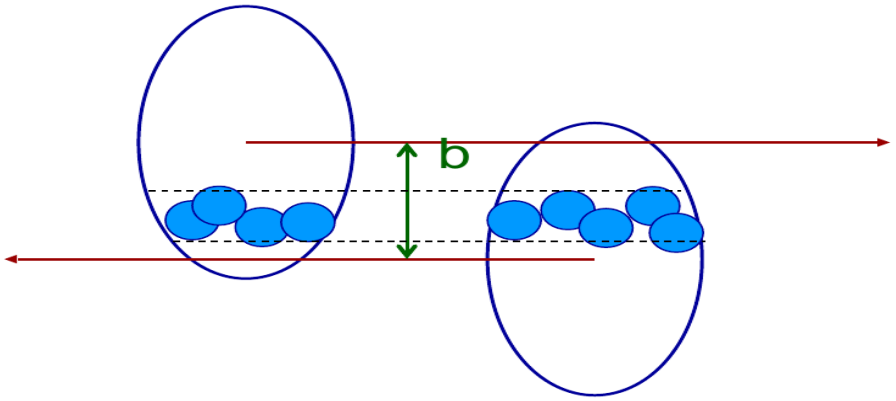




- Large impact parameter **b**
- Overlap region is strongly asymmetric in the x-y plane
- Many spectators
- Few produced particles

Geometry of Heavy-Ion Collisions



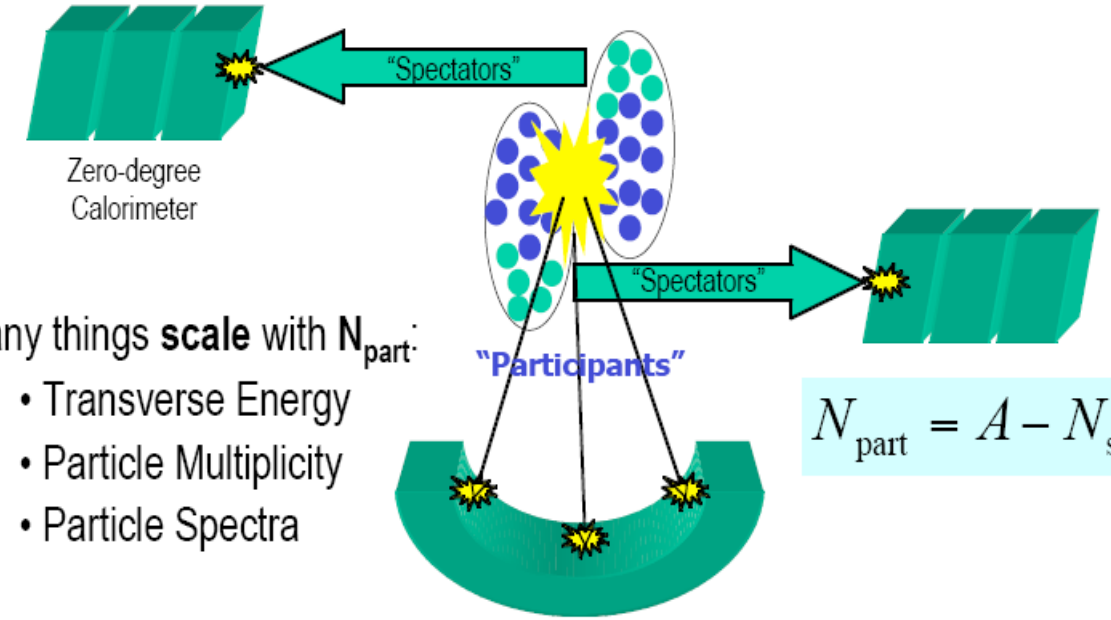


- $N_{participants}$: number of nucleons in the overlap region
- $N_{collisions}$: number of inelastic nucleon-nucleon collisions
- $N_{spectators}$: number of nucleons which do not interact
- Reaction plane: defined by z axis and impact parameter
- Centrality: percentile of the total cross section

Two limiting possibilities:

- Each nucleon only **interacts once**, 'wounded nucleons'
  $N_{part} = n_A + n_B$ (ex: 4 + 5 = 9 + …)
  Relevant for soft production; long timescales: $\sigma \propto N_{part}$
- Nucleons **interact with all** nucleons they encounter
  $N_{coll} = n_A \times n_B$ (ex: 4 x 5 = 20 + …)
  Relevant for hard processes; short timescales: $\sigma \propto N_{coll}$

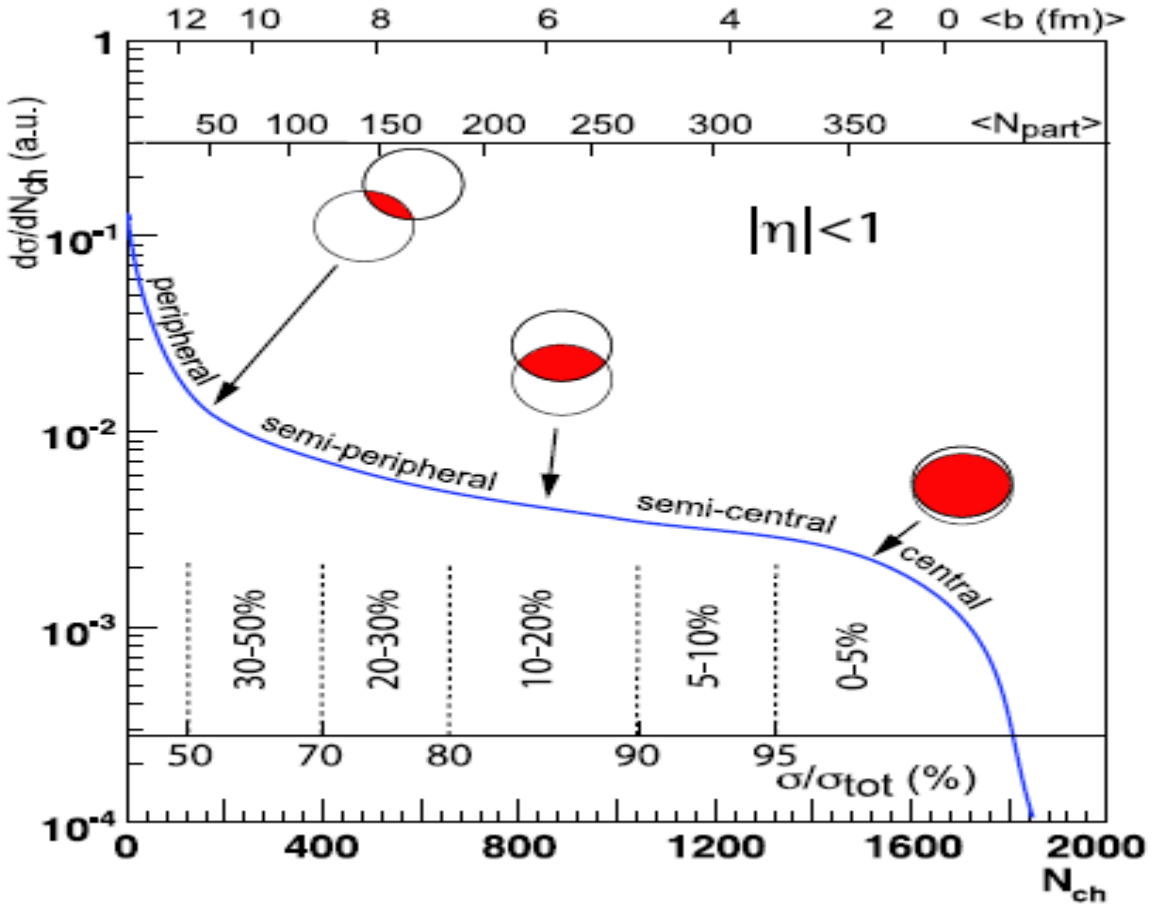
HIC: Centrality of the collision



Many things **scale** with N_{part}:

- Transverse Energy
- Particle Multiplicity
- Particle Spectra

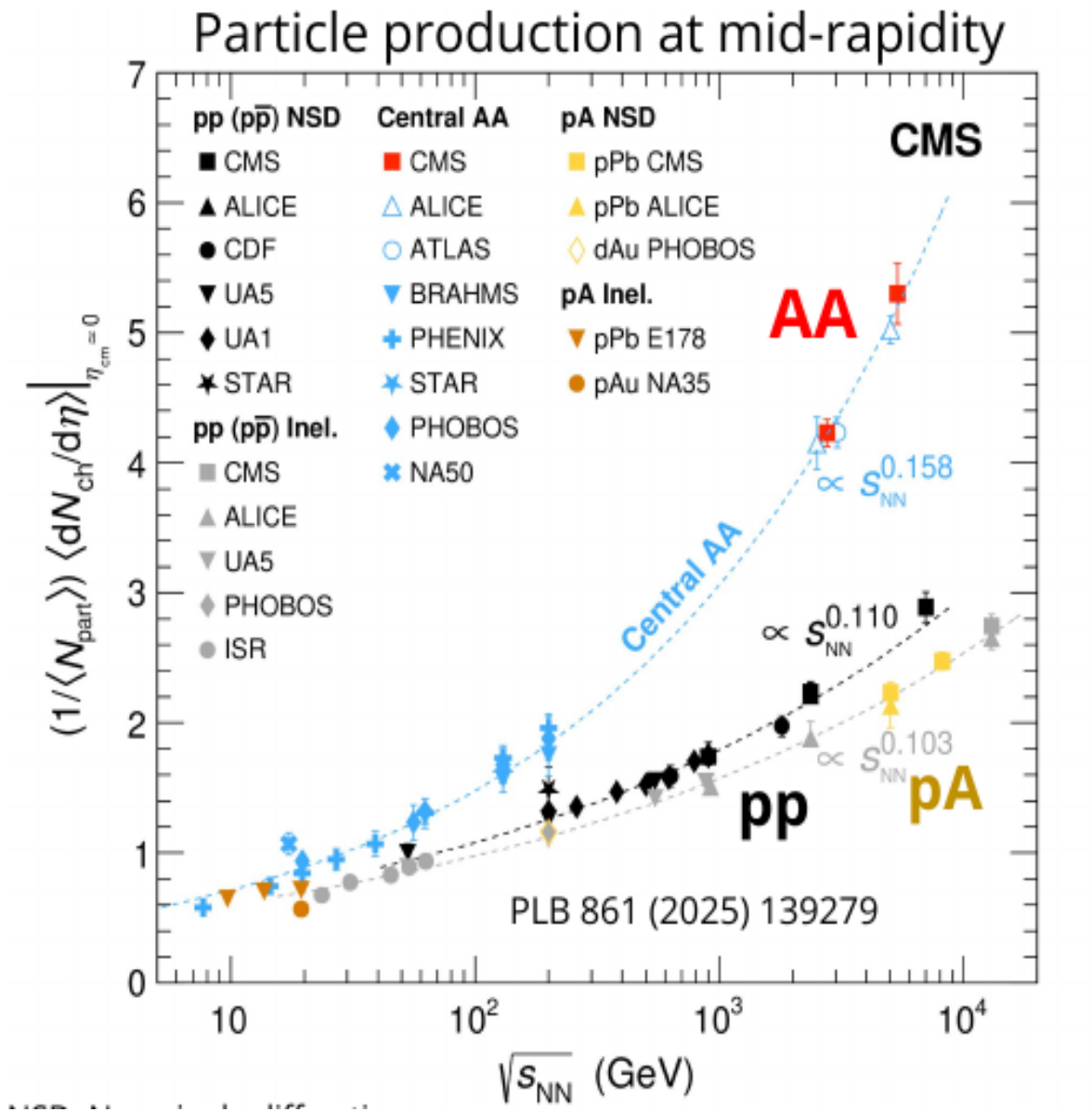
$$N_{\text{part}} = A - N_{\text{spec}}$$



"Centrality classes": percentiles
(fraction of total integral) of centrality distribution.

Convention: 0% = most central,
100% = most peripheral
peripheral → low mult, central → high mult

Particle production in heavy-ion collisions



- Higher yield per participant in HIC than in pp
- HIC more efficient in transforming the initial energy into particles
- Particle production in HIC increased by > x2 from RHIC (200 GeV) to LHC (5 TeV) energies
- Particle multiplicity can be used to constrain the energy density created in HIC

Estimating the initial energy density

Bjorken's formula:

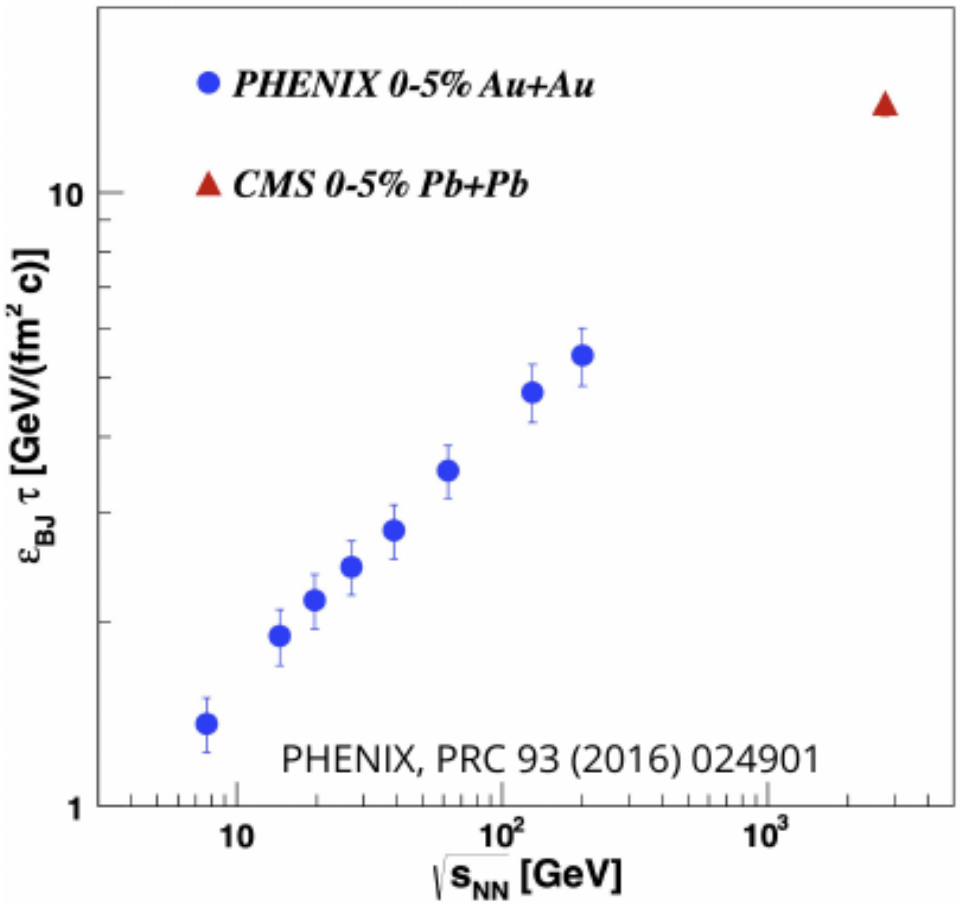
$$\epsilon = \frac{1}{A \cdot \tau_0} \frac{dE}{dy}\bigg|_{y=0} = \frac{1}{A \cdot \tau_0} J \frac{dE}{d\eta}\bigg|_{\eta=0}$$

Jacobian

Considering for PbPb collisions at 2.76 TeV:

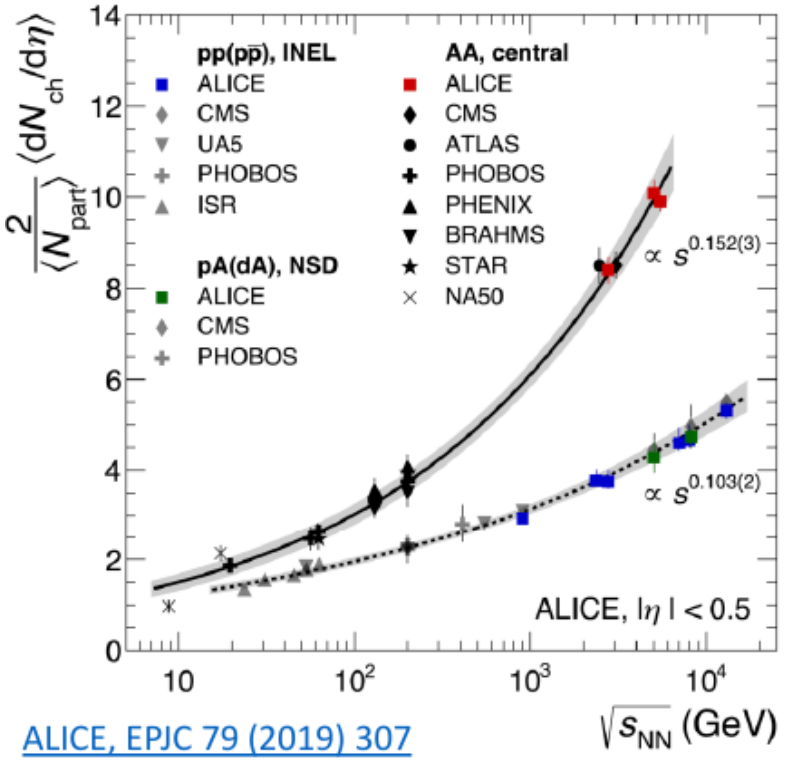
- $A = \pi R^2_{Pb} = \pi(6.7\ \text{fm})^2 \approx 141\ \text{fm}^2$
- $\tau_0 \sim 1$ fm , $J \approx 1.1$
- $dE_T/d\eta\,|_{y=0} \approx 2$ TeV

Estimated energy density → $\varepsilon \approx 15.6\ \text{GeV/fm}^3$

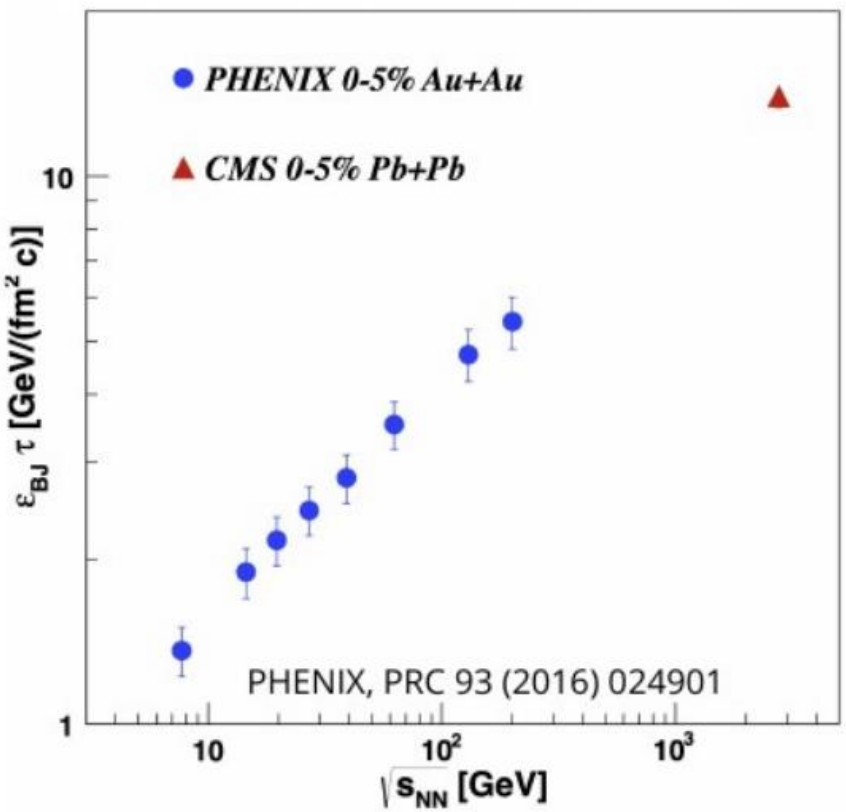


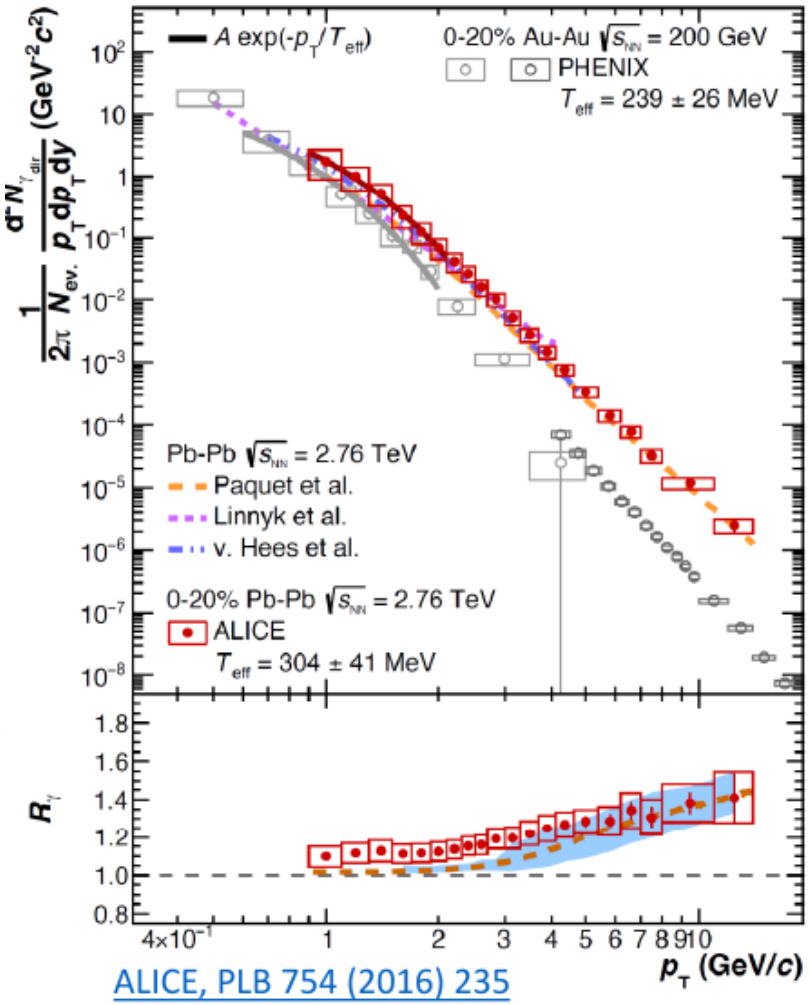
Estimated initial energy density is above the density ($\varepsilon_c \approx 0.4\ \text{GeV/fm}^3$) for phase transition from lattice QCD

Global properties



ALICE, EPJC 79 (2019) 307



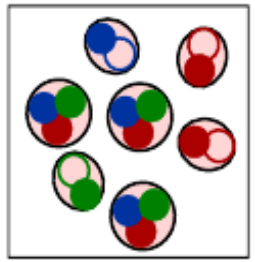


ALICE, PLB 754 (2016) 235

- Charged hadron production per nucleon maximal in Pb-Pb at the LHC
- Initial energy density in central Pb-Pb collisions is 30 times larger than ε_c!
- Effective photon temperature T_{eff} = 304 ± 41 MeV twice larger than T_c ~ 160 MeV

Thermal statistical hadronization

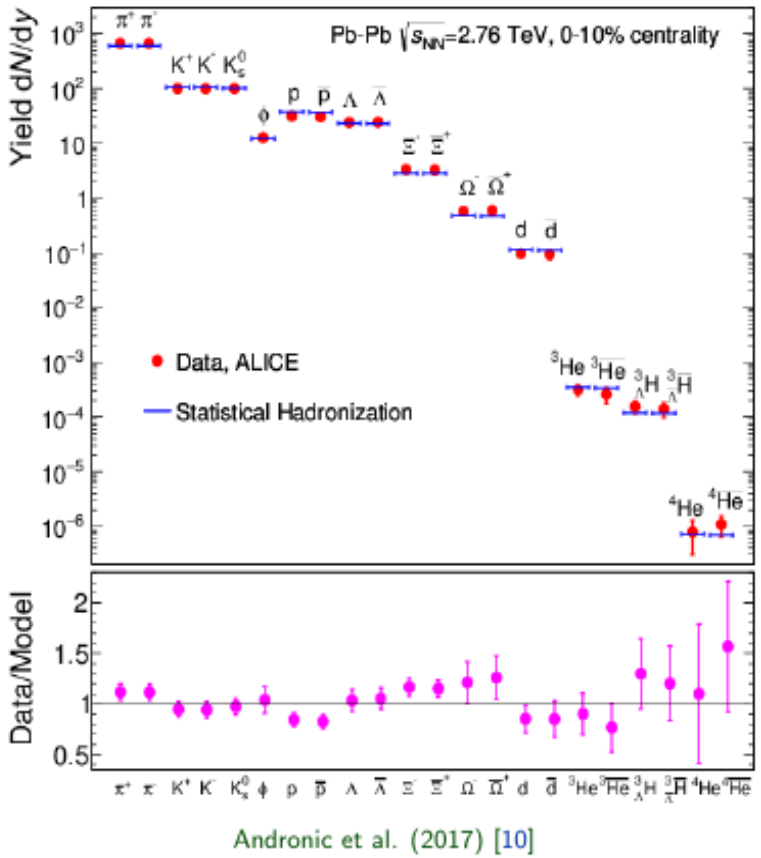
Observed particle yields show remarkable thermal ordering



