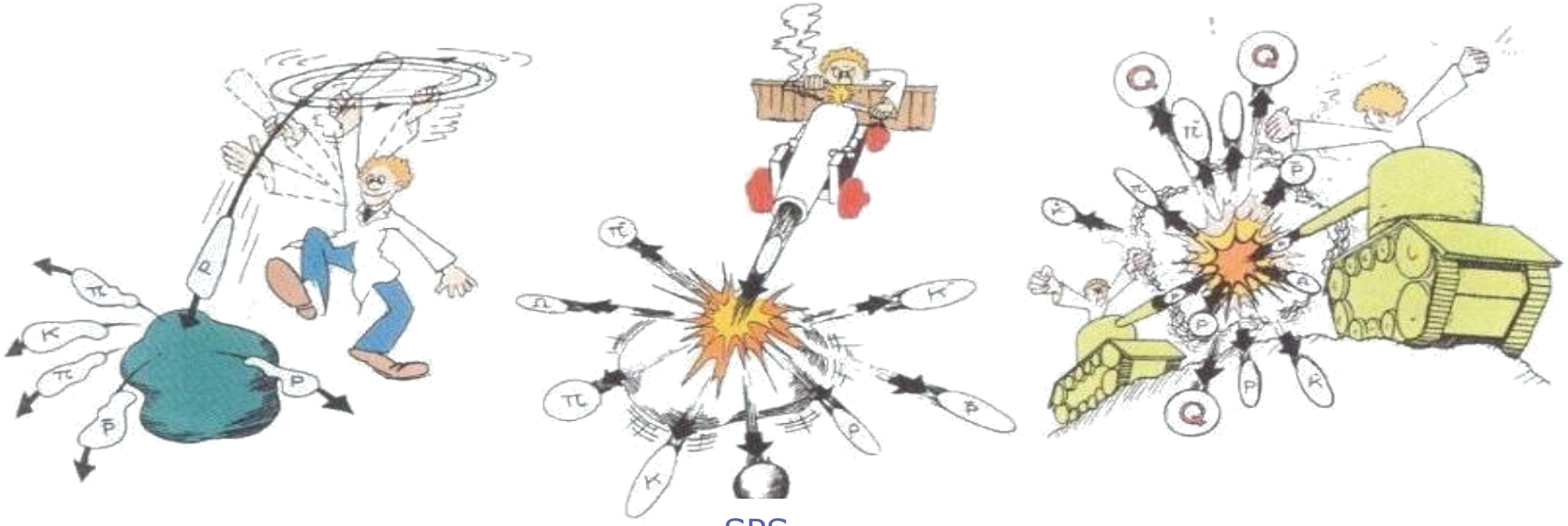
Phenomenology of heavy-ion collisions



SIS SPS RHIC/LHC

Arkadiy Taranenko (ataranenko@jinr.ru)
(JINR, NRNU MEPhI)

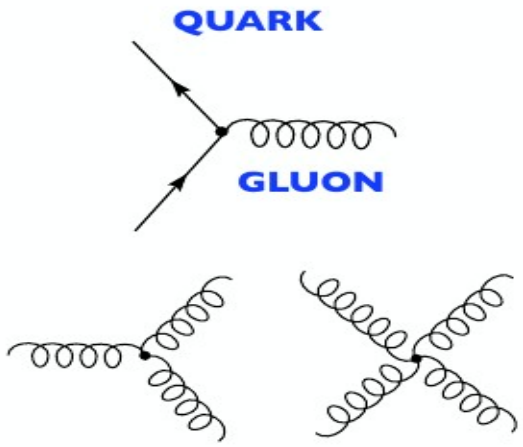
The International School "Nuclear Dynamics: from Stars to Colliders", JINR, Dubna 2026

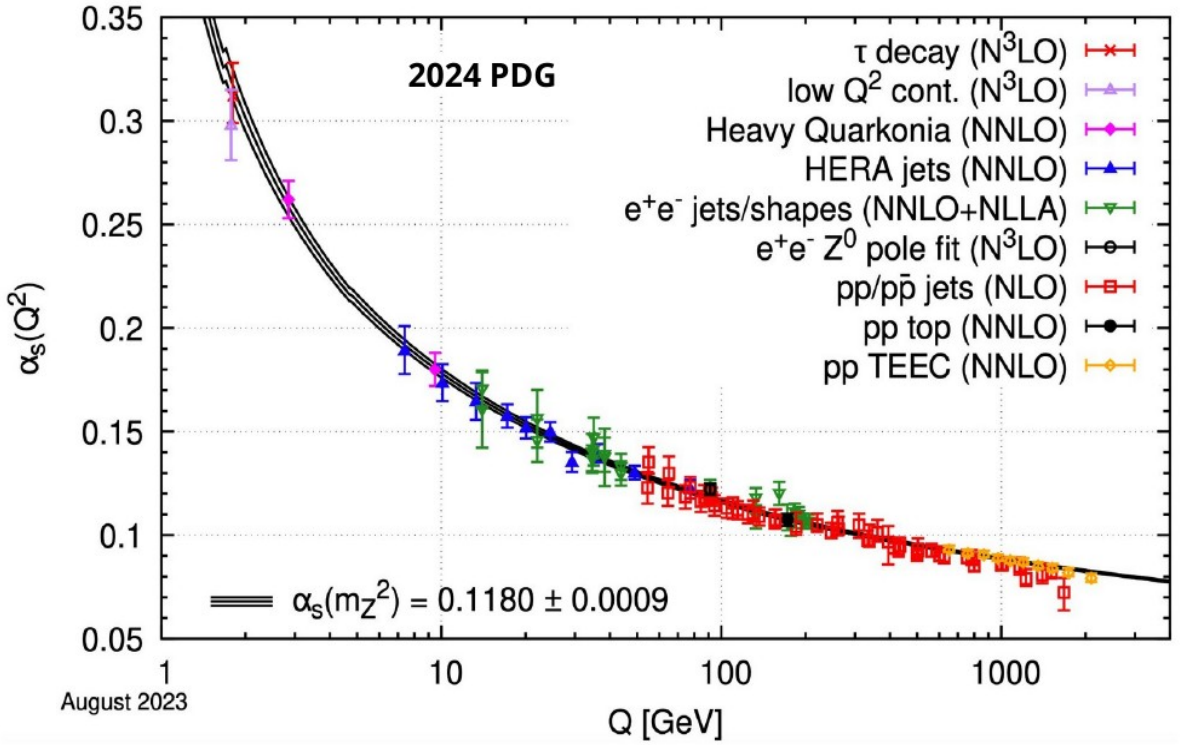
Theory of strong interactions: Quantum chromodynamics (QCD)

$$\mathcal{L} = \sum_{q=u,d,s,\ldots} \bar{q}\left[i\gamma^{\mu}(\partial_{\mu} - igA^{a}_{\mu}\lambda_{a}) - m_{q}\right] q - \frac{1}{4} G^{a}_{\mu\nu} G^{\mu\nu}_{a}$$

QCD - non-Abelian gauge theory

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3





0.2 fm 0.02 fm 0.002 fm 0.0002 fm

In vaccum: Colour neutral hadrons (confinement): mesons and baryons.
Mass from chiral symmetry breaking (mp= 938 MeV vs 2mu + md ~ 10 MeV)
Large Q transfer / small distances: Perturbative QCD (pQCD).
Small Q transfer / large distances: Lattice QCD (LQCD)

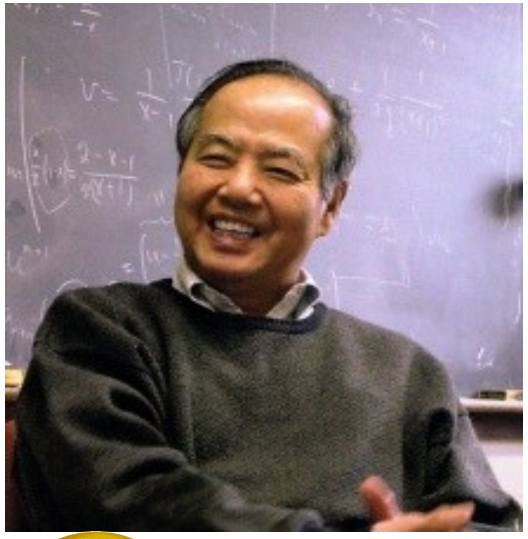
At high temperature or density ($\alpha_S \rightarrow 0$): quarks and gluons become deconfined, no bound states: new state of matter QGP (Quark-Gluon-Plasma)



2004

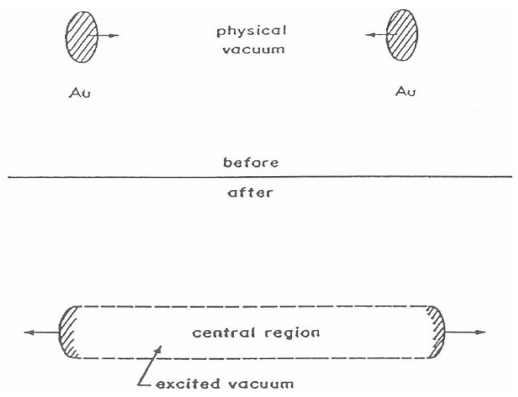
Asymptotic freedom
Politzer, Gross and Wilczek (1973)

Tsung-Dao Lee and the Origin of Relativistic Heavy Ion Collisions





1957



Prime Motivation:

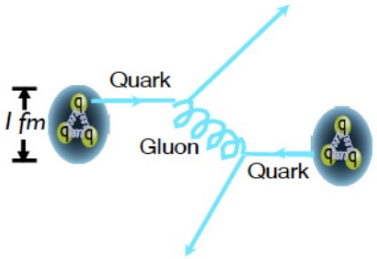
"Hitherto, we have concentrated on experiments which distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of the 'vacuum' . . . we must turn to a different direction: we should investigate some 'bulk' phenomena by distributing high energy or high nucleon density over a relatively large volume. *The fact that such directions have never been explored should*, by itself, *serve as an incentive for doing such experiments*."

The Bear Mountain Workshop, New York, Nov. 29 to Dec. 1, 1974 …. physicists began to take seriously the possibility of using heavy ion collisions as a tool to study the properties of matter under extreme conditions of high energy and baryon densities, to ask whether was there a "nuclear world quite different from the one we have learned to accept as familiar and stable?"

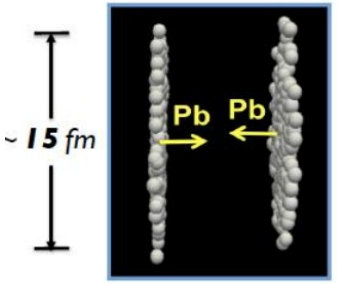
Gordon Baym, NPA956 (2016)

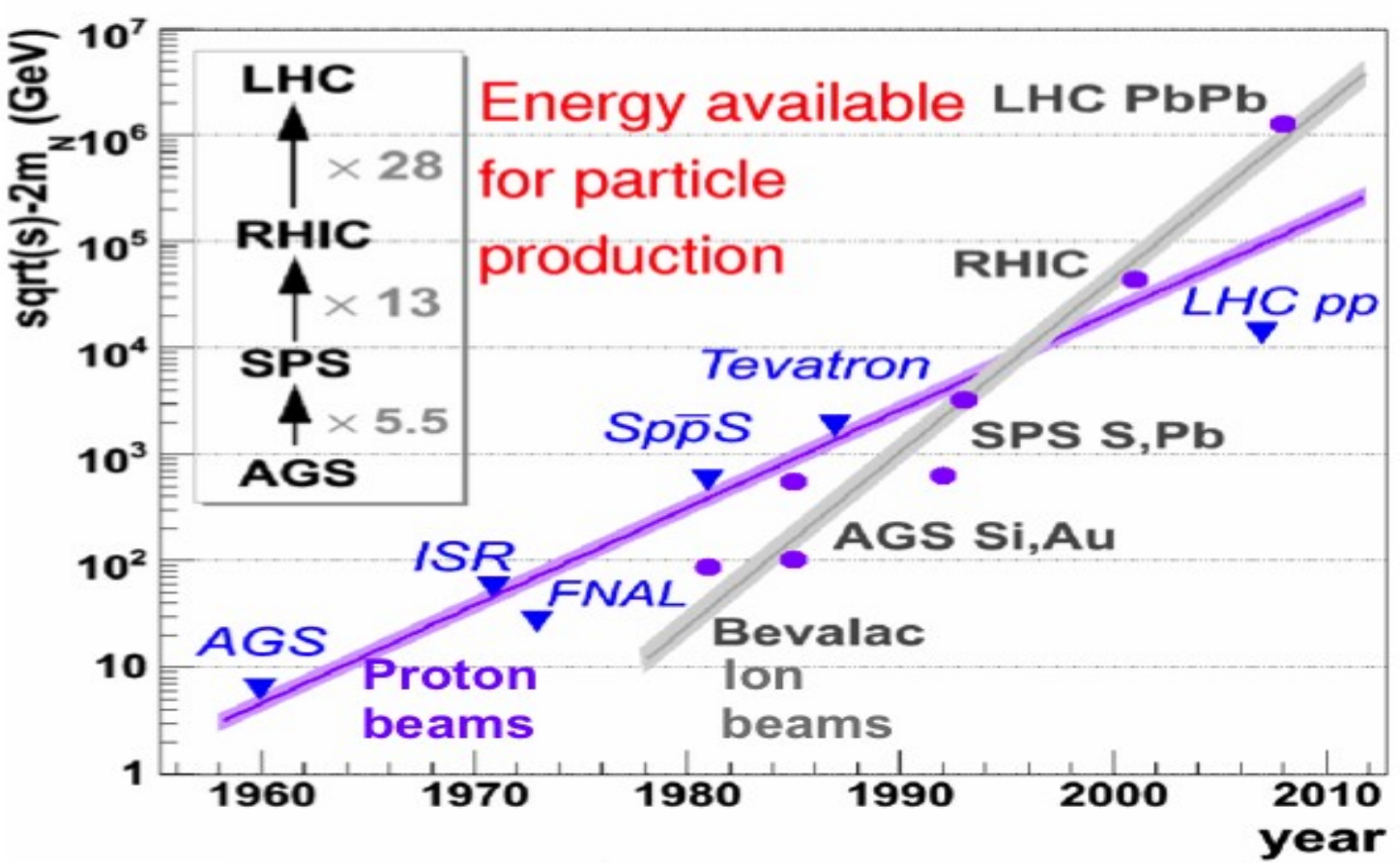
p+p and A+A collisions

HEP: concentrate higher energy in smaller and smaller volume.

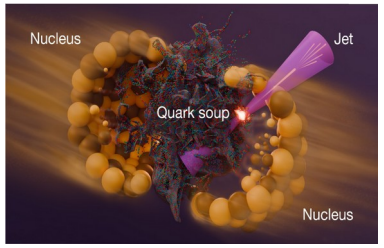


$V \gg 1\text{fm}^3$





LHC



Beam Energy Scan programs:

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

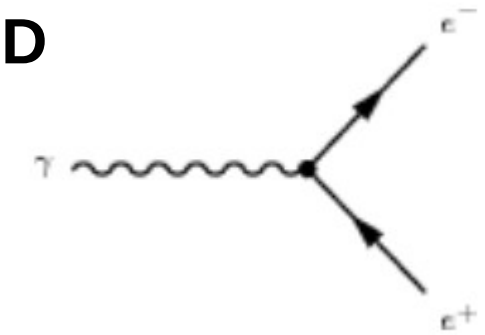
MPD (NICA)
BM@N (NICA)
CBM (FAIR)
CEE(HIAF)
NA60+(SPS)
JPARC-HI

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

Lecture 1: Introduction: Why heavy-ions? The QCD phase transition, Basics of HIC Collisions and Experiments
Lecture 2: Main results from the study of HIC at RHIC and LHC (at zero baryon density), Properties of QGP.
Lecture 3: QCD matter at high baryon density: Beam Energy Scan programs and physics at NICA.

Condensed matter phenomena at extreme conditions: Physics of Complex Systems

QED

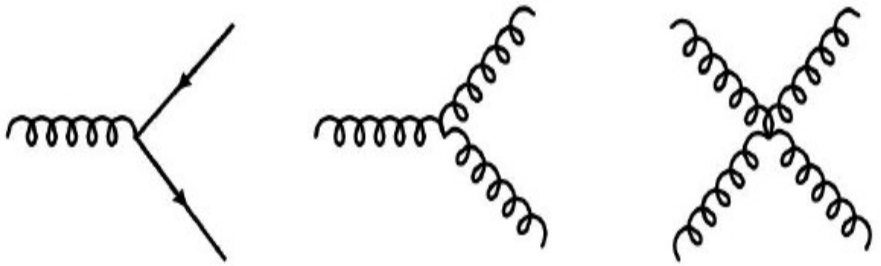


?

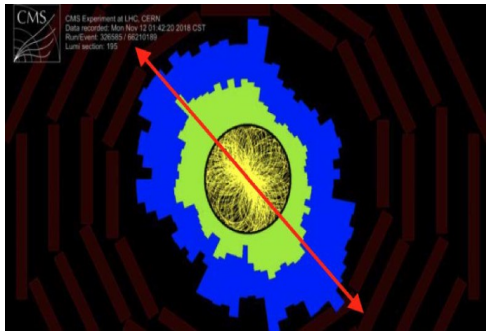


Superconductivity

QCD



?



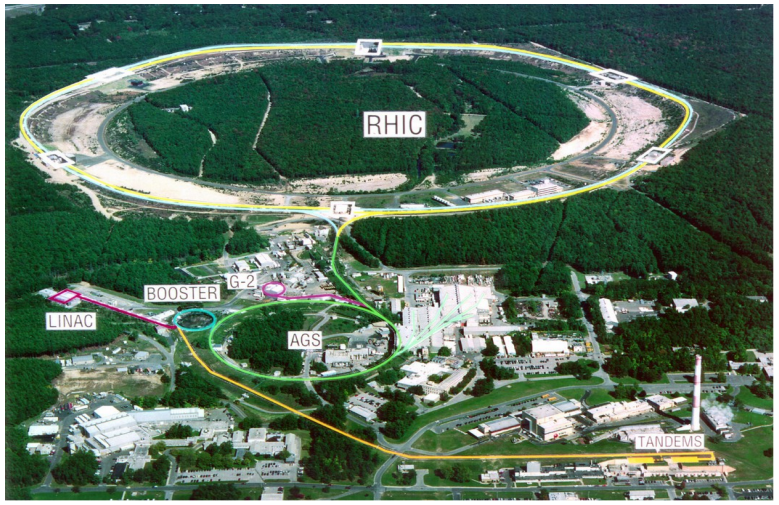
Anisotropic flow
In HIC at LHC

- 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)

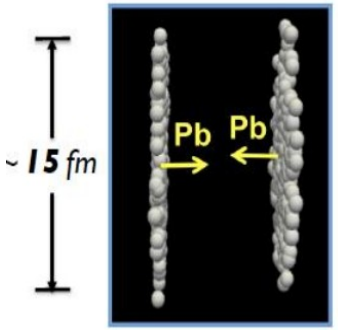
Even a fully unified fundamental theory does not solve the issue of complex systems, of the states of matter...

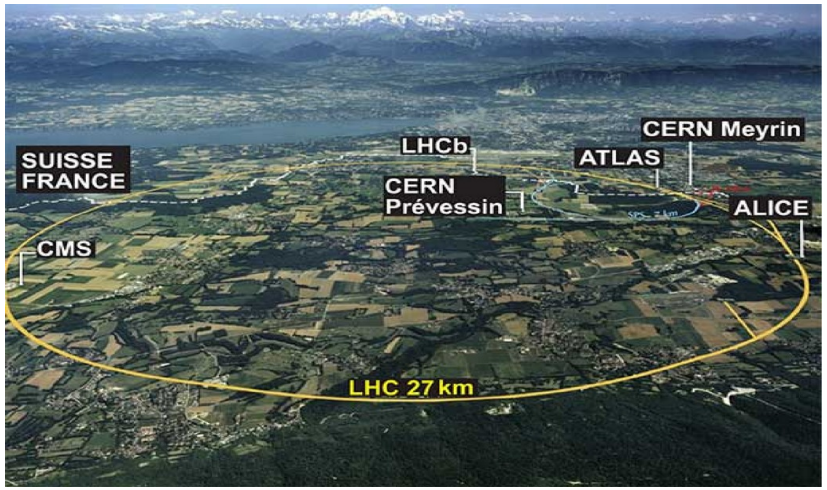
Heavy Ions for QCD laboratories



RHIC@BNL (2000-2025), 3-200 GeV, **Au+Au**

Au (197 = 79 protons + 118 neutrons)





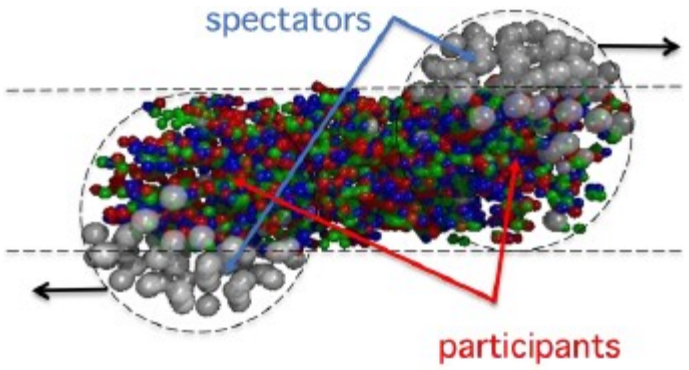
LHC@CERN (2010-...), 3-200 GeV, **Pb+Pb**

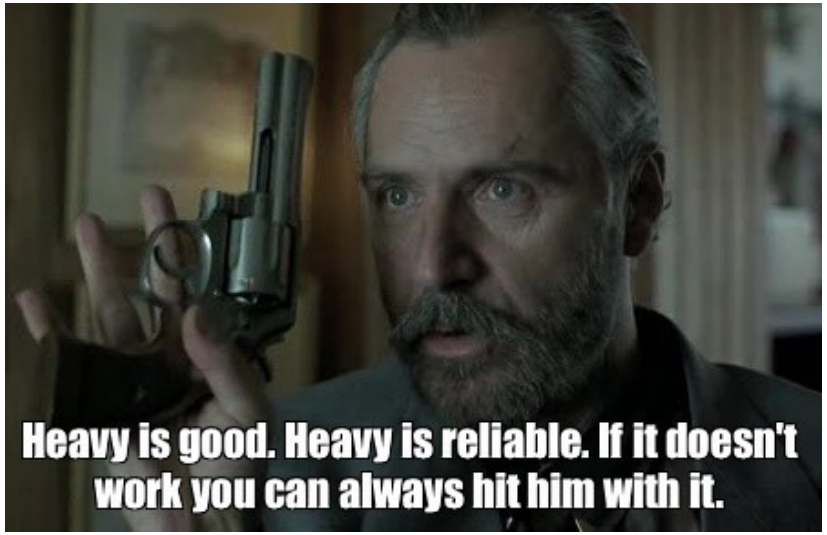
Pb (208= 82 protons + 126 neutrons)

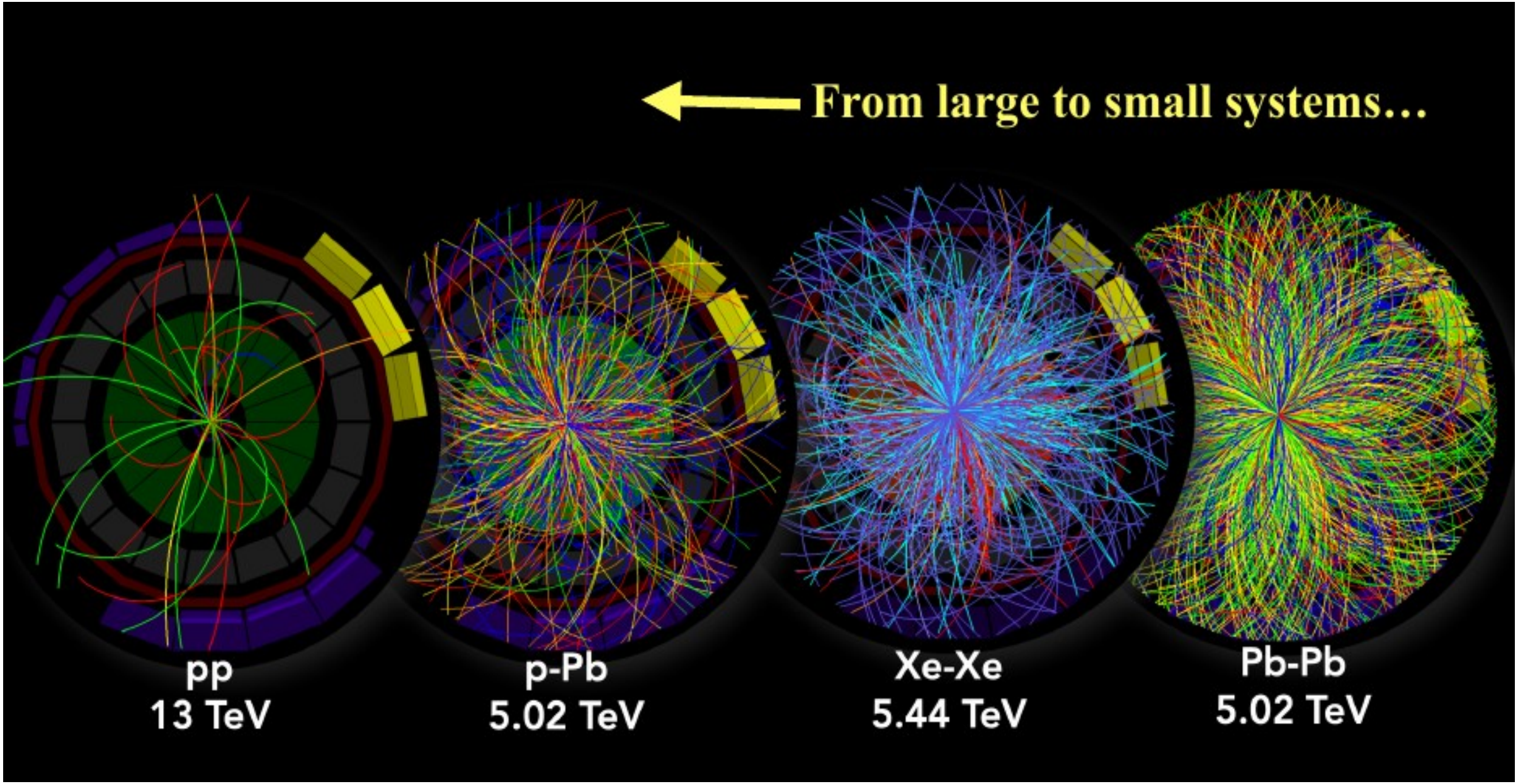


NICA@JINR (2026-), 4-11 GeV, **Bi+Bi**

Bi (209=83 protons+126 neutrons)






From large to small systems…
pp
13 TeV
p-Pb
5.02 TeV
Xe-Xe
5.44 TeV
Pb-Pb
5.02 TeV

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:

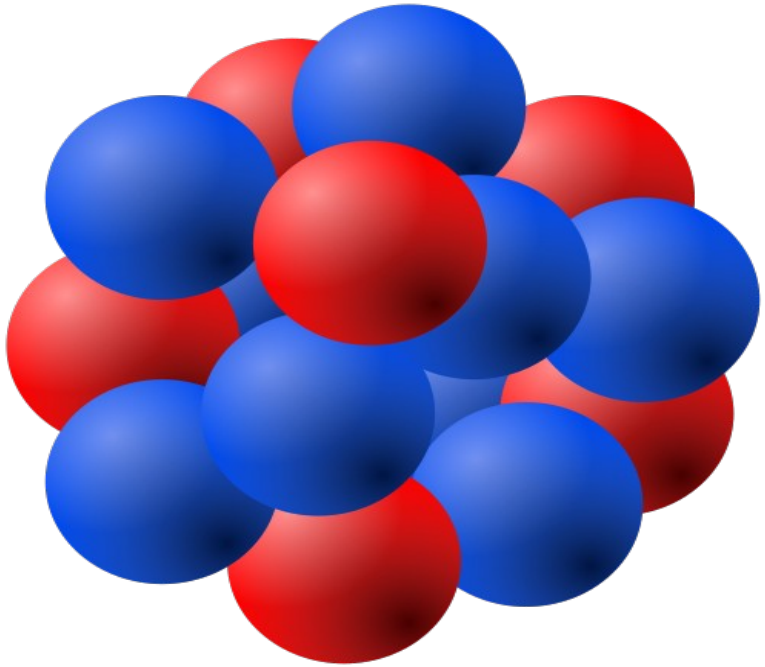
  $f = A v_n / V_N \quad v_n = 4/3\ \pi r_n^3$

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

  ~ 0.38

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

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

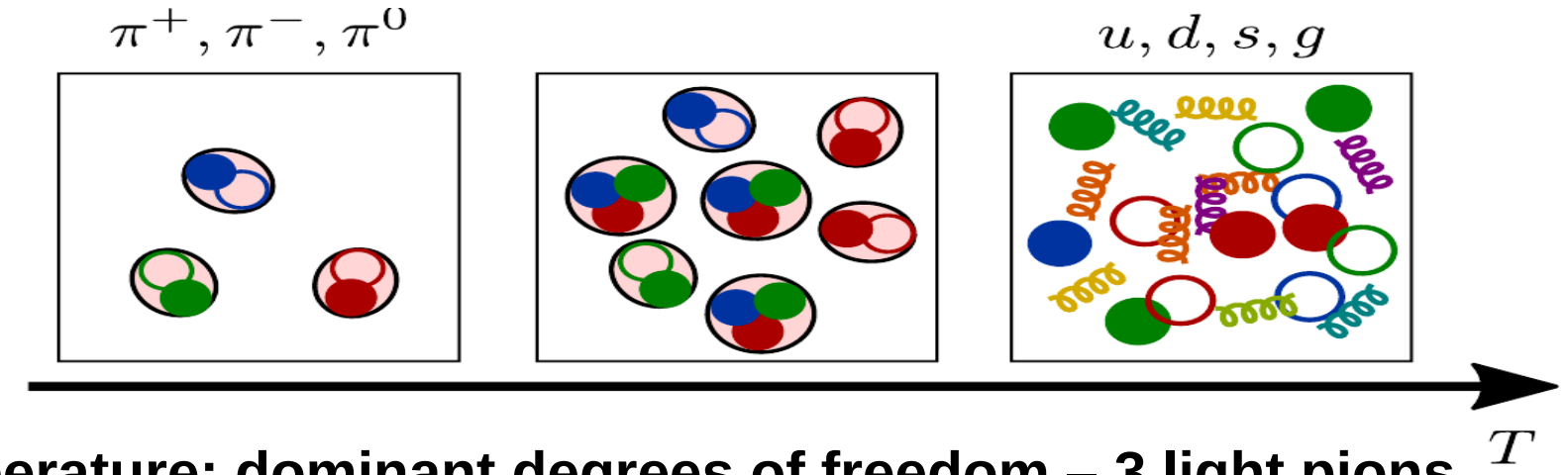


Units:
Energy and momentum: GeV
Length: fm ("Fermi") 1 fm = 10^{-15} m
Time: fm/c 1 fm/c = 0.33 10^{-23} s