- Number of hadrons in volume V at T, μ

$$\frac{dN}{dy} = \underbrace{V}_{\text{volume per rapidity}} \underbrace{\nu_g \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{(E(p)-\mu)/T} \pm 1}}_{\text{number density at } T,\mu}.$$

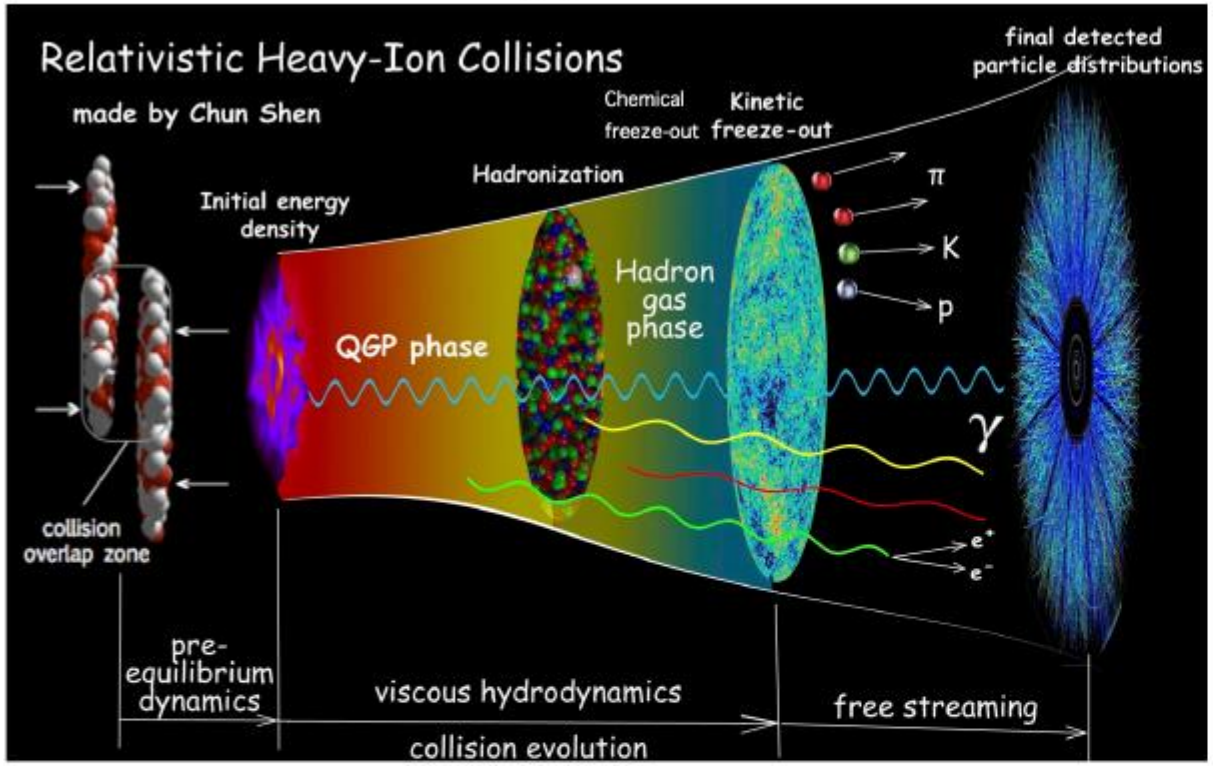
- Compare to measured yields (after decays).
- At LHC light and strange hadron and even light (anti)-nuclei are well fitted by $T_{\text{chem}} \approx 155\,\text{MeV}, \mu_B \approx 0$.
- $\Longrightarrow$ particle production as if from completely thermalized fireball (including strangeness).

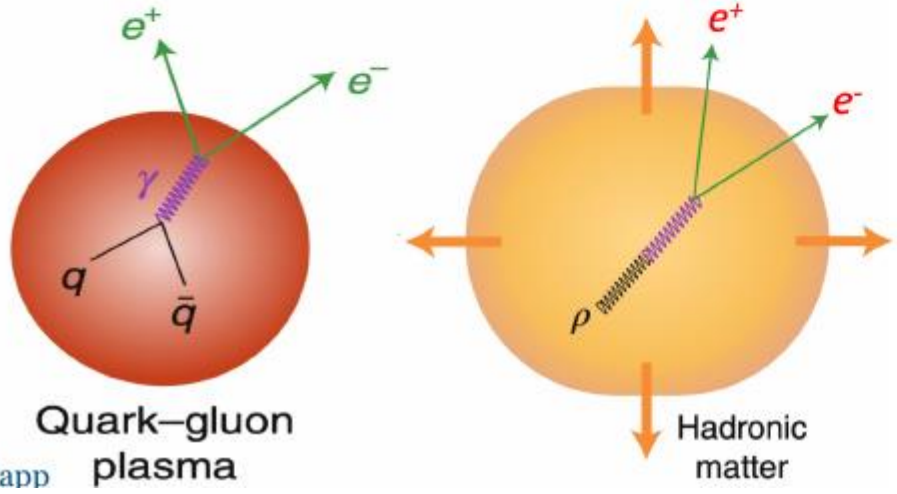


Andronic et al. (2017) [10]

What is the more detailed picture of QCD thermalisation in heavy-ion collisions?

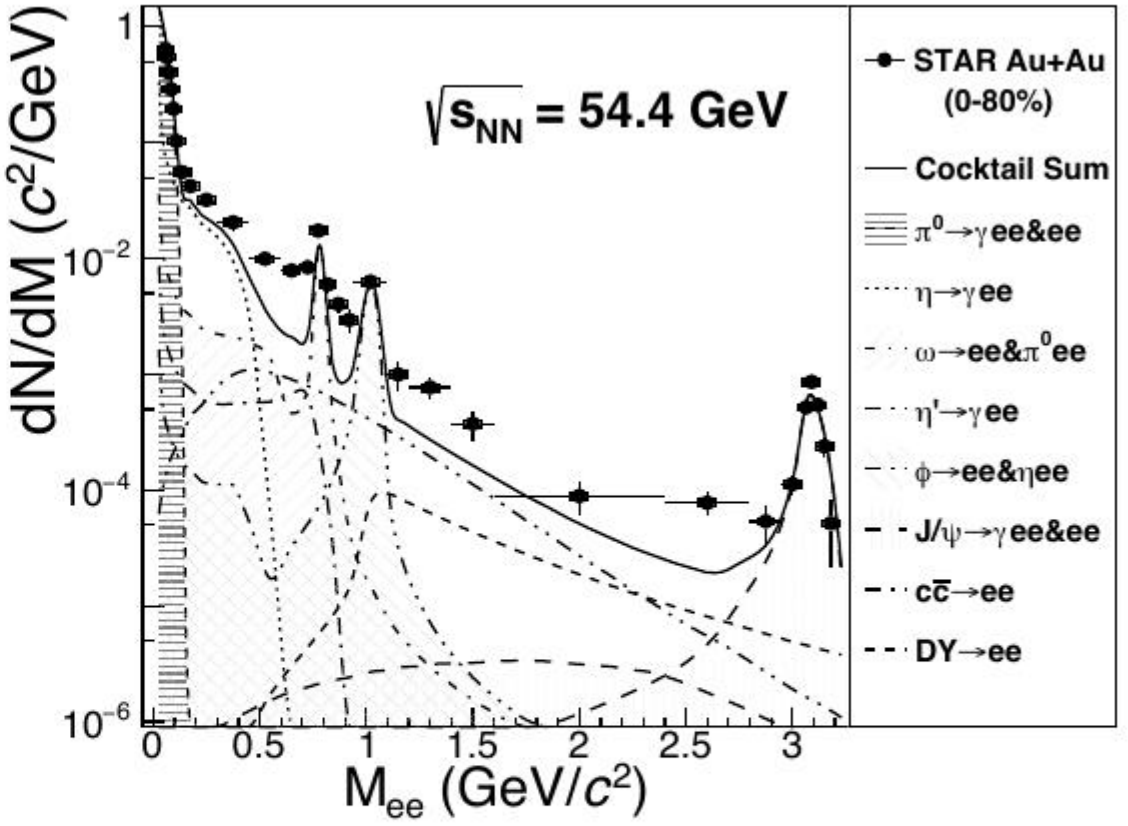
Electromagnetic Probes





Courtesy of Ralf Rapp

Nature Communications 16, 9098 (2025)



- Photons and leptons: penetrating probes, produced in ALL stages
- Can access temperature in both QGP phase and hadronic phase

Temperature Measurements

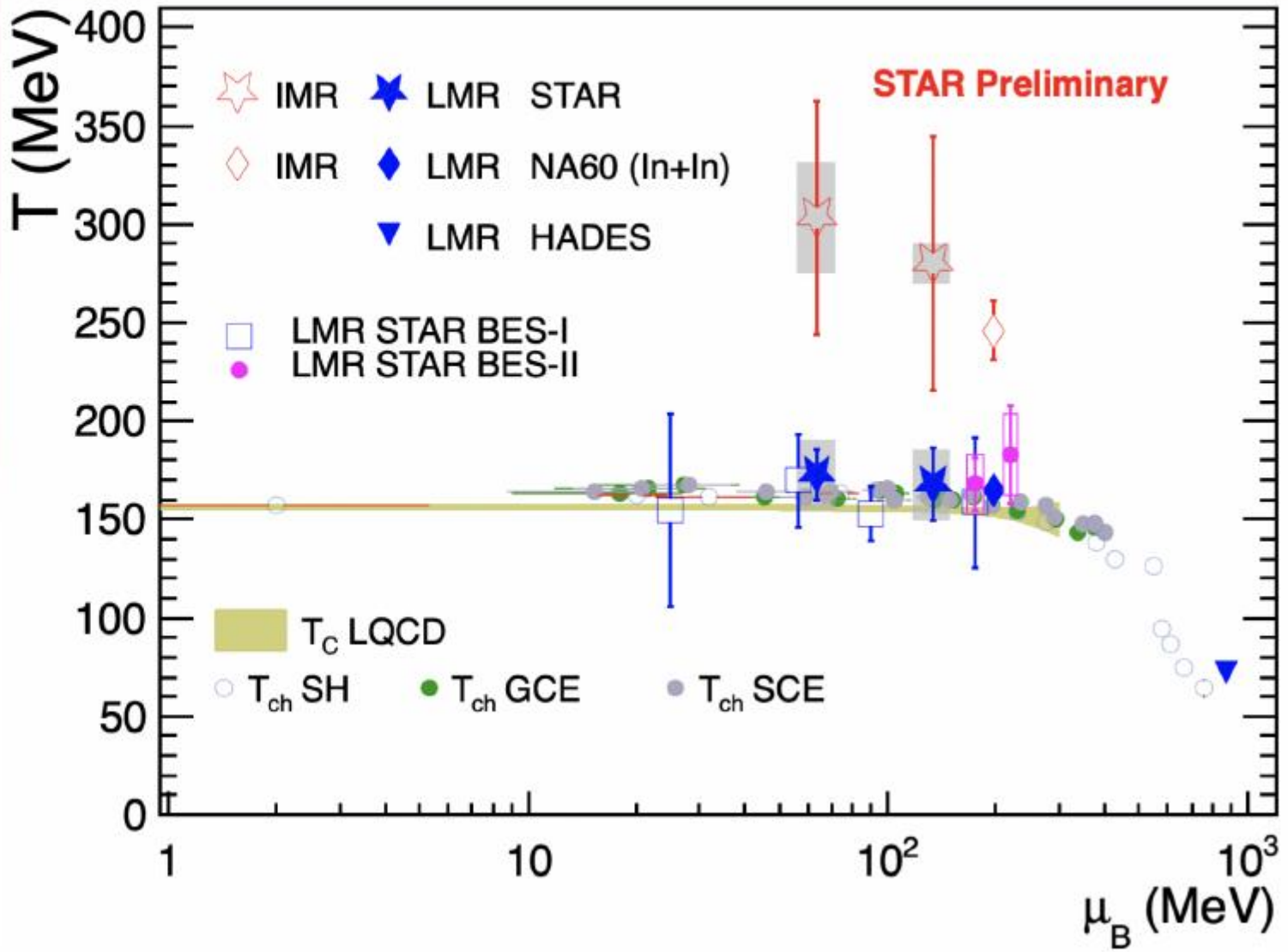
Nature Communications
16, 9098 (2025)

- **Thermal dileptons in LMR**
  - T close to T_{ch} and T_C

Predominantly emitted from hadronic phase, around phase transition

- **Thermal dileptons in IMR**
  - T is higher than T_C

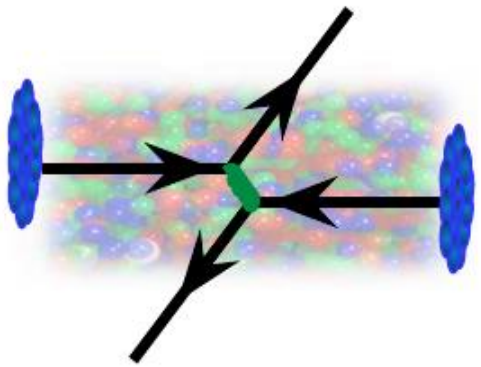
Predominantly emitted from QGP phase



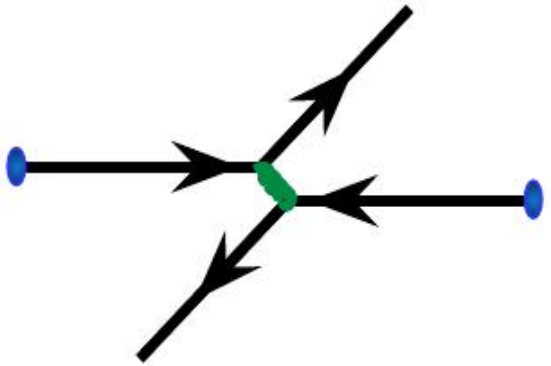
Nuclear modification factor: R_{AA}

One way to quantify the medium effects is to compare HIC to pp reference measurements

Heavy ion (AA) collisions



pp collisions



Nuclear modification factor:

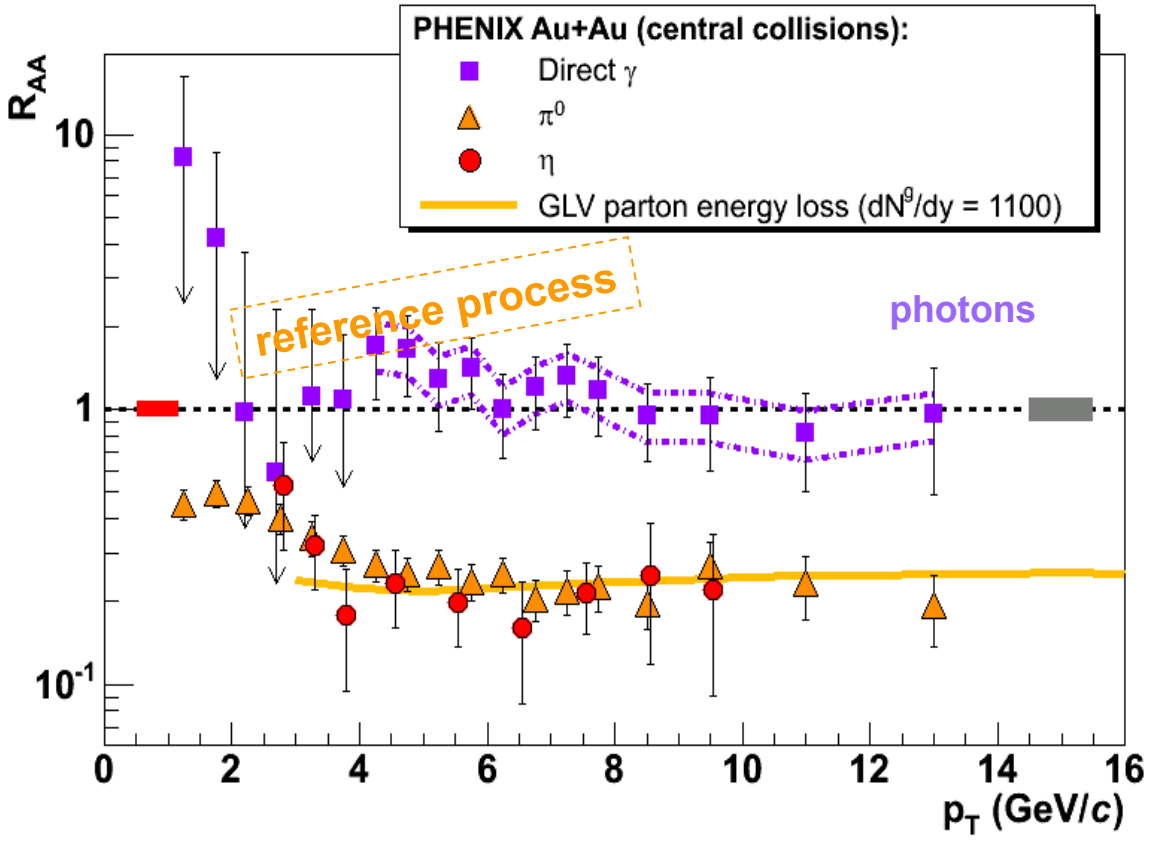
$$R_{\mathrm{AA}} = \frac{\sigma_{pp}^{\mathrm{inel}}}{N_{\mathrm{coll}}} \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}{\mathrm{d}^2 \sigma_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} \sim \frac{\text{"QCD medium"}}{\text{"QCD vacuum"}}$$

- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effects)
- $R_{AA} < 1$ (suppression)

N_{coll} → Averaged number of binary scattering

How can we validate the Glauber model calculations?

PHENIX: The nuclear modification factor: R_{AA}



Phys.Rev.Lett.88:022301,2002

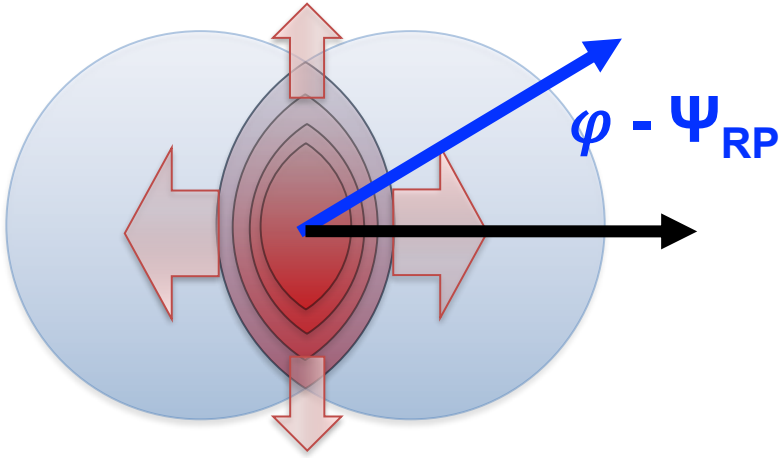
If $R_{AA} < 1$ at high p_T
→ **the medium is opaque to the passage of partons**
→ parton-medium final state interactions, energy loss, modification of fragmentation in the medium

$R_{AA} = 1$ at high p_T
→ the medium is transparent to the passage of partons

$$\kappa_{AA} = \frac{{}_A/\mathrm{d}p_\mathrm{T}}{N_{coll} \cdot \mathrm{d}N_{pp}/\mathrm{d}p_\mathrm{T}}$$

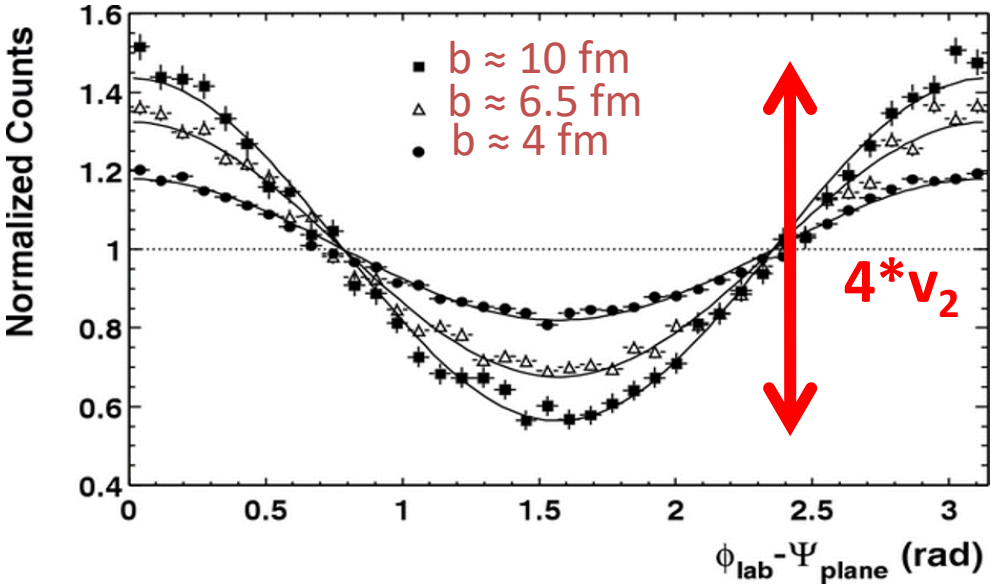
The **meson yield** in central Au-Au is 5 times lower than expected from pp collisions
the **direct photons** are not affected by the dense medium

Anisotropic flow of particles at HIC



Sergei Voloshin, Y. Zhang, Z. Phys. C70,(1996), 665

STAR, PRL**90** 032301 (2003)



$$\frac{dN}{d(\varphi-\Psi_{RP})}=\frac{N_0}{2\pi}\left(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos(2(\varphi-\Psi_{RP}))+\ldots.\right)$$

- The sinus terms are skipped by symmetry arguments
- From the properties of Fourier's series one has

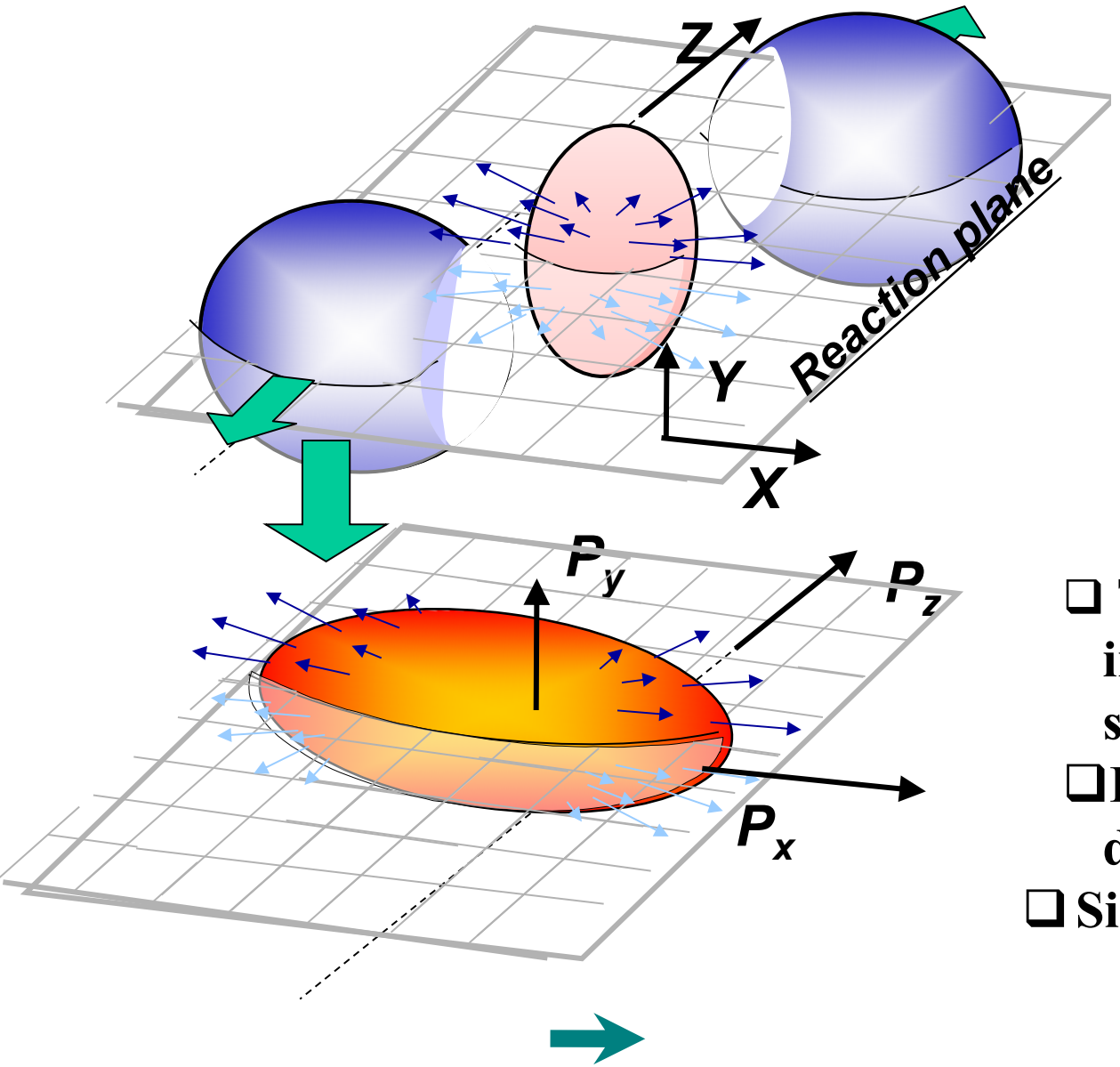
$$v_n=\langle\cos[n(\varphi-\Psi_{RP})]\rangle$$

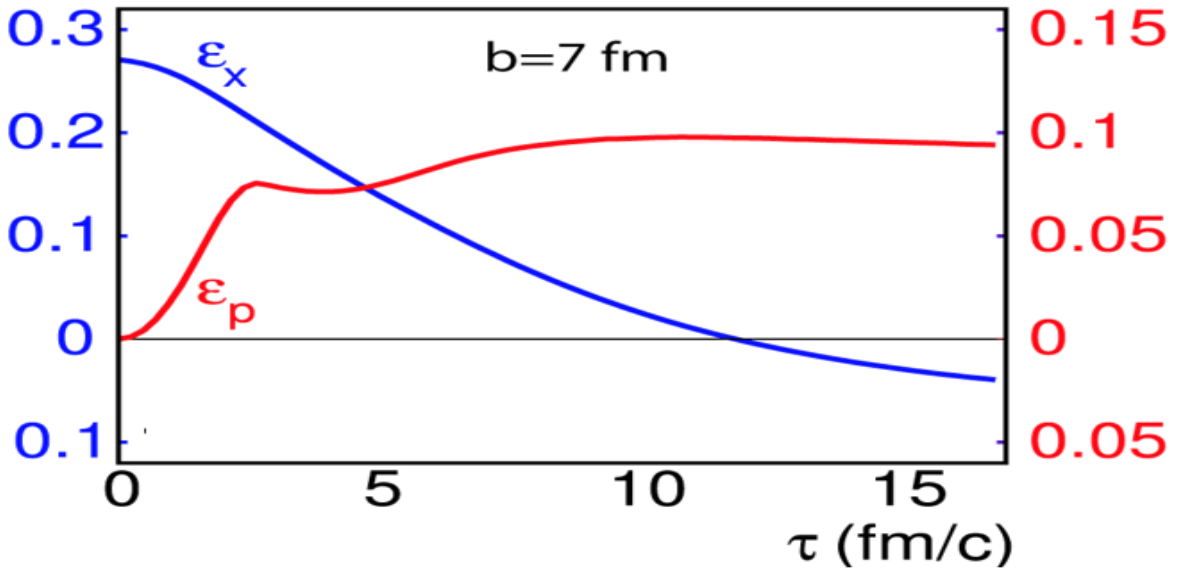
- Fourier coefficients $\mathbf{V_n}$ quantify anisotropic flow:

v_1 is directed flow, v_2 is elliptic flow, v_3 is triangular flow, etc.

Term "flow" does not mean necessarily "hydro" flow – used only to emphasize the collective behavior of particles in event or multiparticle azimuthal correlation

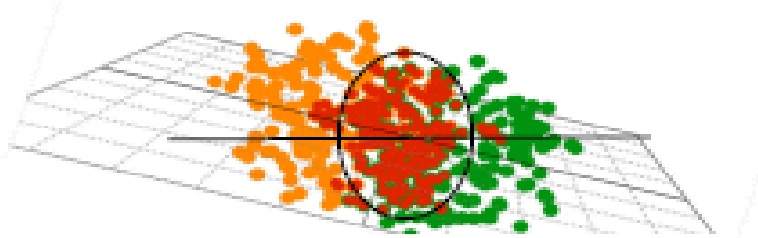
2005 - Elliptic Flow at RHIC

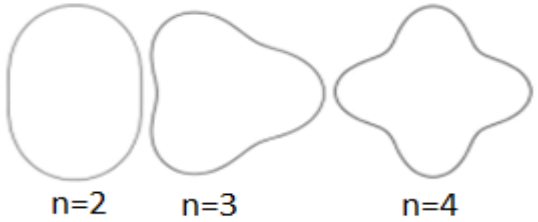




- The initial spatial anisotropy ε evolves (via interactions and density gradients) → Momentum-space azimuthal anisotropy v_2
- Pressure gradient is largest in the shortest direction of the ellipsoid.
- Signal is self-quenching with time

Anisotropic Flow at RHIC-LHC



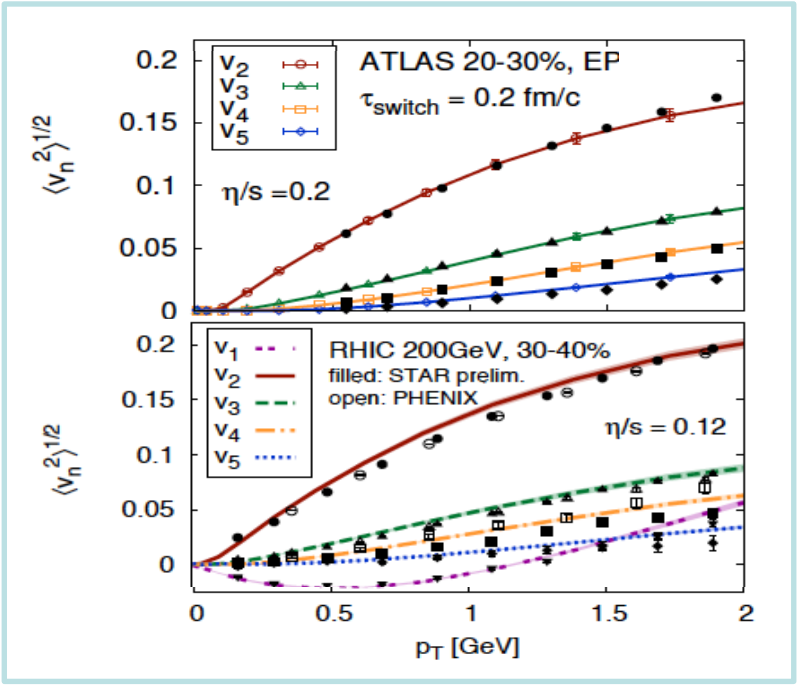


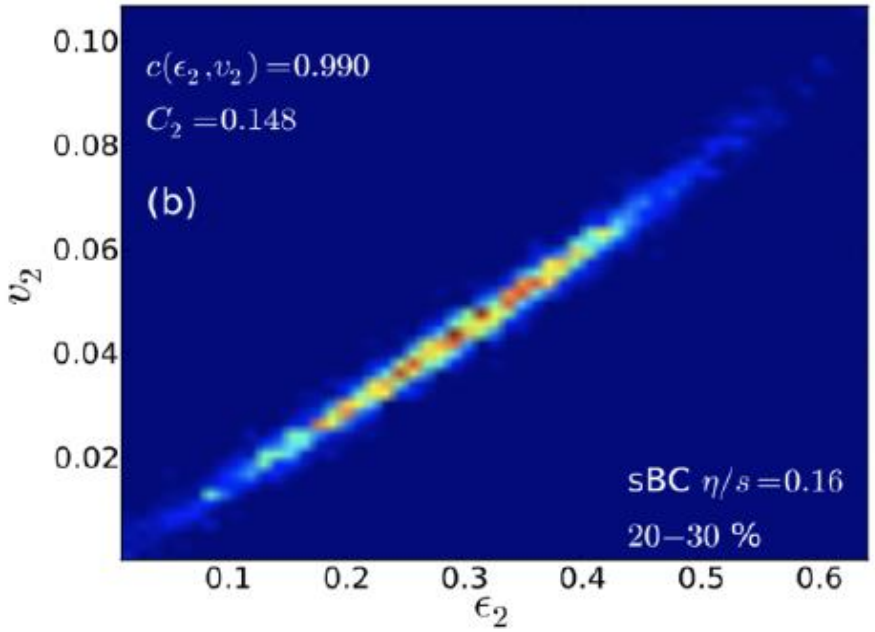
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

Initial eccentricity (and its attendant fluctuations) ε_n drive momentum anisotropy v_n with specific viscous modulation

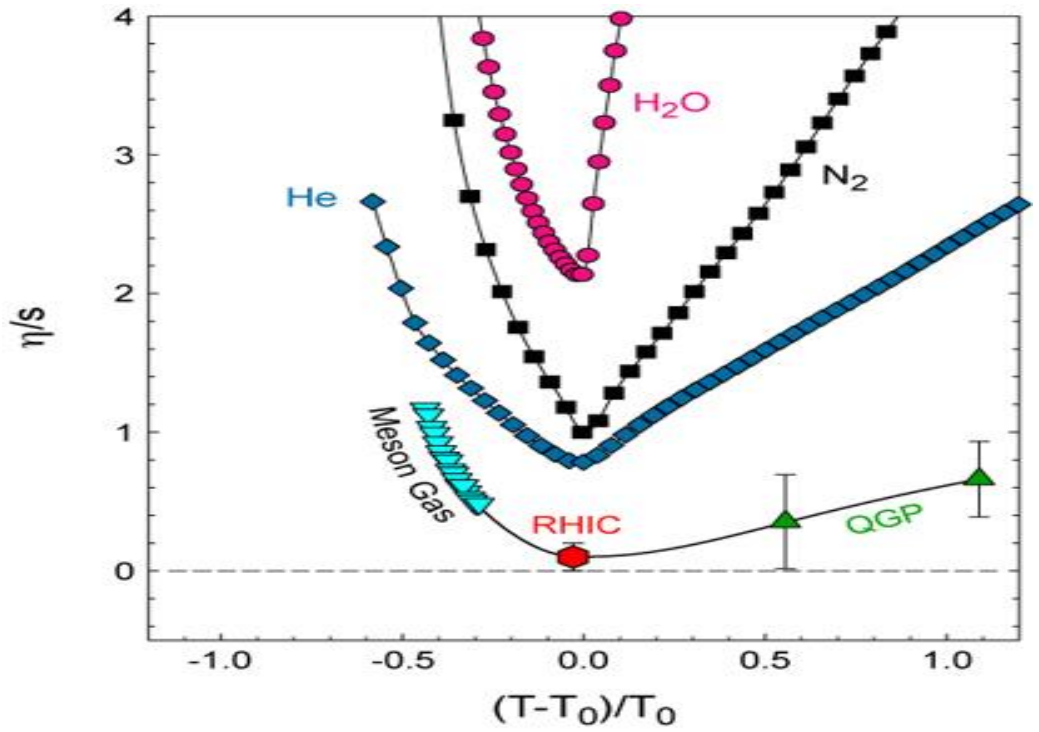
Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302



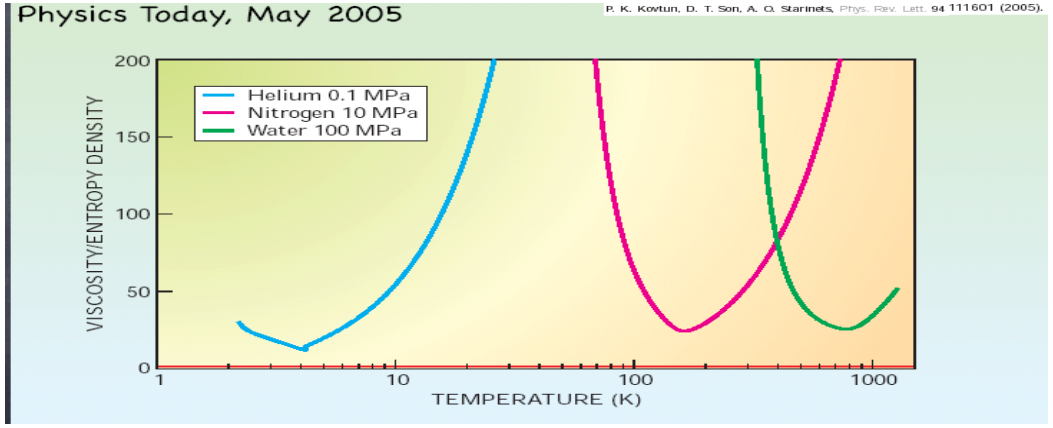


Change of paradigm

Lacey, Taranenko et. al, PRL.98:092301,2007

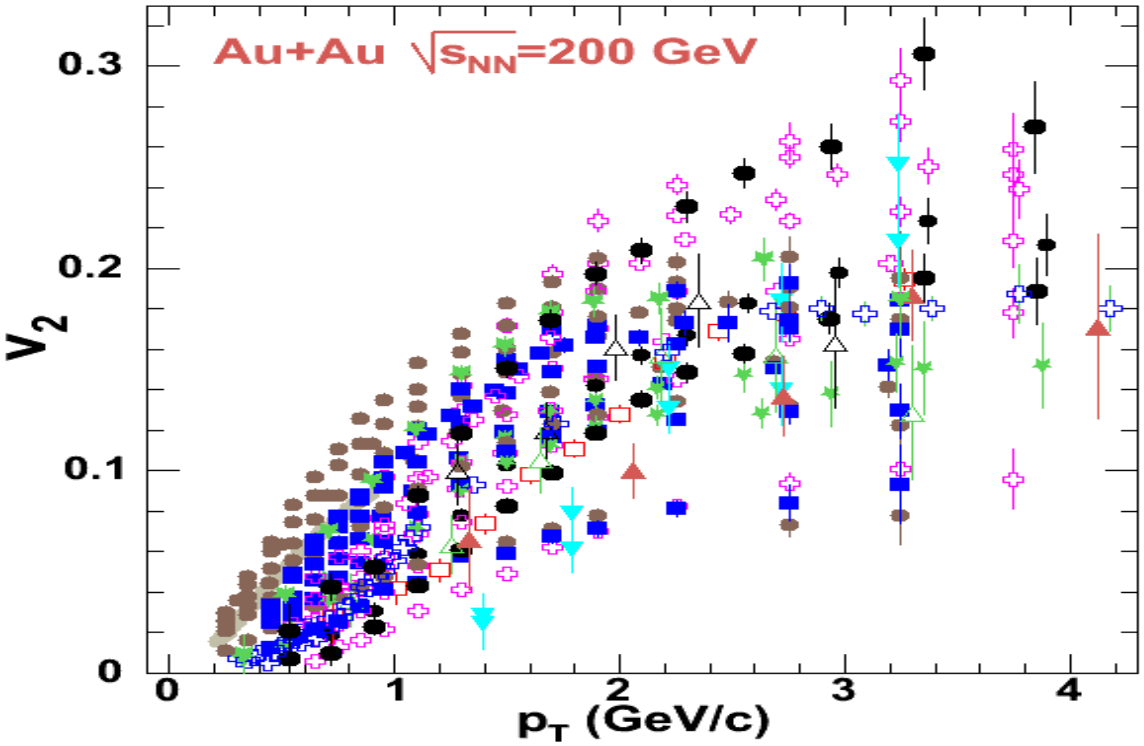






- Manifestation of strongly coupled QGP
- Not a gas of free quarks and gluons
- Instead, strongly coupled nearly perfect liquid reaching almost the minimum value of shear viscosity to entropy density ratio (η/s)

2006 - Anisotropic Flow at RHIC – partonic?



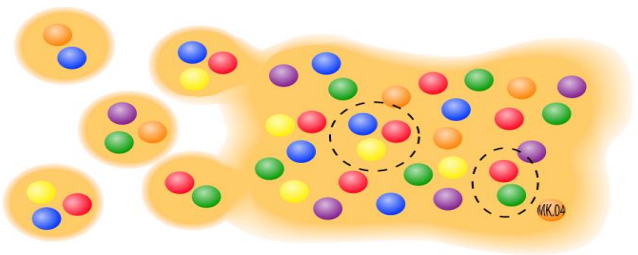
PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)

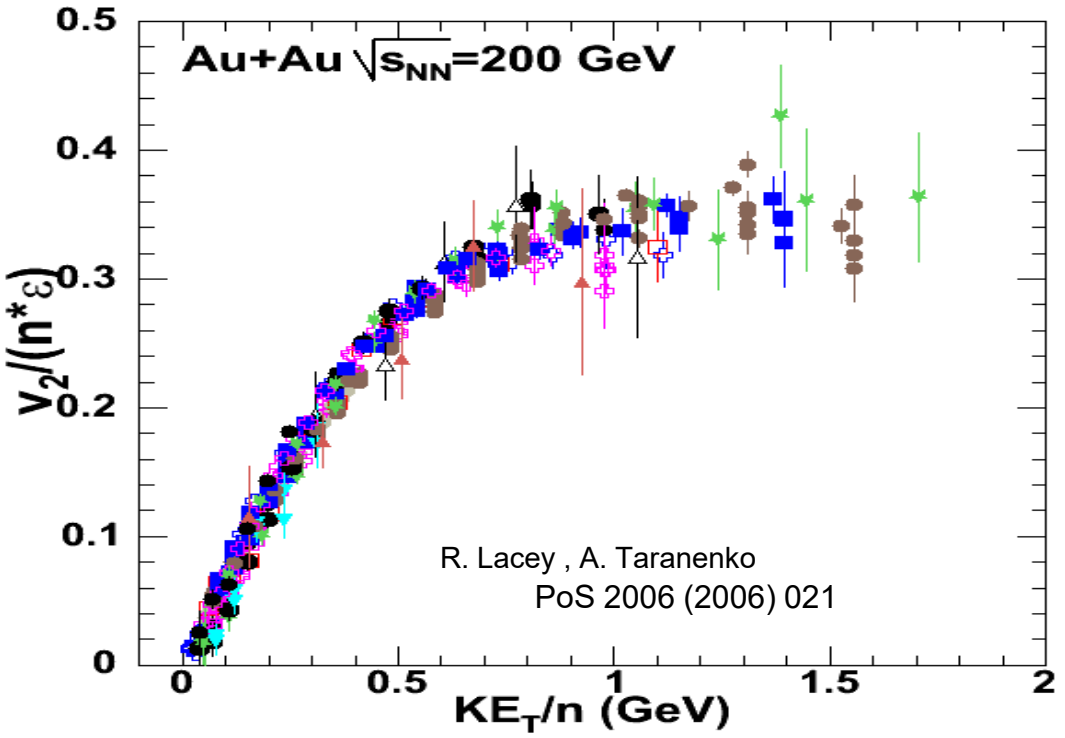
- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $p + \bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- d : min.bias, 10-50%
- ϕ : 20-60%

STAR (Phys. Rev. Lett. 92,Phys. Rev. C 72 (2005), Preliminary QM05, SQM06)

- $\pi^+ + \pi^-$: min.bias
- K^0_S : min.bias, 5-30%,30-70%
- $p + \bar{p}$: min.bias
- $\Lambda + \bar{\Lambda}$: min.bias, 5-30%,30-70%
- $\Xi + \bar{\Xi}$: min.bias
- $\Omega + \bar{\Omega}$: min.bias
- ϕ : min.bias

$$KE_T = m\,(\gamma_T - 1) = m_T - m$$

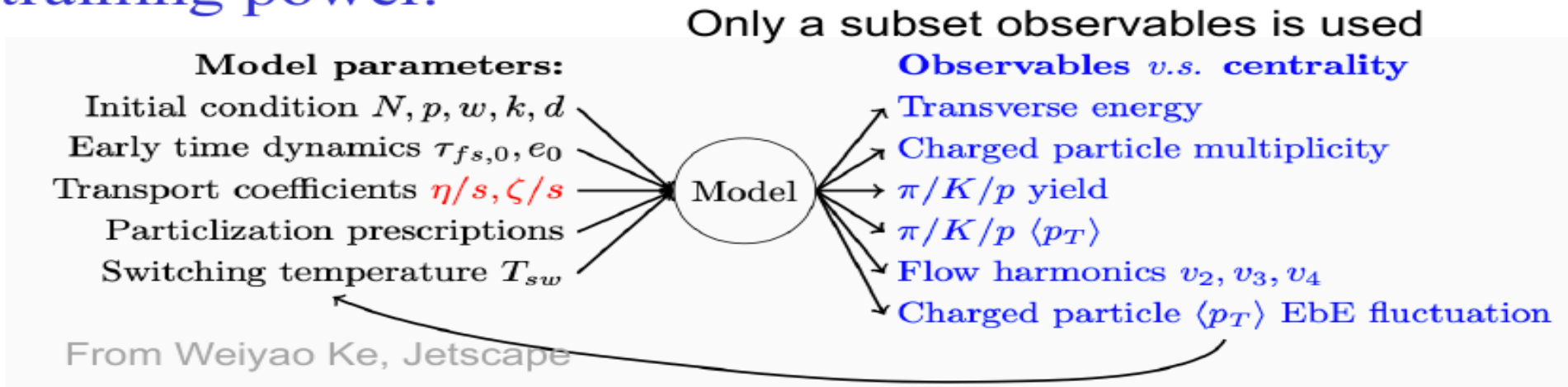




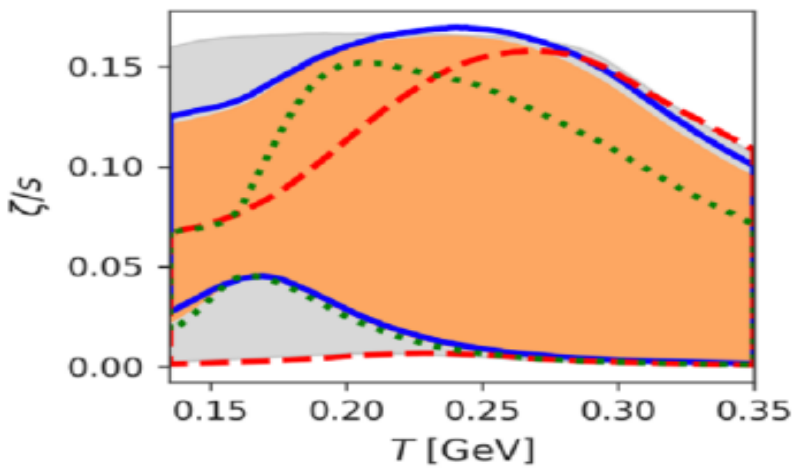
n=2 for mesons and
n=3 for baryons

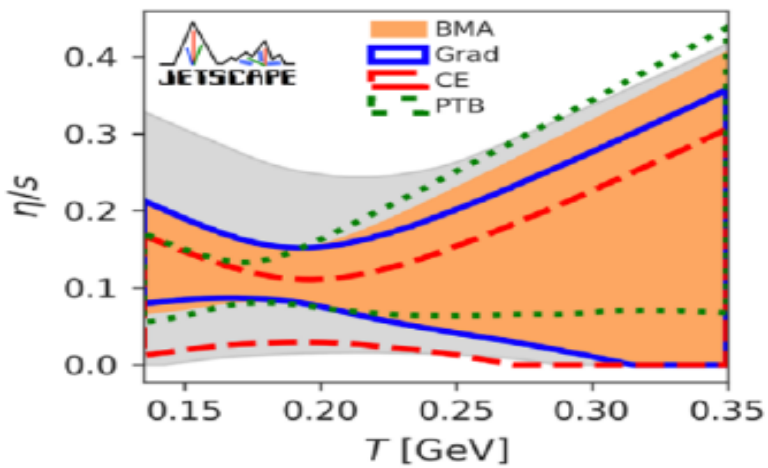
State-of-the-art modeling of HI collisions

- Data-model comparison via Bayesian inference to optimize constraining power.



- Detailed temperature dependence of viscosity!