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

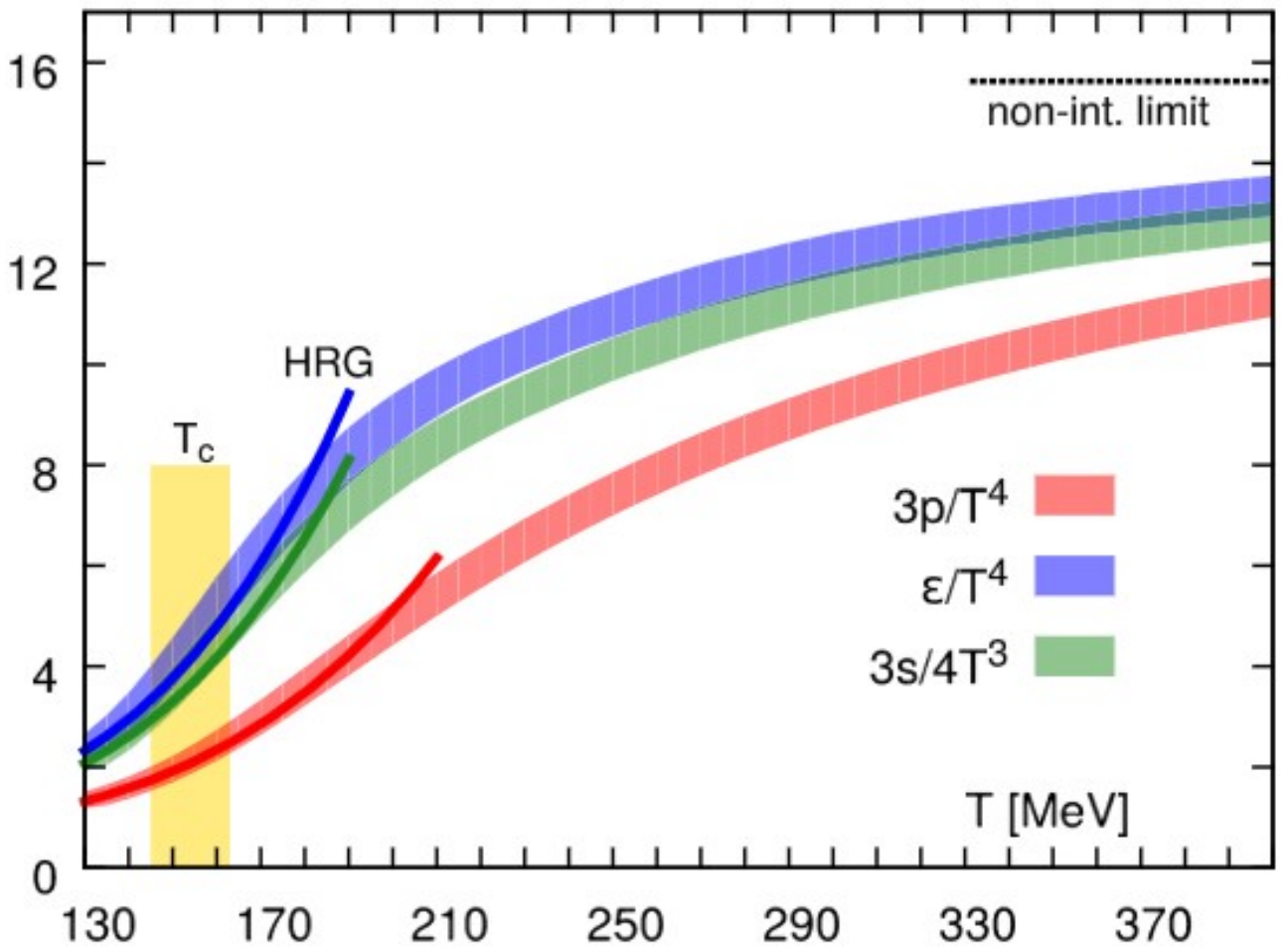
$$e = \frac{\pi^2}{30}\Big(\underbrace{2}_{\text{polarization}} \times \underbrace{8}_{\text{colour}} + \underbrace{2}_{\text{anti-/particle}} \times \underbrace{2}_{\text{spin}} \times \underbrace{3}_{\text{colour}} \times \underbrace{3}_{\text{flavour}} \frac{7}{8}\Big)T^4 \approx 16T^4.$$

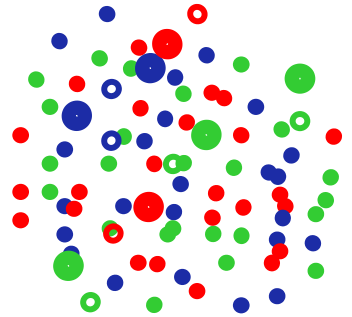
Phase transition in Lattice QCD

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

Energy density ε
Pressure p
Entropy density s

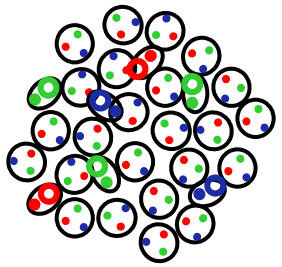
[PRD 90 094503 (2014)]





deconfined:
many d.o.f

confined:
few d.o.f.



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

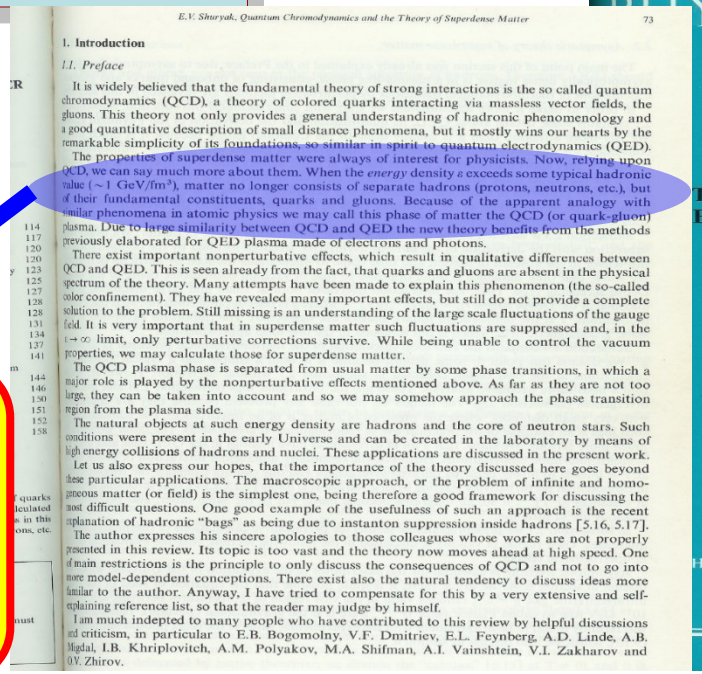
Crossover transition at $T_c \approx 156$ MeV $\approx 2 \cdot 10^{12}$ K $\approx 130{,}000 \cdot T$ [Sun's core]

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.

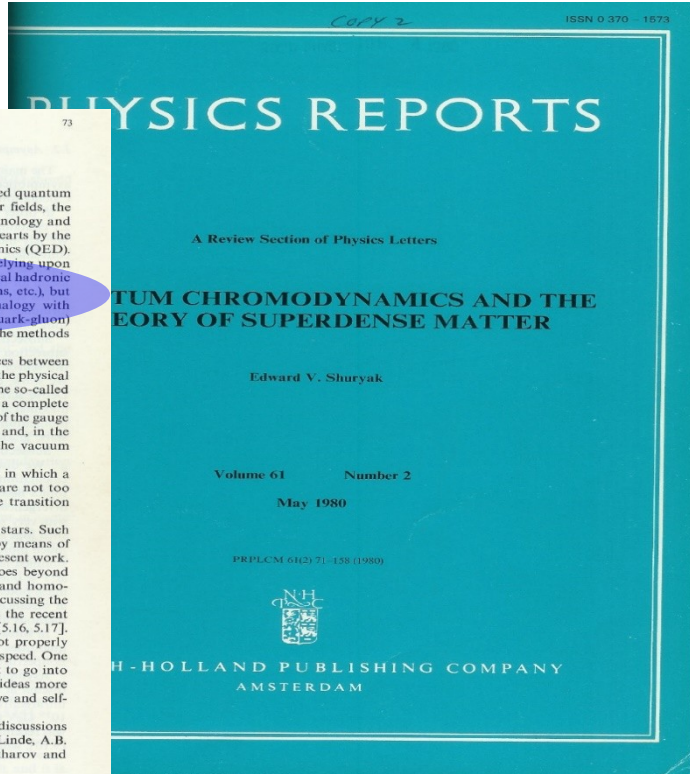
The QCD plasma phase is separated from usual matter by some phase transitions, in which a major role is played by the nonperturbative effects mentioned above. As far as they are not too large, they can be taken into account and so we may somehow approach the phase transition region from the plasma side.

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.



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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)

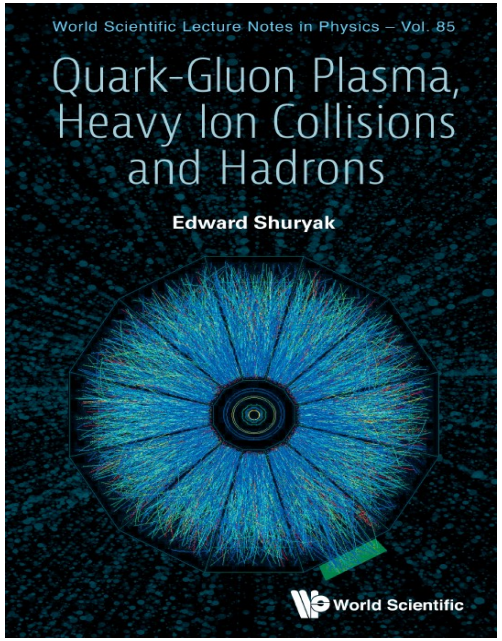
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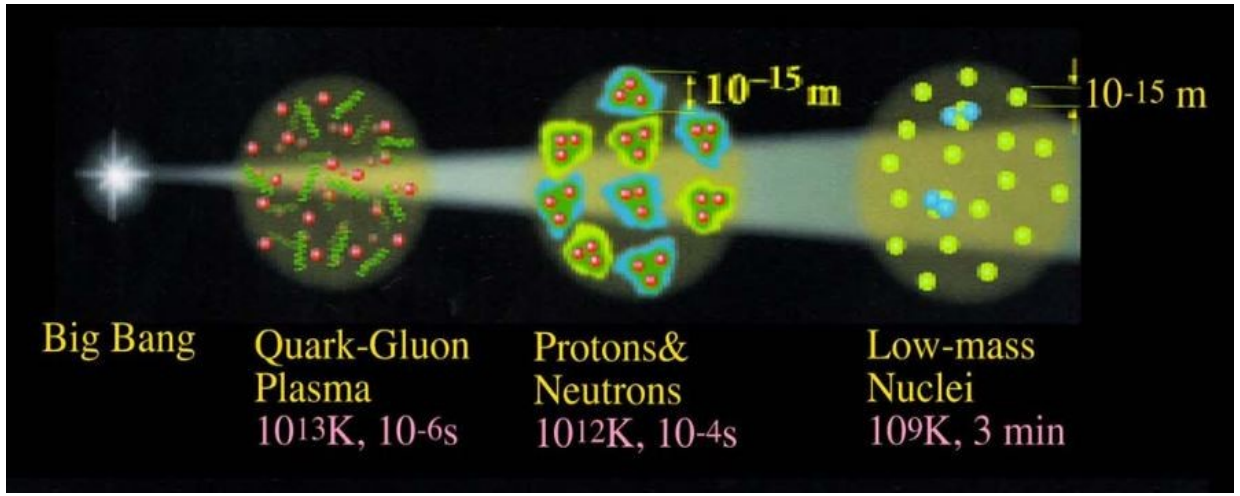
"Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the QCD

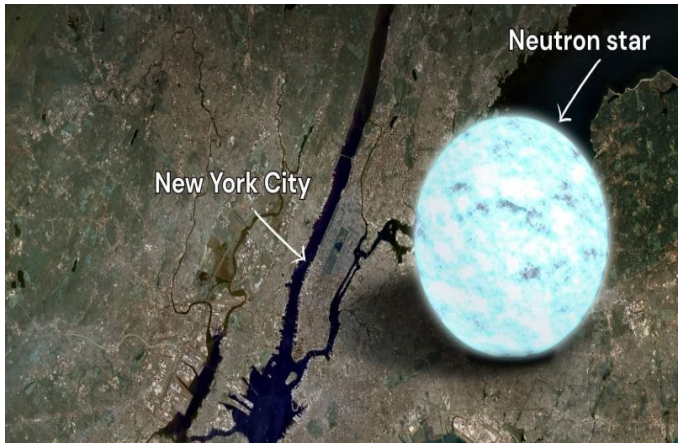
(or quark-gluon) plasma."





Big Bang vs Little Bang / QGM in Neutron Stars?

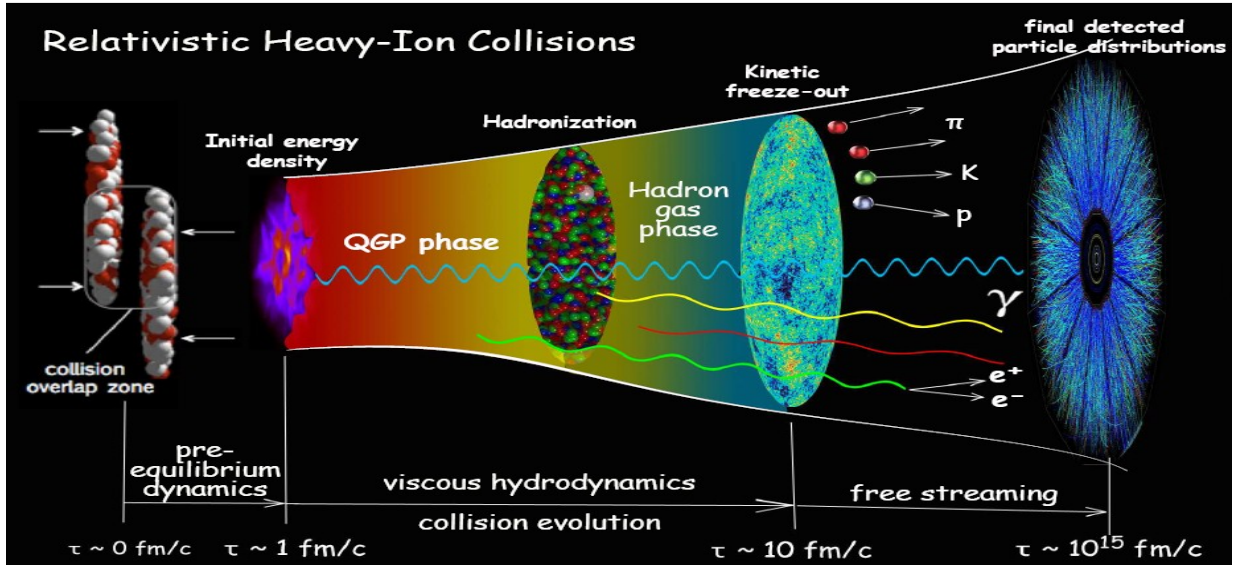


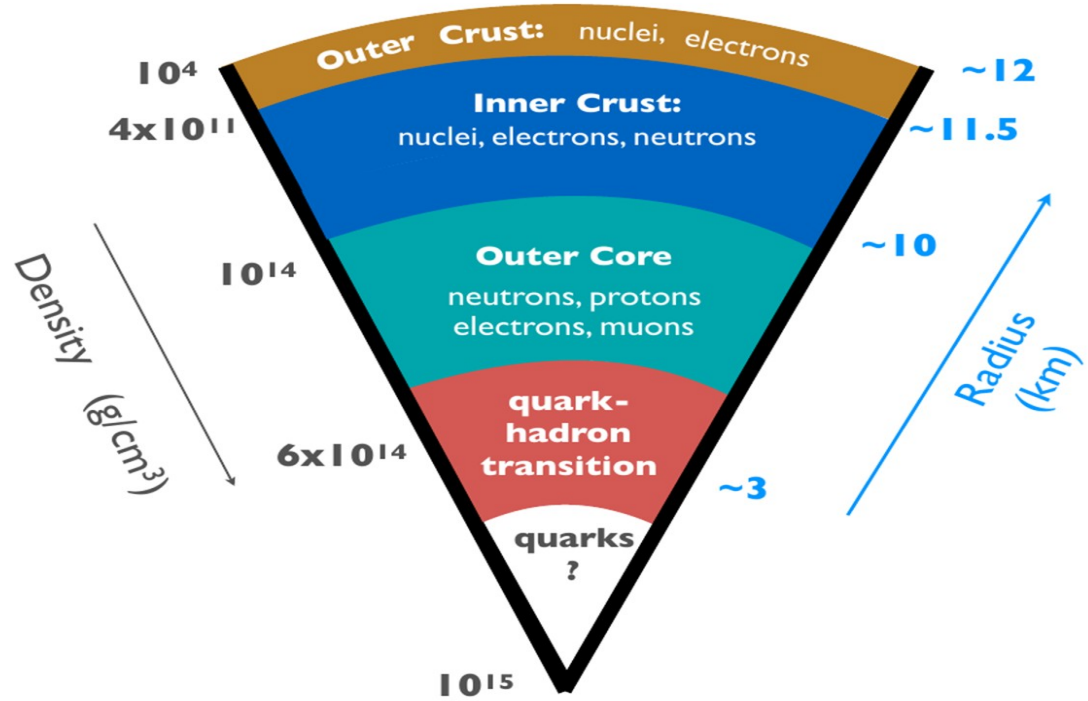


1 Event, slow expansion, long-lived

Time

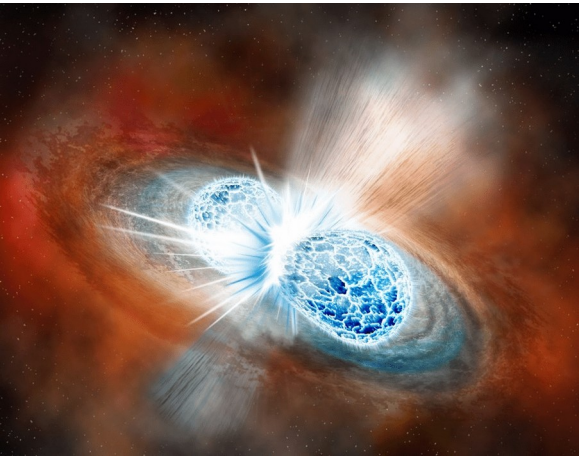
Millions of events, rapid expansion, short-lived



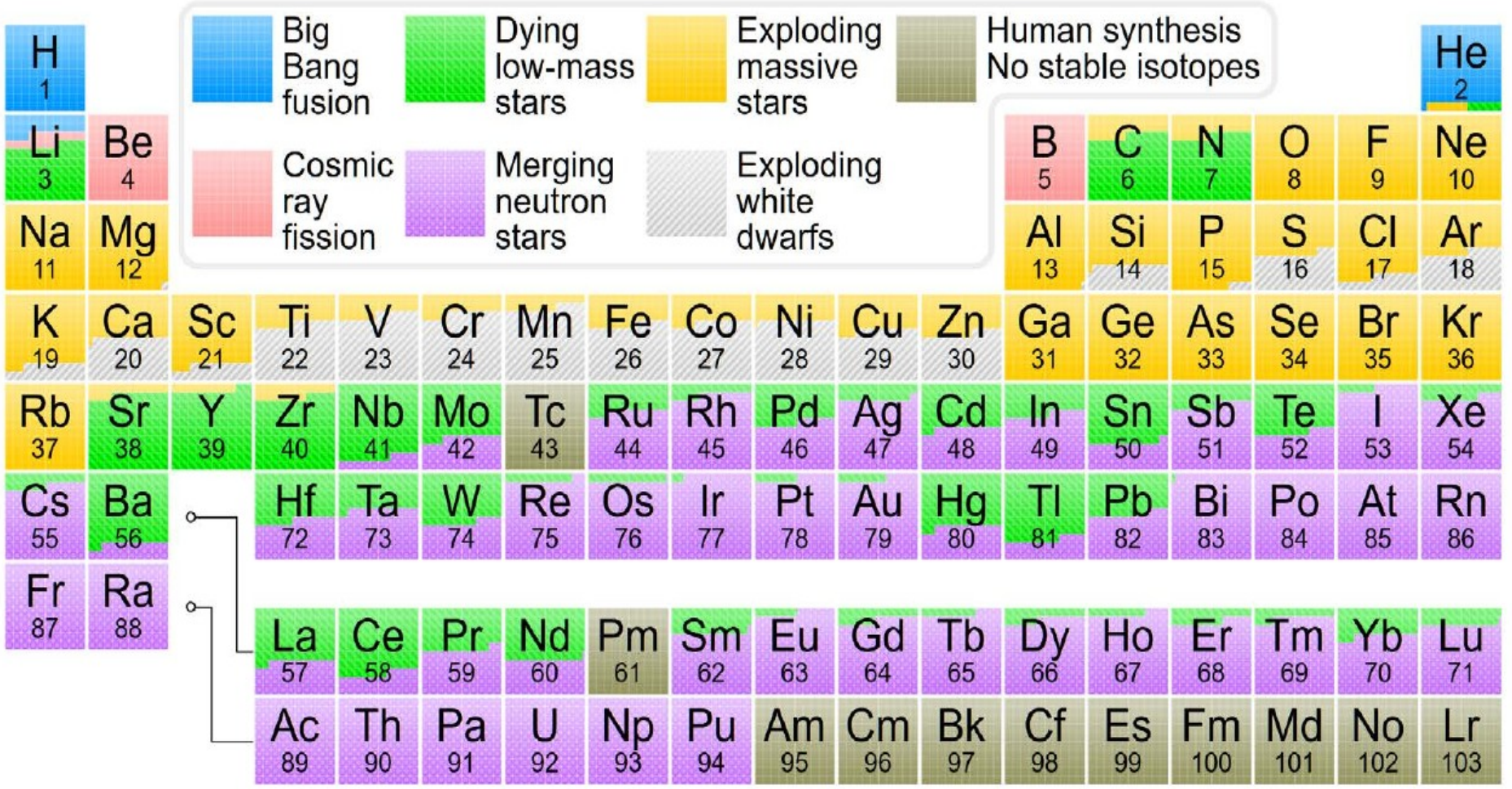


Extreme densities up to 5-10ρ_0

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

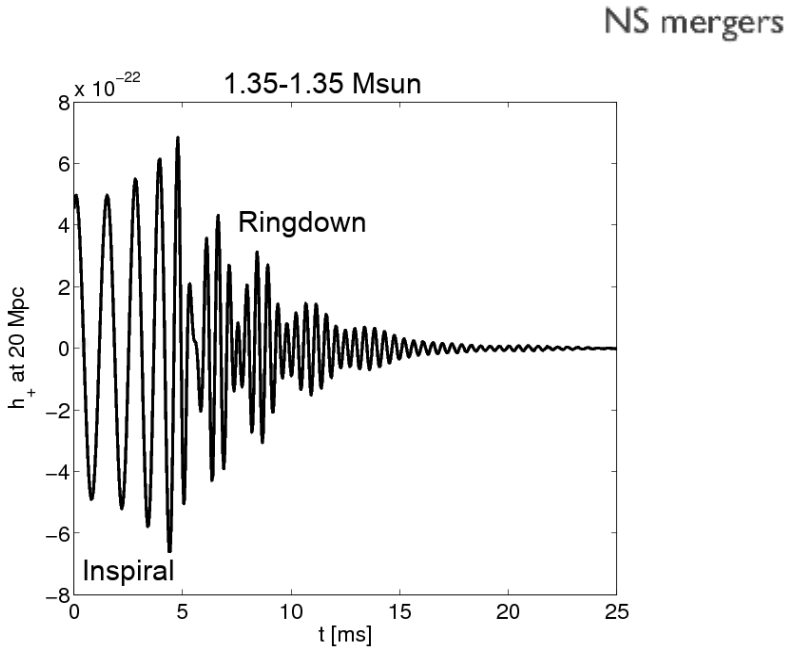






r-process - source of heavy elements including gold, platinum, and uranium.

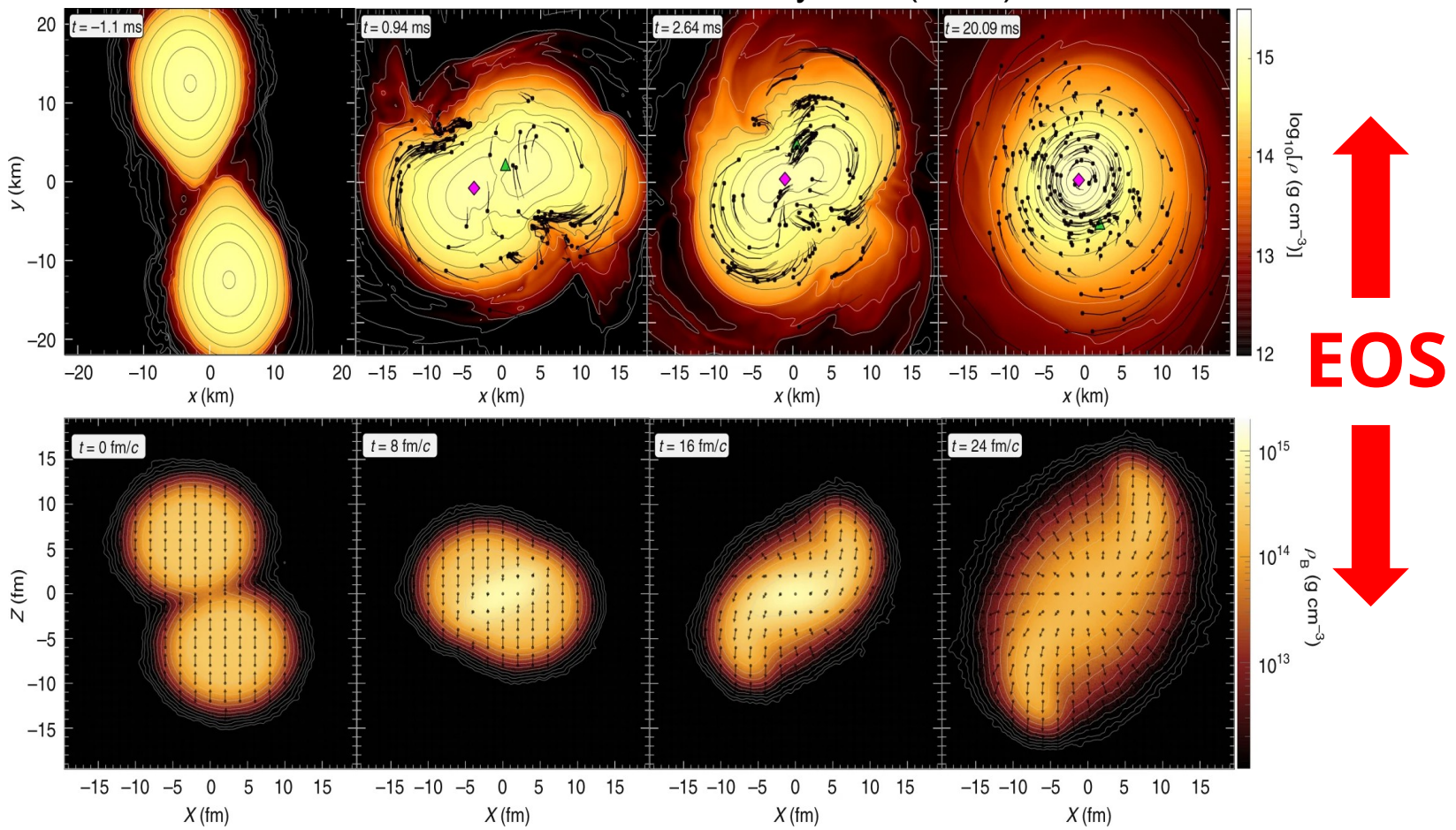
Neutron star mergers and heavy-ion collisions



Gravitational Wave Signal

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

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



EOS

Au+Au 1.25A GeV

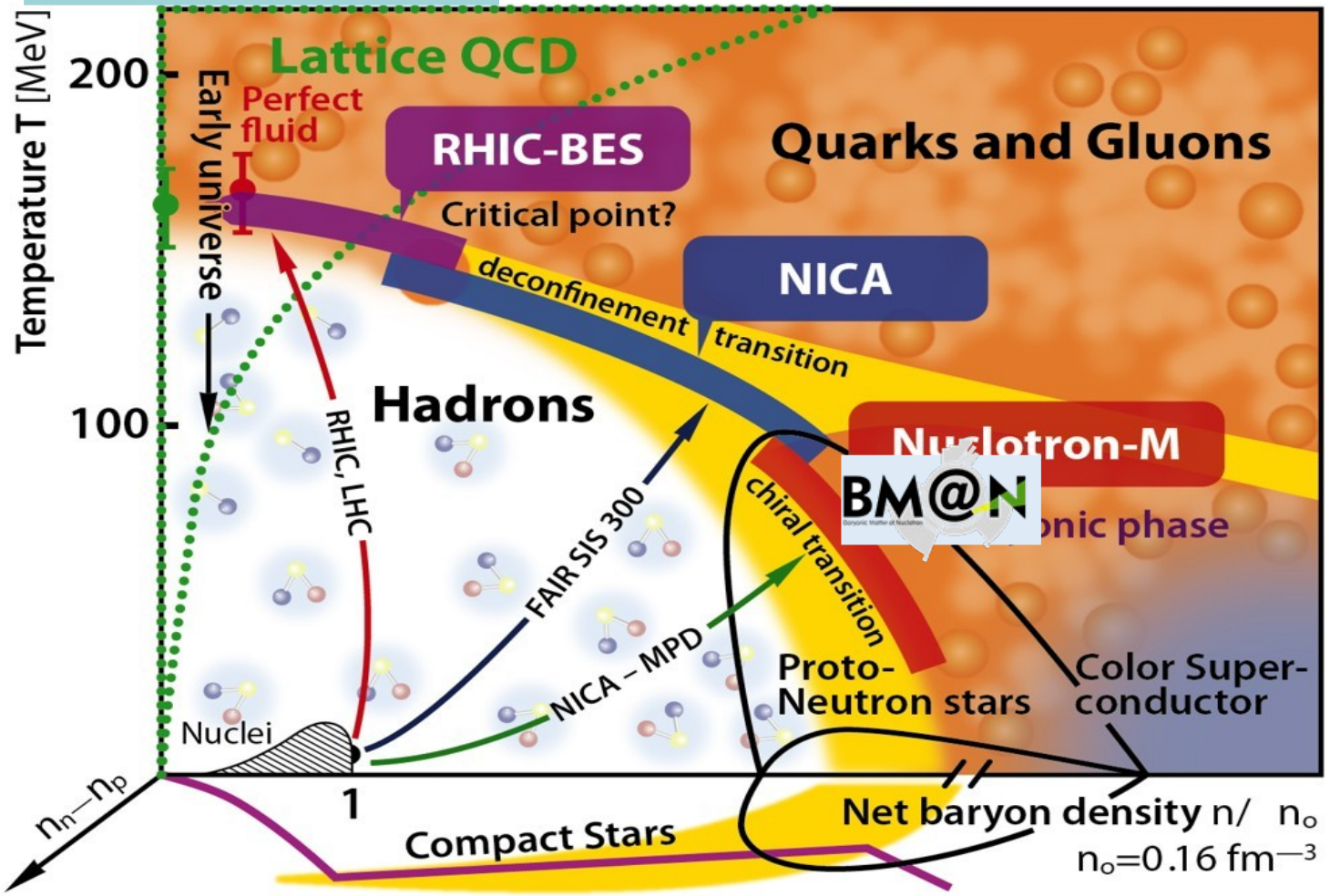
- Confirmation by astronomical observations after gravitational wave detection from GW170817 (August 2017).
- Source of heavy elements including gold, platinum, and uranium.