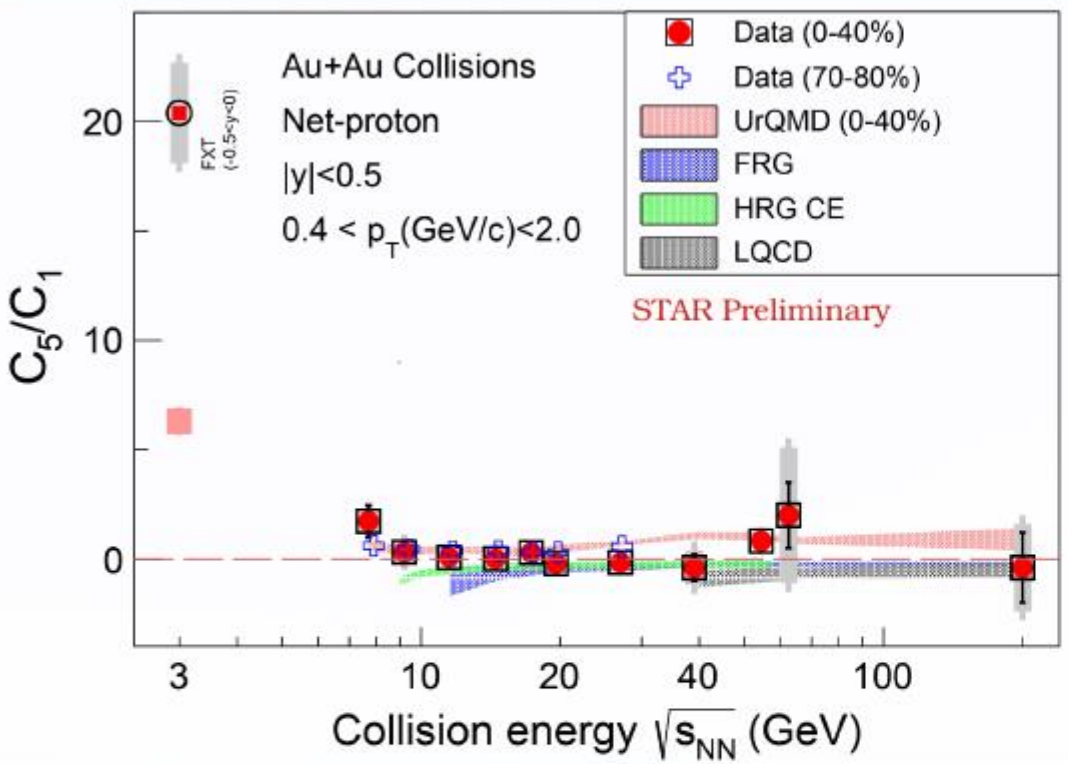


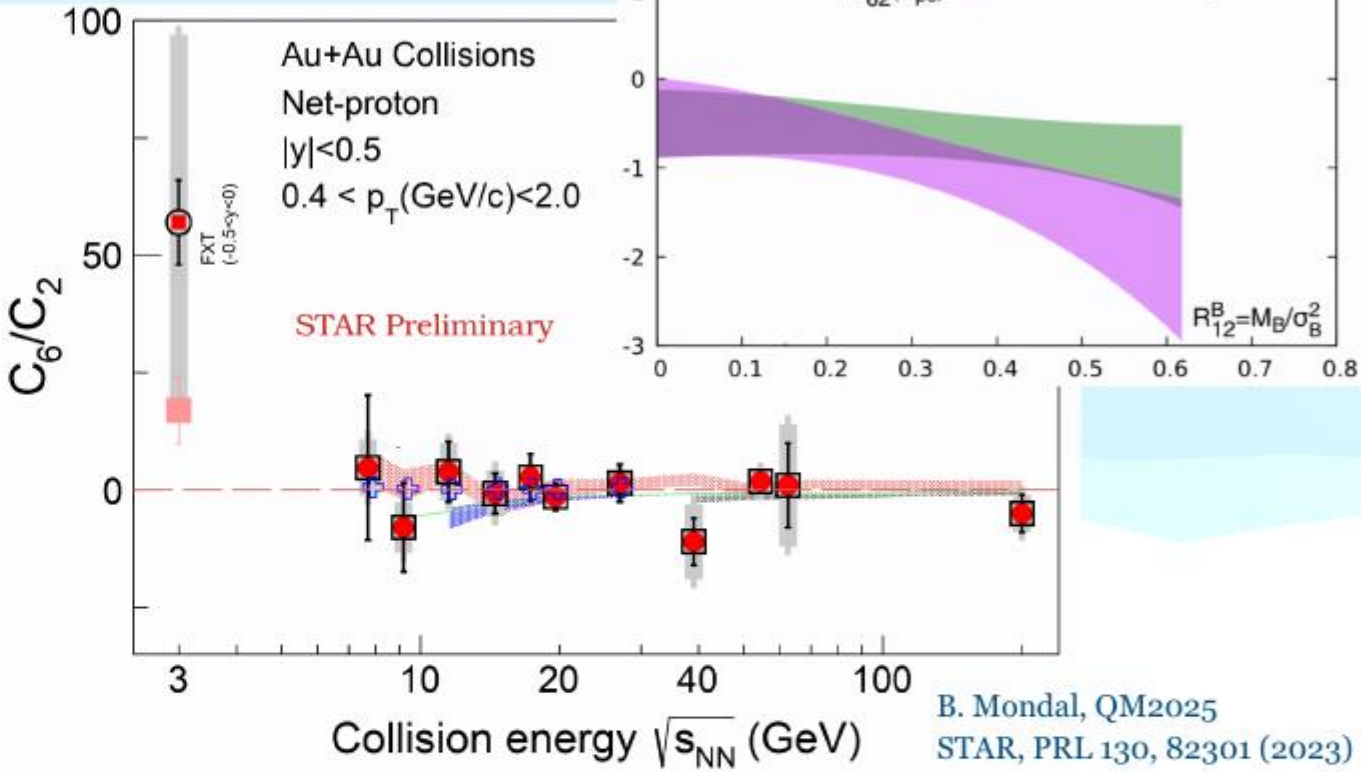


Jetscape PRL.126.242301
Trjactum PRL.126.202301

Major uncertainty: initial condition and pre-hydro phase

Hyper Order Cumulants





B. Mondal, QM2025
STAR, PRL 130, 82301 (2023)

- For crossover, LQCD and FRG predict negative sign of C_5/C_1 and C_6/C_2 at transition temperature

Wei-jie Fu et. al, PRD 104, 094047 (2021)
HotQCD, PRD 101,074502 (2020)

- Results from 7.7 GeV and above are consistent with LQCD and FRG for a **smooth crossover**

LQCD ↔ Experiment

Google Translate

Detect language | English | German | Spanish | **LQCD** ⇄ **EXPERIMENT** | Spanish

$$\chi^{BQSC}_{klmn} = \left.\frac{\partial^{(k+l+m+n)}[P(\hat{\mu}_B,\hat{\mu}_Q,\hat{\mu}_S,\hat{\mu}_C)/T^4]}{\partial\hat{\mu}_B^k\partial\hat{\mu}_Q^l\partial\hat{\mu}_S^m\partial\hat{\mu}_C^n}\right|_{\vec{\mu}=0}$$

Baryon number **(B)**, Strangeness **(S)**, Electric charge **(Q)**, Cham **(C)** 0 / 5,000

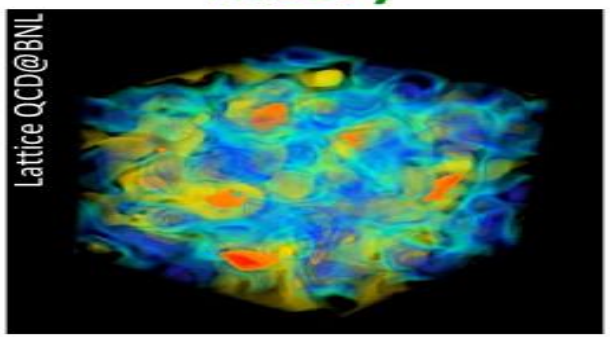
Translation

$$\chi_2^B = \frac{\kappa_2(\Delta N_B)}{VT^3} \Rightarrow \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\chi_4^B}{\chi_2^B}$$

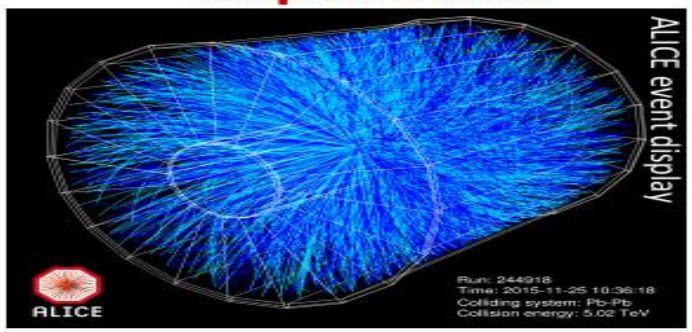
$\kappa_n \rightarrow$ cumulants of $\Delta N_B = N_B - N_{\bar{B}}$

Bridge experimental data to LQCD calculations

Theory



Experiment



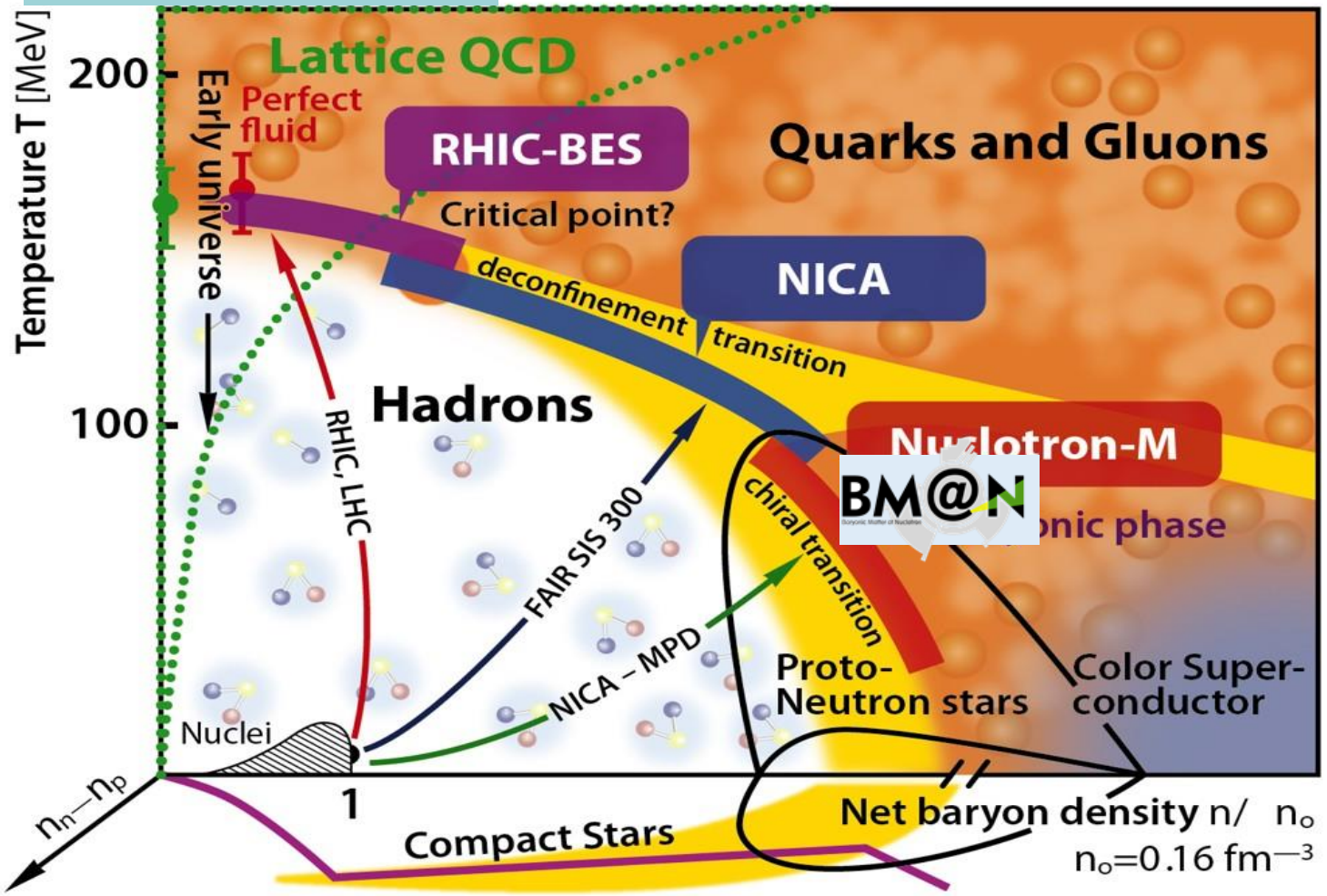
Static	Dynamic
Coordinate space	Momentum space
Net-baryon	Net-proton
Fixed V	Fluctuating V
...	...

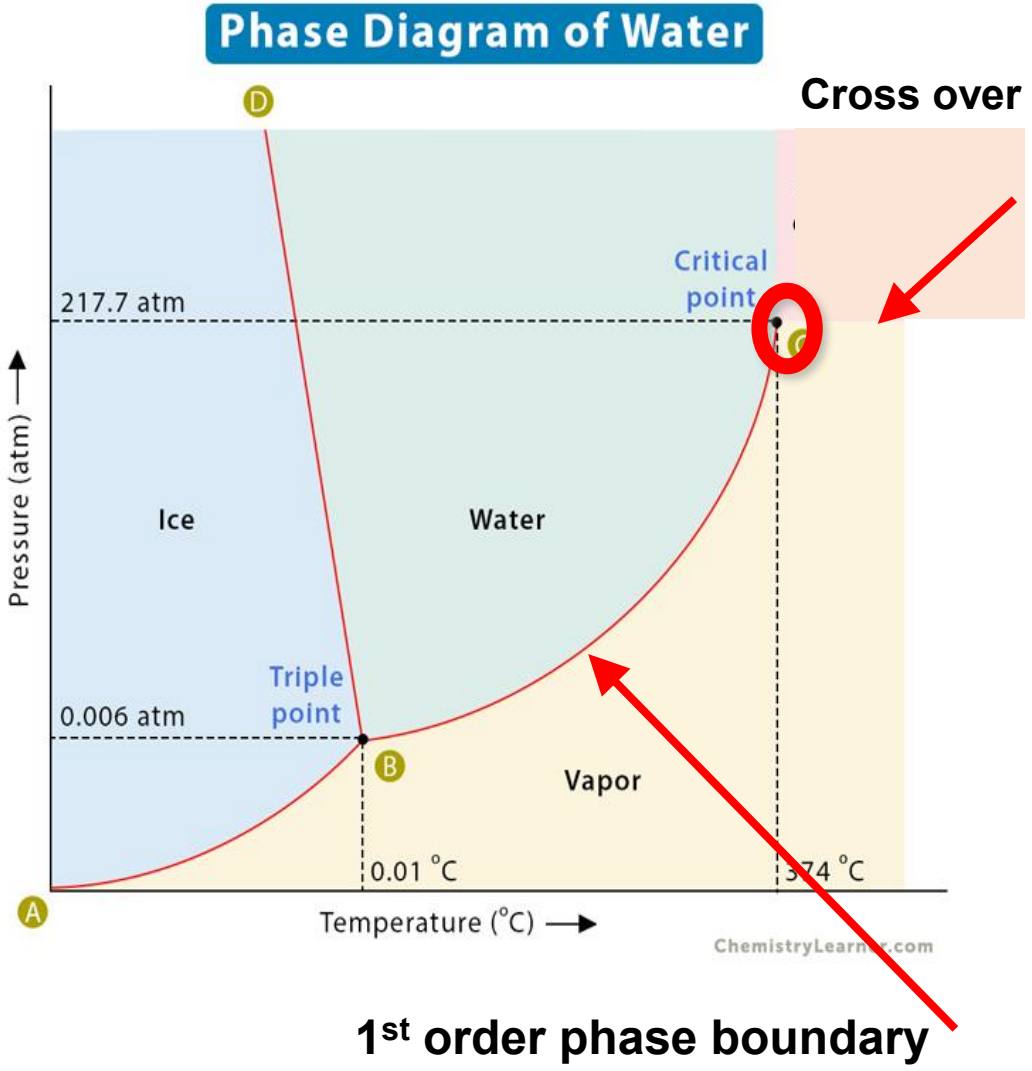
- **Experimental challenges:** Particle identification, efficiency correction, effect of event pileup, volume fluctuations ...
- **Theoretical/phenomenological challenges:** Effect of resonances, charge conservation, effect of magnetic field, cluster formation, baryon annihilation, excluded volume ...

Relativistic Heavy-Ion Collisions and QCD Phase Diagram

Critical Temperature
$T_c \approx 156$ +/- 9 MeV

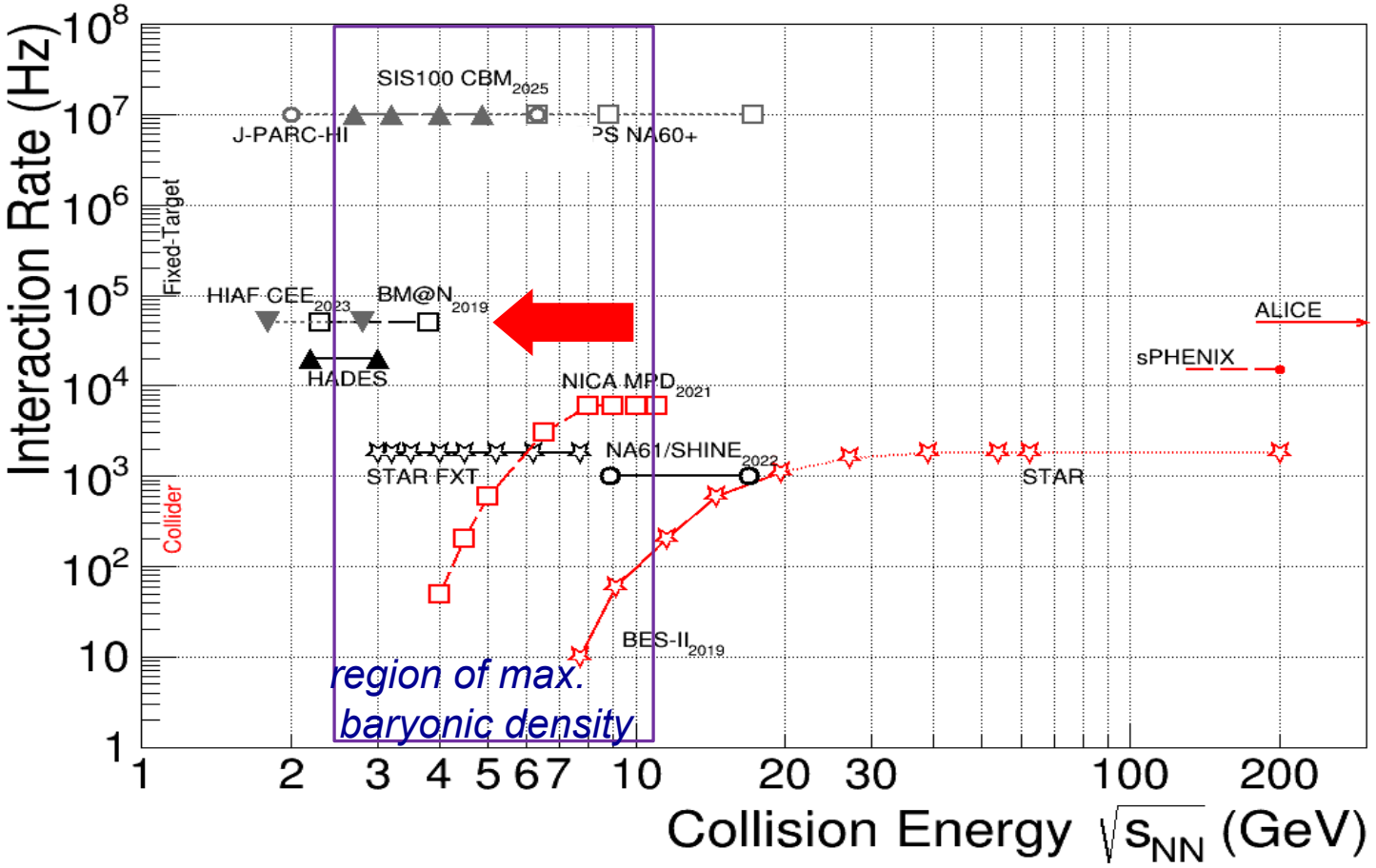
[PRD 90 094503 (2014)]





Smooth *transition from hadronic degrees of freedom to quark-gluon degrees of freedom at zero baryonic density*

Relativistic Heavy Ion Collision Experiments



MPD, BM@N competitors:

Present:

RHIC/STAR (USA) 3-200 GeV
NA61/SHINE (CERN): 5.1-17.3 GeV
SIS18/HADES (Germany) 2.4-2.55 GeV

Future:

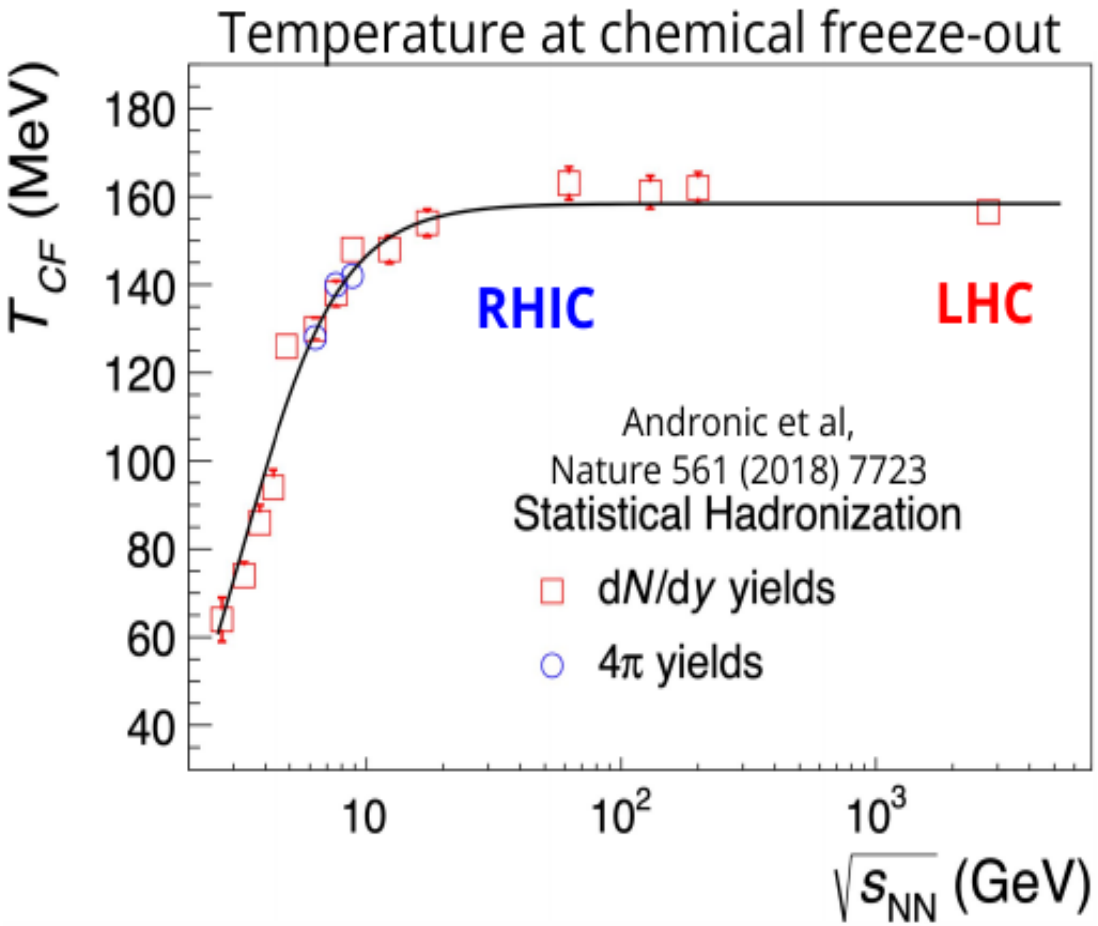
HIAF/CEE (China) 2.1-4.5 GeV (2026-?)
FAIR/CBM (Germany) 2.4-4.9 GeV (2029-?)
JPARC-HI (Japan) 2-5 GeV (2030-?)
NA60+(CERN) 6.1-16.4 GeV (2029-?)

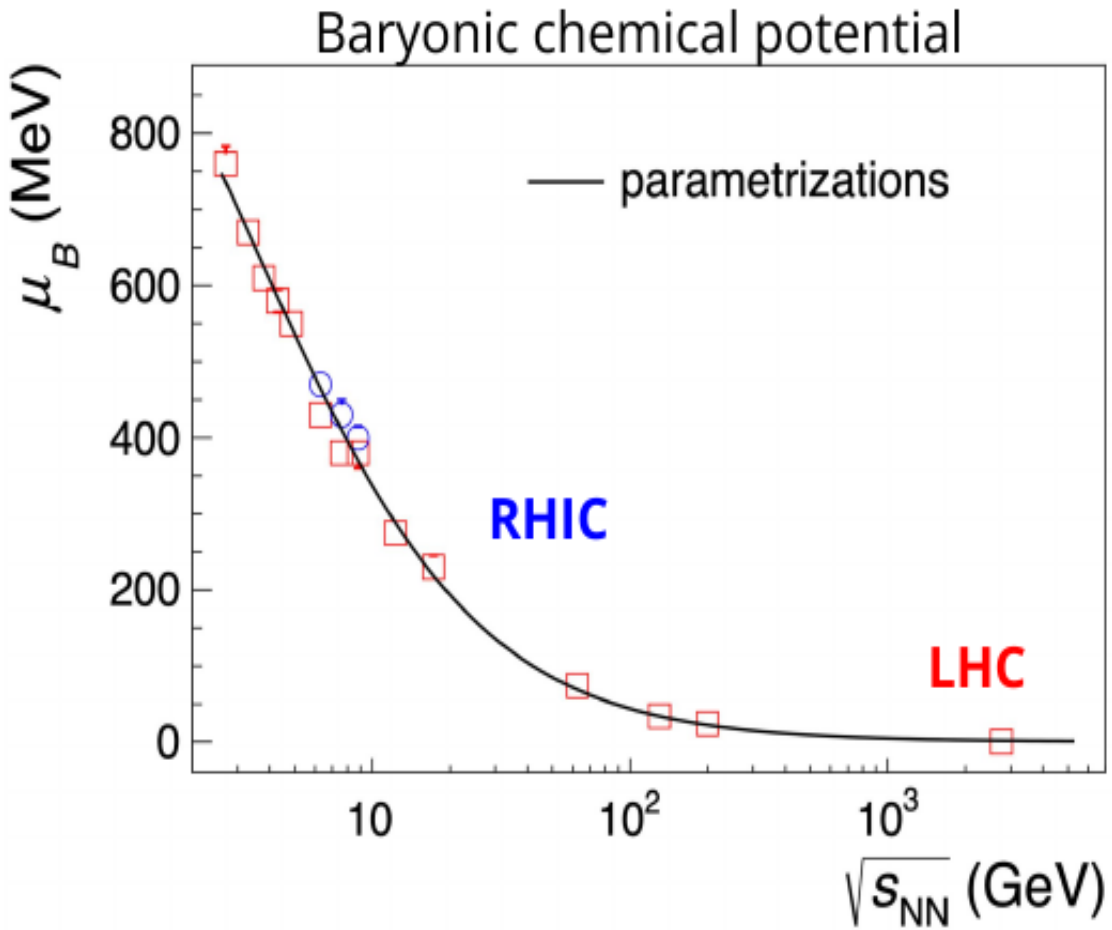
Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

$(\mu_c, T_c) = (495 - 654, 100 - 119)$ MeV ➡ $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

BM@N and MPD are both in the collision energy range of the predicted CEP location.

Energy dependence of chemical freeze-out parameters

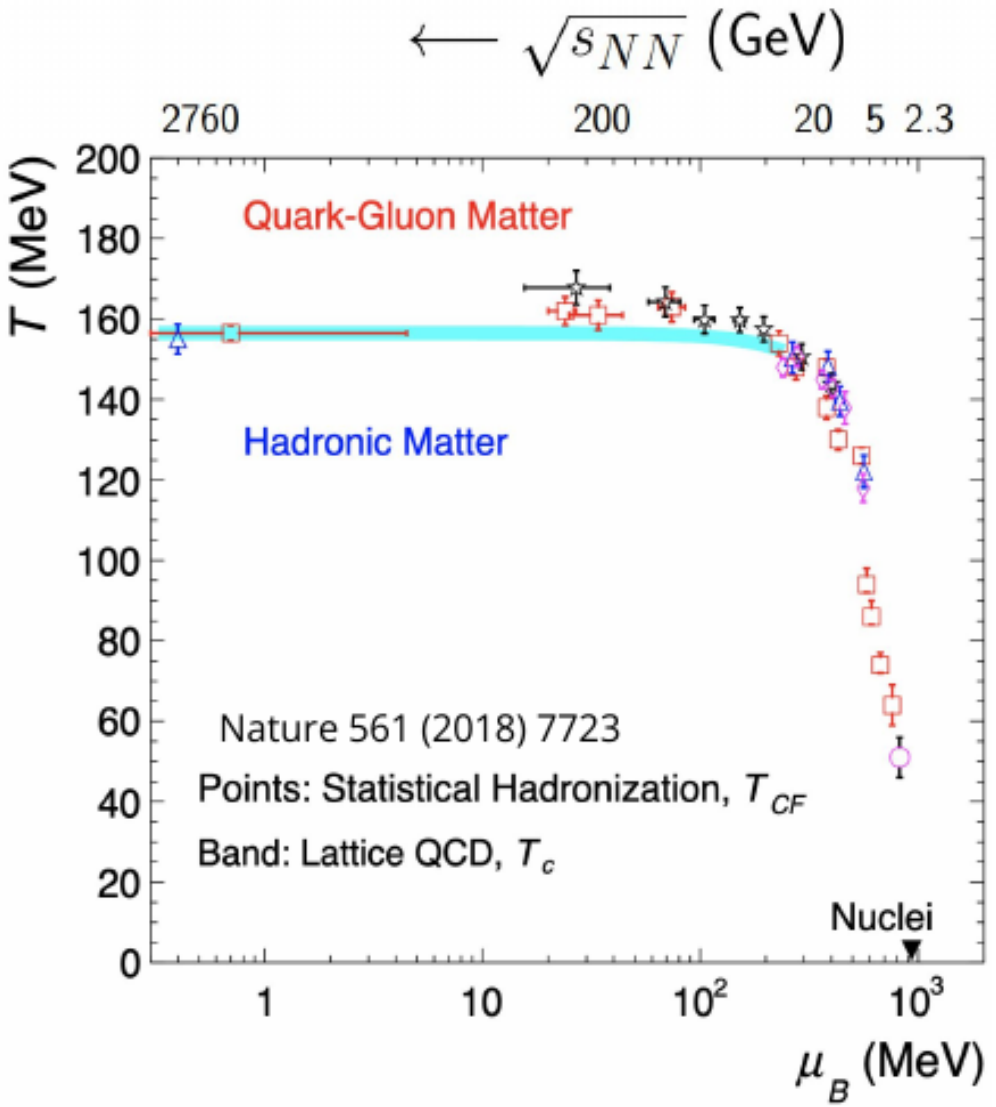




Smooth evolution of T_{CF} and μ_B with beam energy:

→ T_{CF} reaches limiting value close to pseudo-critical temperature.

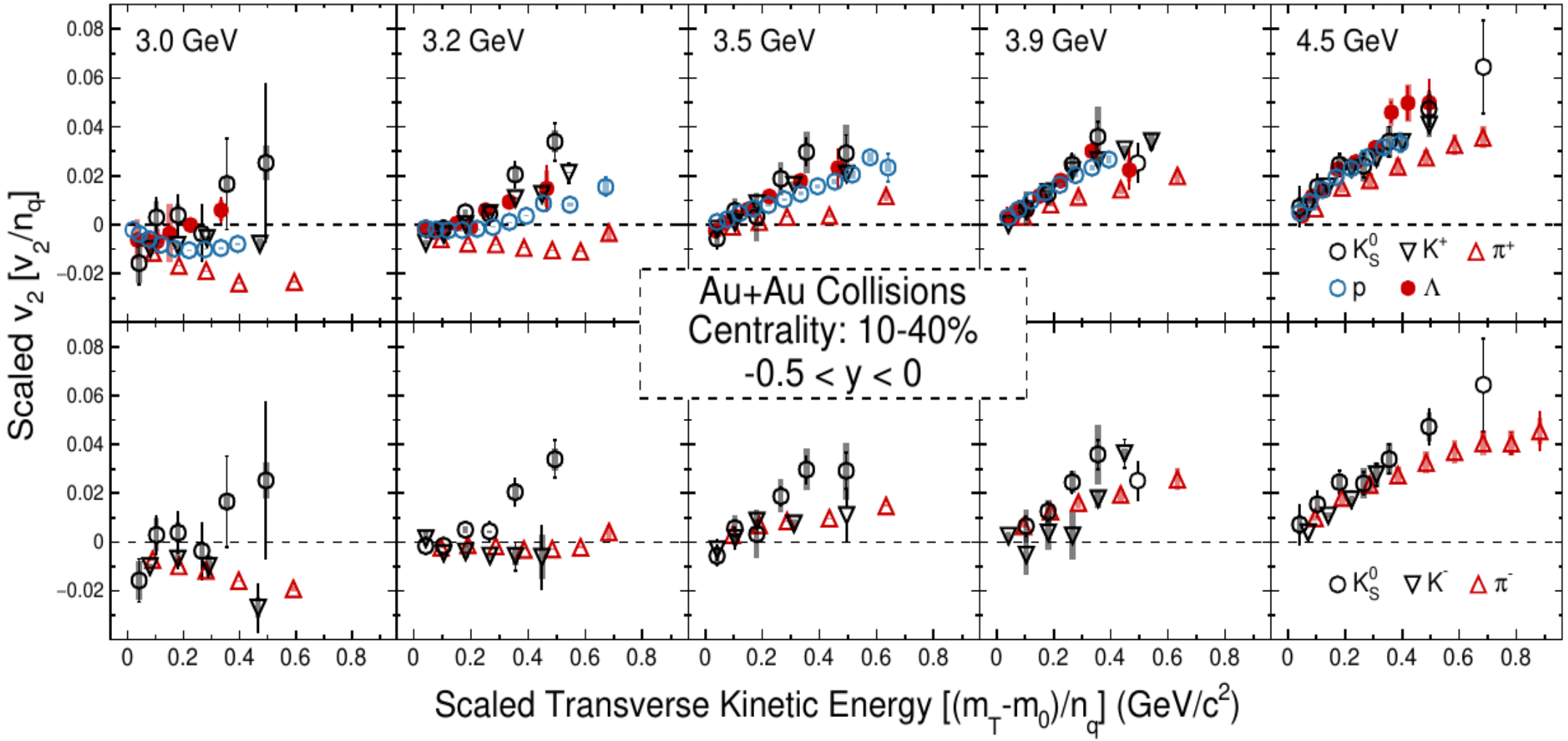
QCD phase diagram from SHM



- Extracted result from LHC: remarkable coincidence with Lattice QCD results.
- At LHC, baryon chemical potential μ_B~0: produced matter and antimatter as in the Early Universe.
- At lower collision energy: more matter from beam remnants of the colliding nuclei, larger μ_B.
- Critical point still to be located (RHIC Beam Energy Scan, FAIR).

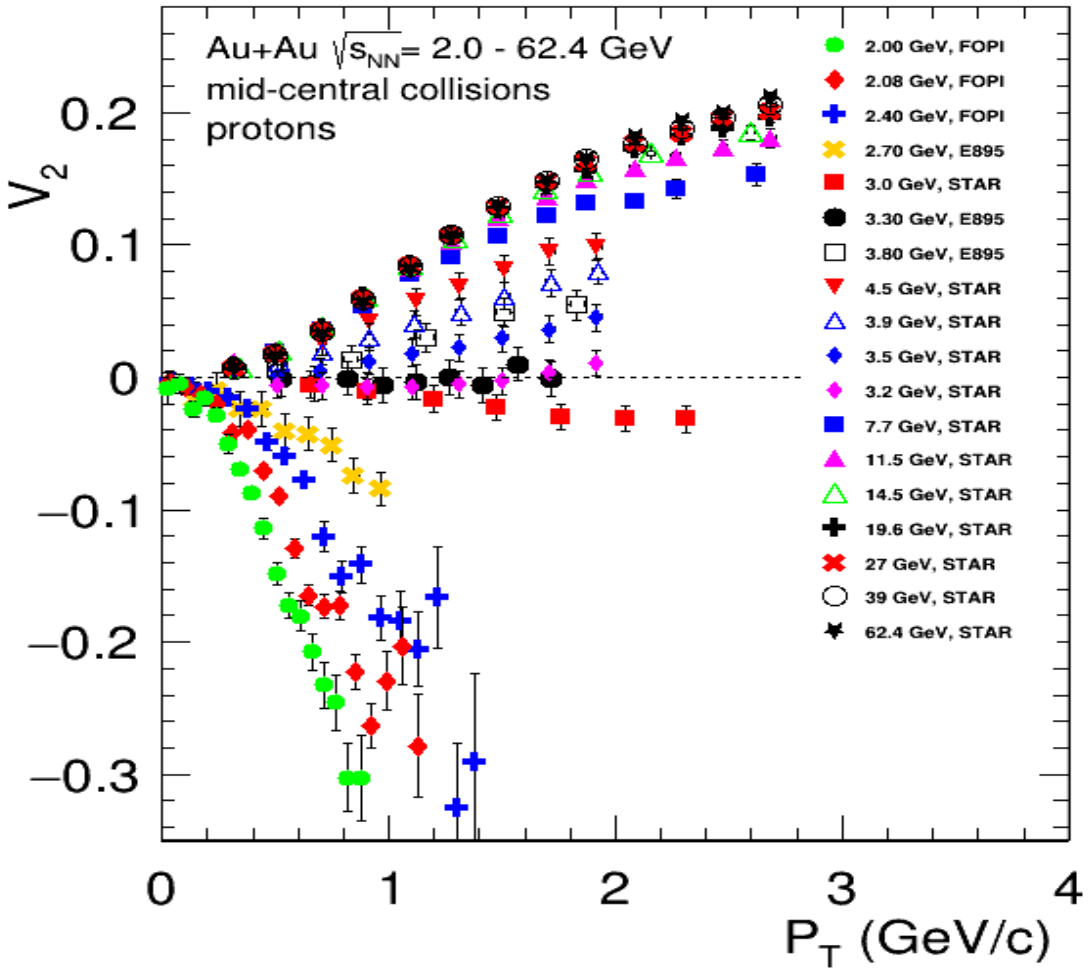
Anisotropic Flow at RHIC BES

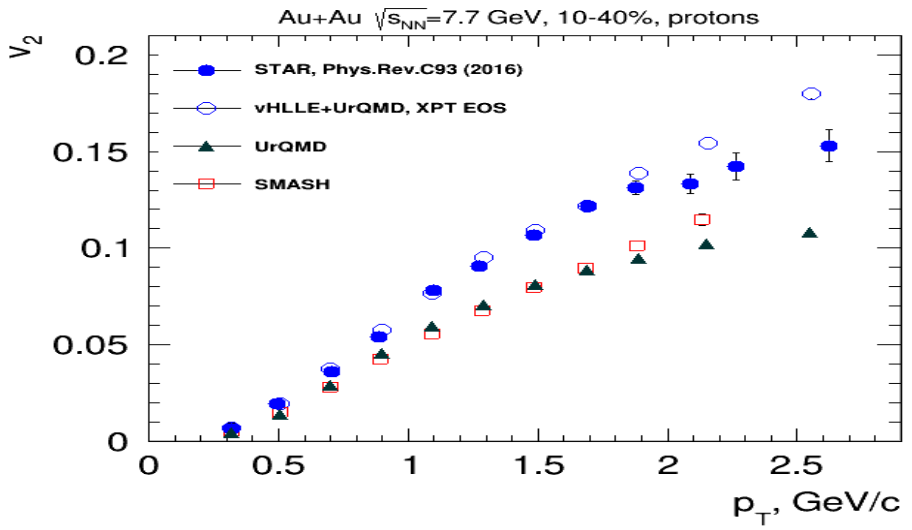
Li-Ke Liu (CCNU), STAR Collaboration, CPOD 2024

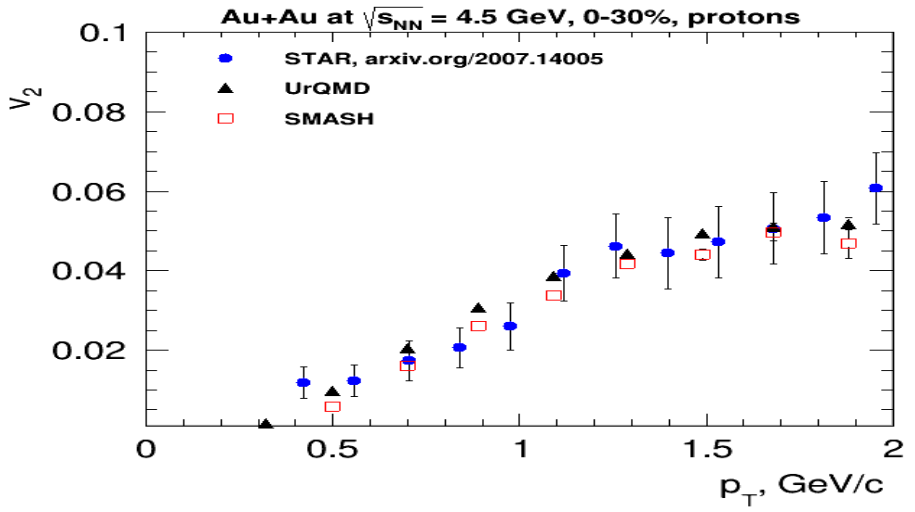


At high energies, data follows NCQ scaling, indicating partonic collectivity???
NCQ scaling for v2 breaks completely at 3.5 GeV and below,

Beam Energy Dependence of Elliptic Flow (v_2)







- Strong energy dependence of v_2 at $\sqrt{s_{NN}}$ = 2.4-7 GeV

MPD experiment at NICA

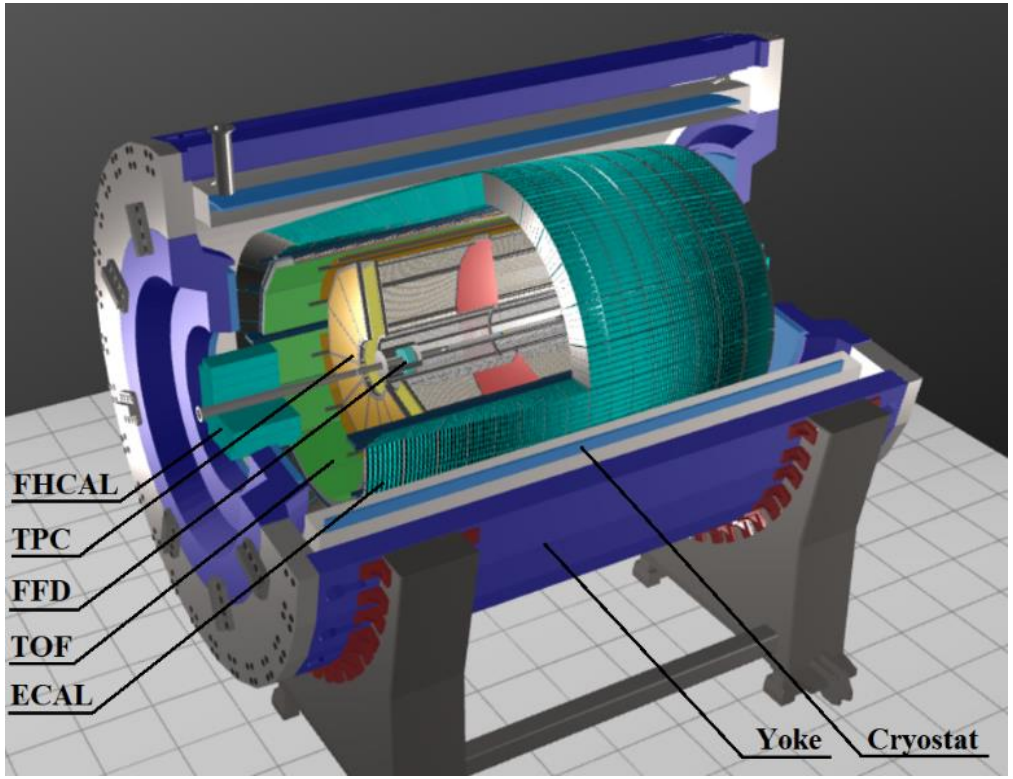
Main subsystems at Stage-I:

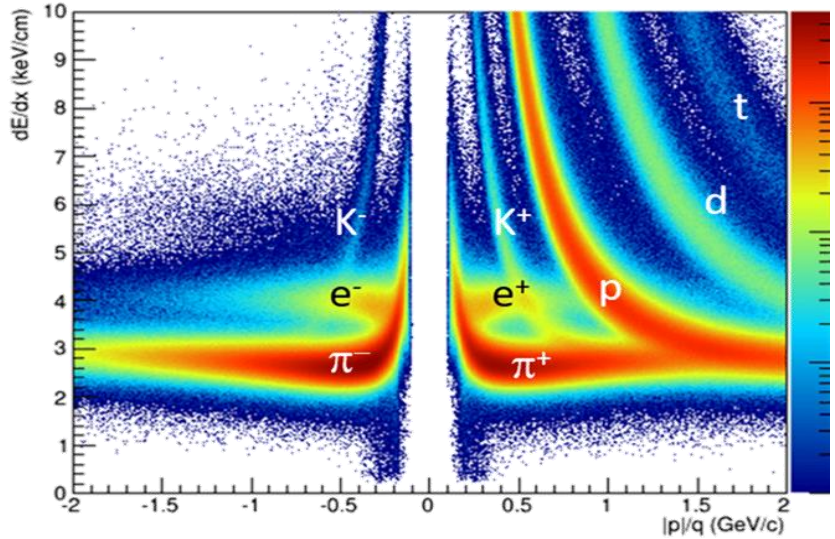
TPC ($|\eta| \leq 1.6$): charged particle tracking + momentum reconstruction + dE/dx identification

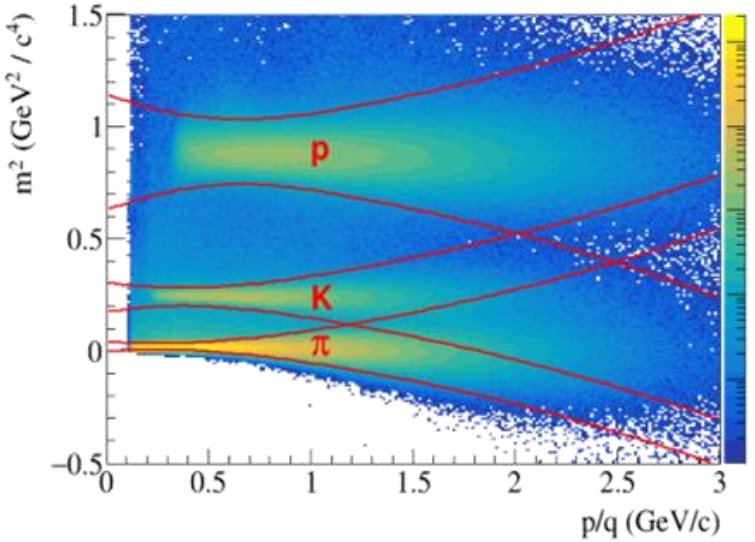
TOF ($|\eta| \leq 1.4$): charged particle identification

ECal ($2.9 < |\eta| < 1.4$): energy and PID for $\gamma/e^{\pm}$

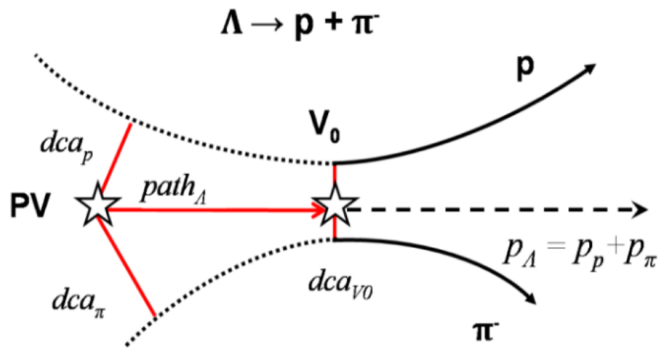
FHCal ($2 < |\eta| < 5$) and **FFD** ($2.9 < |\eta| < 3.3$): event triggering + event geometry

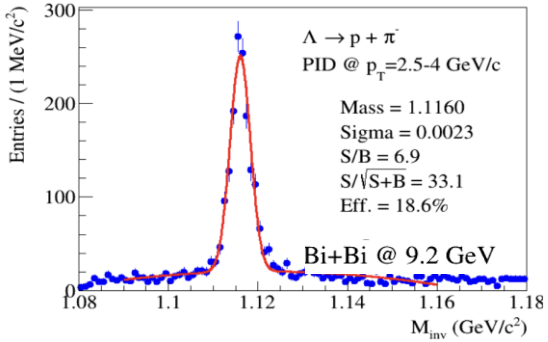


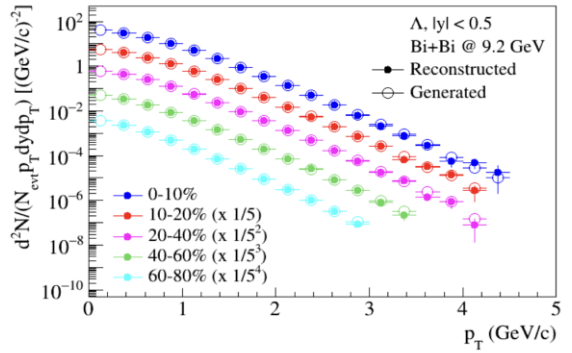


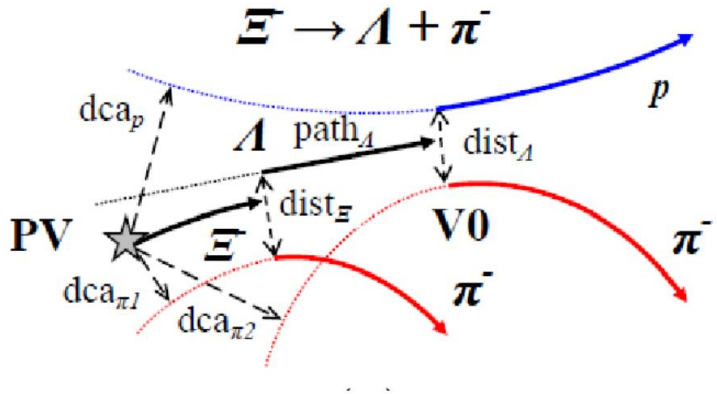


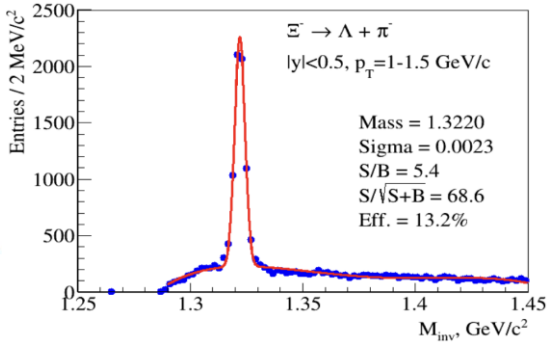
PID via Topology and Invariant Mass

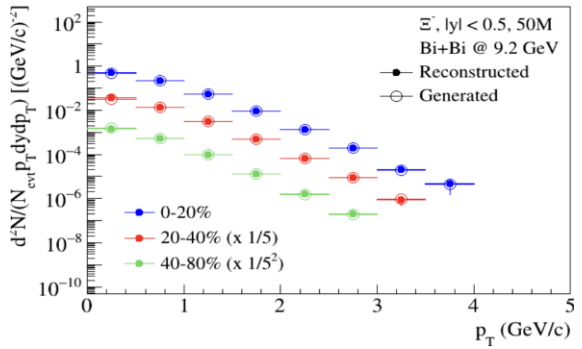












$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$
$$= m_1^2 + m_2^2 + 2\left(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2\right).$$