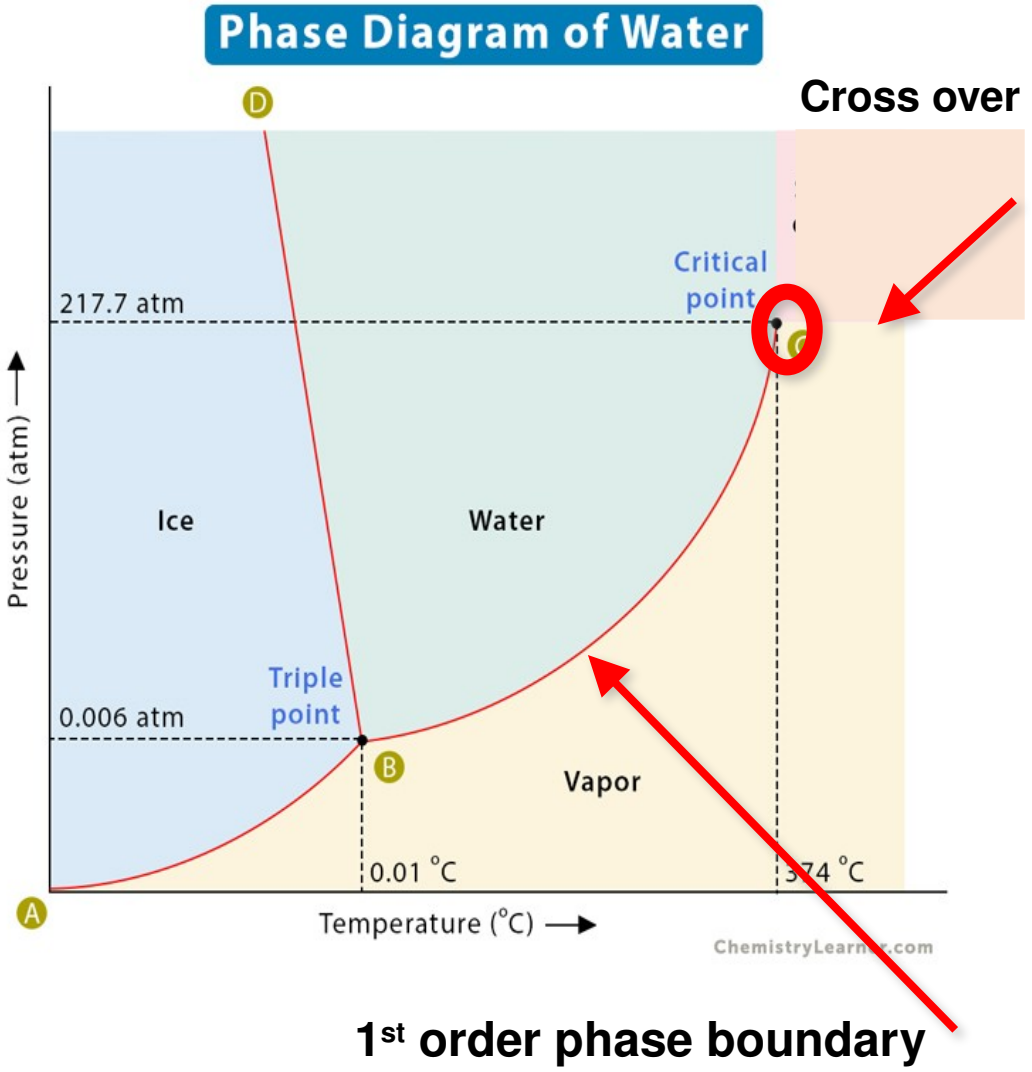
- T<70 MeV, $\rho \cong 3\rho_0$ for both
- Probe NS merger matter in the laboratory

Relativistic Heavy-Ion Collisions and QCD Phase Diagram

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

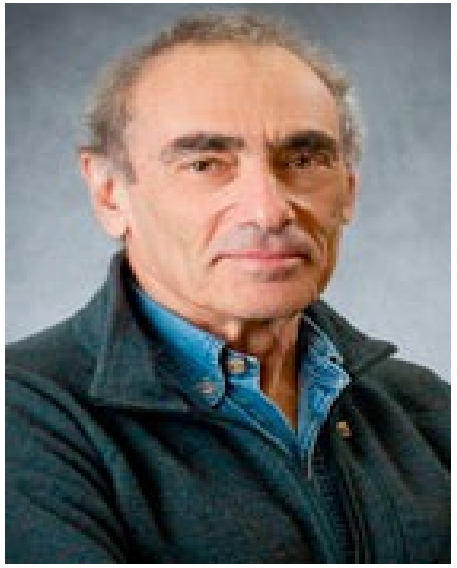
[PRD 90 094503 (2014)]





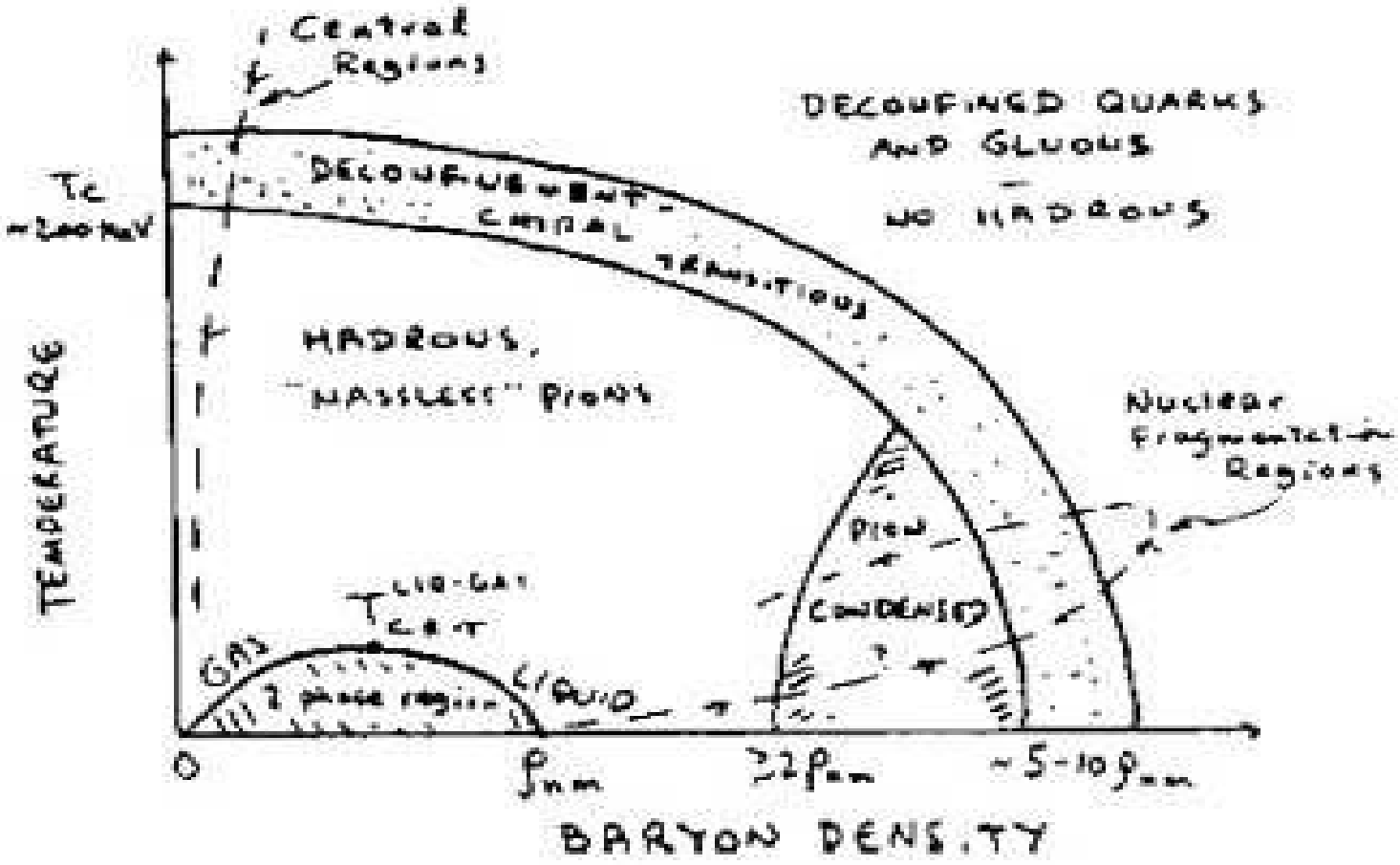
Smooth *transition from hadronic degrees of freedom to quark-gluon degrees of freedom at zero baryonic density*

QCD Phase Diagram (1983)



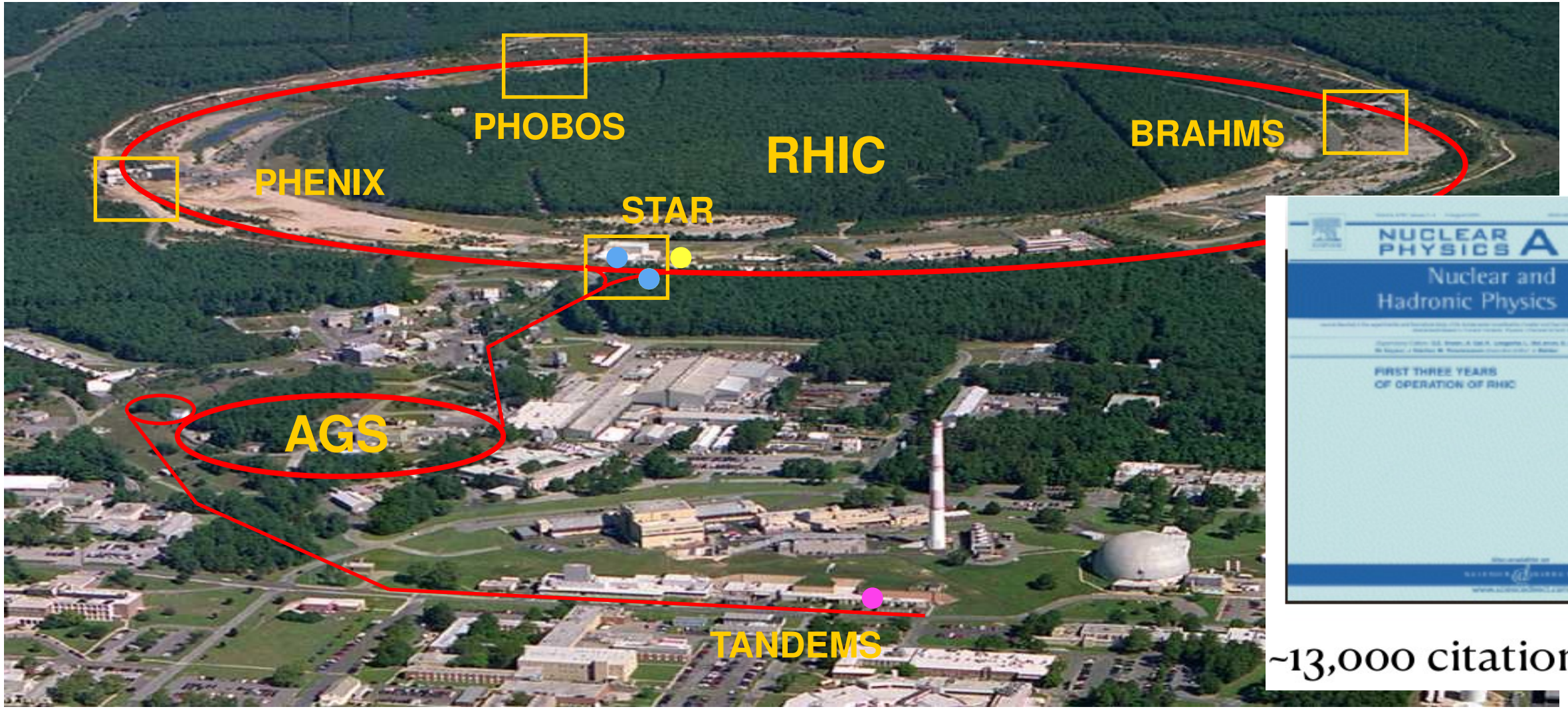
Gordon Baym

1983 US Long Range Plan - *by Gordon Baym*



Gordon Baym, "Ultrarelativistic heavy ion collisions: the first billion seconds", NPA956 (2016) 1

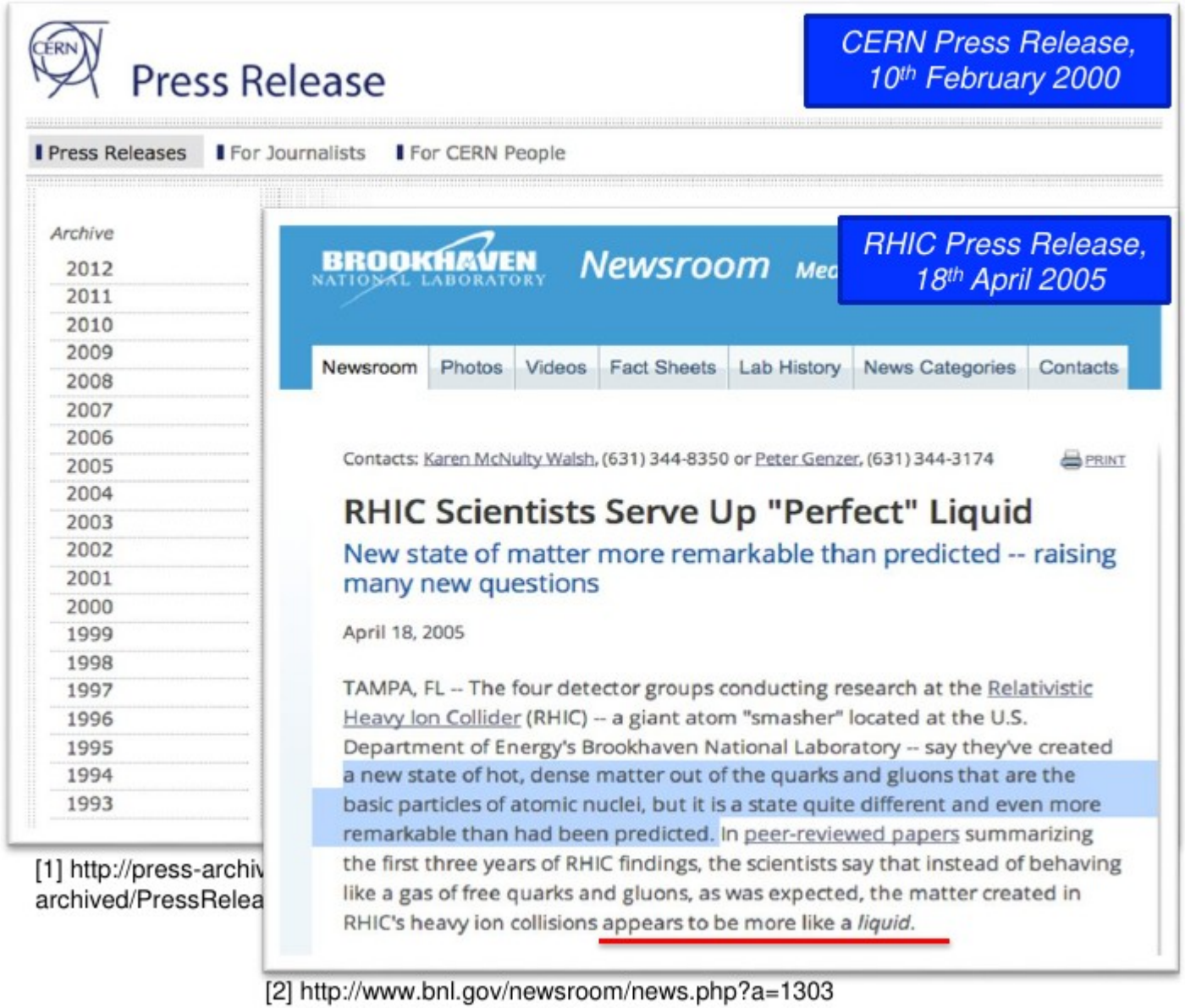
Relativistic Heavy Ion Collider (RHIC): 2000-2025



~13,000 citations!

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

Perfect Liquid Discovered at RHIC: 2005



[1] http://press-archiv
archived/PressRelea

[2] http://www.bnl.gov/newsroom/news.php?a=1303

First "compelling" evidence of QGP at SPS

The "remarkable" evidence at RHIC that the hot matter formed is
- Extremely **strongly interacting (sQGP)**

- Absorbing energy of traversing partons → **Almost opaque medium**

- Reacting to pressure gradients by flowing with very small shear viscosity → **Almost perfect liquid**

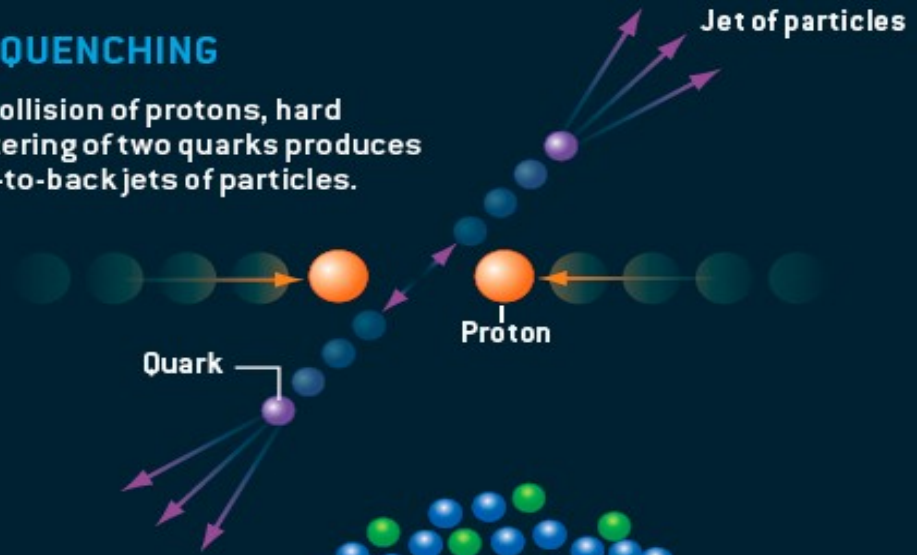
Perfect Liquid Discovered at RHIC: 2005

EVIDENCE FOR A DENSE LIQUID

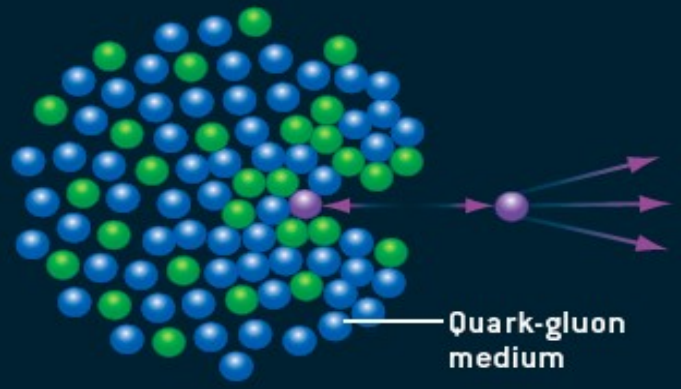
Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

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

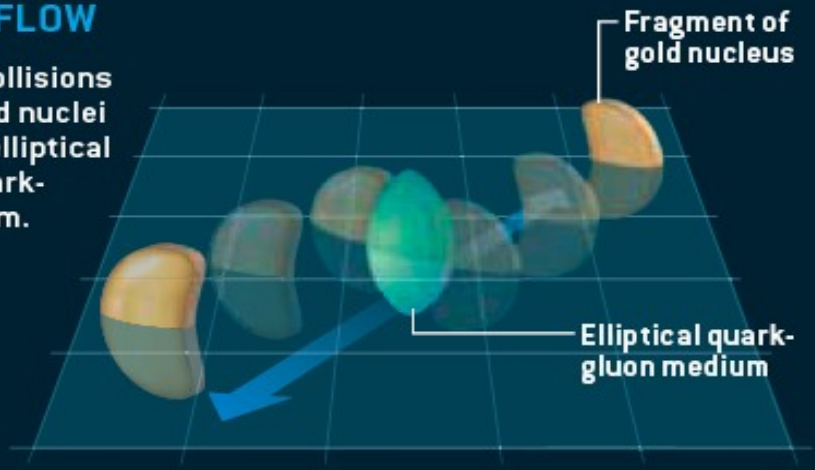


In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

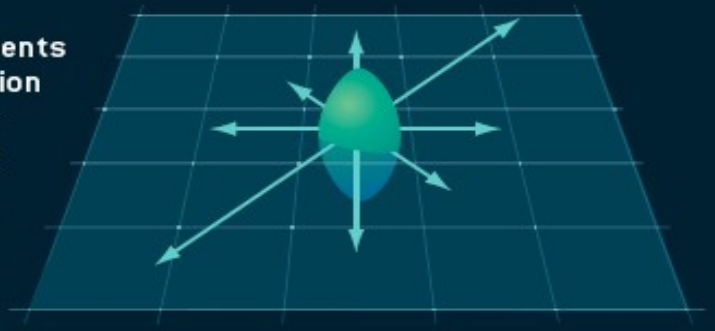


ELLIPTIC FLOW

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

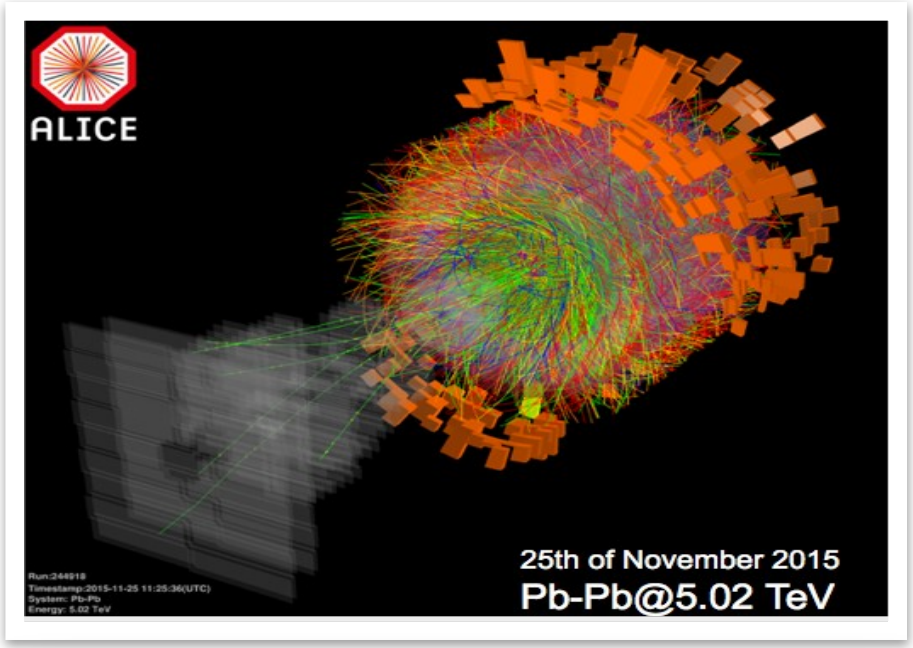


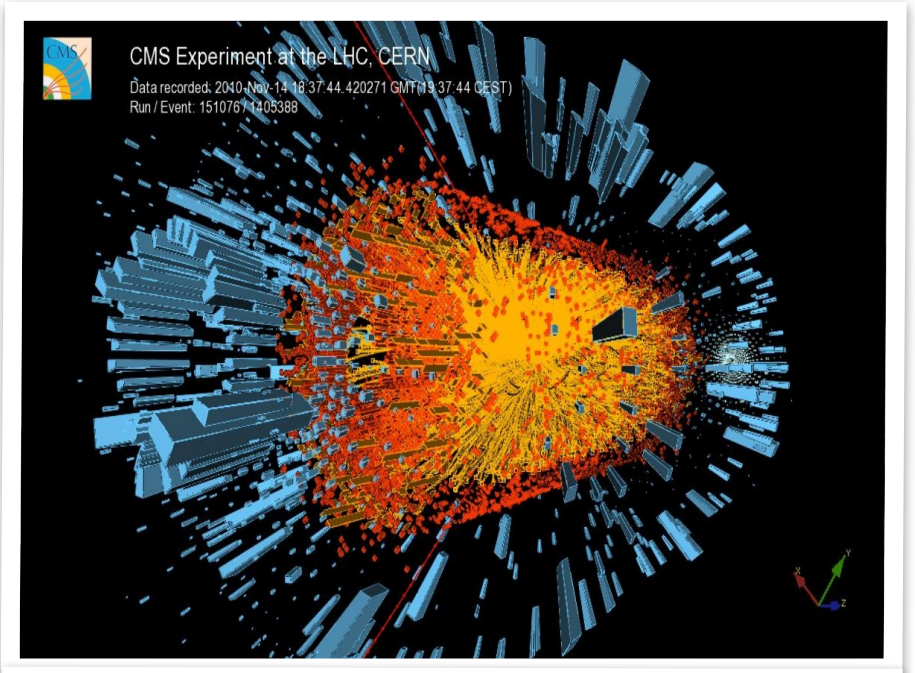
The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (*arrows*).