Full-scale simulation of the MPD (NICA): collider mode

Nuclear Physics Revista Mexicana de Física **71** 041201 1–45 JULY-AUGUST 2025

MPD physics performance studies in Bi+Bi collisions at $\sqrt{s_{NN}} = 9.2$ GeV

R. Abdulin[20], V. Abgaryan[1], R. Adhikary[16], K.G. Afanaciev[16,13], S.V. Afanaciev[16], G. Agakishiev[16], E.I. Alexandrov[16], I.N. Alexandrov[16], M. Alvarado-Hernández[14], D.I. Andreev[16], S.V. Andreeva[16], T.V. Andreeva[16], E.V. Andronov[28], N.V. Anfimov[16], A. Anikeev[21], A.V. Anufriev[28], A.A. Aparin[16], R. Arteche-Diaz[16], V.I. Astakhov[16], T. Aushev[23], S.P. Avdeev[16], G.S. Averichev[16], A.V. Averyanov[16],A. Ayala[14], V.N. Azorskiy[16], L. Bavichev[32], V.A. Babkin[16], P. Bakhtin[19], A.I. Balandin[16], N.A. Balashov[16], A. Baranov[10], D.A. Baranov[16], N.V. Baranova[31], R.V. Baratov[16], N. Barbashina[21], V. Barbasová[23], V.M. Baryshnikov[16], K.D. Basharina[16], A.E. Baskakov[16], V.G. Bayev[13], A.G. Bazhazhin[16], S.N. Bazylev[16], P. Beletsky[25], S.V. Belokurova[28], A.V. Belyaev[16], E.V. Belyaeva[16], D.V. Belyakov[16], Y. Berdnikov[24], F. Berezov[22], M. Bhattacharjee[16], W. Bietenholz[14], D. Blau[19], G.A Bogdanova[31], D.N. Bogoslovsky[16], I.V. Boguslavski[16], E.A. Bondar[12], E.E. Boos[31], A. Botvina[10], A. Brandin[21], S.A. Bulychjov[19], V. Burdelnaya[25], N. Burmasov[20], M.G. Buryakov[16], J. Busa Jr.[16], A.V. Butenko[16], S.G. Buzin[16], A.V. Bychkov[16], Z. Cao[35], C. Ceballos-Sánchez[16], V.V. Chalyshev[16], V.F. Chepurnov[16], Vl.V. Chepurnov[16], G.A. Cheremukhina[16], A.S. Chernyshov[31],

https://doi.org/10.31349/RevMexFis.71.041201

(40+ pages, 445 auhors)

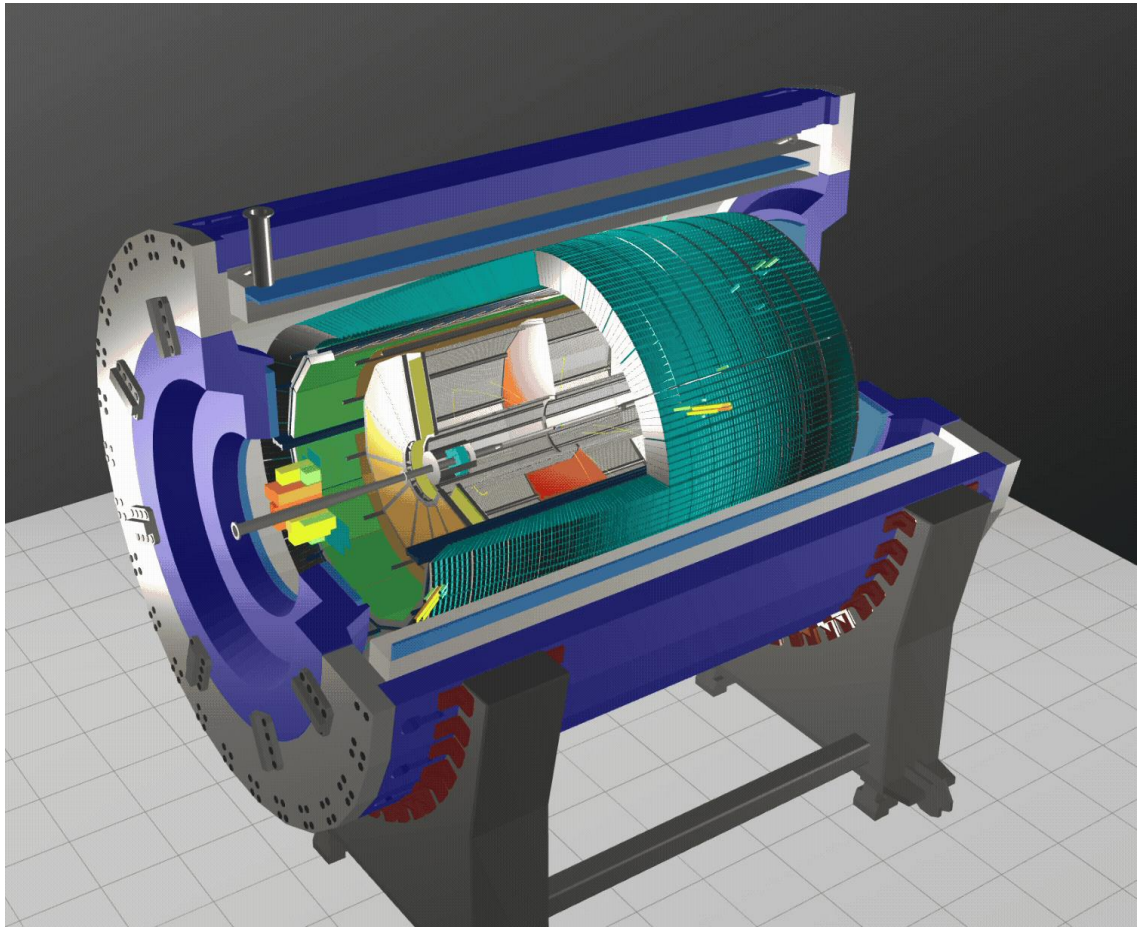


TABLE I. The list of centralized MC productions for physics feasibility studies.

No.	Generator	Events	Purpose
1	UrQMD	50 M	General purpose
2	DCM-QGSM-SMM	1 M	Trigger
3	PHQMD	20 M	(Hyper)nuclei
4	PHSD	15 M	Global polarization
5	vHLLE+UrQMD	15 M	Flow, correlations

MPD physics program

G. Feofilov, P. Parfenov

Global observables

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

V. Kolesnikov, Xianglei Zhu

Spectra of light flavor and hypernuclei

- Light flavor spectra
- Hyperons and hypernuclei
- Total particle yields and yield ratios
- Kinematic and chemical properties of the event
- Mapping QCD Phase Diag.

K. Mikhailov, A. Taranenko

Correlations and Fluctuations

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

D. Peresunko, Chi Yang

Electromagnetic probes

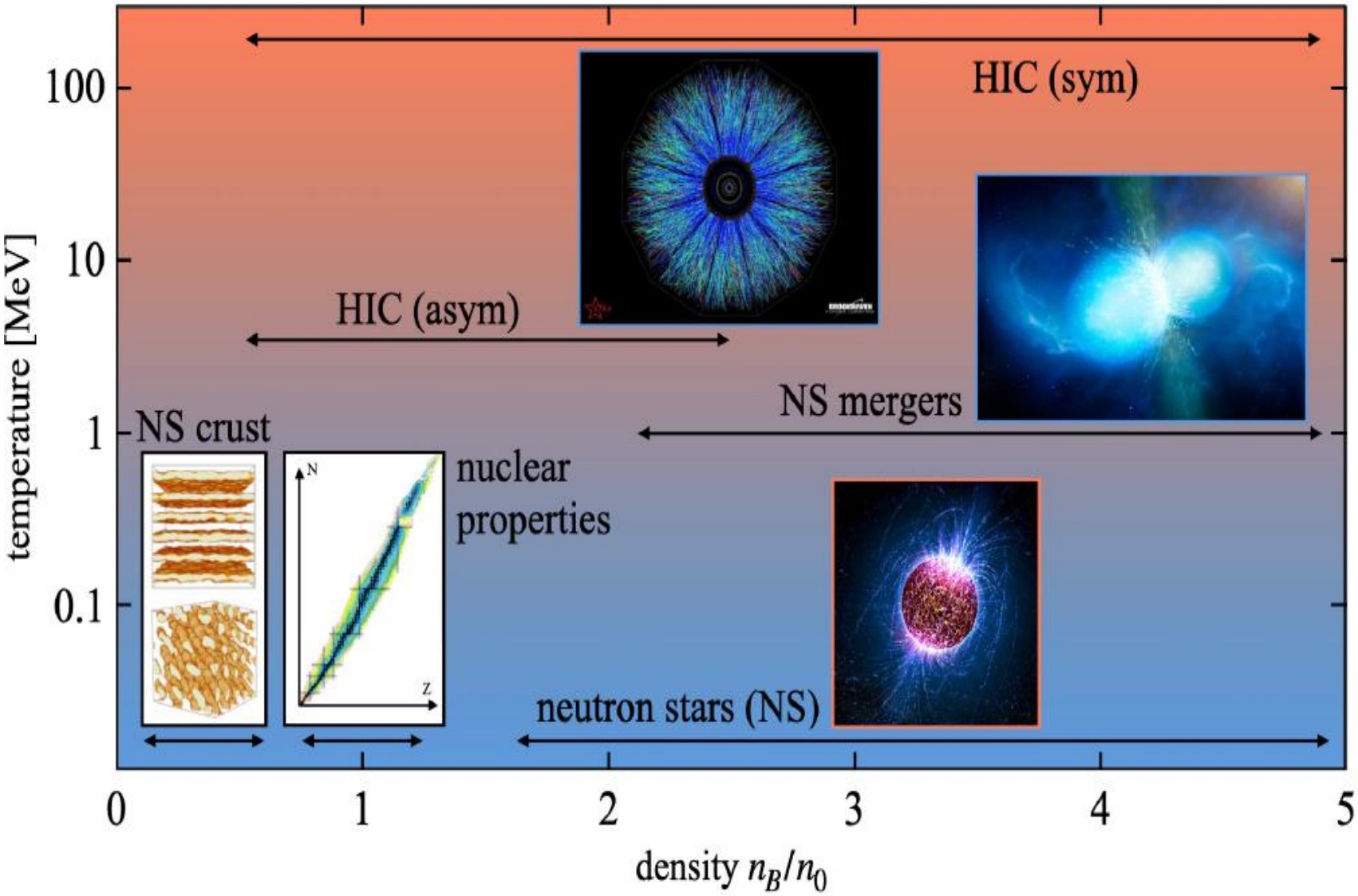
- Electromagnetic calorimeter meas.
- Photons in ECAL and central barrel
- Low mass dilepton spectra in-medium modification of resonances and intermediate mass region

Wangmei Zha, A. Zinchenko

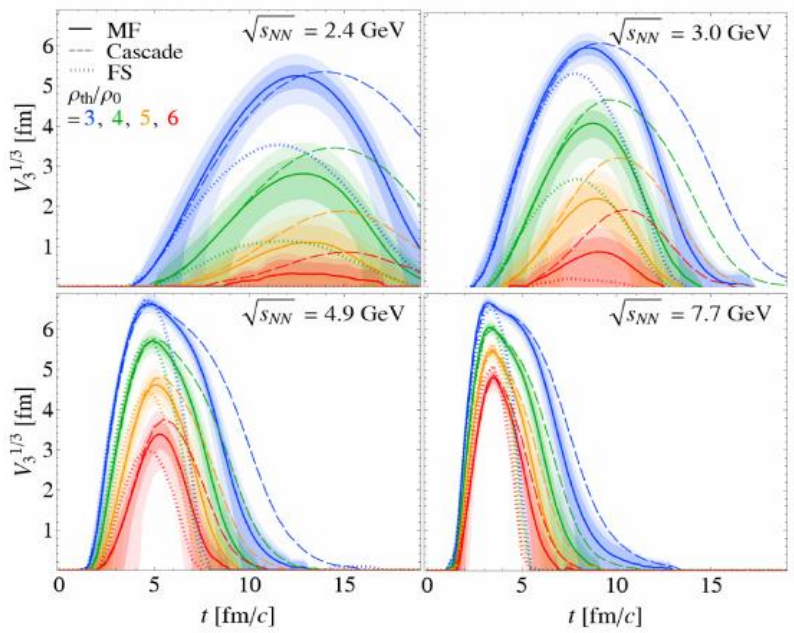
Heavy flavor

- Study of open charm production
- Charmonium with ECAL and central barrel
- Charmed meson through secondary vertices in ITS and HF electrons
- Explore production at charm threshold

Dense Nuclear Matter



J.Subatomic Part.Cosmol. 3 (2025) 100015



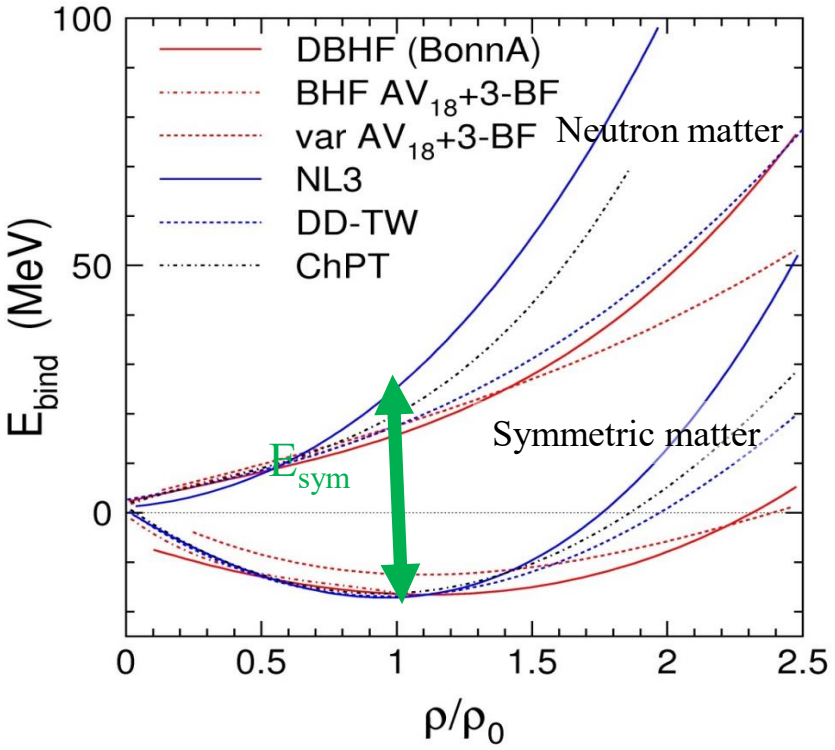
Relativistic heavy-ion collisions provide a unique and controlled experimental way to study the properties of nuclear matter at high baryon density.

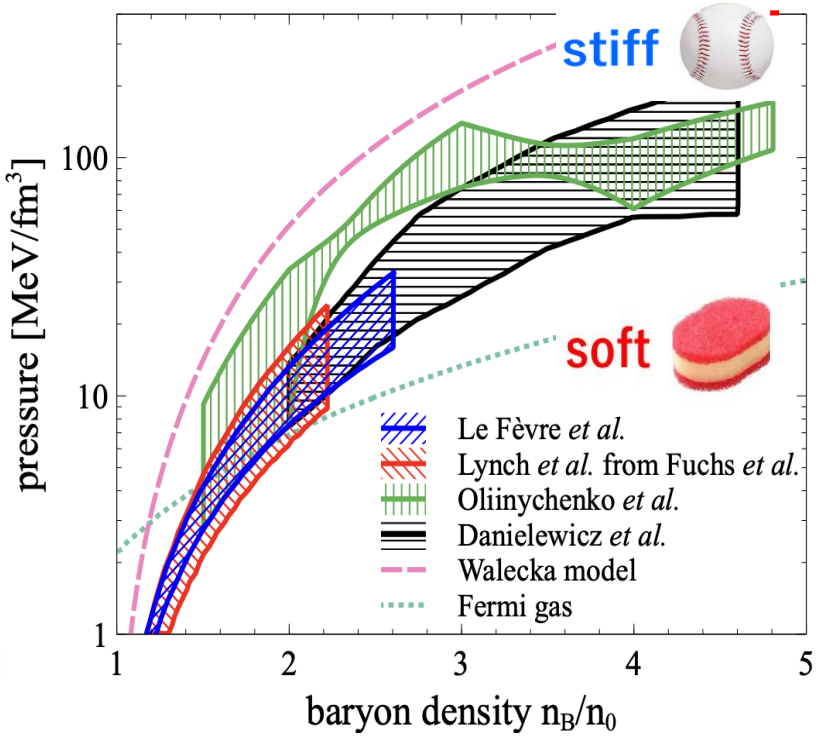
Equation of state (EoS) for high baryon density matter

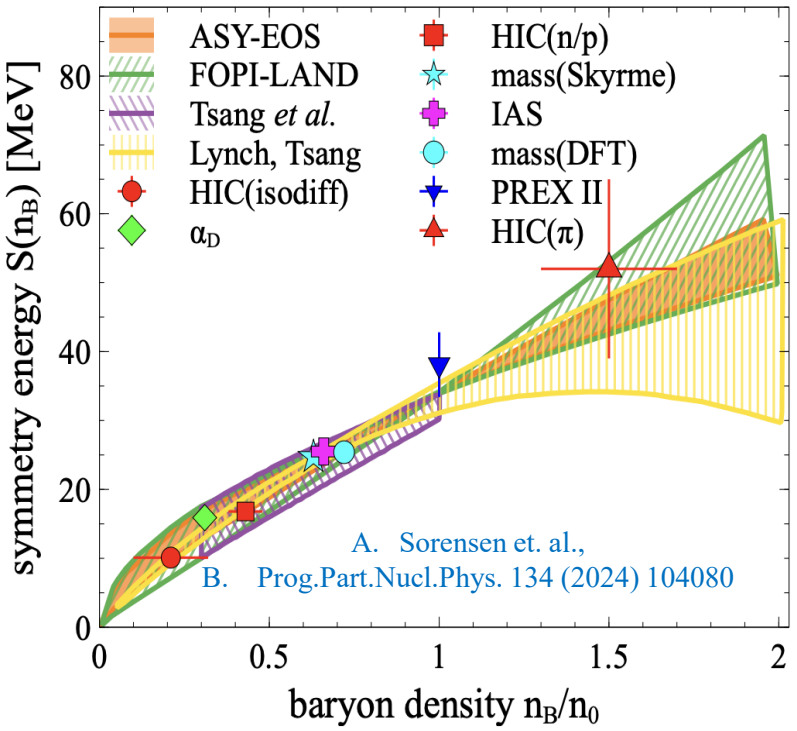
pressure $P = n^2 \frac{\mathrm{d}(E/A)}{\mathrm{d}n_b}$ *energy per nucleon* $\frac{E}{A} = m_N + E_A(n_\mathrm{B}) + E_\mathrm{sym}(n_\mathrm{B}) \frac{(n_p - n_n)^2}{n_\mathrm{B}^2}$ isospin asymmetry

$n_\mathrm{B} = n_p + n_n$

Symmetric matter **Symmetry energy**



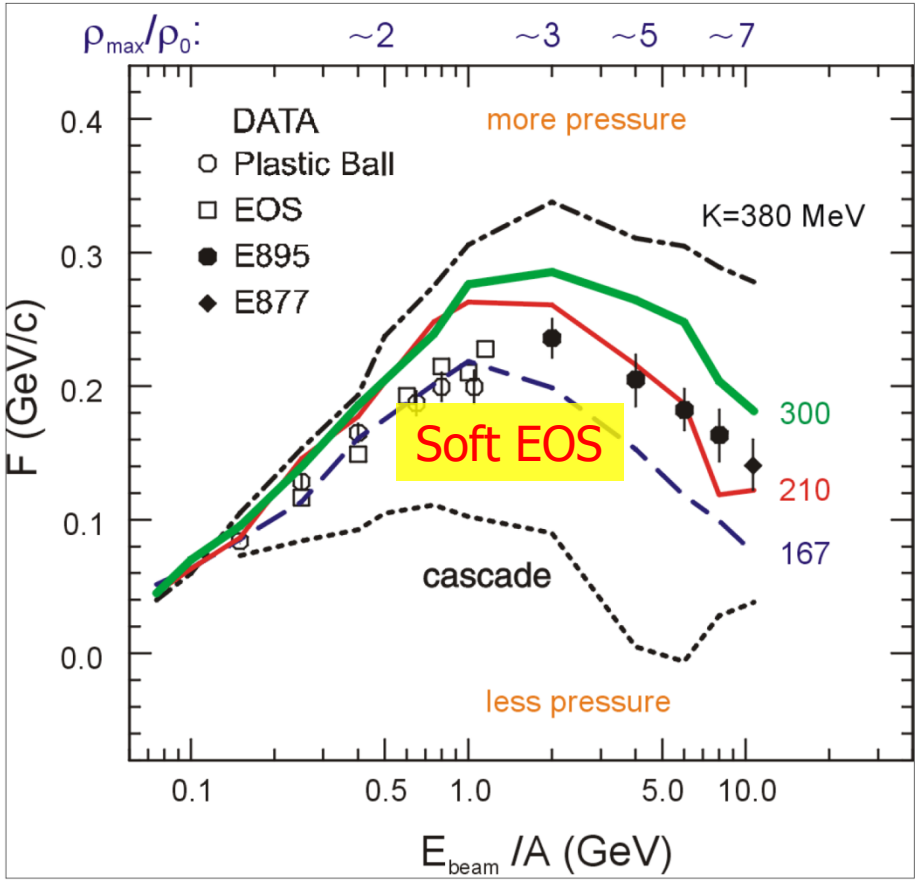


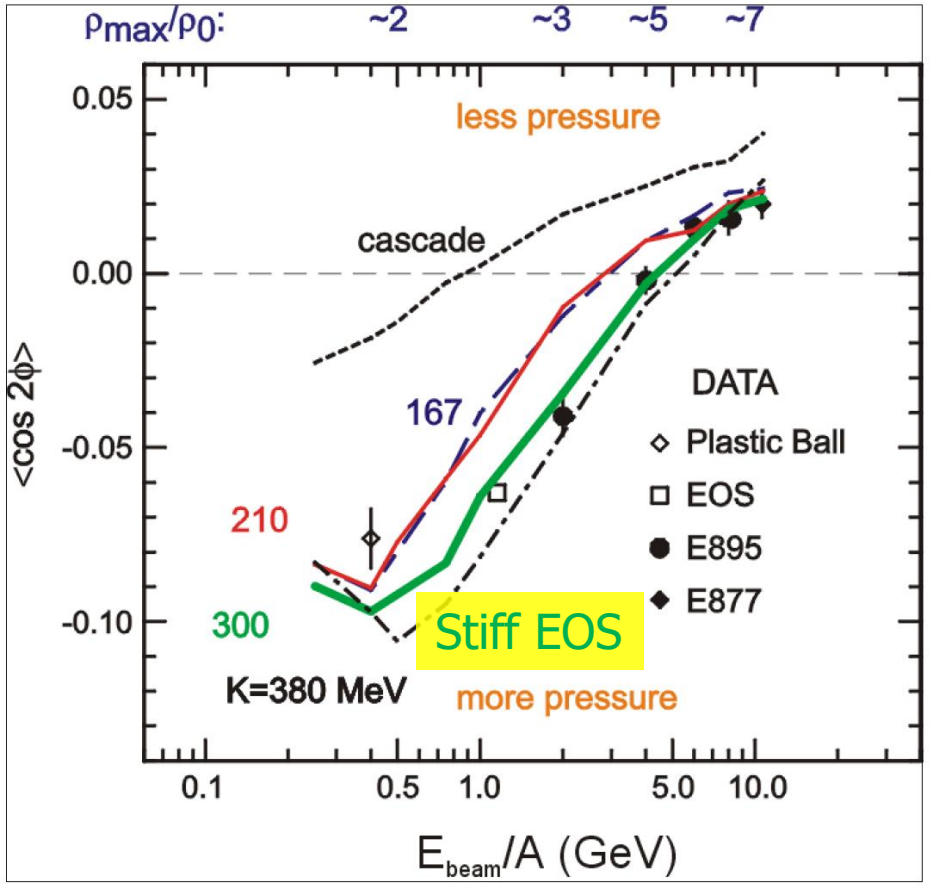


EOS describes the relation between density (n_B), pressure (P), temperature (T), energy (E), and isospin asymmetry (n_p-n_n)/n_B

Nuclear incompressibility from collective proton flow

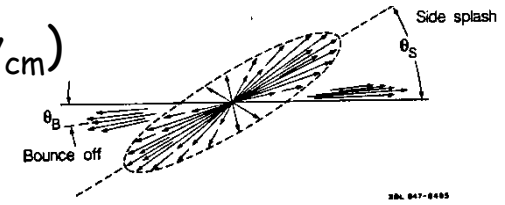
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



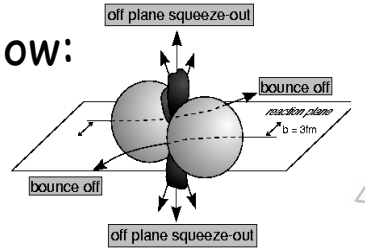


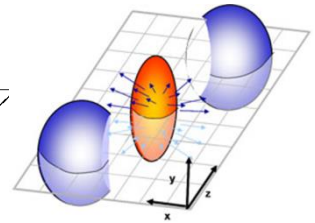
Transverse in-plane flow:

$F = d(p_x/A)/d(y/y_{cm})$



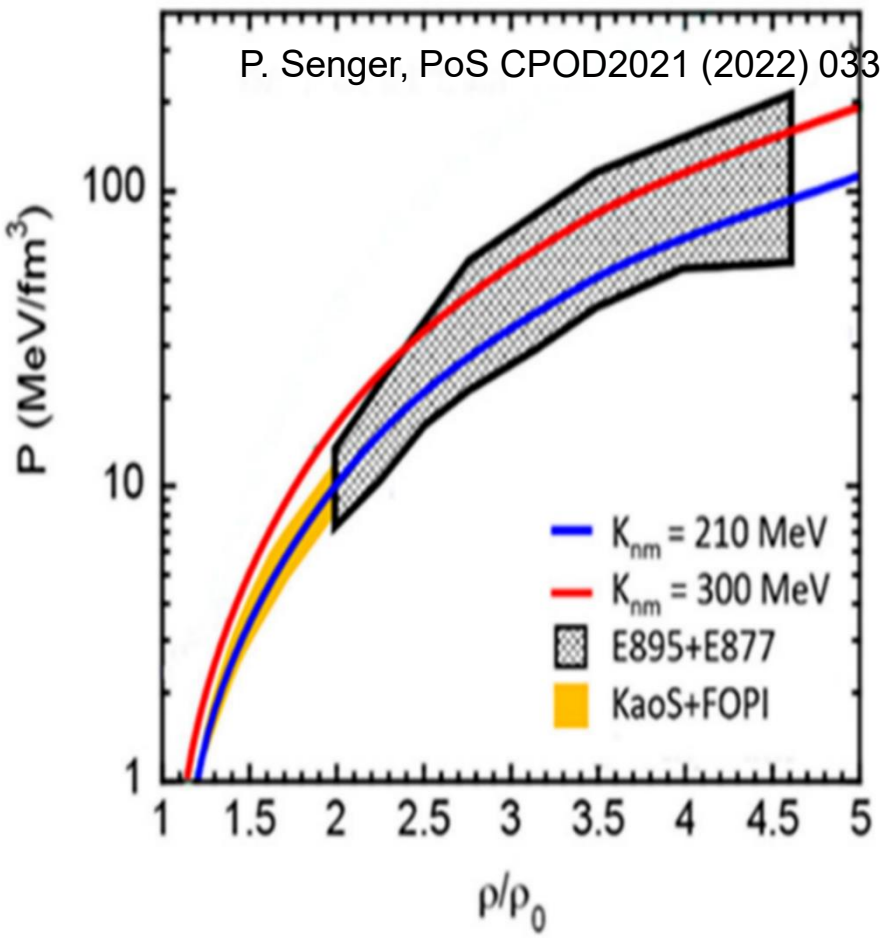
Elliptic flow:

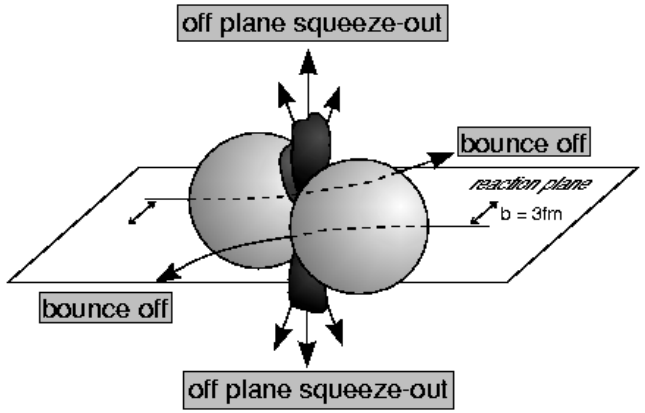


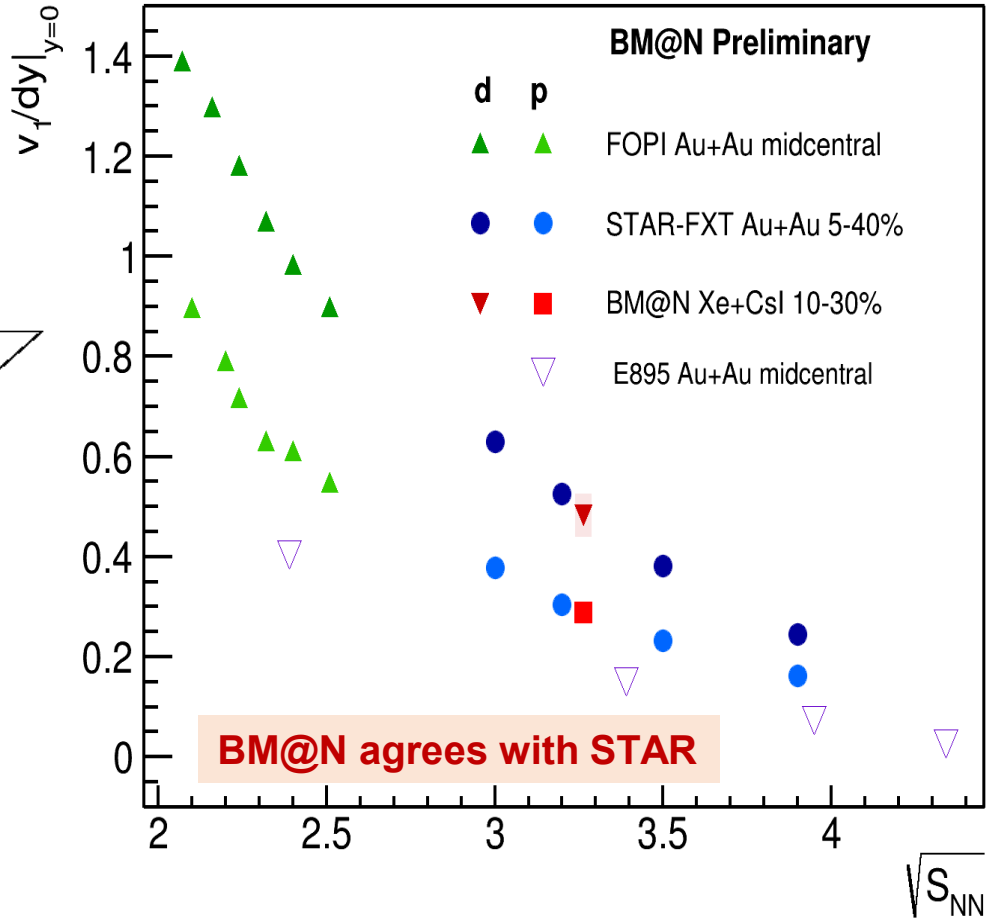


$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

Directed flow of protons and EOS of symmetric matter





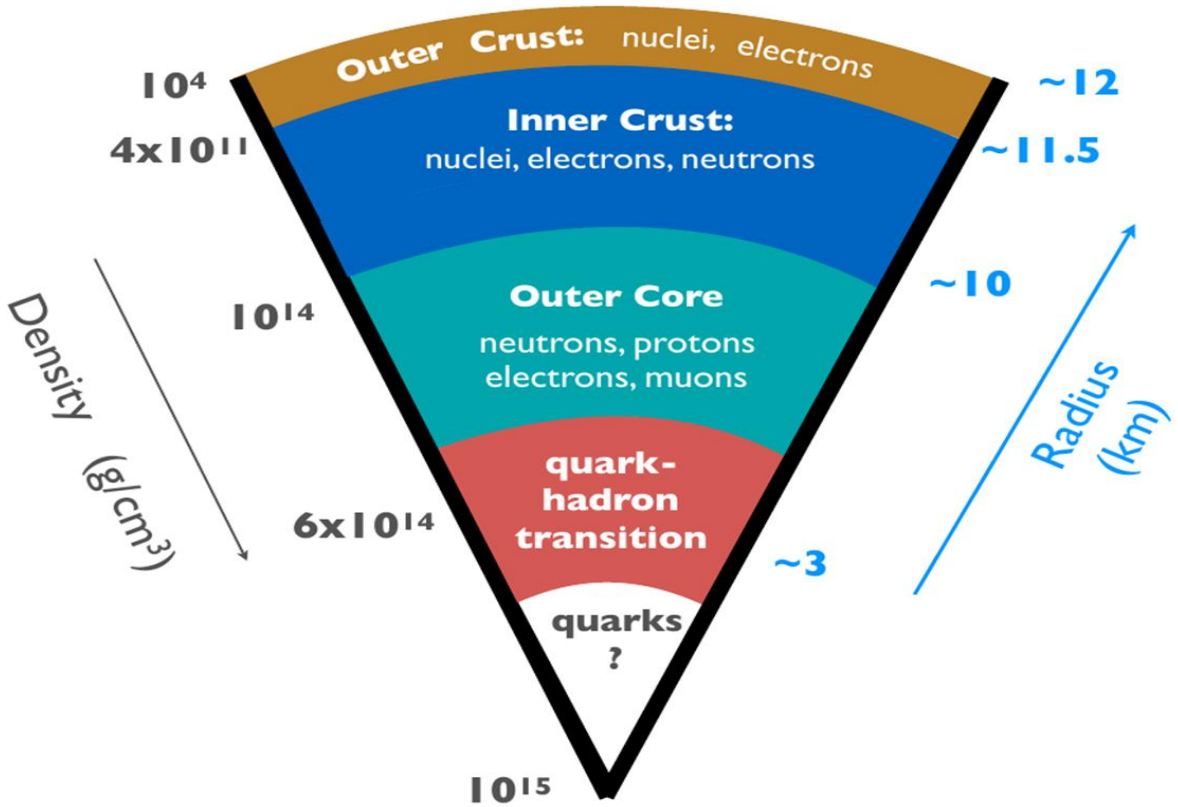


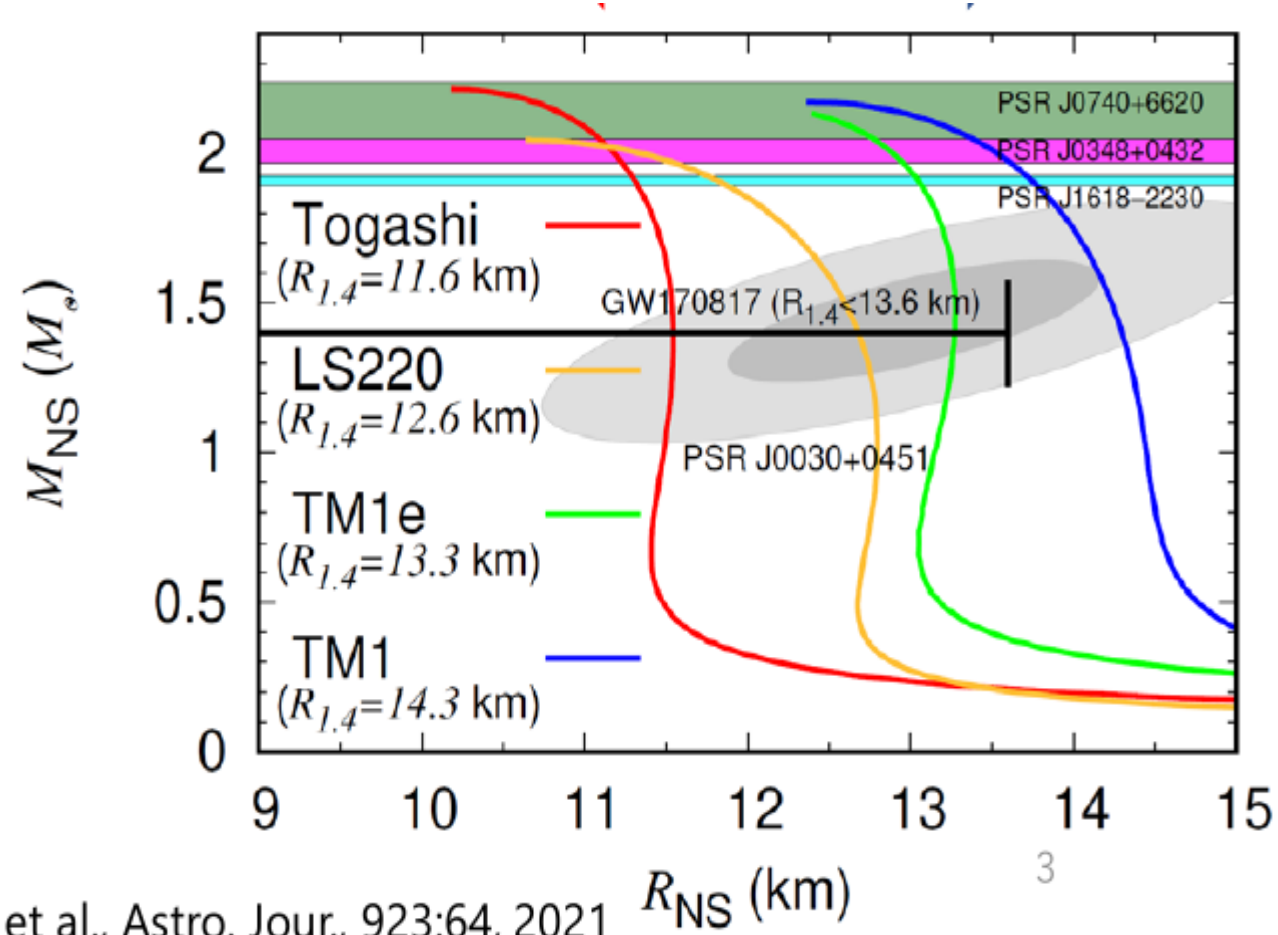
Nuclear incompressibility from collective proton flow

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Both STAR and BM@N results for directed flow prefer stiff EOS

Neutron Stars (NS): Mass and Radius



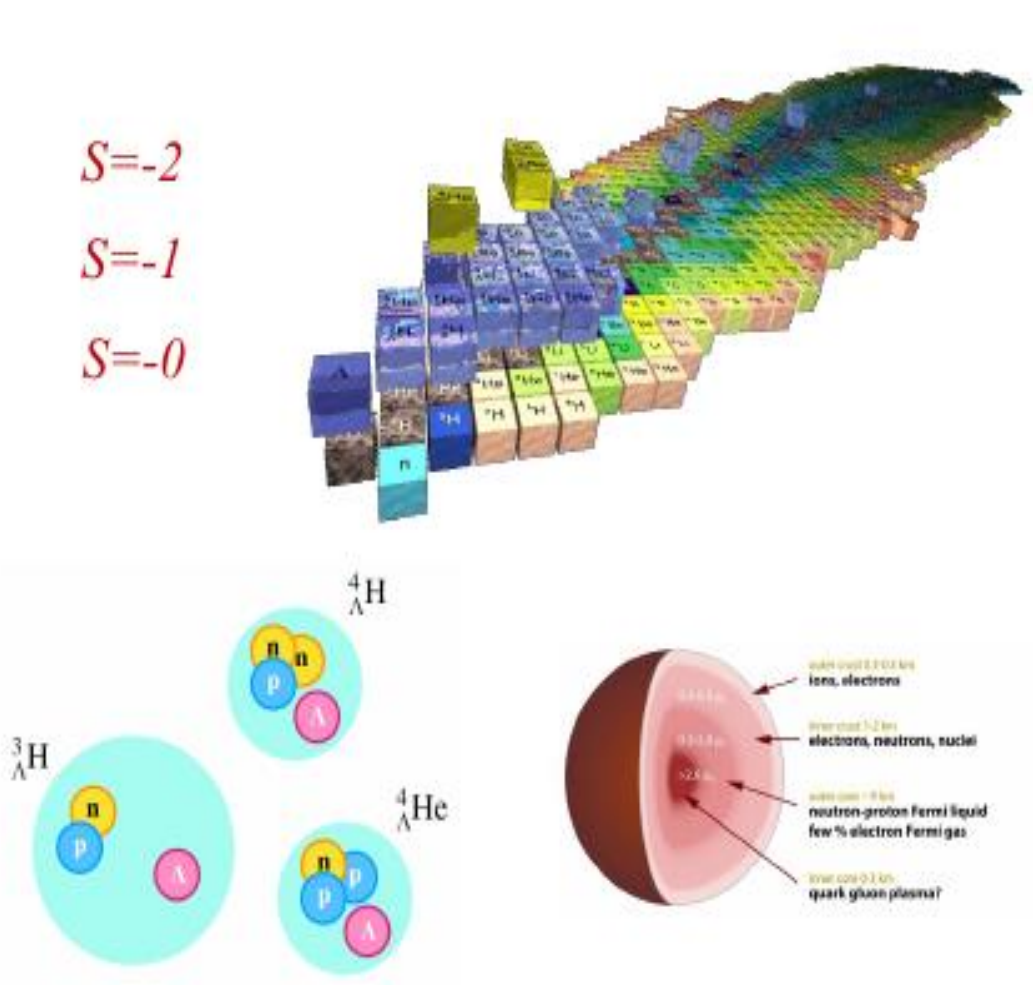


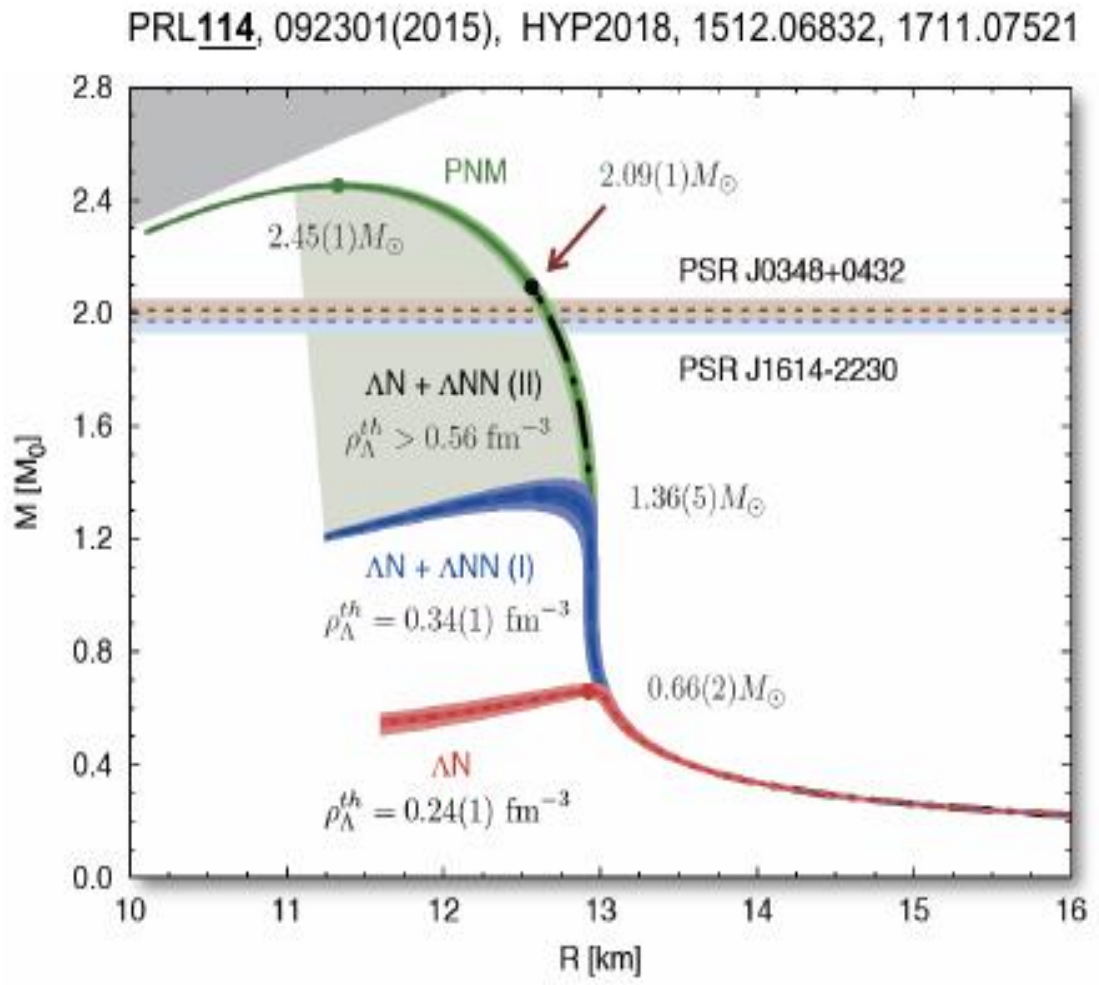
Dohi et al., Astro. Jour., 923:64, 2021

Mass-Radius relation is "unique" to the underlying EoS

- Soft EoS: low maximum mass and small radii
- Stiff EoS: high maximum mass and large radii

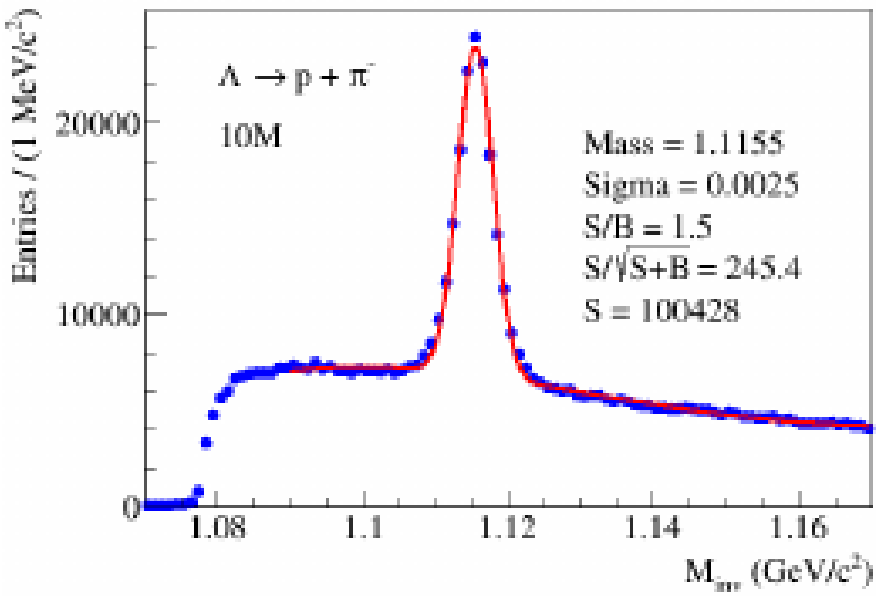
Hyperon and Hyper-Nuclei Production in Heavy-Ion Collisions and Neutron Stars

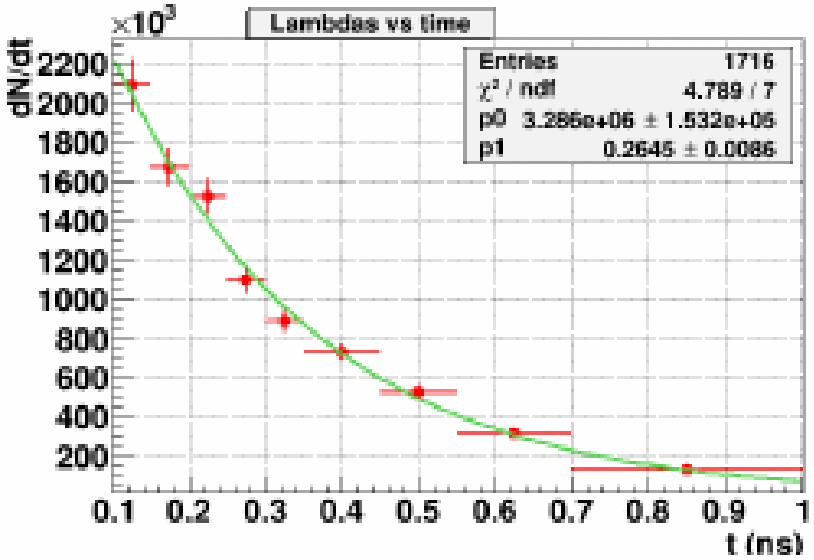




Hyperon and Hyper-Nuclei production provide access to the hyperon–nucleon interactions: NY, YNN, : key to understand the EoS at high baryon density and inner structure of neutron star.