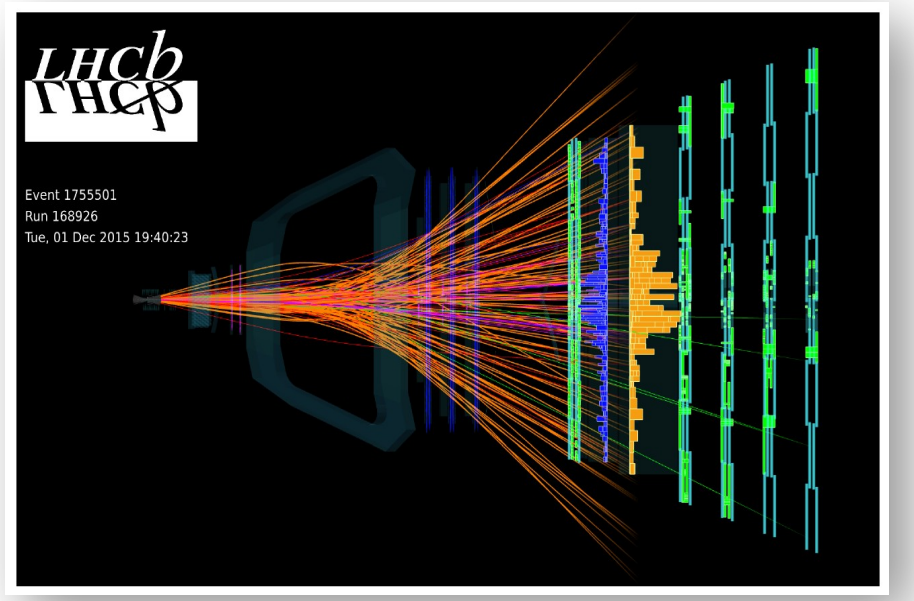


M. Roirdan and W. Zajc, Scientific American, May 2006

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



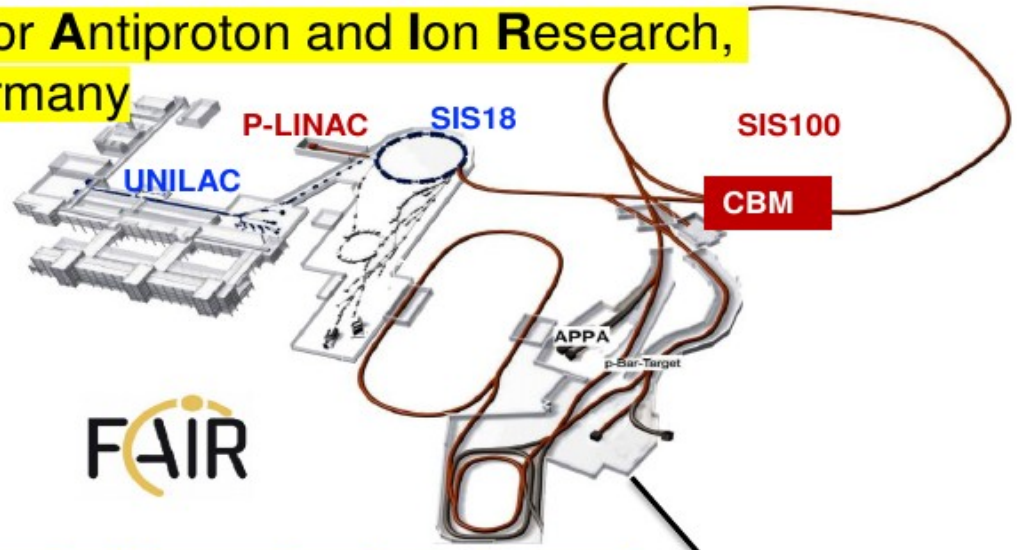




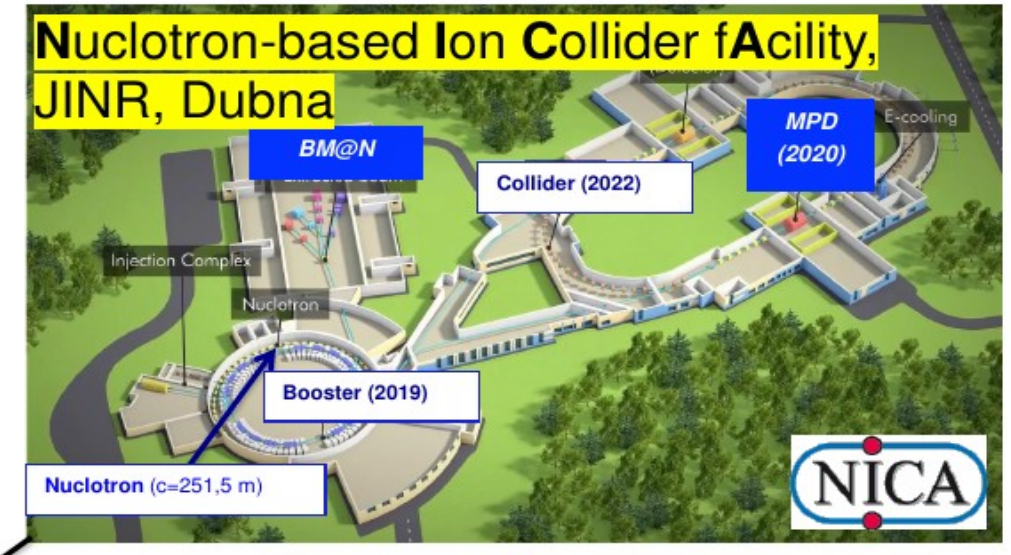


Relativistic Heavy-Ion Collisions: Beam energy Scan programs

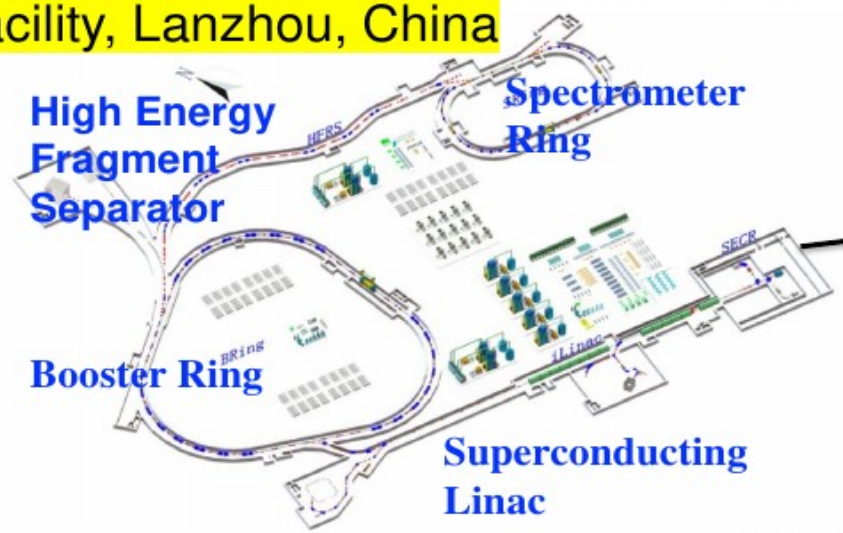
Facility for **A**ntiproton and **I**on **R**esearch, GSI, Germany

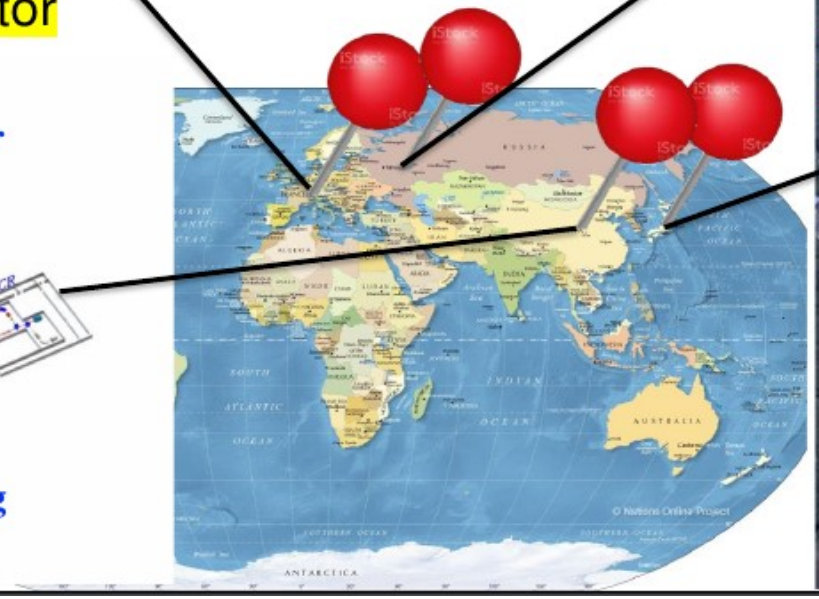


Nuclotron-based **I**on **C**ollider f**A**cility, JINR, Dubna

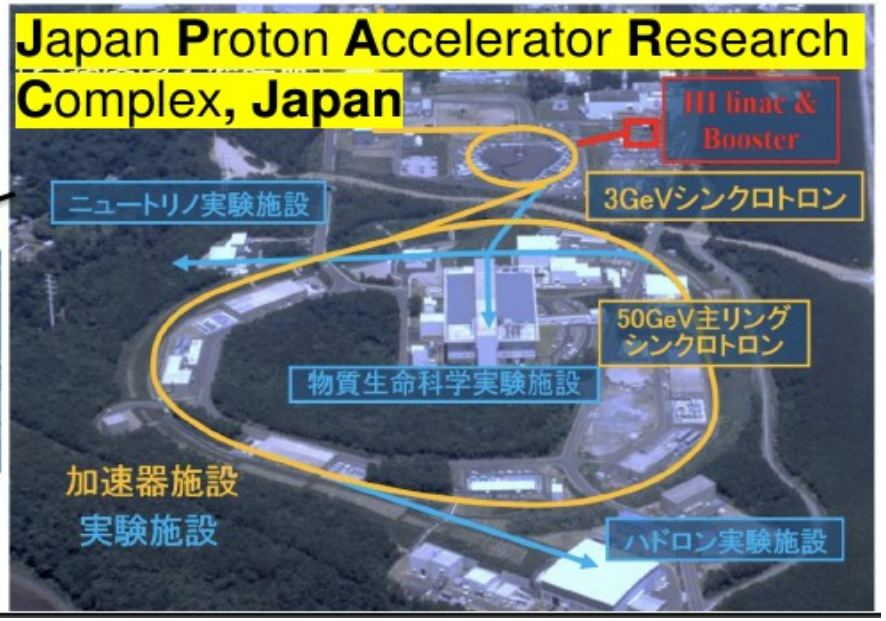


High-**I**ntensity Heavy Ion **A**ccelerator **F**acility, Lanzhou, China



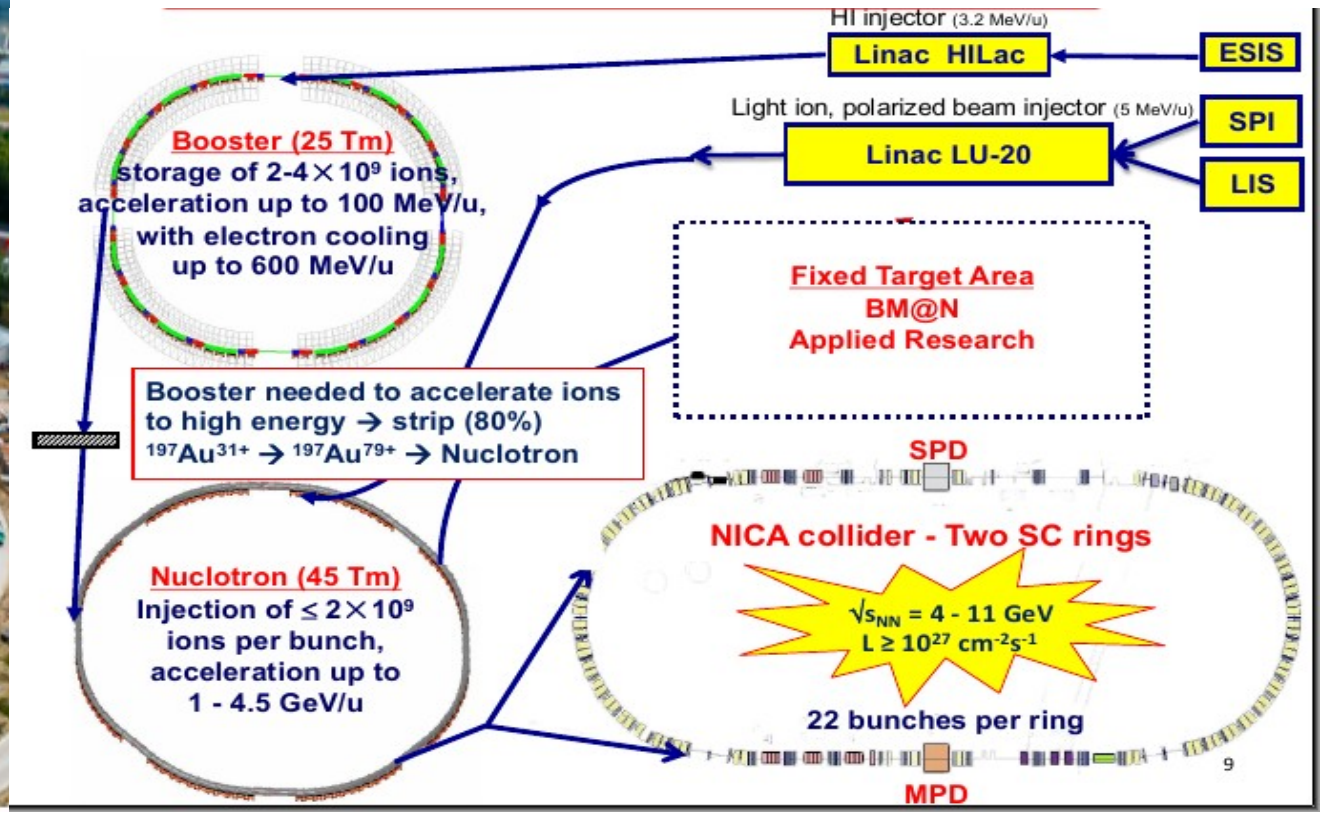


Japan **P**roton **A**ccelerator **R**esearch **C**omplex, **J**apan



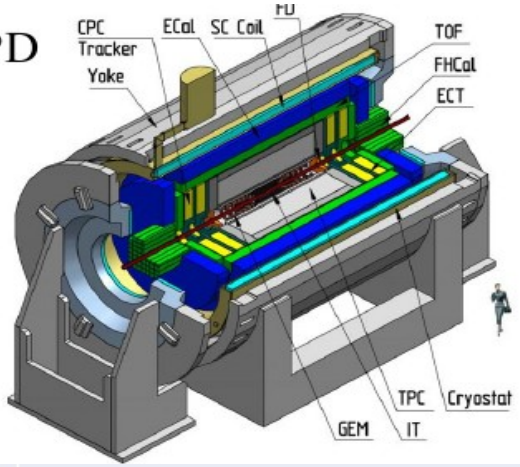
Relativistic Heavy-ion Collisions at NICA





NICA (Nuclotron based Ion Collider fAcility) - a superconducting collider of protons and heavy ions, being built at the Laboratory of High Energy Physics (LHEP, JINR), first beams: 2026

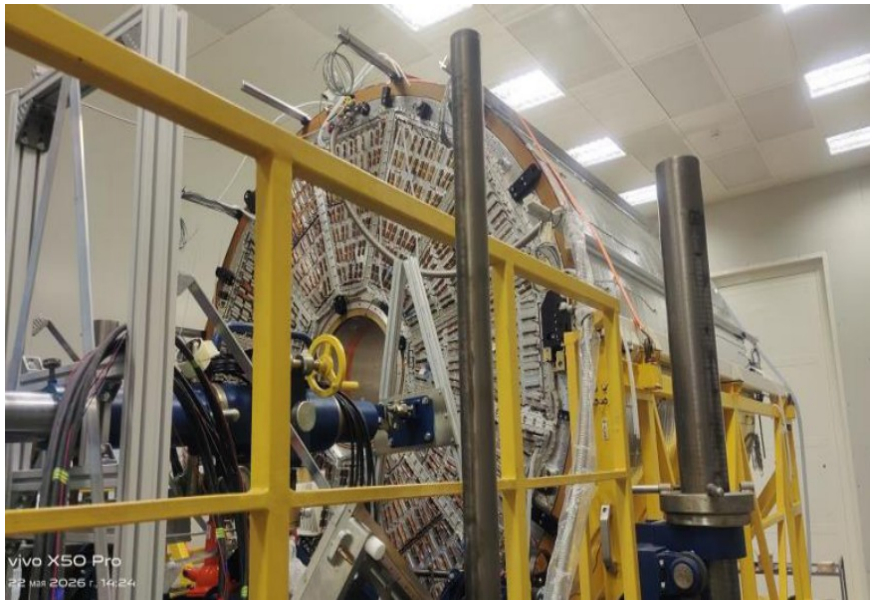
- **BM@N ("Baryonic Matter at Nuclotron") – fixed-target experiment,**
  first physics run Xe+CsI at 3.8 A GeV (2023), BES program: 1.6, 2.2 and 3.0 AGeV (2026)
- **MPD ("Multi-Purpose Detector") - collider+fixed target experiment, NICA, 2026**



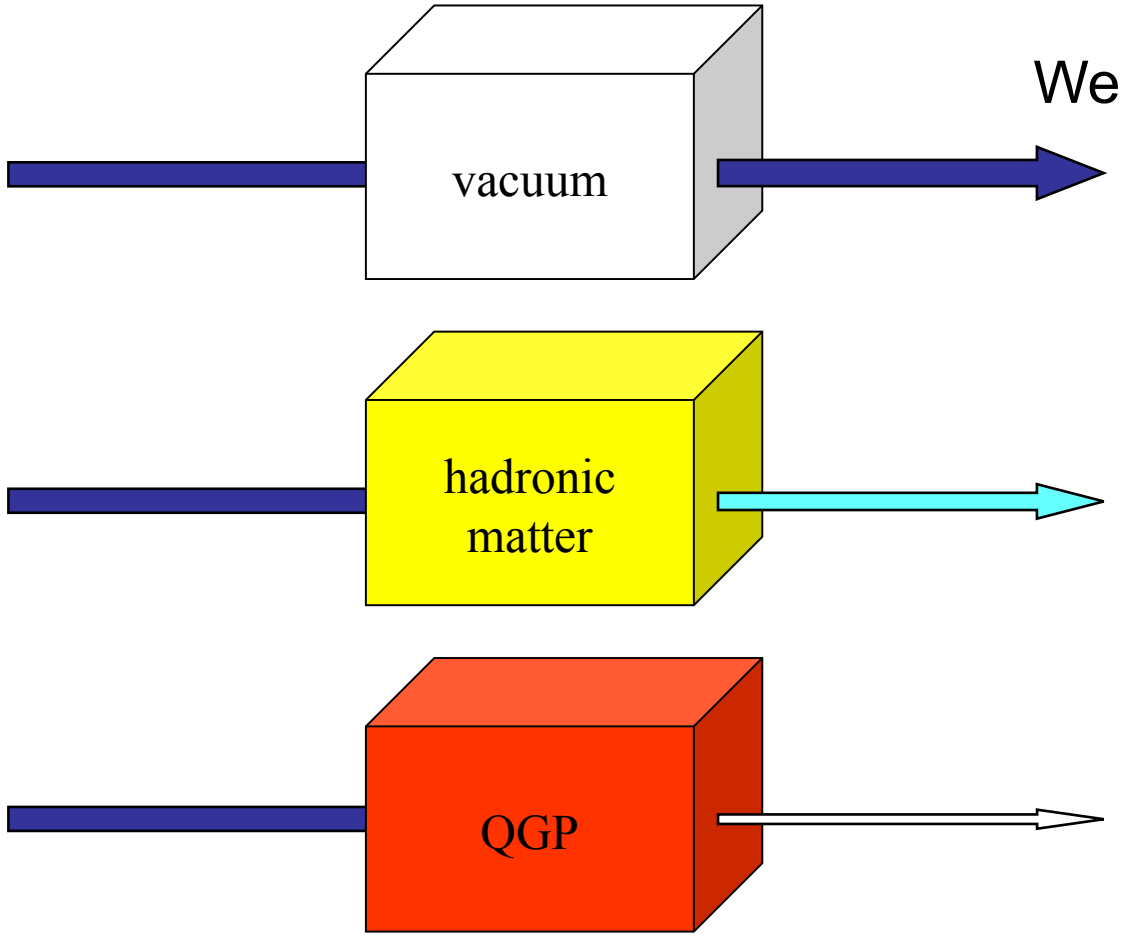




		2026
1	January 12th – January 23d	Fixation the Current leads cooling problem
2	January 26th February 15th	Cooling the Solenoid to working temperature
3	February 25 – March 25th	Magnetic field measurements at nominals 0.5T
4	March 30th - April 17th	Support Frame installation into Magnet
5	April 30th – May 30th	Ecal installation from the East side
6	May 27th	West platform mounted
7	May 28th – June 15th	Installation of the TOF modules (access from bc
8	June 10th	Ecal module installation finishing
9	June 15 – June 20	Installation the Mapper into Magnet
10	June 22th - July 12th	Magnetic field measurements at 0.5T
11	July 15th – August 10th	Ecal&TOF cooling pipes and cabling laying
12	July 20th - August 10th	FHCal mounting
13	August 10th – September 30th	TPC installation and test
14	October 1st – October 15th	Beam pipe installation
15	October 20 - October 25th	Closing MPD (Installation of Poles)
16	October 30th	Moving MPD on the Collider beam line



The good QCD matter probes should be:

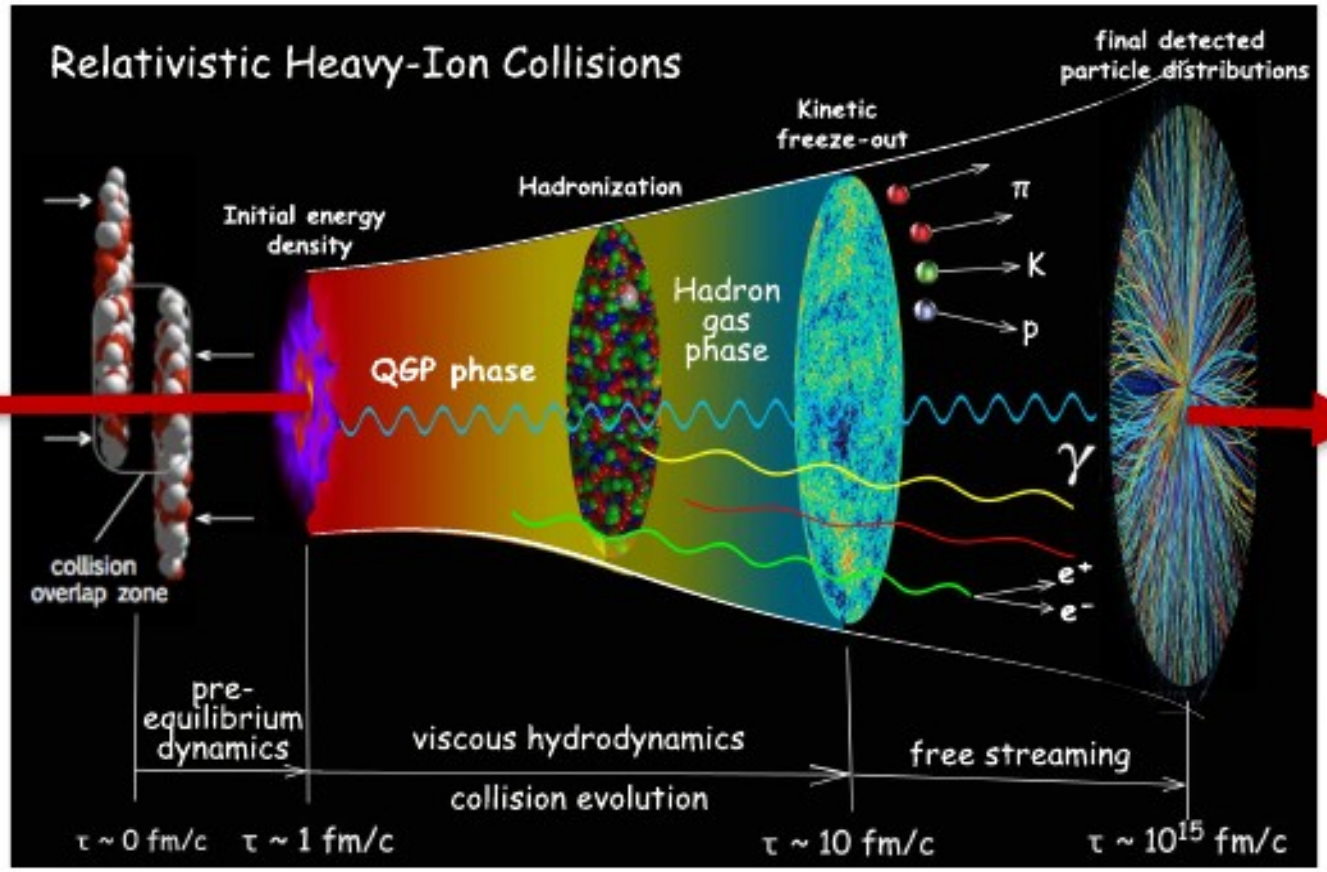


Well understood in “p+p collisions”

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

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



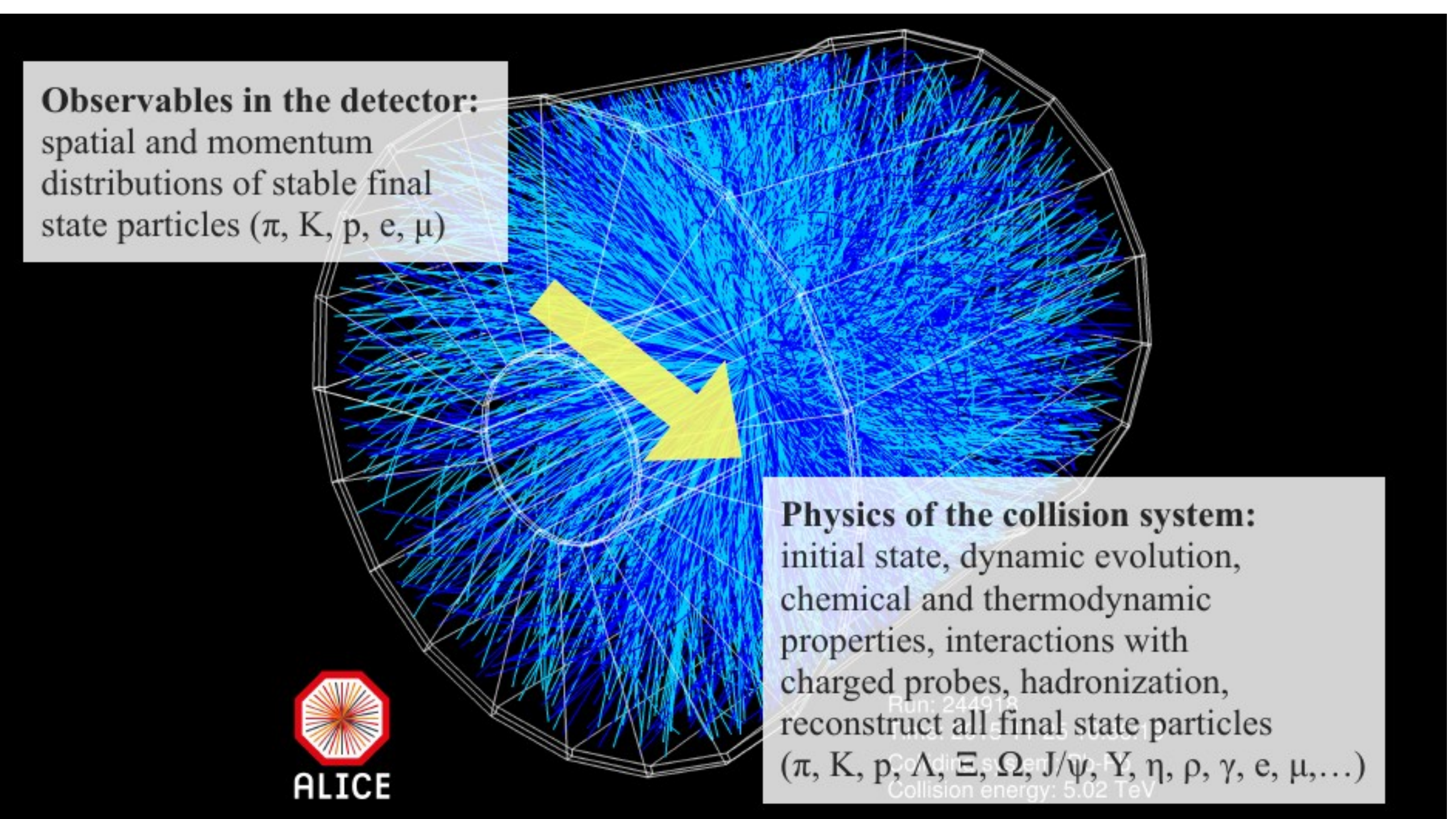




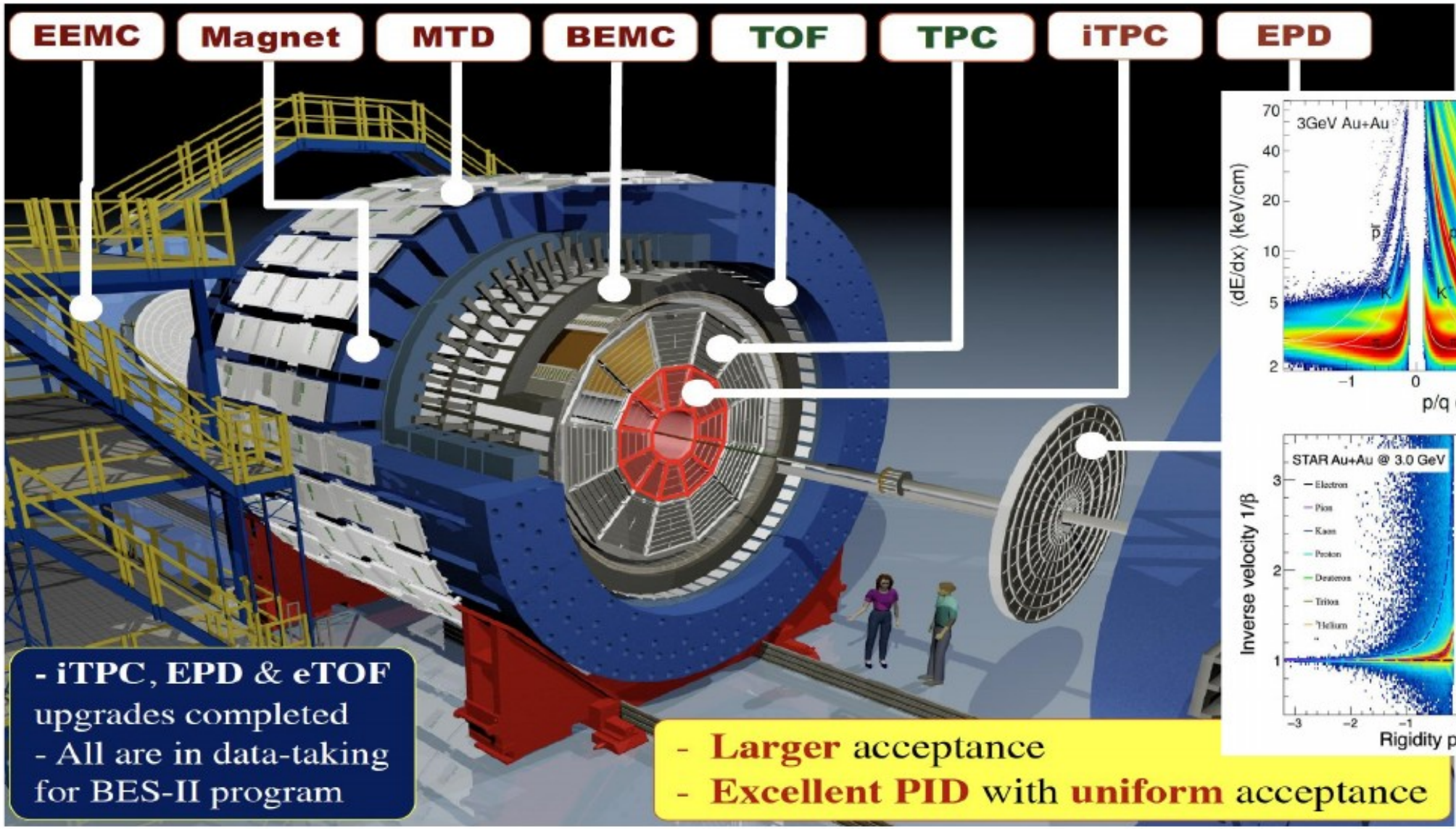
"Psychoanalysis" of Matter

~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,…)
Run: 244918
Collision energy: 5.02 TeV
ALICE

STAR Experimental



MPD experiment at NICA

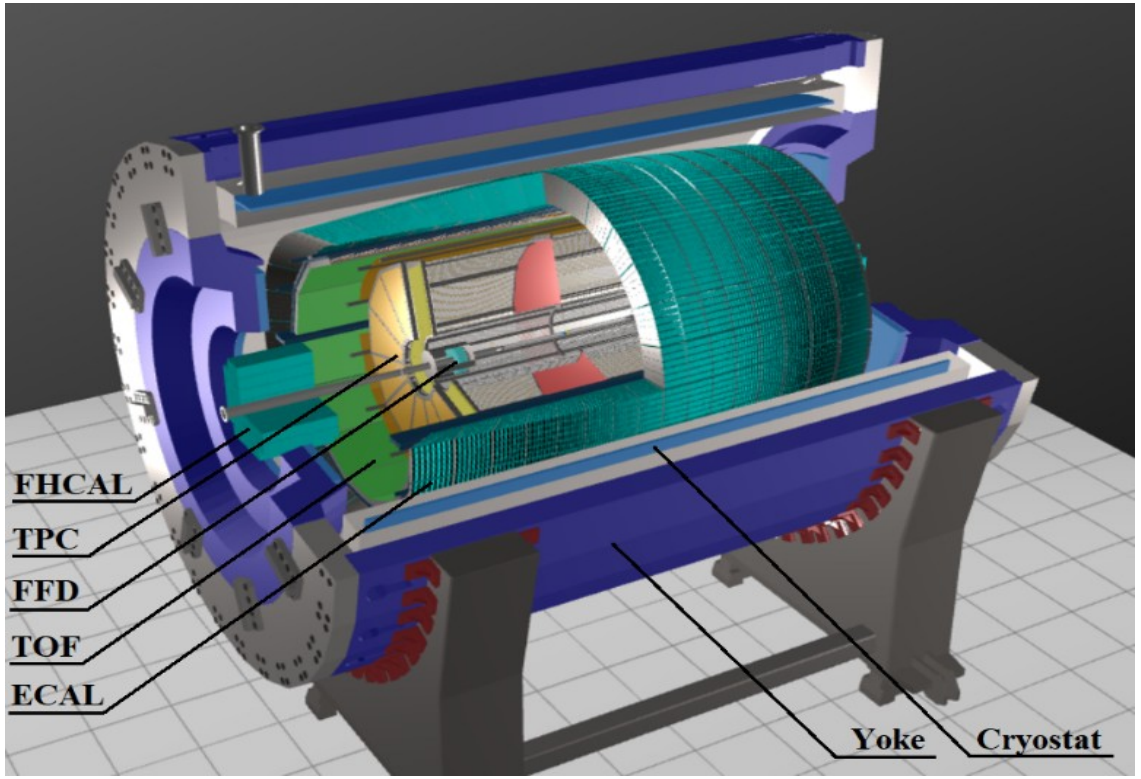
Main subsystems at Stage-I:

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

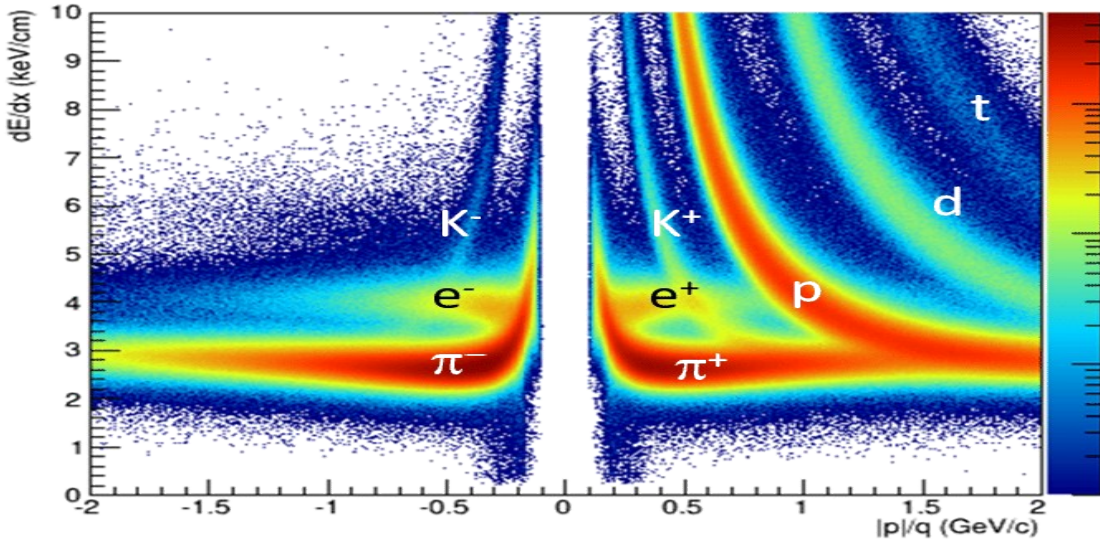
TOF ($|\eta| \leq 1.4$): charged particle identification

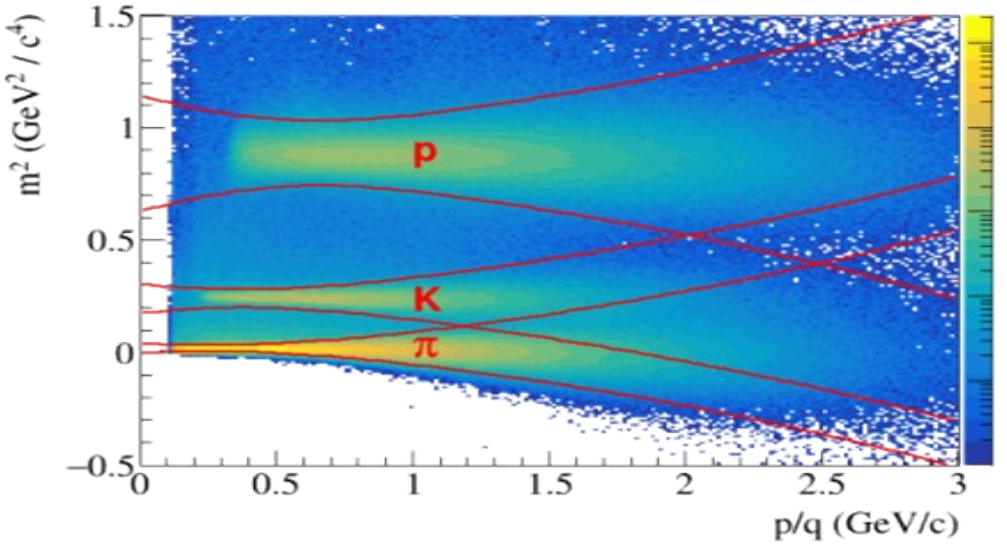
ECal ($2.9 < |\eta| < 1.4$): energy and PID for $\gamma/e^{\pm}$

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

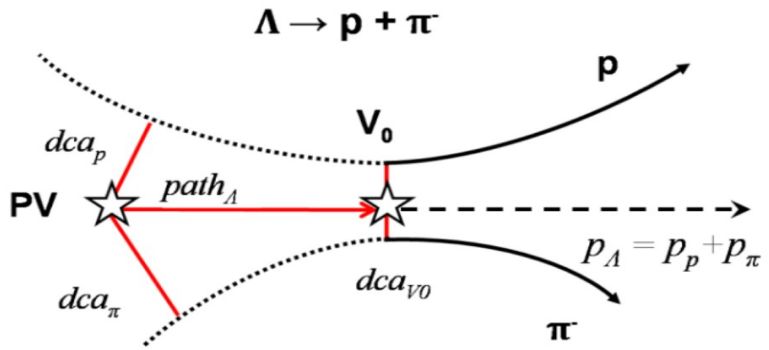


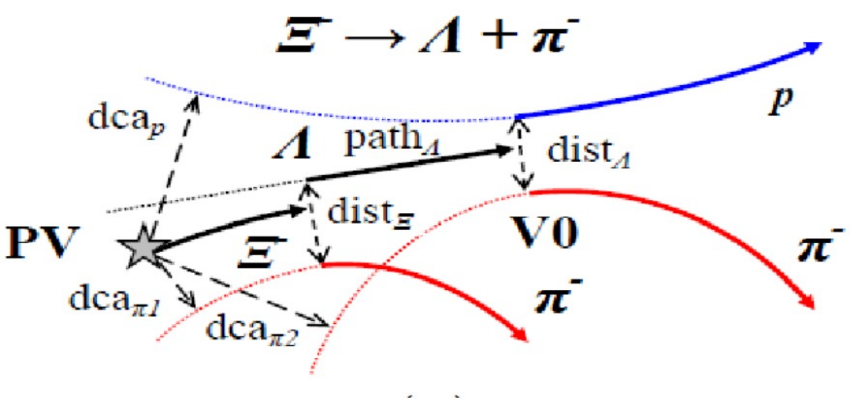
γ, e, μ, π, K, p

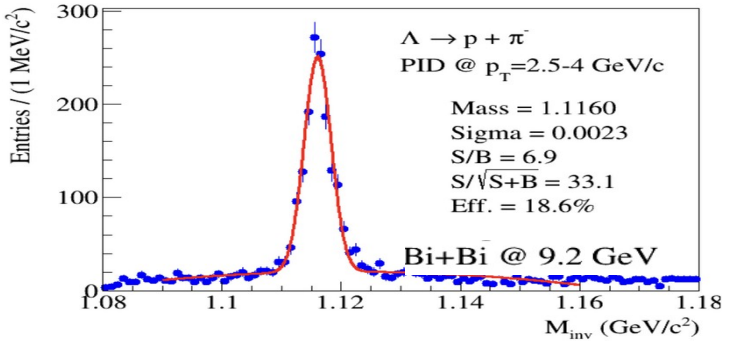


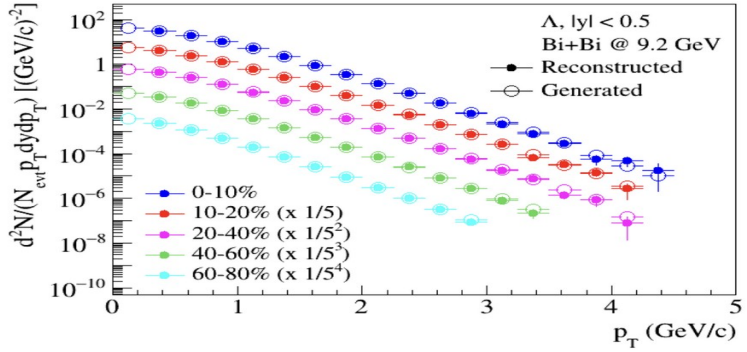


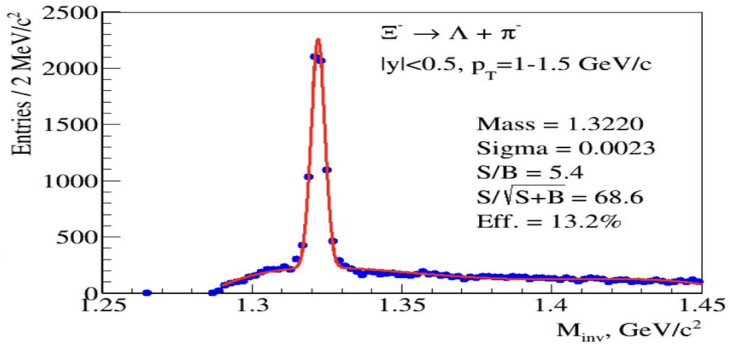
PID via Topology and Invariant Mass

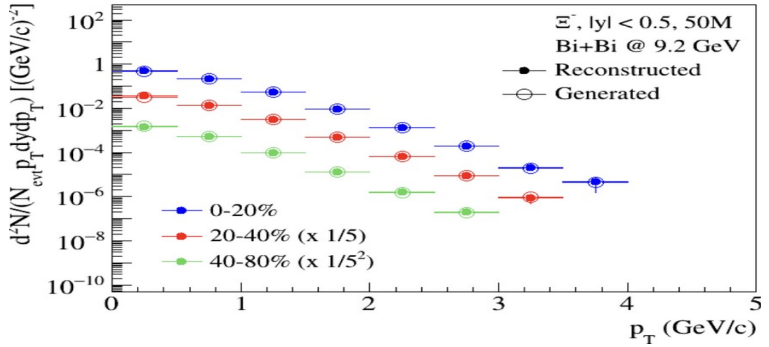








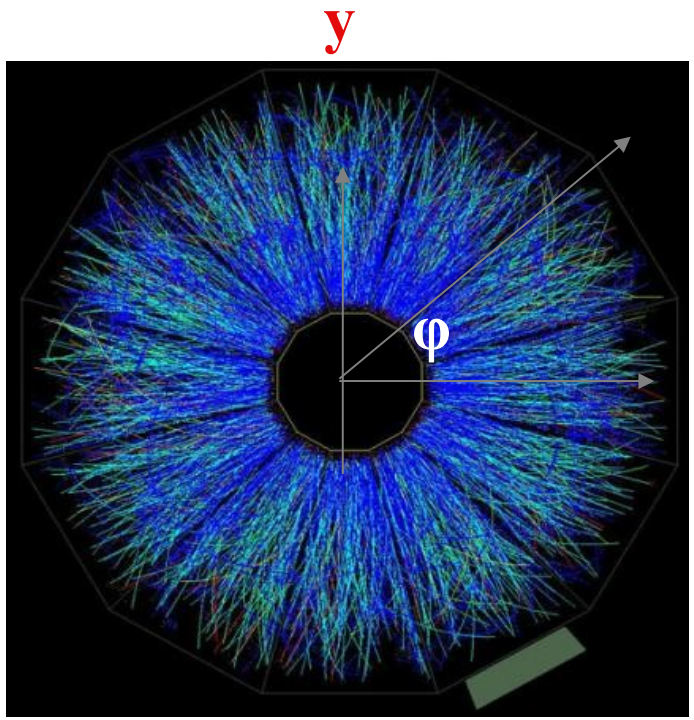


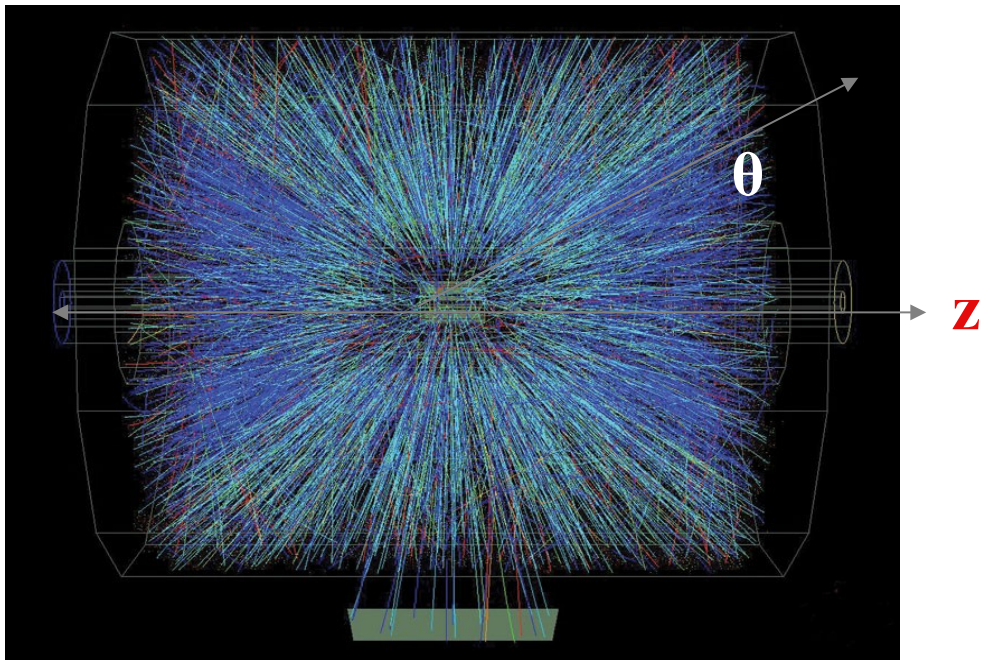


$$M^2 = (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2$$
$$= m_1^2 + m_2^2 + 2\left(E_1 E_2 - \mathbf{p}_1 \cdot \mathbf{p}_2\right).$$

Definition of kinematical variables

Momentum , azimuthal angle φ, rapidity (y) and pseudo-rapidity (η) of the emitted particles





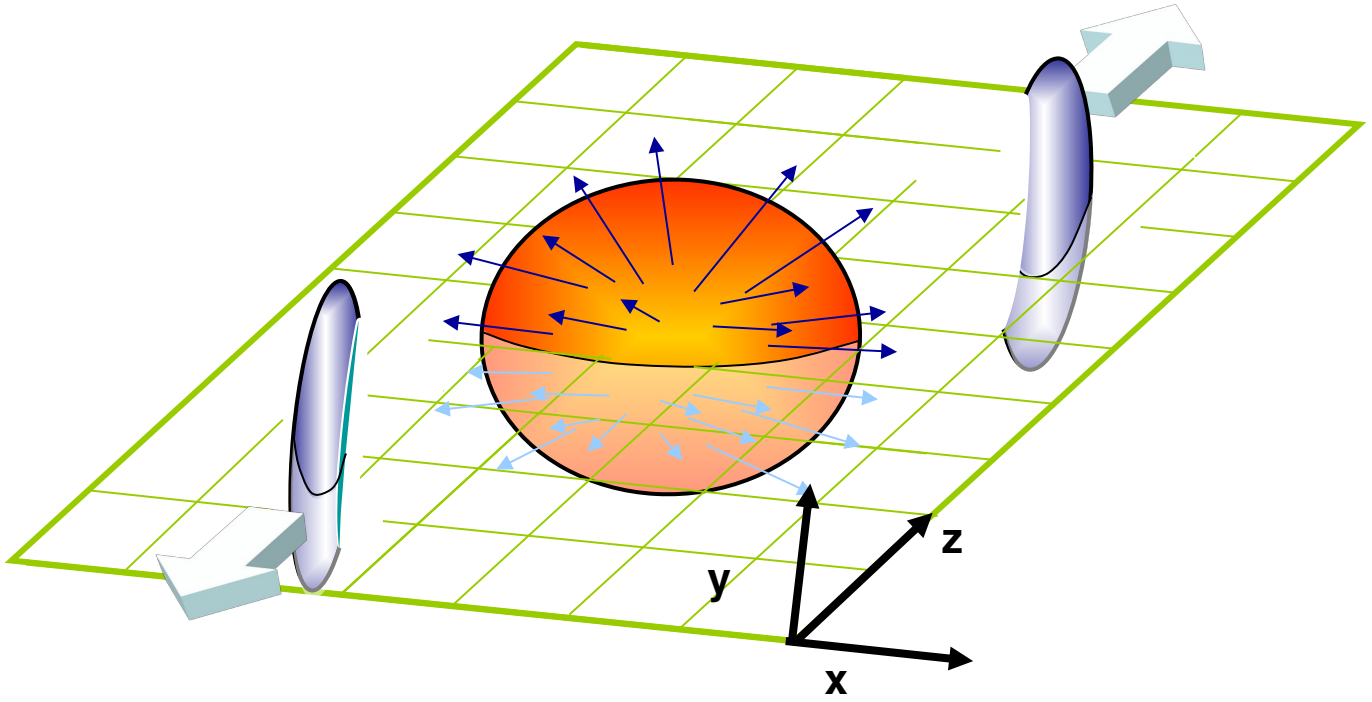
$$p_T = \sqrt{p_x^2 + p_y^2}$$

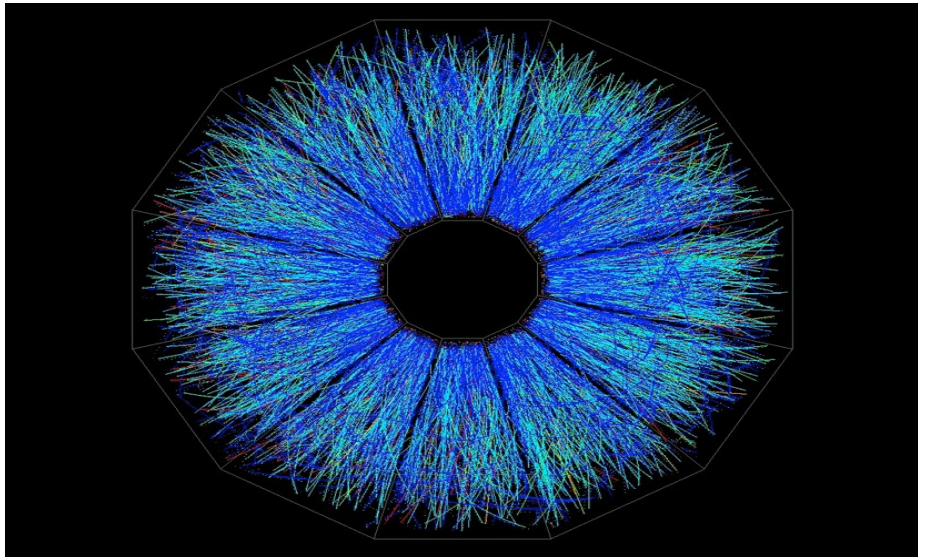
$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

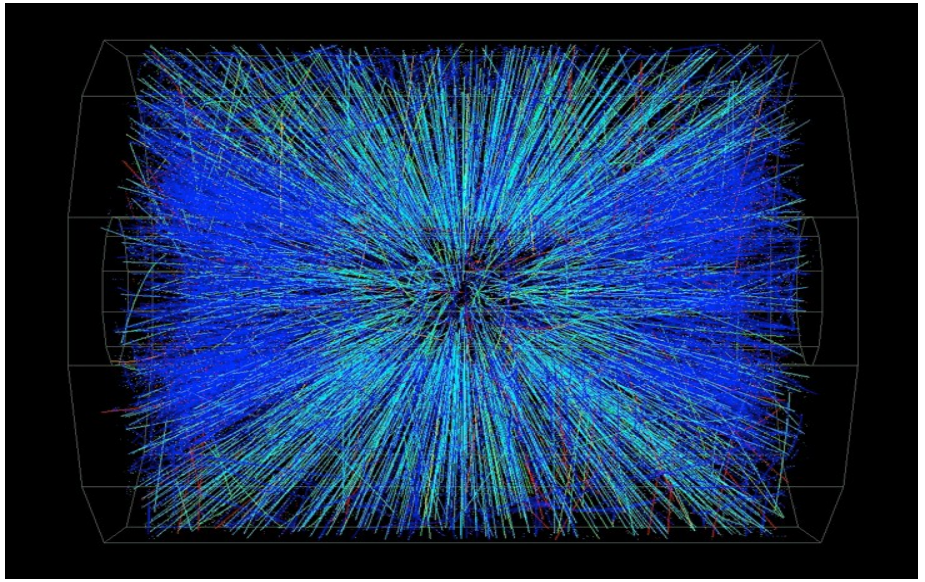
$$\eta = \frac{1}{2}\log\left(\frac{|p| + p_z}{|p| - p_z}\right) = -\log\left[\tan\left(\frac{\theta}{2}\right)\right]$$

- p_T: Lorentz-invariant with respect to acceleration in the beam direction and generated during a collision
- y: not a Lorentz invariant, but an additive transformation law ⇝ y'=y-ycm (ycm – rapidity of the ref system)

HIC: Central Collision

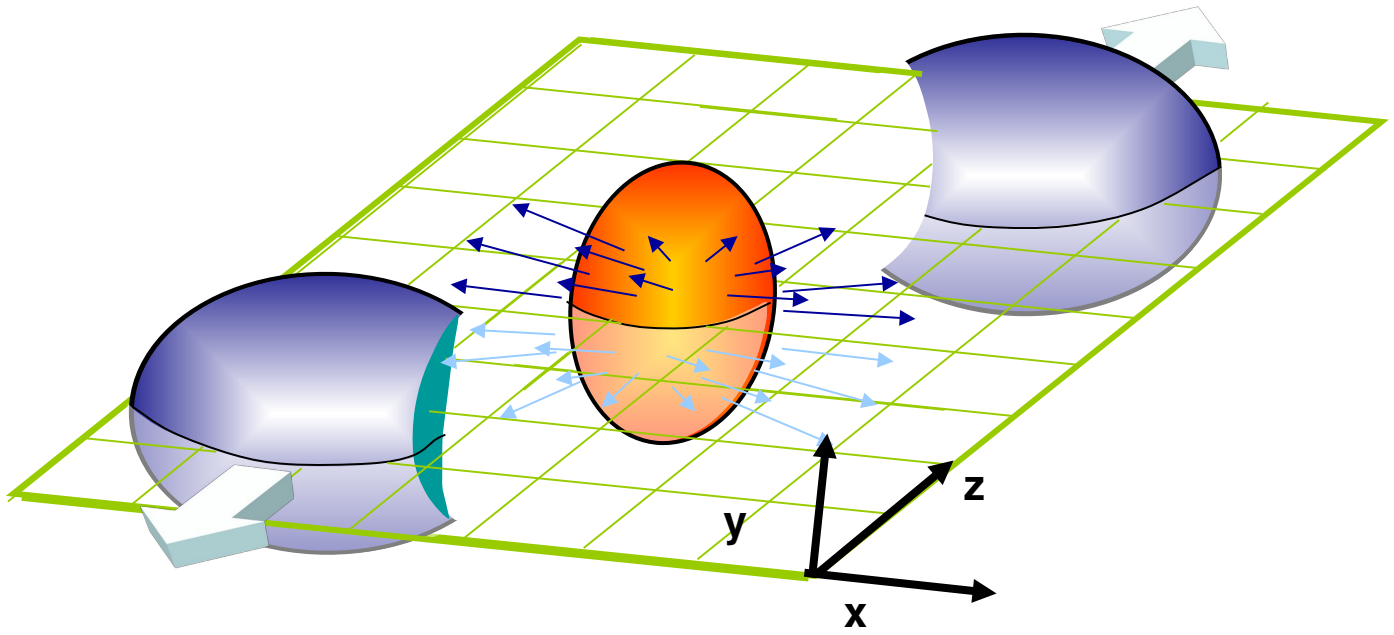


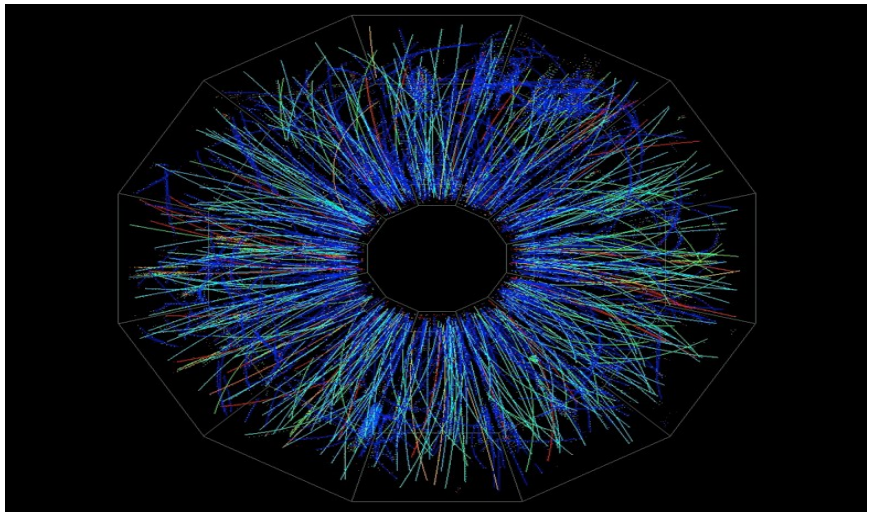


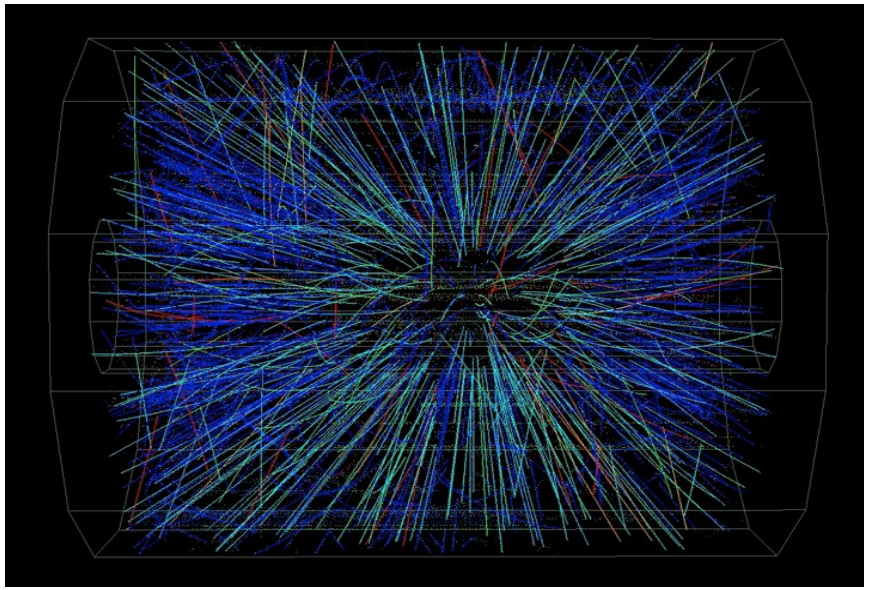


- Small impact parameter **b**
- Overlap region is close to be symmetric in the x-y plane
- Few spectators
- Many produced particles