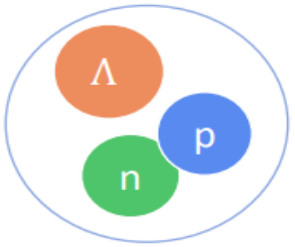
Hyperons and Hyper-Nuclei Production in Xe+Cs(I) at 3.8 AGeV (BM@N)







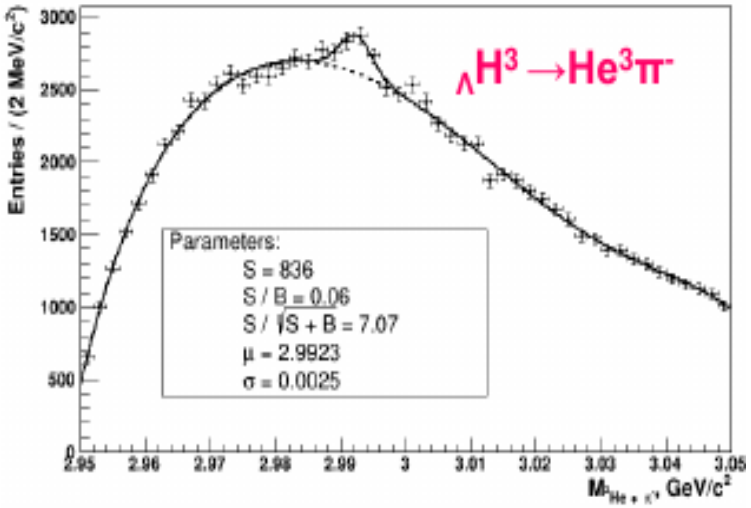
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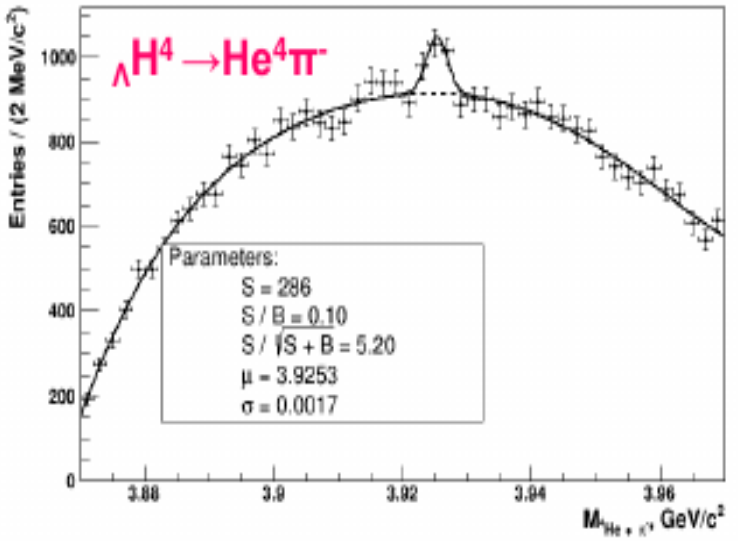


$^{3}_{\Lambda}H$



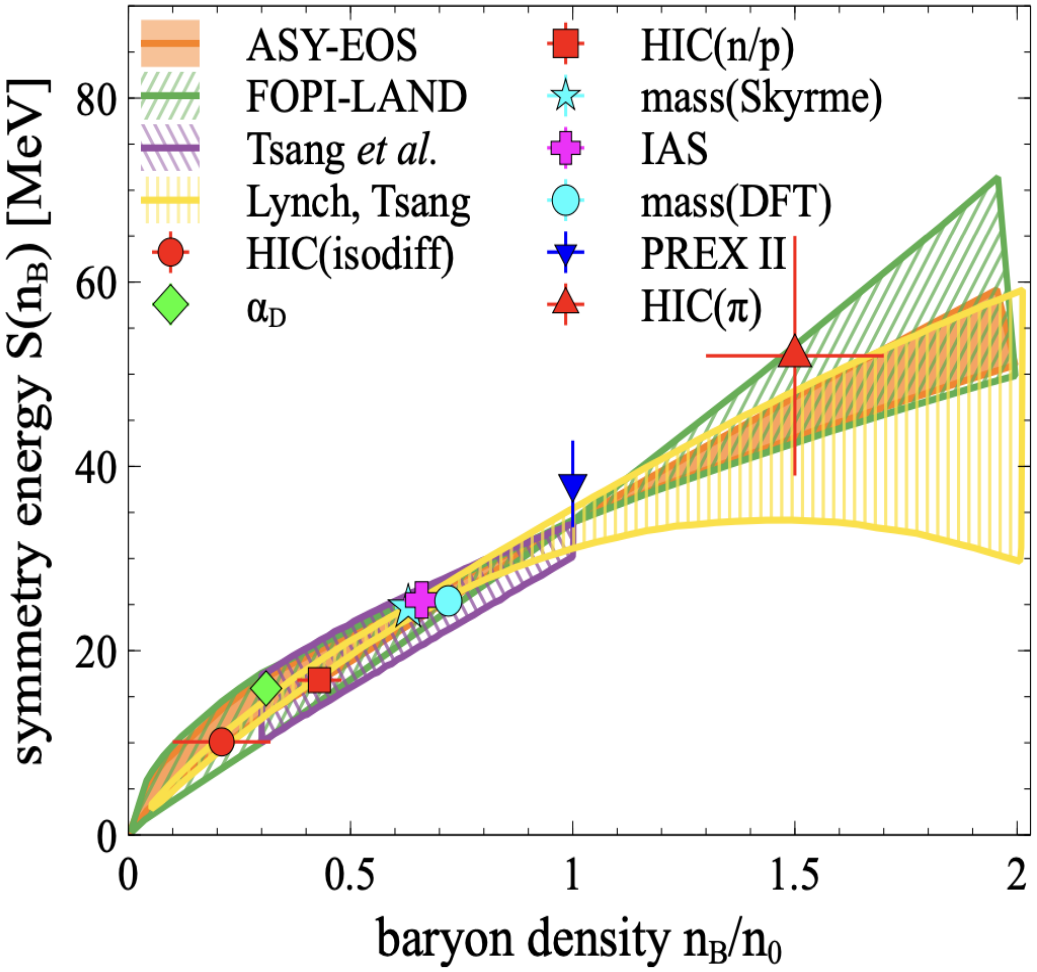
$^{4}_{\Lambda}H$





Observables to study symmetry energy (EoS)

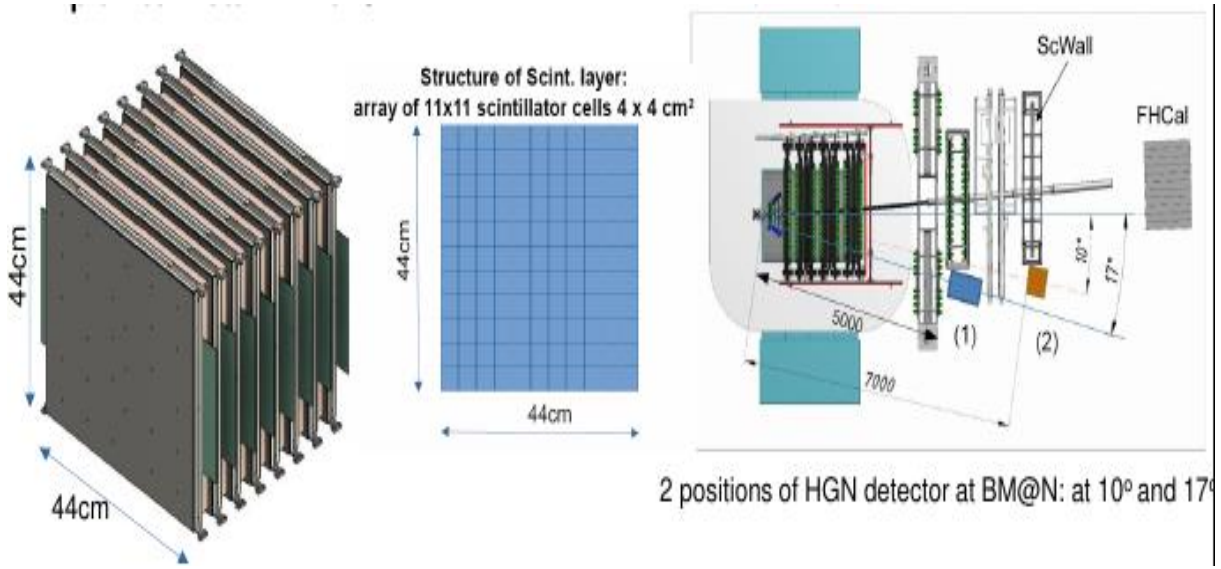
A. Sorensen et. al., Prog.Part.Nucl.Phys. 134 (2024) 104080



Nuclotron-NICA density region: $2 < n_B/n_0 < 8$

Symmetry energy E_{sym} has strong density dependence

BM@N Neutron Detector (2027-)

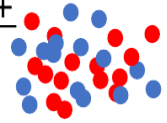


The Highly-Granular time-of-flight Neutron Detector for the BM@N experiment, Nucl. Instrum. Meth. A 1072 (2025) 170152

Stiff symmetry energy (large L)

→ lower ρ_n/ρ_p in higher dense region

→ lower n/p, lower π^-/π^+



Soft symmetry energy (small L)

→ larger ρ_n/ρ_p in higher dense region

→ larger n/p, higher π^-/π^+

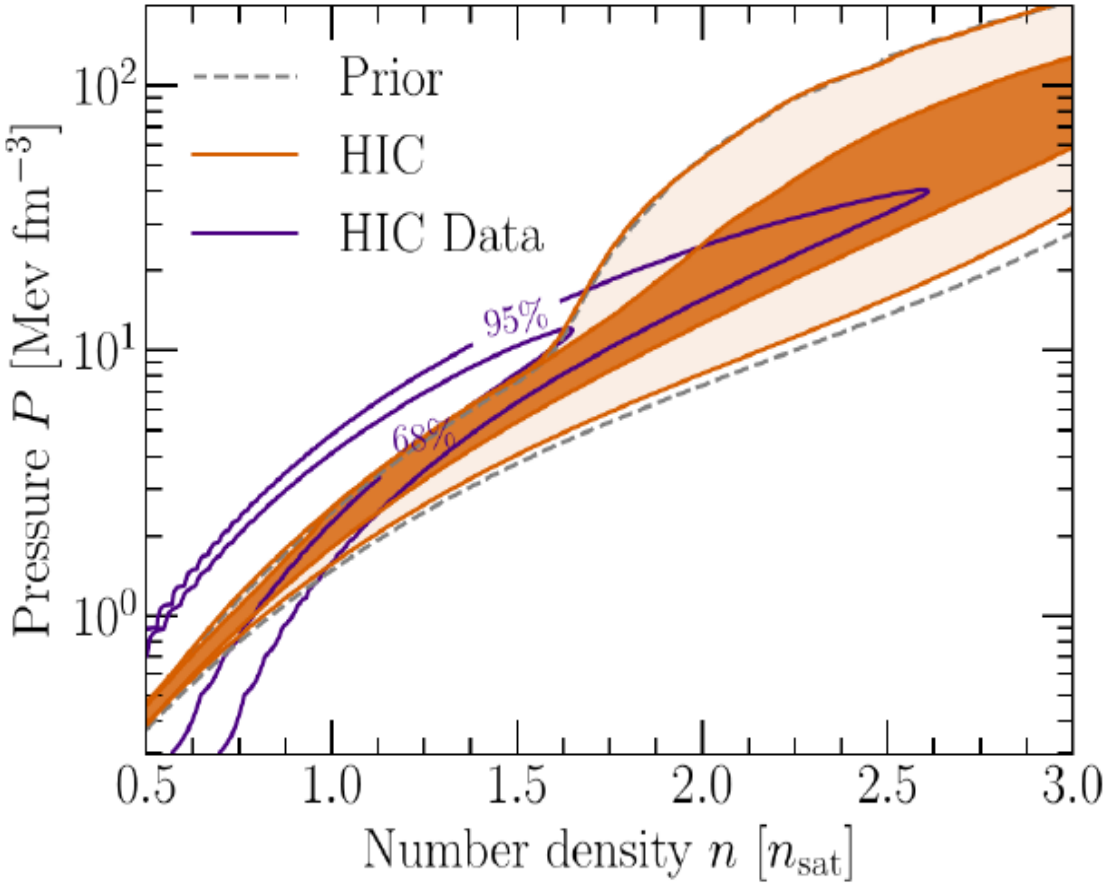


Constraining neutron-star matter with microscopic and macroscopic collisions

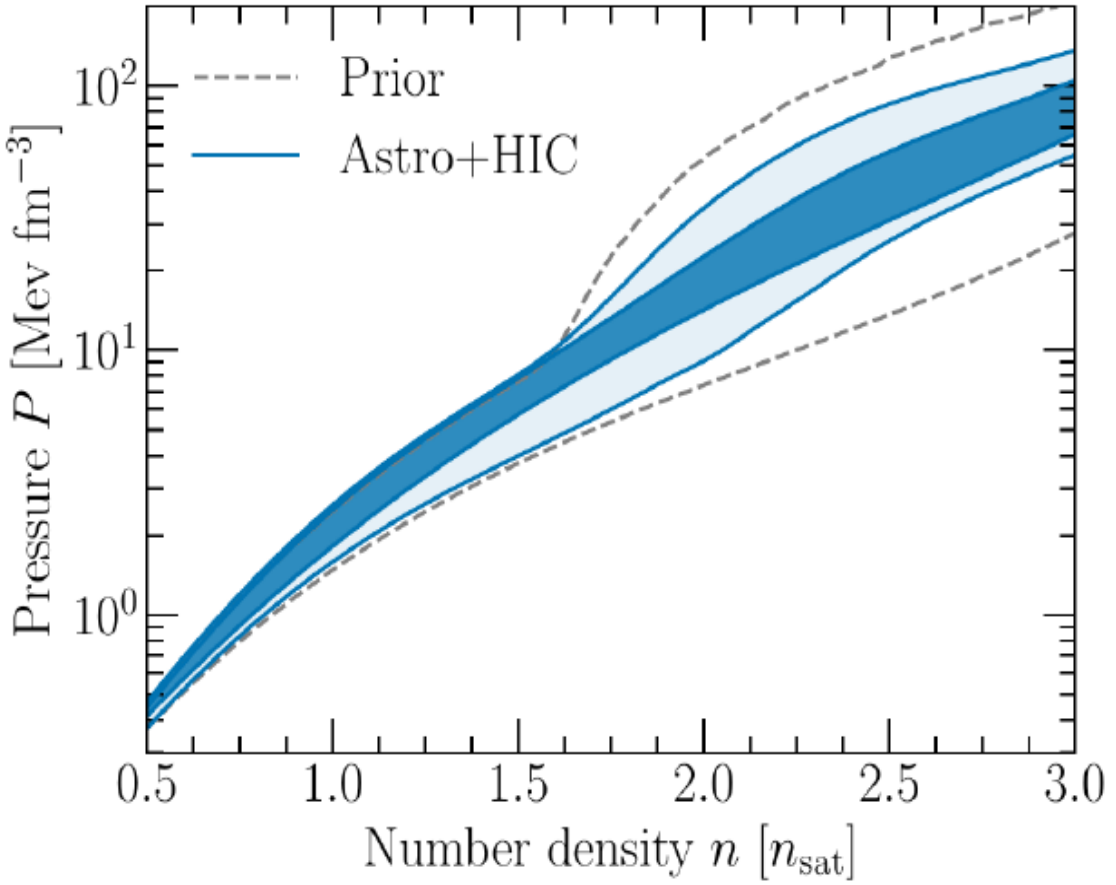
Huth, Pang et al. Nature 606(22)276

HIC experiments:

Bayesian combinations



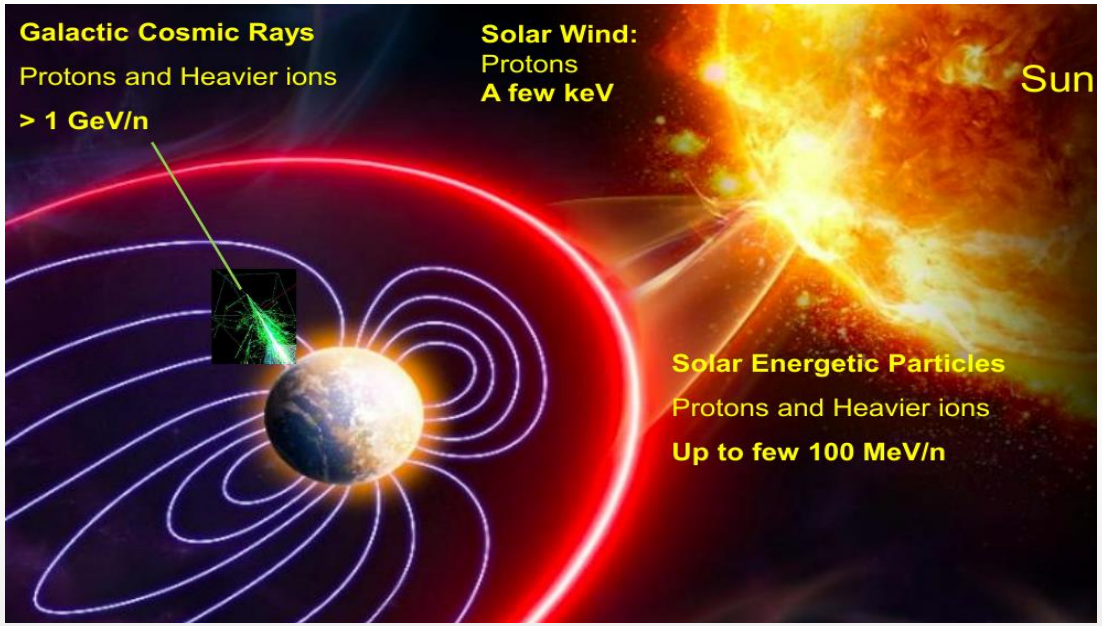
HIC and Astro combined:

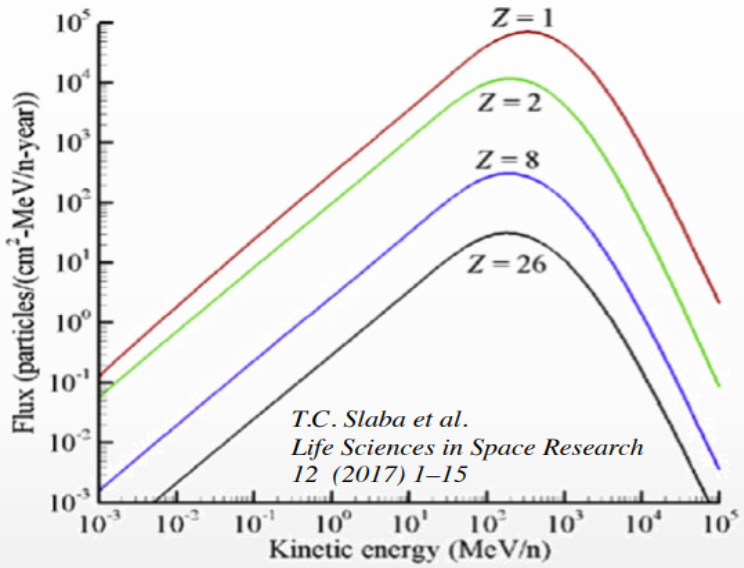


Astrophysical observations narrow constraints above 2 n_{sat}

High-energy heavy-ion reaction data

- Galactic Cosmic Rays composed of nuclei (protons, … up to Fe) and E/A up to 50 GeV
- These high-energy particles create cascades of hundreds of secondary, etc. particles



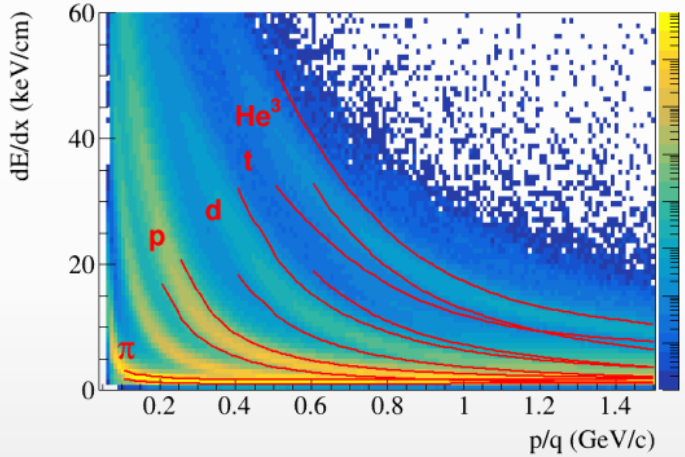


- Cosmic rays are a serious concern to astronauts, electronics, and spacecraft.
- The damage is proportional to Z^2, therefore the component due to ions is important
- Damage from secondary production of p, d, t, ^{3}He, and ^{4}He is also significant
- Need input information for transport codes for shielding applications (Geant-4, Fluka, PHITS, etc.):
  - ✓ total, elastic/reaction cross section
  - ✓ particle multiplicities and coallecense parameters
  - ✓ outgoing particle distributions: $d^2N/dEd\Omega$

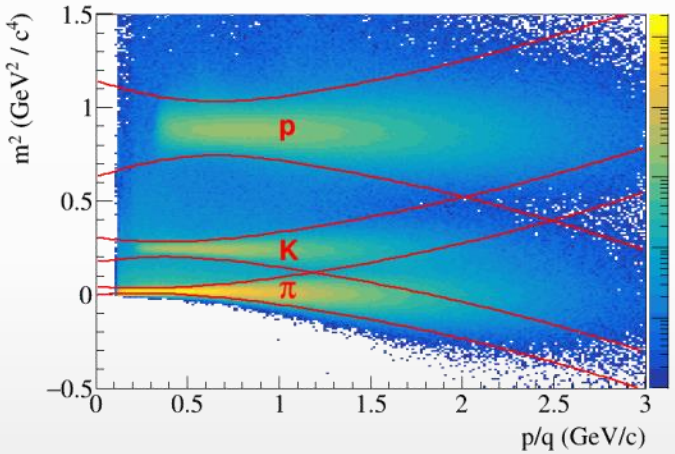
High energy heavy ion reaction data

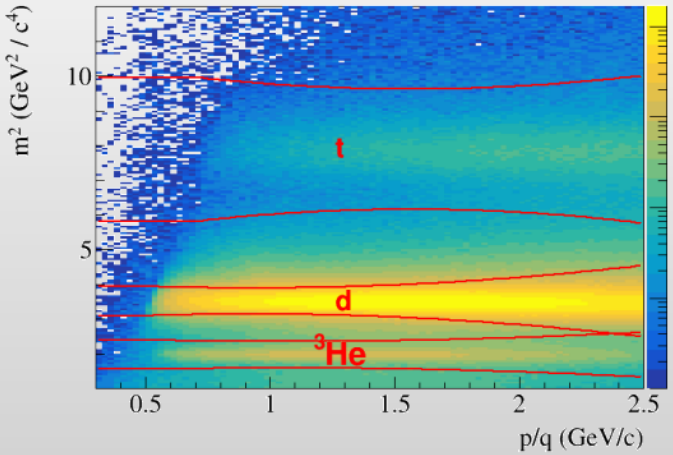
- NICA can deliver different ion beam species and energies:
  - ✓ Targets of interest (C = astronaut, Si = electronics, Al = spacecraft) + He, C, O, Si, Fe, etc.
- No data exist for projectile energies > 3 GeV/n

dE/dx vs momentum in TPC



m^2 vs. momentum in TOF





MPD has excellent light fragment identification capabilities in a wide rapidity range → unique capability of the MPD in the NICA energy range

Conclusions

- Столкновения тяжелых релятивистских ядер позволяет изучать свойства сильновзаимодействующей (КХД) материи в условиях экстремальных температур и высоких барионных плотностей
- Исследование подобных состояний требует измерения импульсных, энергетических и угловых распределений для рождающихся частиц (фотоны, адроны, лептоны) в широком динамическом диапазоне (p_T, быстрота)
- Интерпретация полученных результатов требует тесной кооперации с содружеством теоретиков
- Эксперименты на ускорительном комплексе NICA позволят изучить область фазовой диаграммы, соответствующей сравнительно небольшим температурам, но максимальным барионных плотностям.
- Программа физических исследований на ускорительном комплексе NICA предлагает ряд уникальных возможностей

Backup slides