HIC: Peripheral Collision

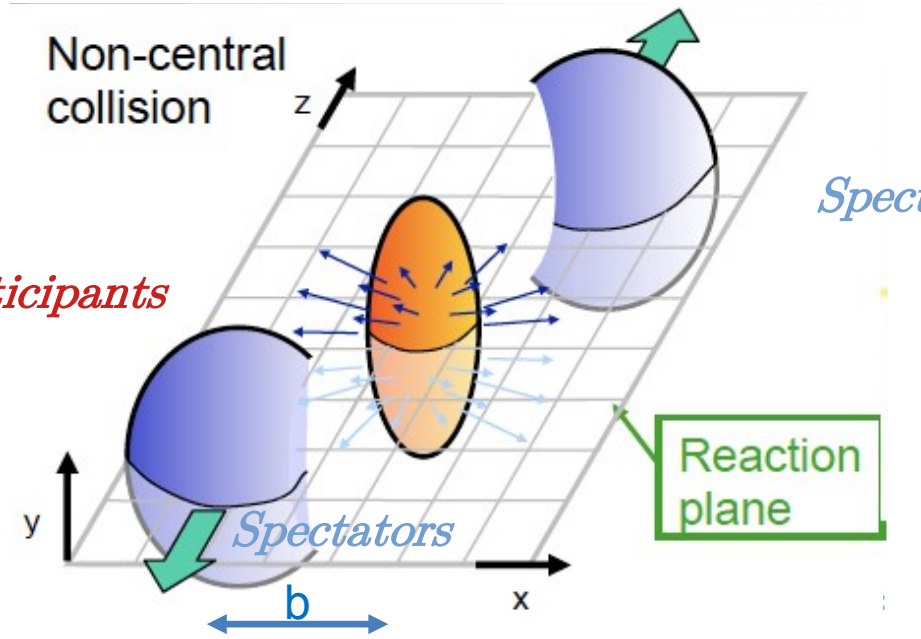


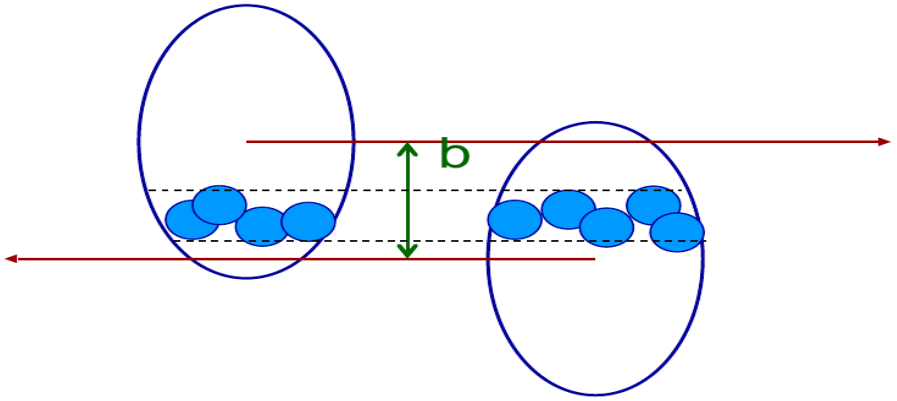




- Large impact parameter **b**
- Overlap region is strongly asymmetric in the x-y plane
- Many spectators
- Few produced particles

Geometry of Heavy-Ion Collisions



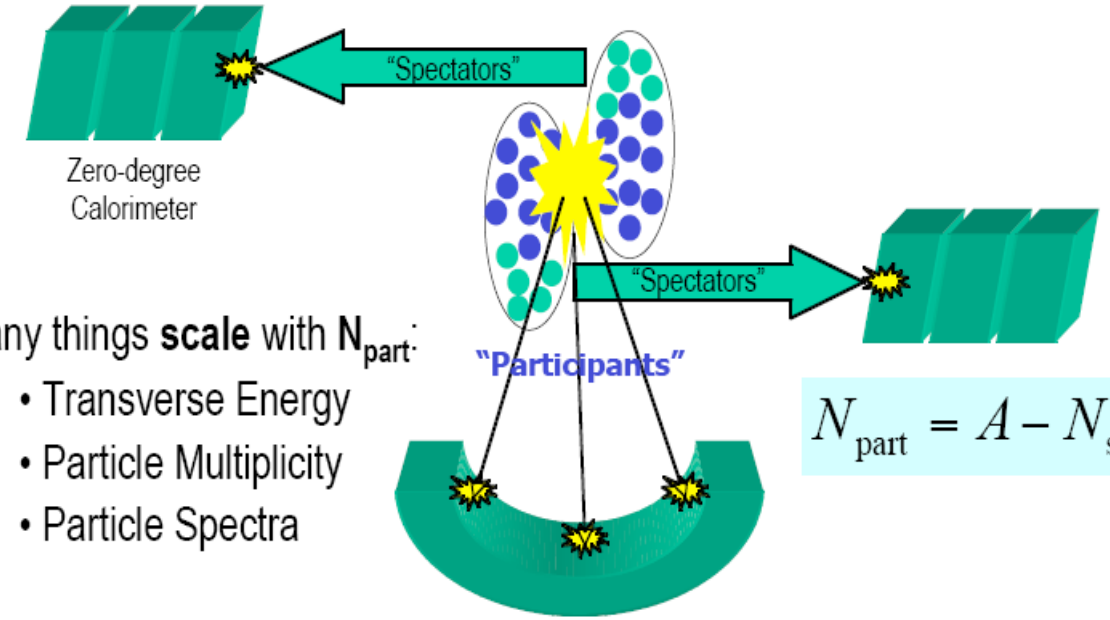


- $N_{participants}$: number of nucleons in the overlap region
- $N_{collisions}$: number of inelastic nucleon-nucleon collisions
- $N_{spectators}$: number of nucleons which do not interact
- Reaction plane: defined by z axis and impact parameter
- Centrality: percentile of the total cross section

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: $\sigma \propto N_{coll}$

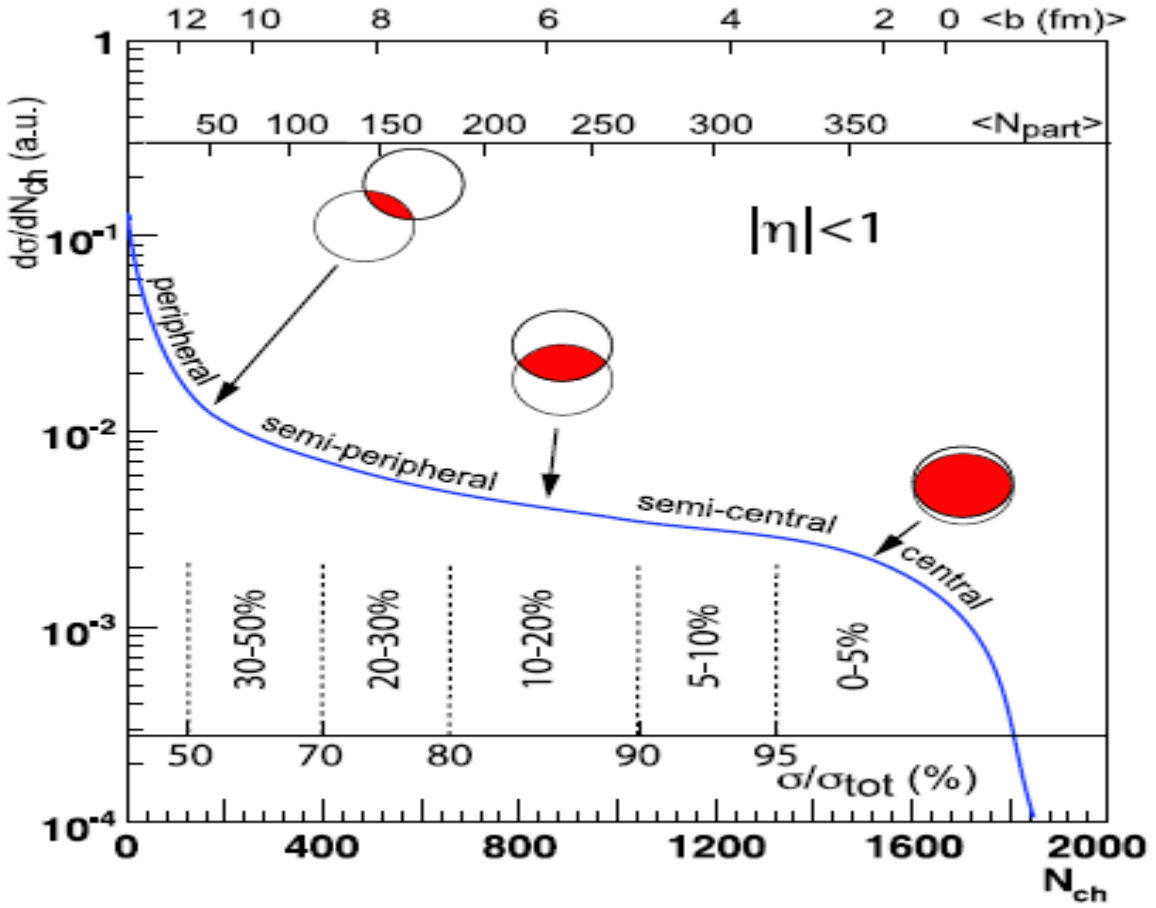
HIC: Centrality of the collision



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

- Transverse Energy
- Particle Multiplicity
- Particle Spectra

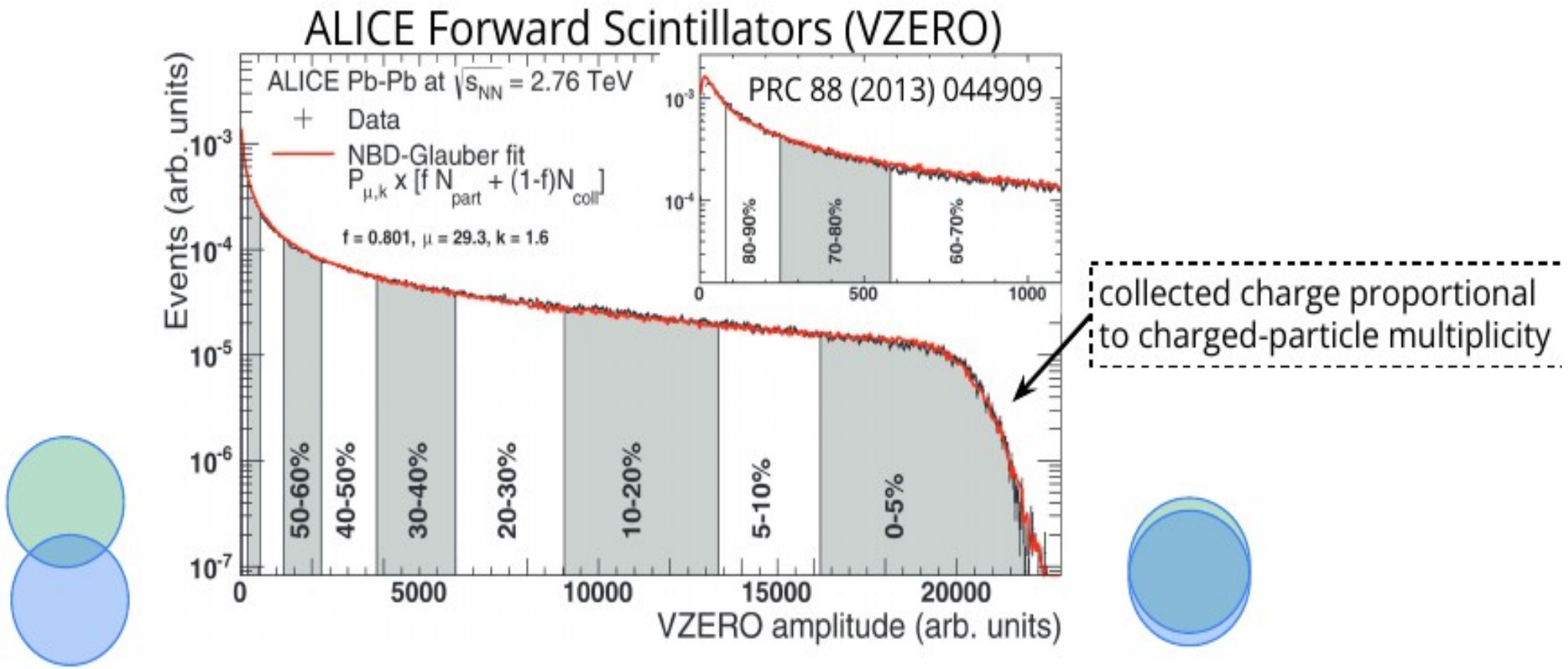
$$N_{\text{part}} = A - N_{\text{spec}}$$



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

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

Centrality of Heavy-Ion Collisions: Experiment



- Centrality measured at forward η to be independent from mid-rapidity measurements
  - Avoid biases/autocorrelations in the measurements
- Fit based on Glauber model provides an excellent description of the detector distribution

High energy HI collisions – the midrapidity region

In **high-energy** collisions (RHIC, LHC), the beams have large rapidity difference before the collision.

After the collision nuclei slow down to lower γ and y, particles are produced with a ''plateau'' in the central rapidity region → **Transparency regime**

The baryon number carried out by the colliding nuclei is outside the centre-of-mass rapidity region, $y_{CM} = 0$.
The **midrapidity region** is the hottest region, where particle production is maximal and the highest temperatures are reached.

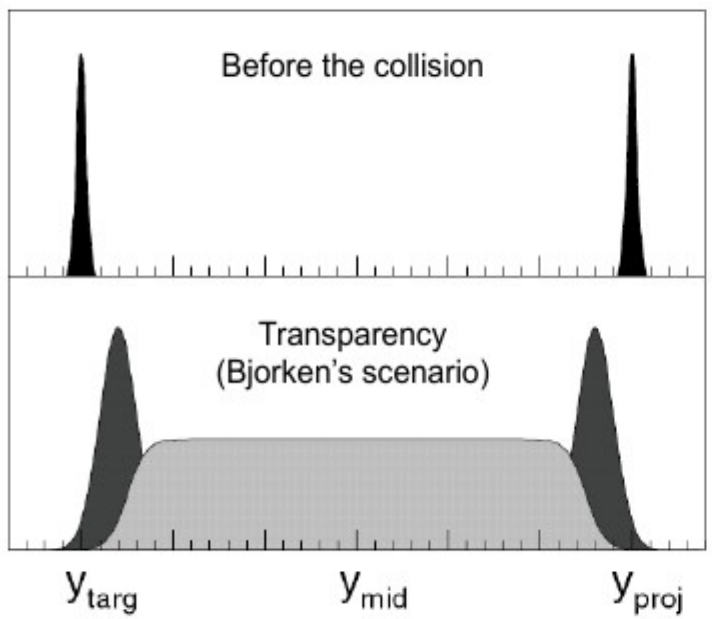
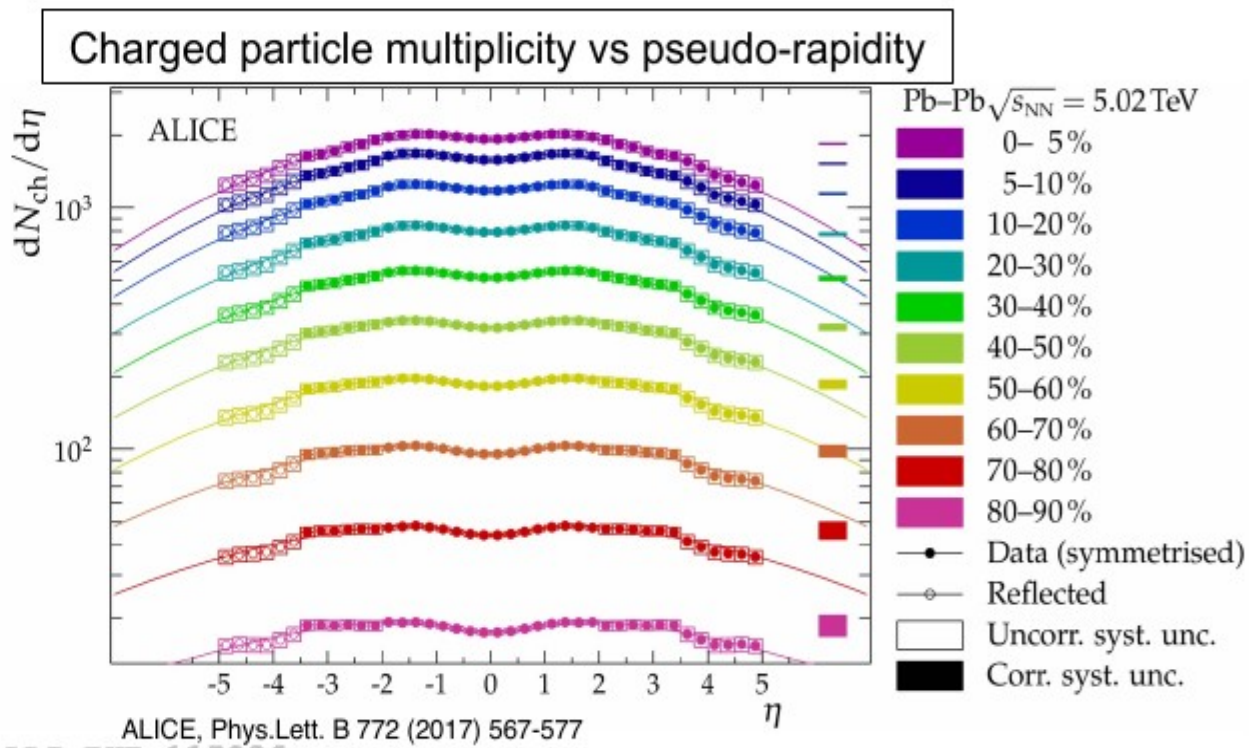


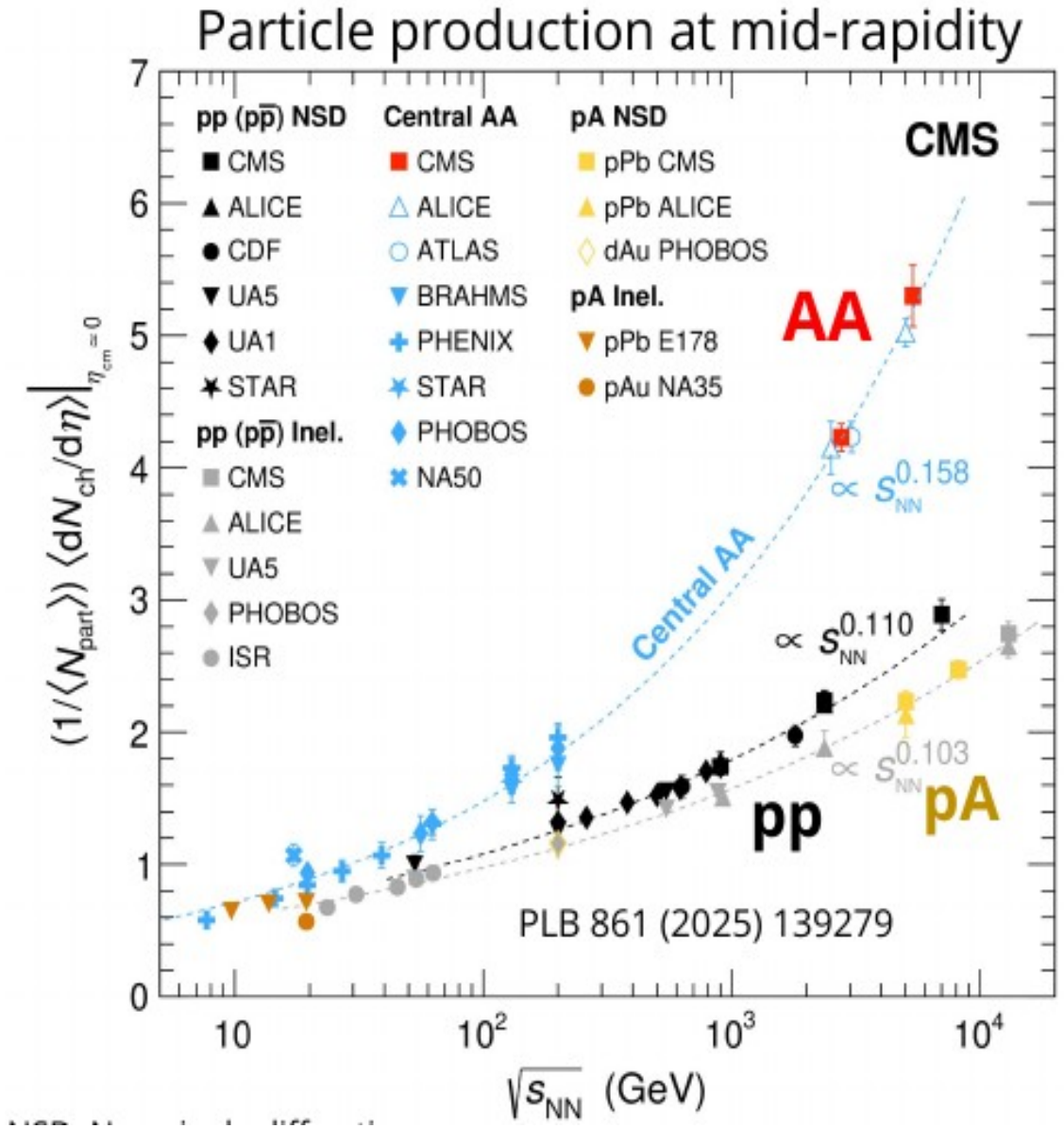
Figure from K. Reygers



ALICE, Phys.Lett. B 772 (2017) 567-577

ALI-PUB-115086

Particle production in heavy-ion collisions



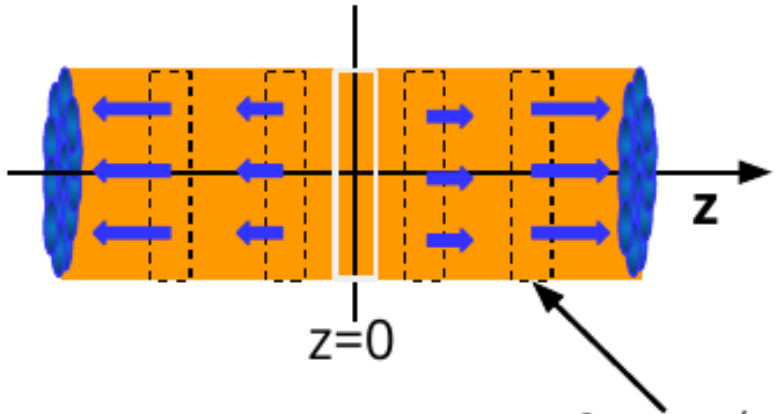
- Higher yield per participant in HIC than in pp
- HIC more efficient in transforming the initial energy into particles
- Particle production in HIC increased by > x2 from RHIC (200 GeV) to LHC (5 TeV) energies
- Particle multiplicity can be used to constrain the energy density created in HIC

Bjorken's model

James Bjorken,
PRD 27 (1983) 140

Consider nuclei as relativistic pancakes:

- Beam remnants continue at forward y
- Mid-y dominated by produced particles



Main assumptions of Bjorken's model:

- Homogenous expansion of cylinder in z direction (1D ideal hydrodynamics)
- Particles produced at formation time τ_0 in their rest frame (proper time)

$$\epsilon = \frac{E}{V} = \frac{1}{A}\frac{dE}{dz}\Big|_{z=0} = \frac{1}{A}\frac{dy}{dz}\Big|_{z=0}\frac{dE}{dy}\Big|_{y=0} = \frac{1}{A\cdot\tau_0}\frac{dE}{dy}\Big|_{y=0}$$

Transverse area = πR^2

$$\sinh(y) = \beta\gamma = \frac{z}{t}\frac{t}{\tau_0} = \frac{z}{\tau_0}$$

Estimating the initial energy density

Bjorken's formula:

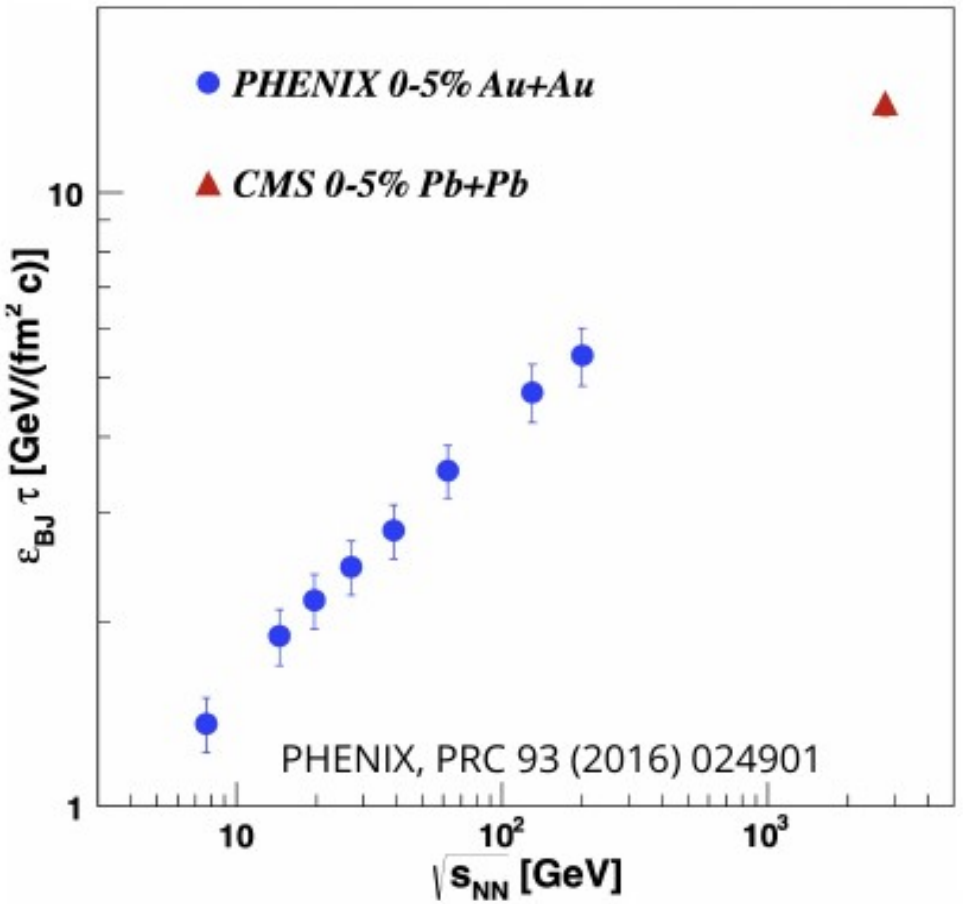
$$\epsilon = \frac{1}{A \cdot \tau_0} \frac{dE}{dy}\bigg|_{y=0} = \frac{1}{A \cdot \tau_0} J \frac{dE}{d\eta}\bigg|_{\eta=0}$$

Jacobian

Considering for PbPb collisions at 2.76 TeV:

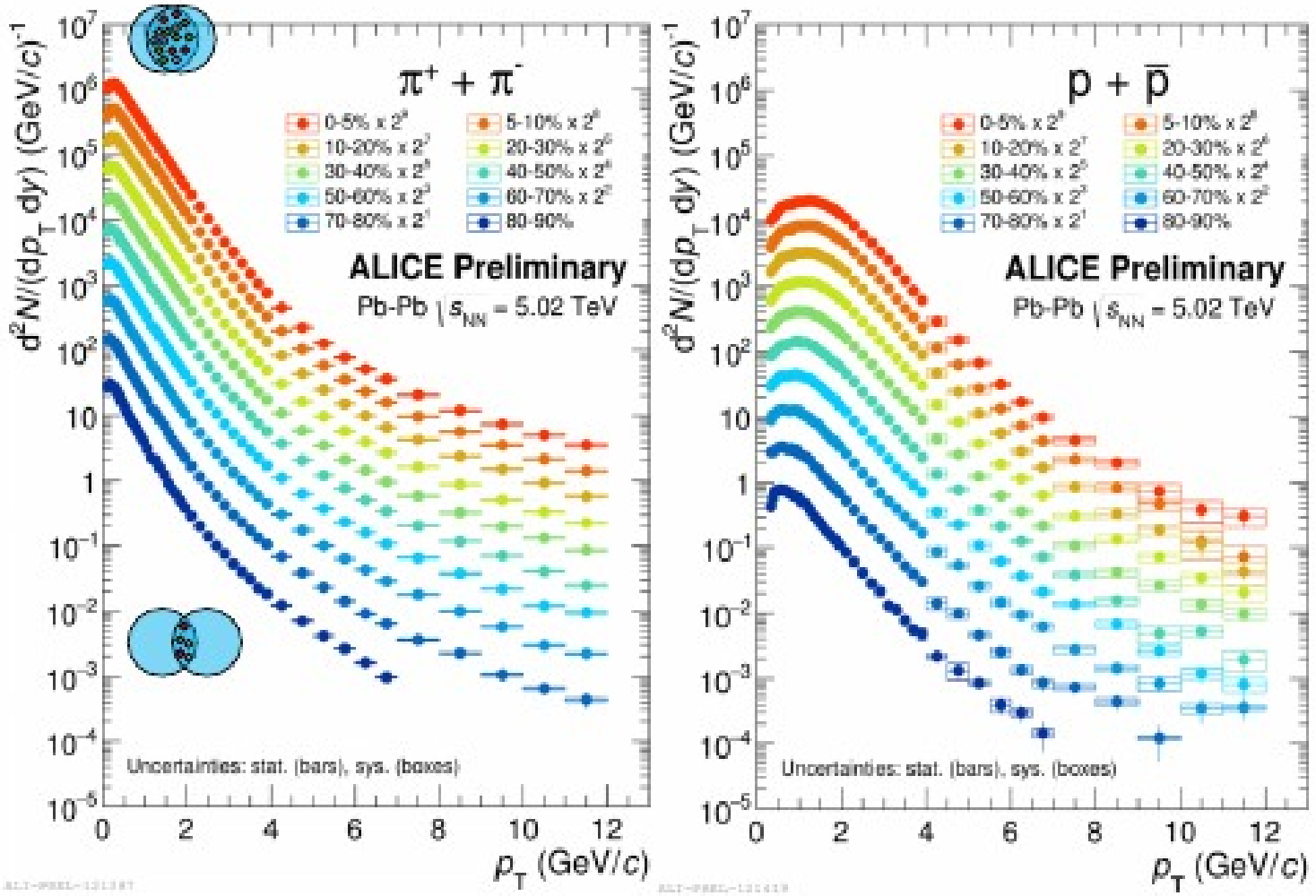
- $A = \pi R^2_{Pb} = \pi(6.7\ \text{fm})^2 \approx 141\ \text{fm}^2$
- $\tau_0 \sim 1$ fm , $J \approx 1.1$
- $dE_T/d\eta\,|_{y=0} \approx 2$ TeV

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

p_T-spectra of identified particles

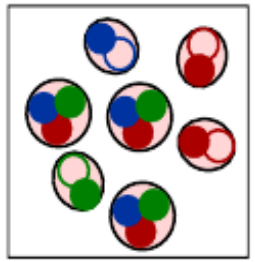


1. Identify particle in the detector (pion, kaon, proton, Lambda, Xi, Omega, anti-deuteron…)
2. Fill p_T-spectrum
3. Interpolate unmeasured region at low p_T (at high p_T negligible)
4. Integrate:

$$\frac{dN}{dy} = \int \frac{d^3N}{dp_T dy d\varphi}\, d\varphi dp_T$$

Thermal statistical hadronization

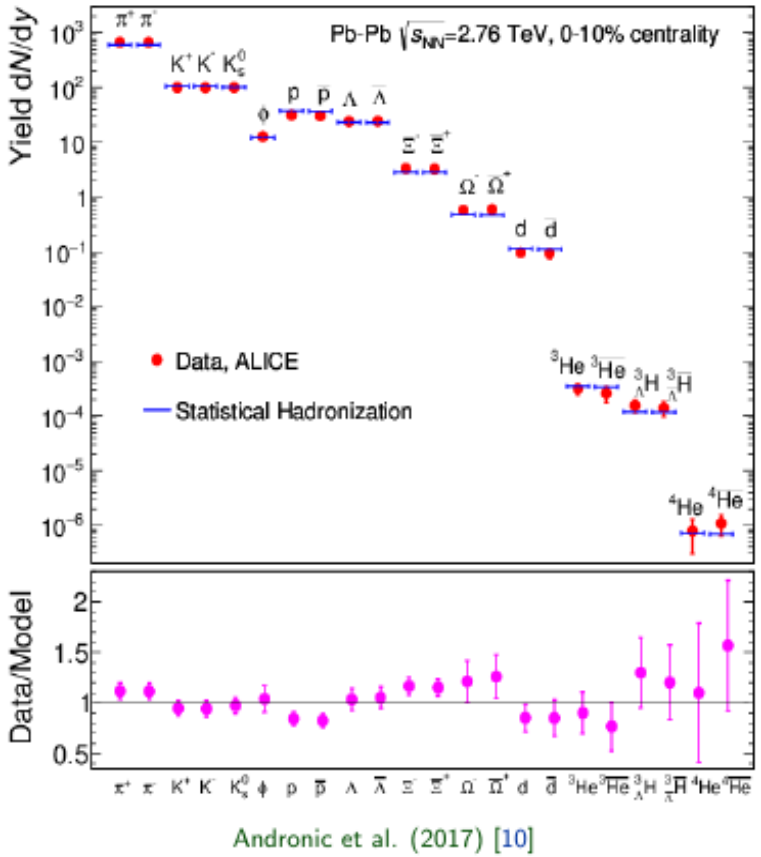
Observed particle yields show remarkable thermal ordering



- Number of hadrons in volume V at T, μ

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

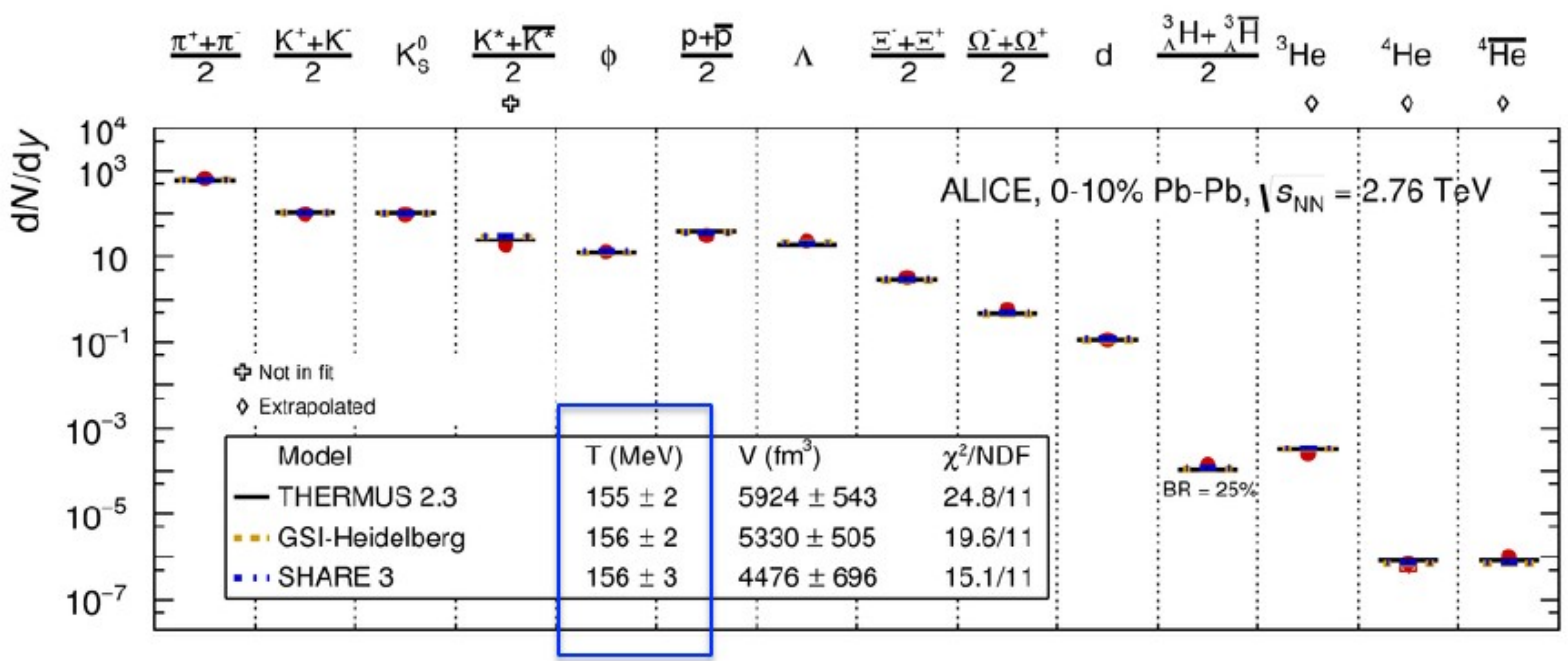
- Compare to measured yields (after decays).
- At LHC light and strange hadron and even light (anti)-nuclei are well fitted by $T_{\text{chem}} \approx 155\,\text{MeV}, \mu_B \approx 0$.
- $\Longrightarrow$ particle production as if from completely thermalized fireball (including strangeness).

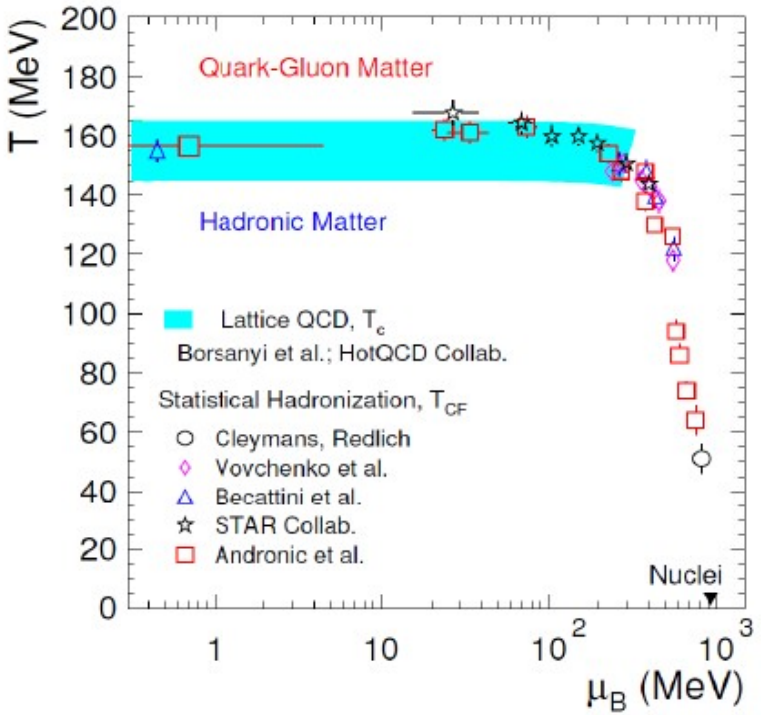


Andronic et al. (2017) [10]

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

Chemical freeze-out temperature



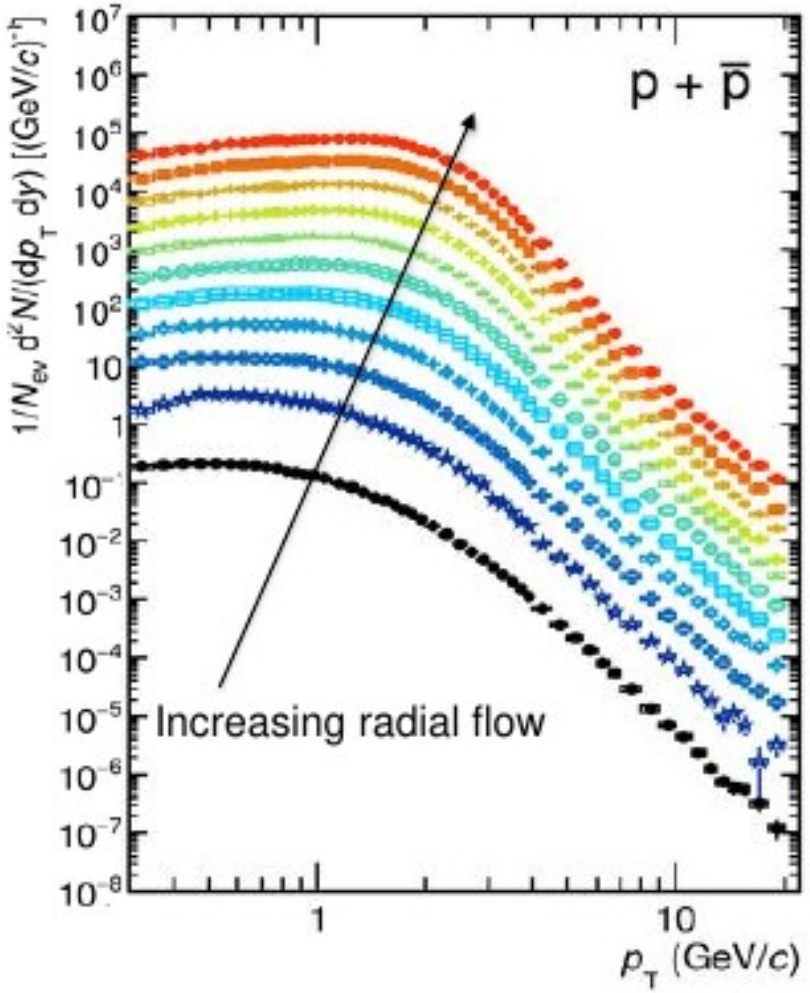


Production of (most) light-flavour hadrons (and anti-nuclei) is described (χ^2/ndf ~ 2) by thermal models with a **single chemical freeze-out** temperature, **$T_{ch} \approx 156$ MeV**

→ Approaches the critical temperature roof from lattice QCD: **limiting temperature** for hadrons!

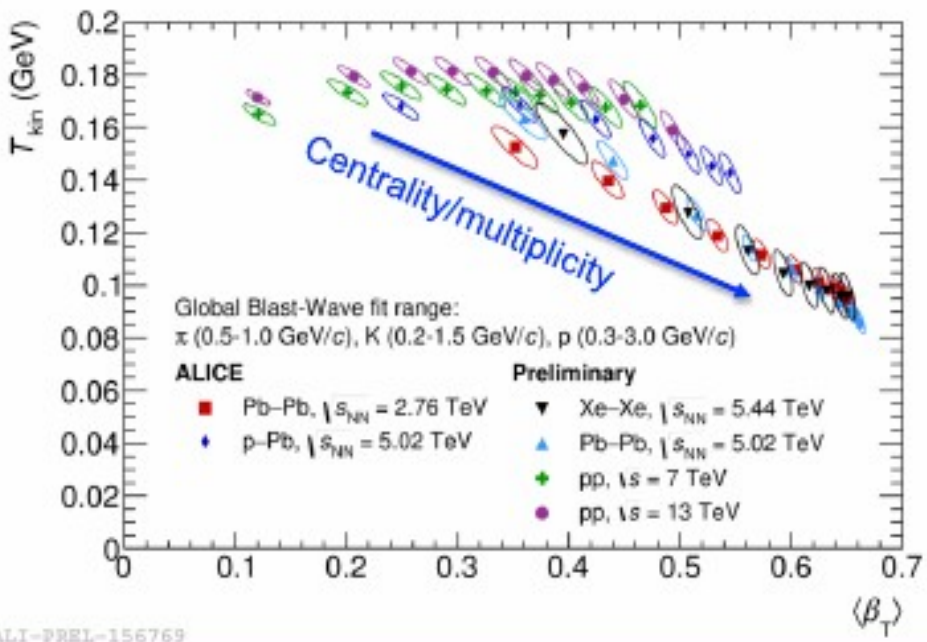
→ the success of the model in fitting yields over 10 orders of magnitude supports the picture of a system in **local thermodynamical equilibrium**

Hydrodynamics at play: radial flow (2/2)



At low p_T, the radial flow "pushes" particles to higher momenta
→ spectra get "harder" for more central collisions
→ mass dependence

A simplified hydrodynamical model, the Boltzmann-Gibbs blast-wave model is used to **quantify radial flow and the kinetic freeze-out temperature.**

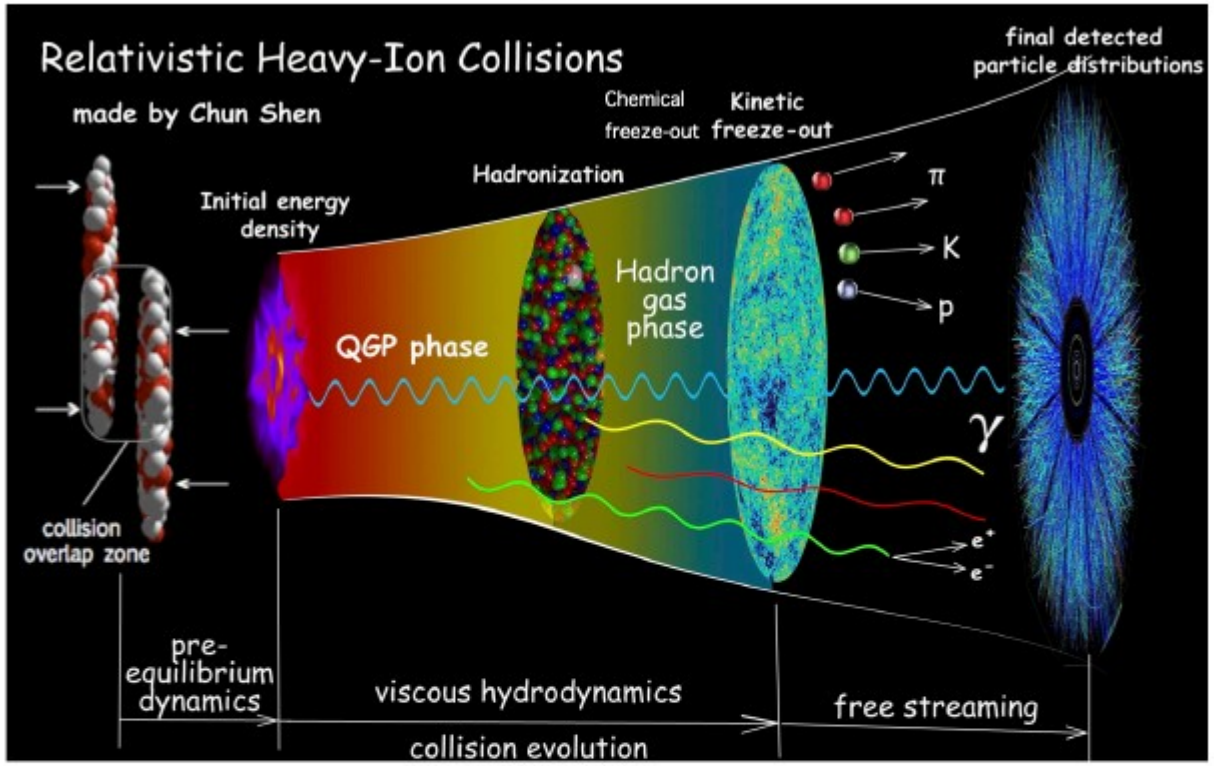


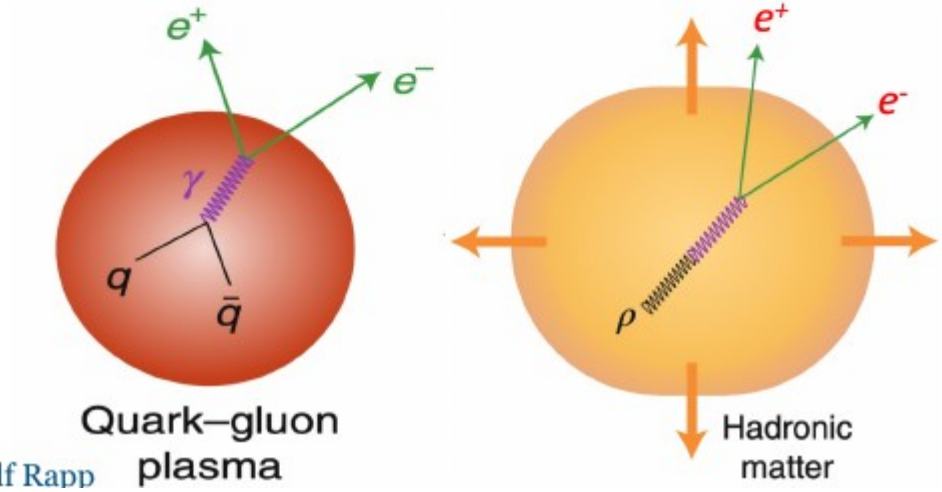
More central (higher multiplicity) events have lower T_{kin} and higher flow velocity

T_{kin} ~ 100-140 MeV

ALI-PREL-156769

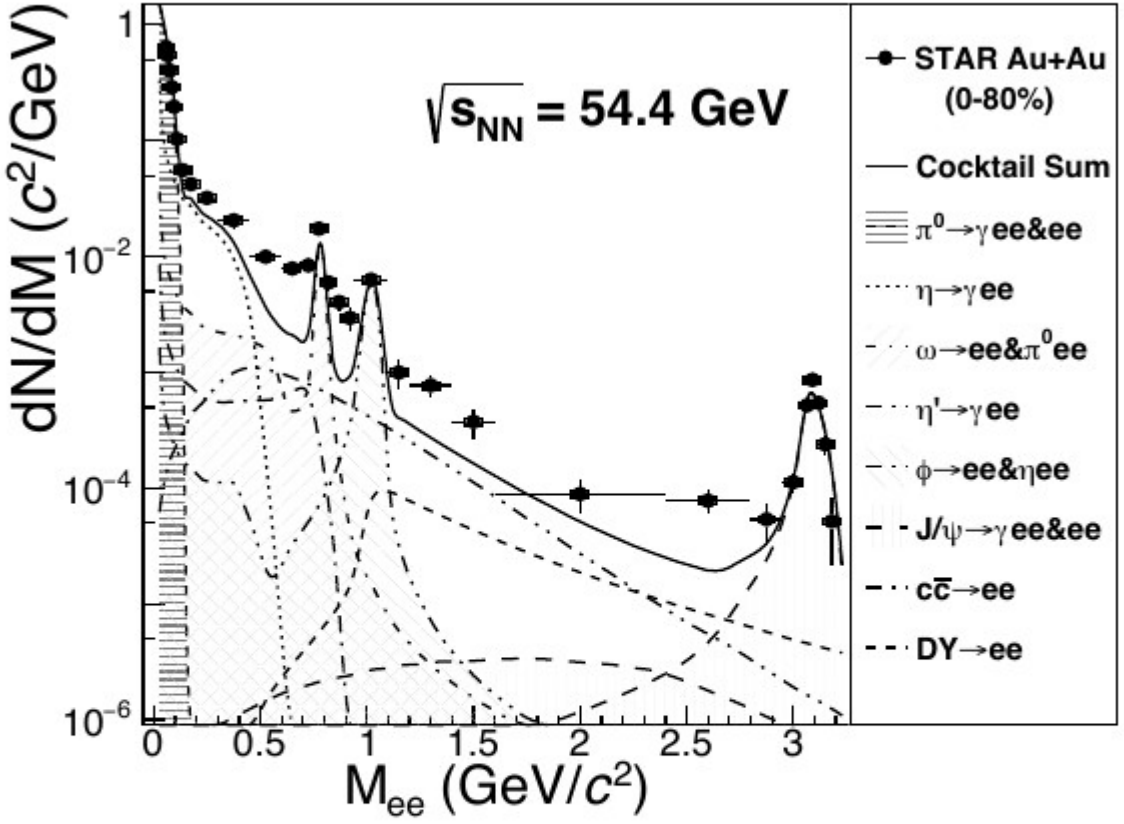
Electromagnetic Probes





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

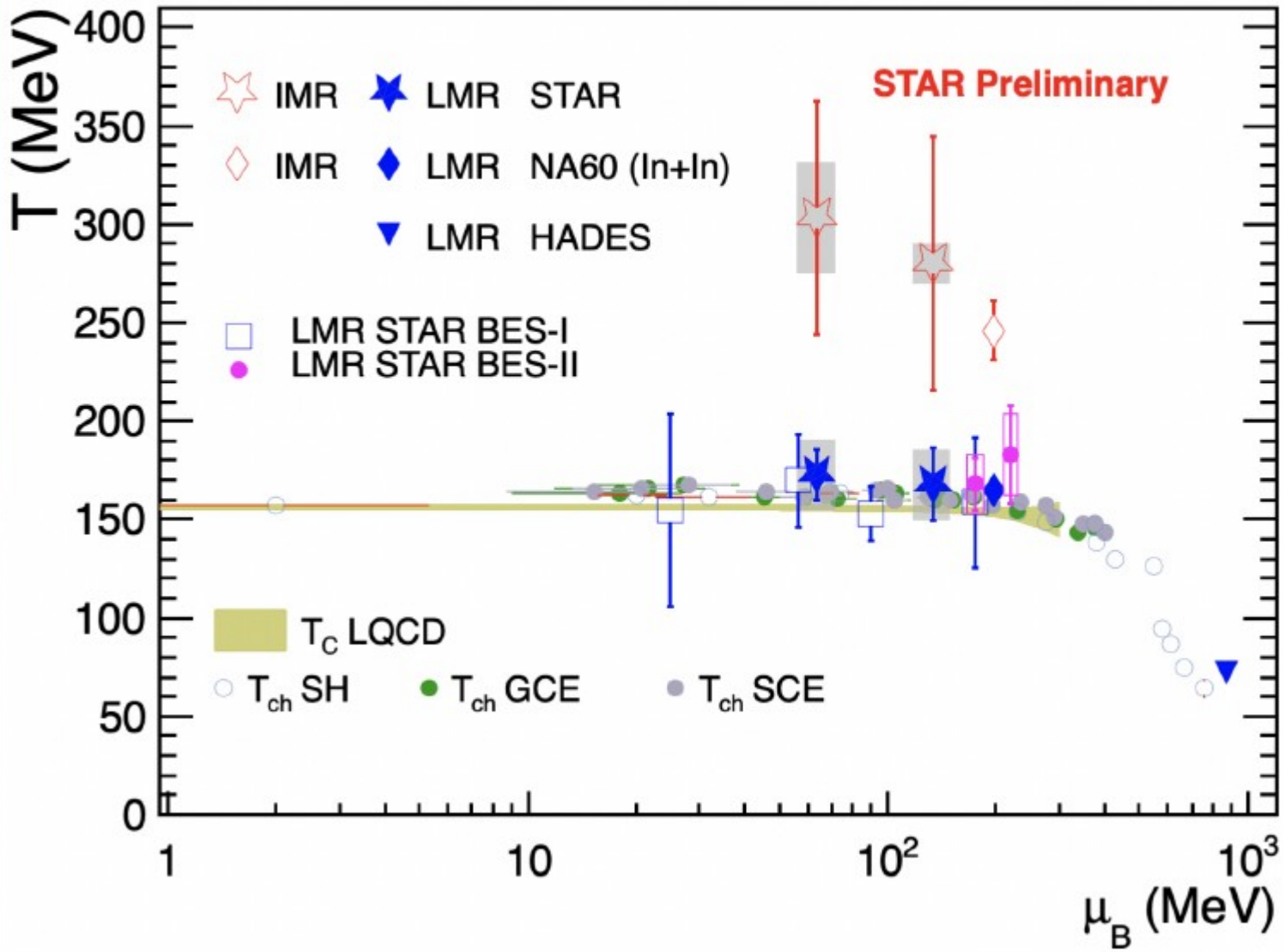
Nature Communications
16, 9098 (2025)

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

Predominantly emitted from hadronic phase, around phase transition

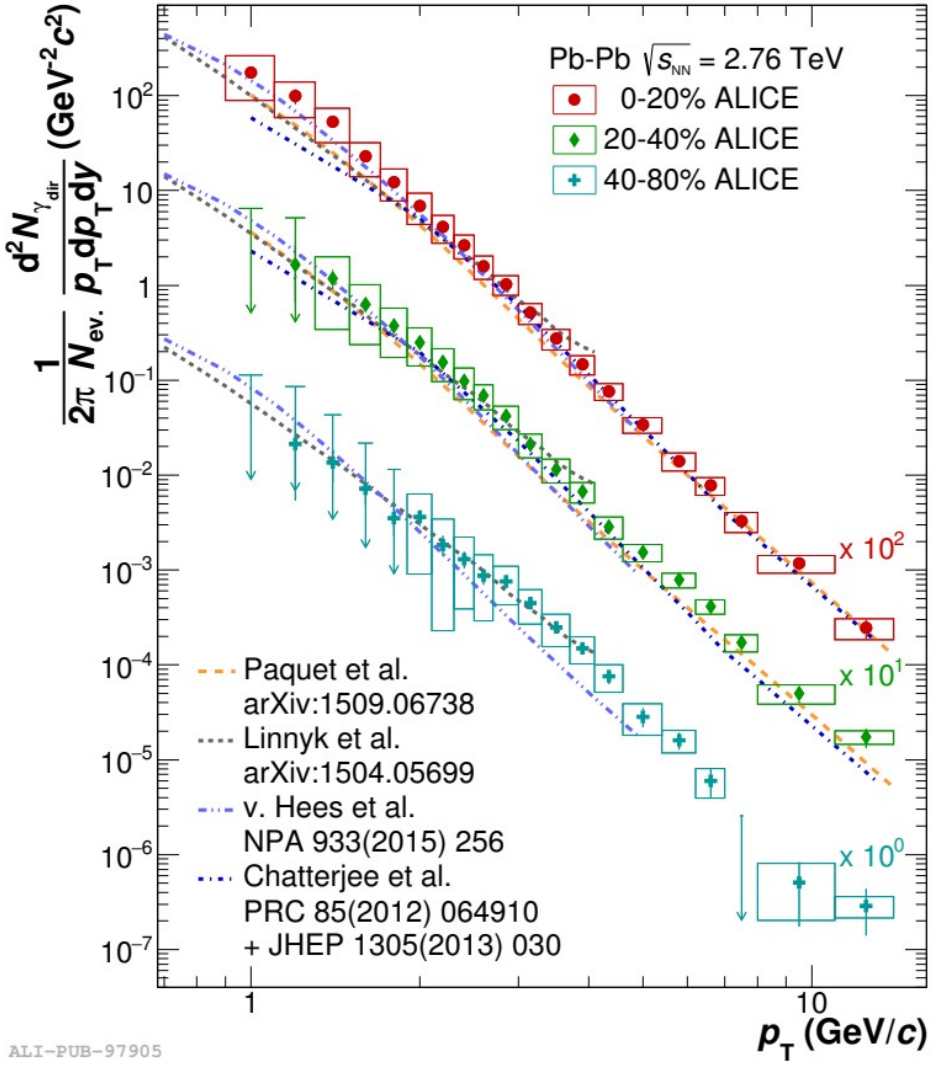
- **Thermal dileptons in IMR**
  - T is higher than T_C

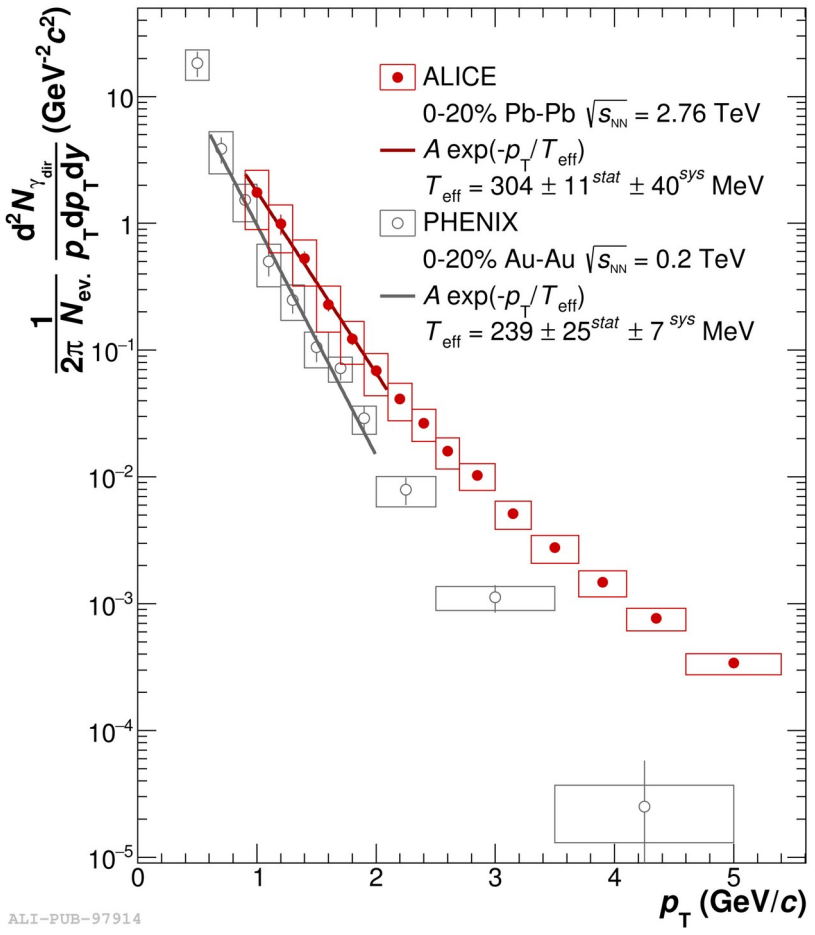
Predominantly emitted from QGP phase



Direct photons – black body radiation from the QGP

The challenging measurement of direct (subtract decay such as $\pi^0 \rightarrow \gamma\gamma$) photons gives access to the initial temperature of the system created in heavy-ion collisions.



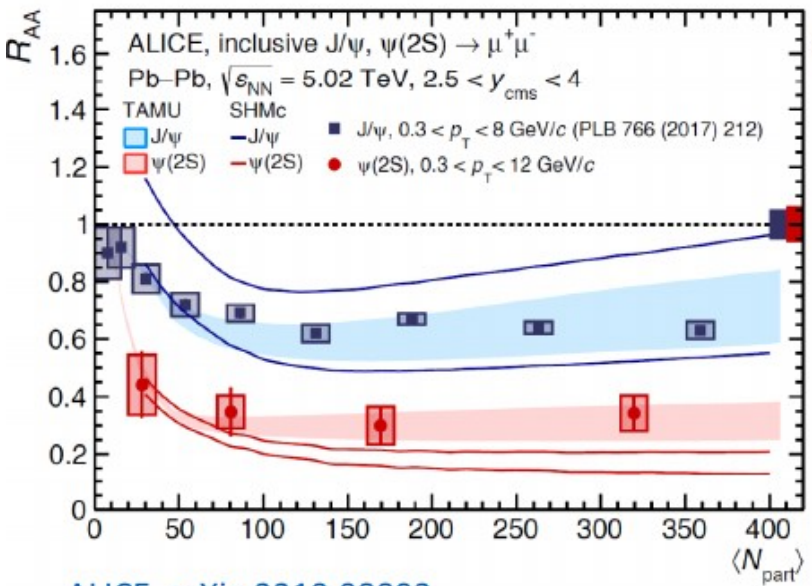


[Phys. Lett. B 754 (2016) 235-248]

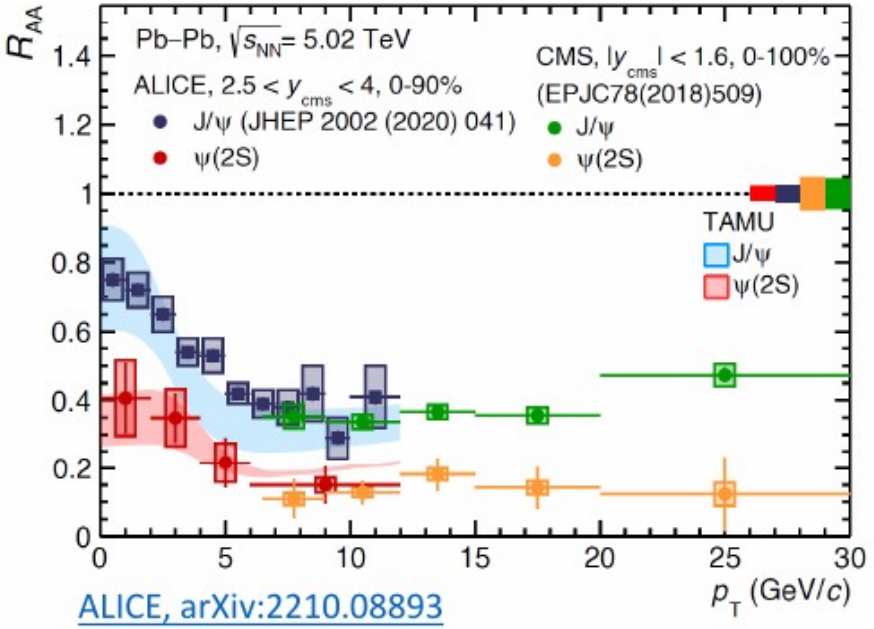
T_{eff} = 304 ± 11 ± 40 MeV

- Effective temperature of approx. 300 MeV is observed as a result of a high initial temperature and the blue-shift due to the radial expansion of the system.

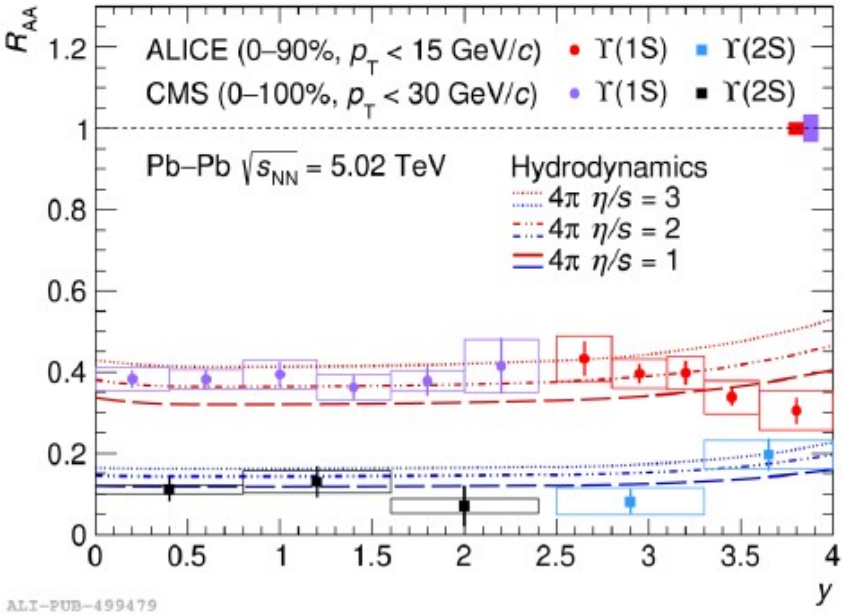
Excited quarkonium states



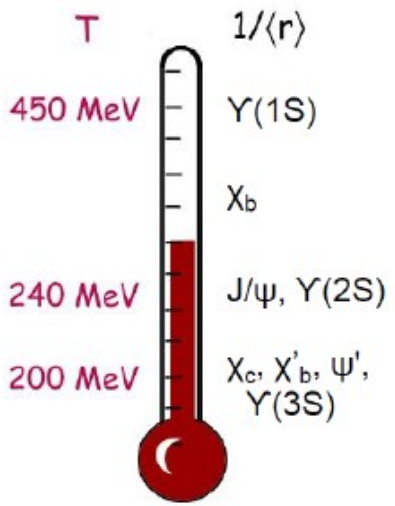
ALICE, arXiv:2210.08893



ALICE, arXiv:2210.08893

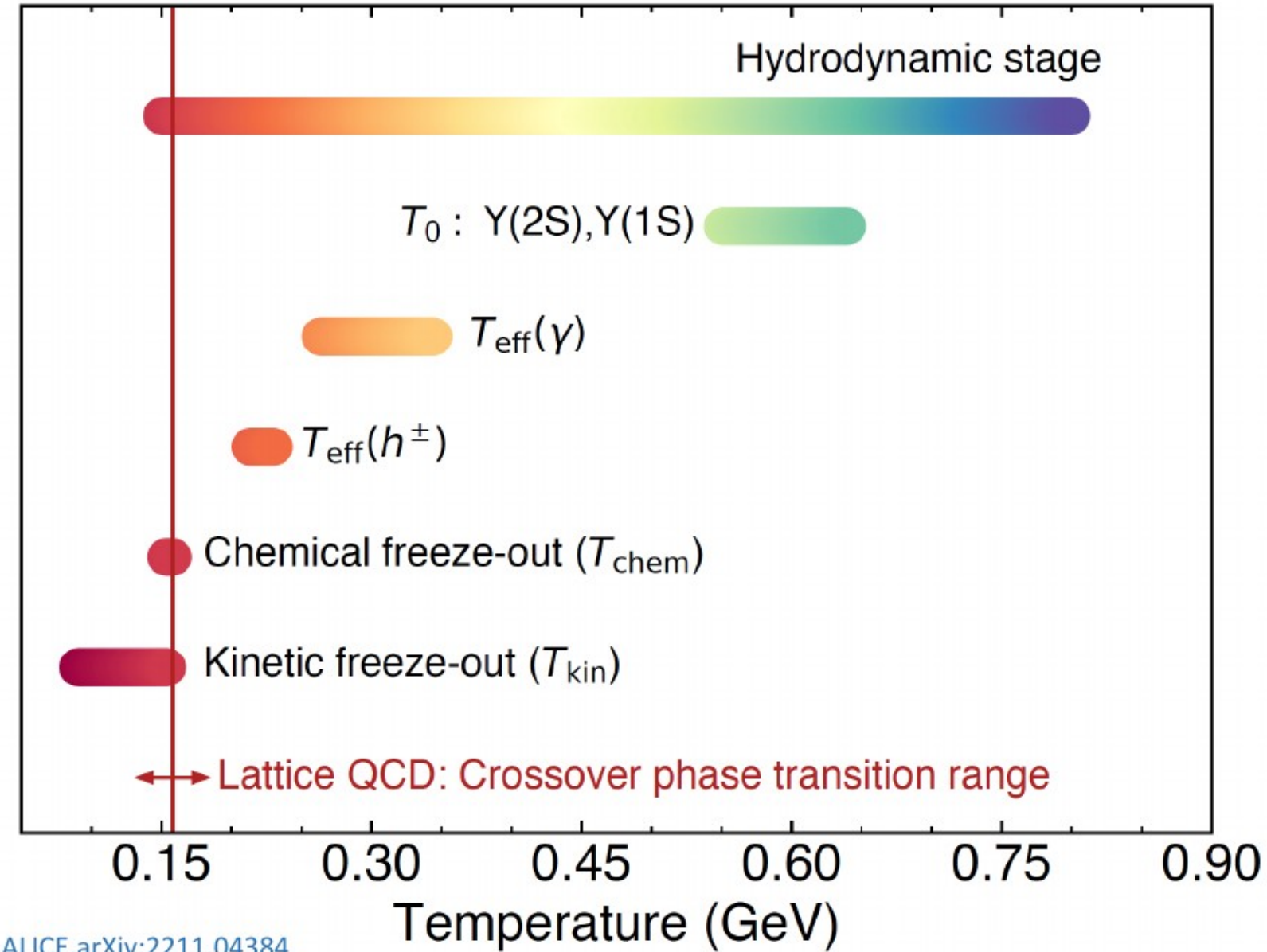


ALICE, PLB 822 (2021) 136579



- Different states have different binding energies. Loosely bound states melt first!
- Sequential suppression of individual states provides a "thermometer" of the QGP
- Charmonium: sequential suppression + regeneration effects
- Bottomonium: sequential suppression

Temperature scales



Many observables imply temperatures far greater than T_c

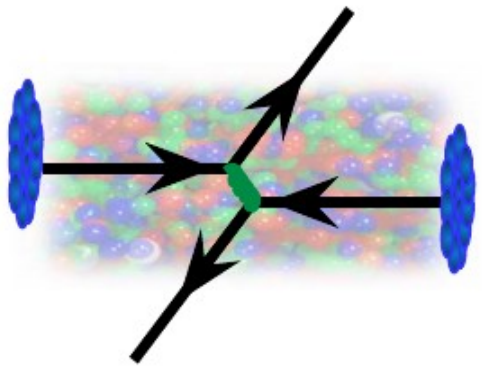
- Sequential melting of quarkonium states
- Effective thermal photon $T \sim 2T_c$
- Chemical freeze-out ~ T_c

ALICE,arXiv:2211.04384

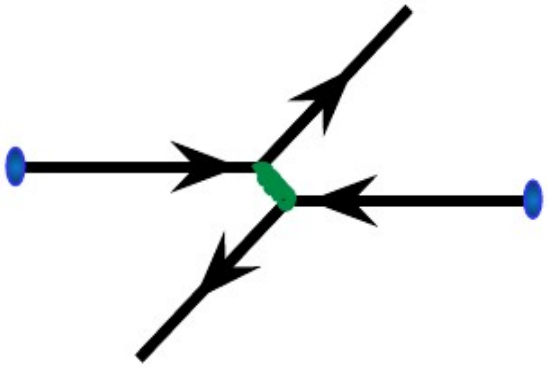
Nuclear modification factor: R_{AA}

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

Heavy ion (AA) collisions



pp collisions



Nuclear modification factor:

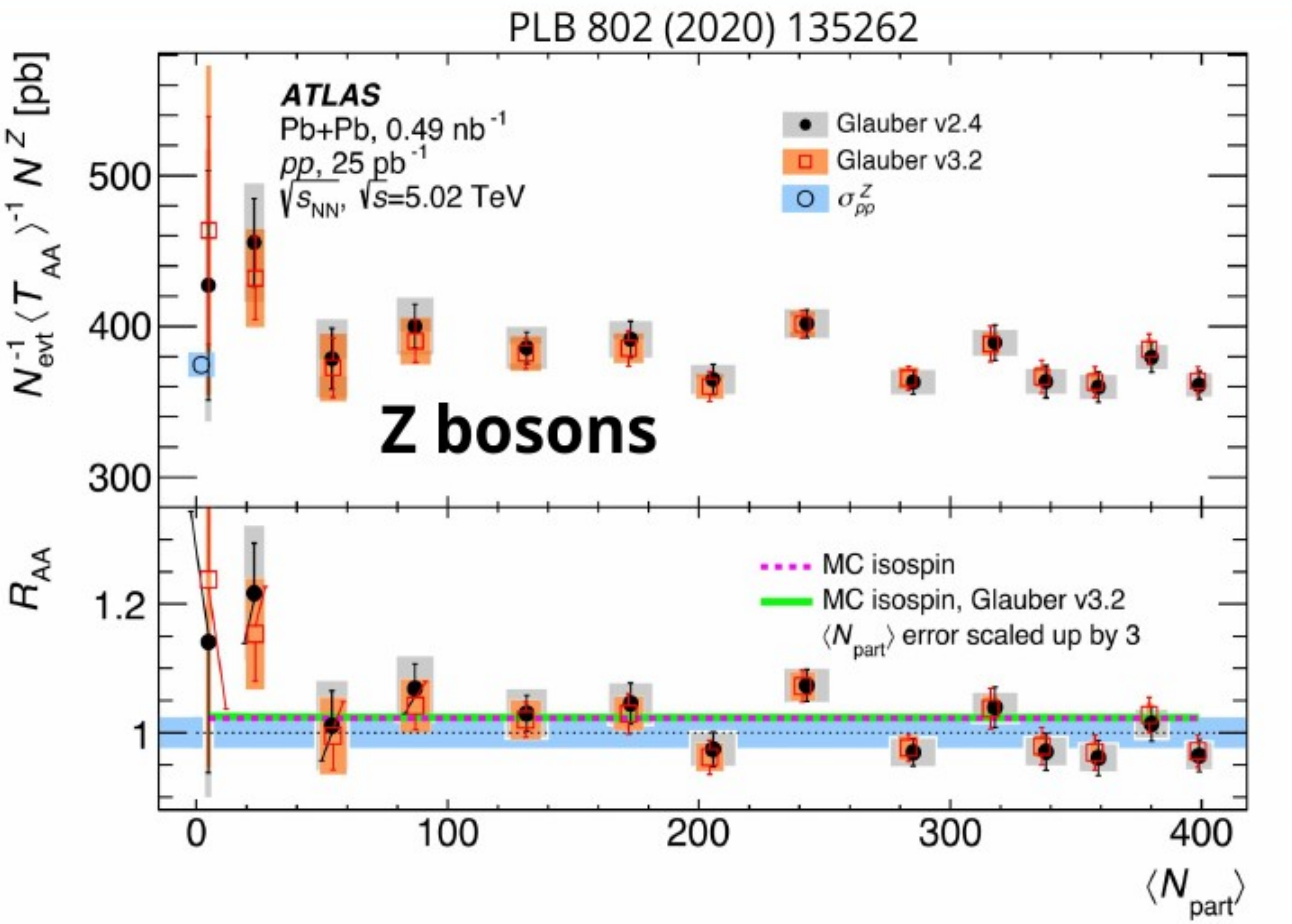
$$R_{\mathrm{AA}} = \frac{\sigma_{pp}^{\mathrm{inel}}}{N_{\mathrm{coll}}} \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}{\mathrm{d}^2 \sigma_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} \sim \frac{\text{"QCD medium"}}{\text{"QCD vacuum"}}$$

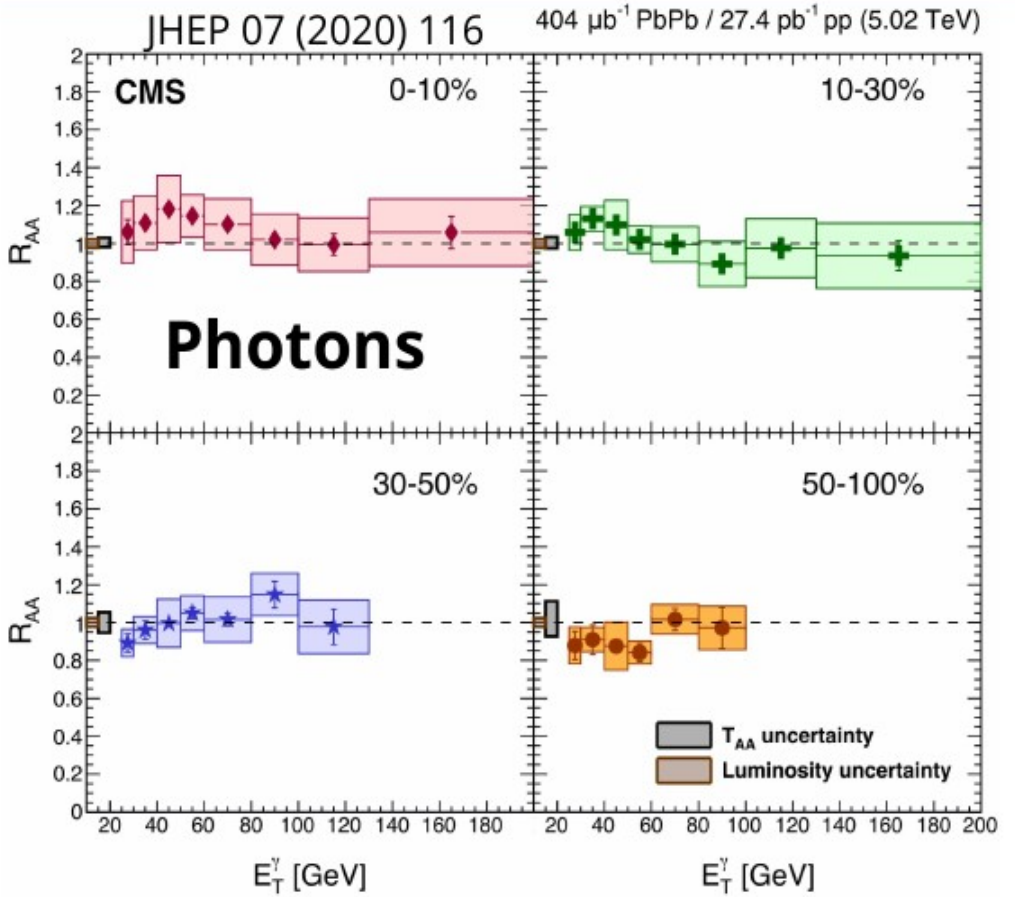
- $R_{AA} > 1$ (enhancement)
- $R_{AA} = 1$ (no medium effects)
- $R_{AA} < 1$ (suppression)

N_{coll} → Averaged number of binary scattering

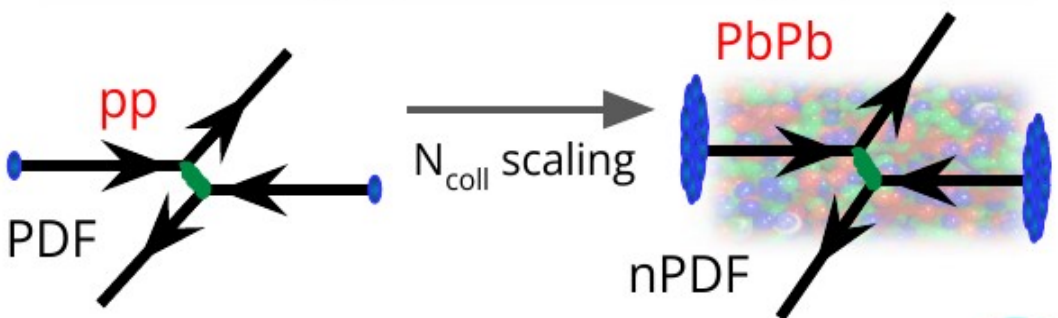
How can we validate the Glauber model calculations?

R_{AA} of electroweak probes

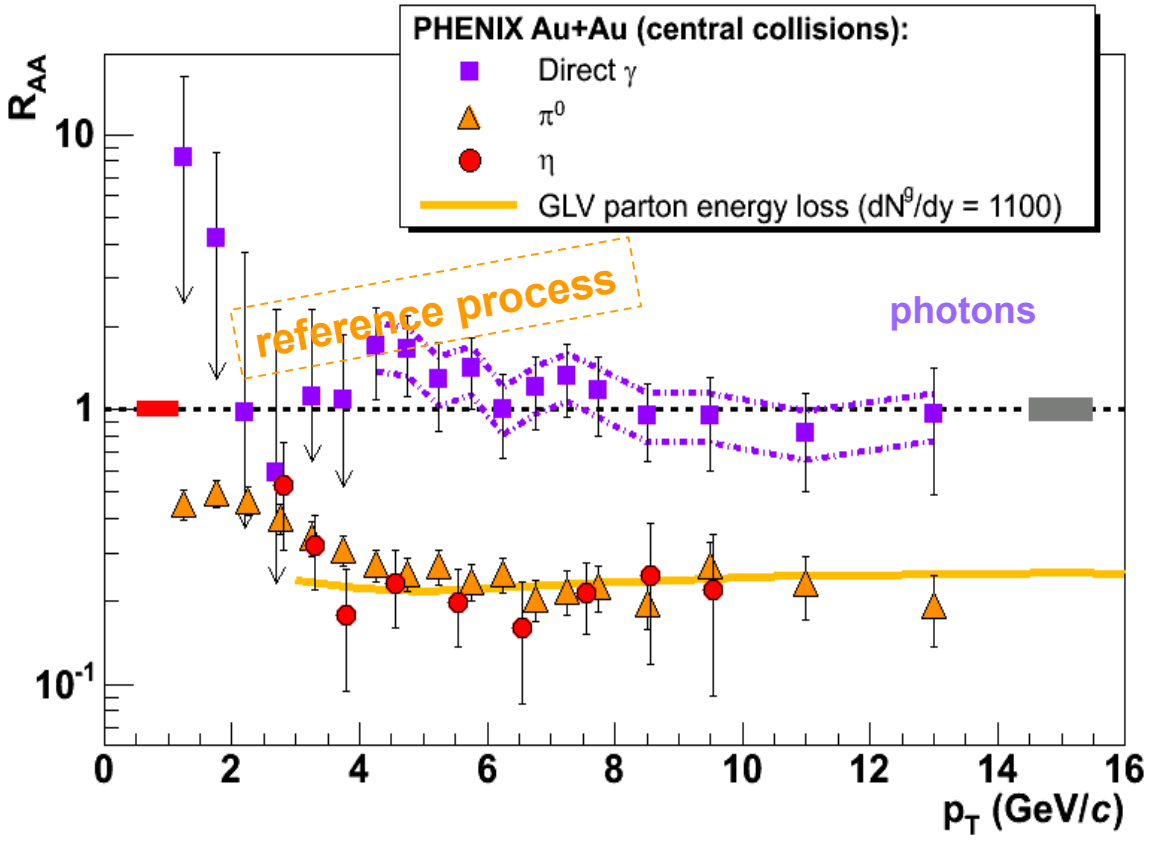




- Electroweak (colorless) probes are unmodified
- Confirm N_{coll} scaling of hard scatterings



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

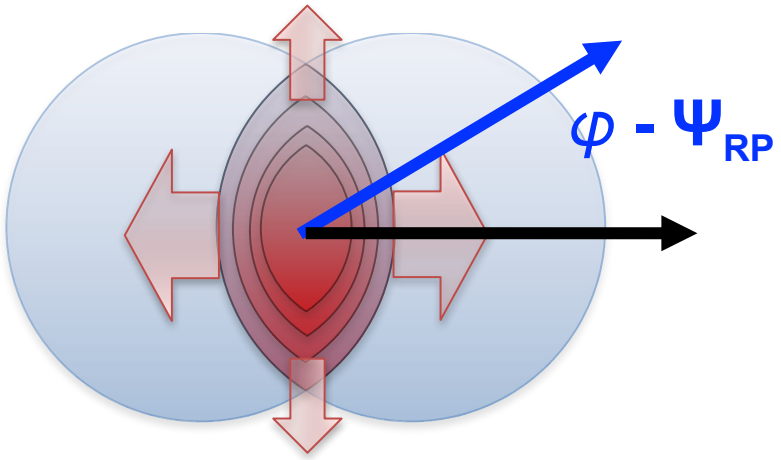
→ the medium is transparent to the passage of partons

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

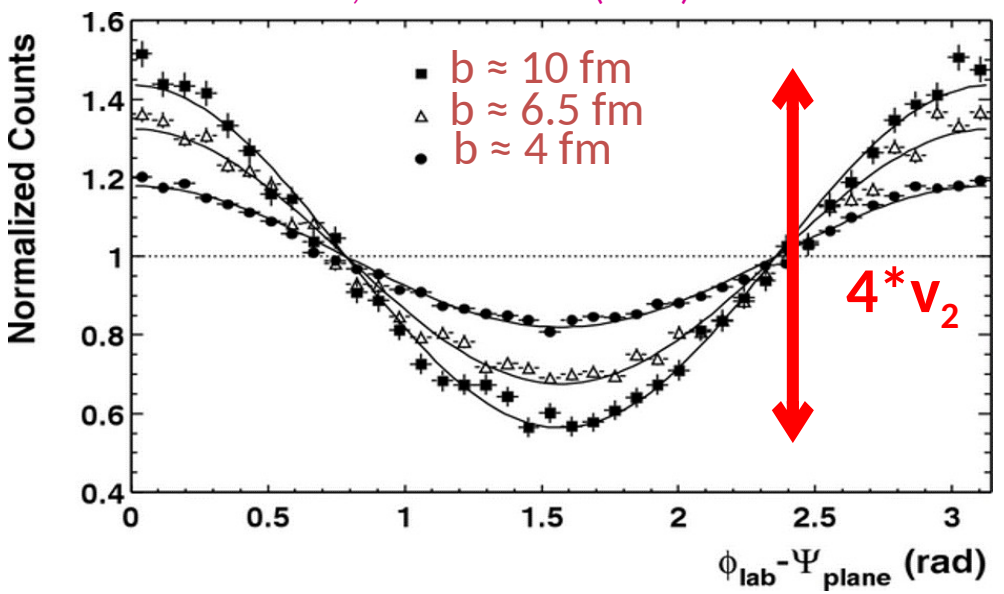
The **meson yield** in central Au-Au is 5 times lower than expected from pp collisions

the **direct photons** are not affected by the dense medium

Anisotropic flow of particles at HIC



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



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

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

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

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

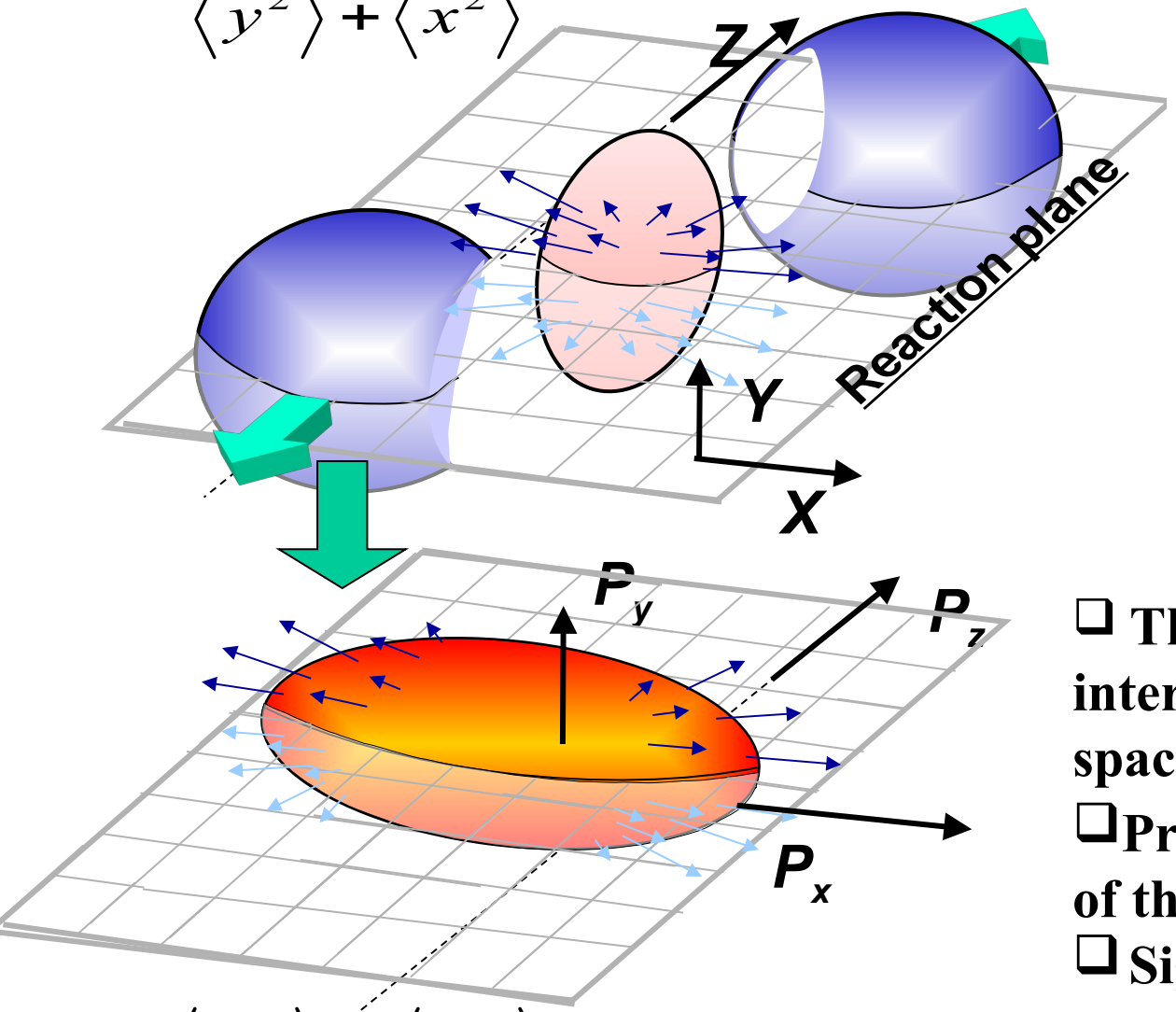
- Fourier coefficients $\mathbf{V_n}$ quantify anisotropic flow:

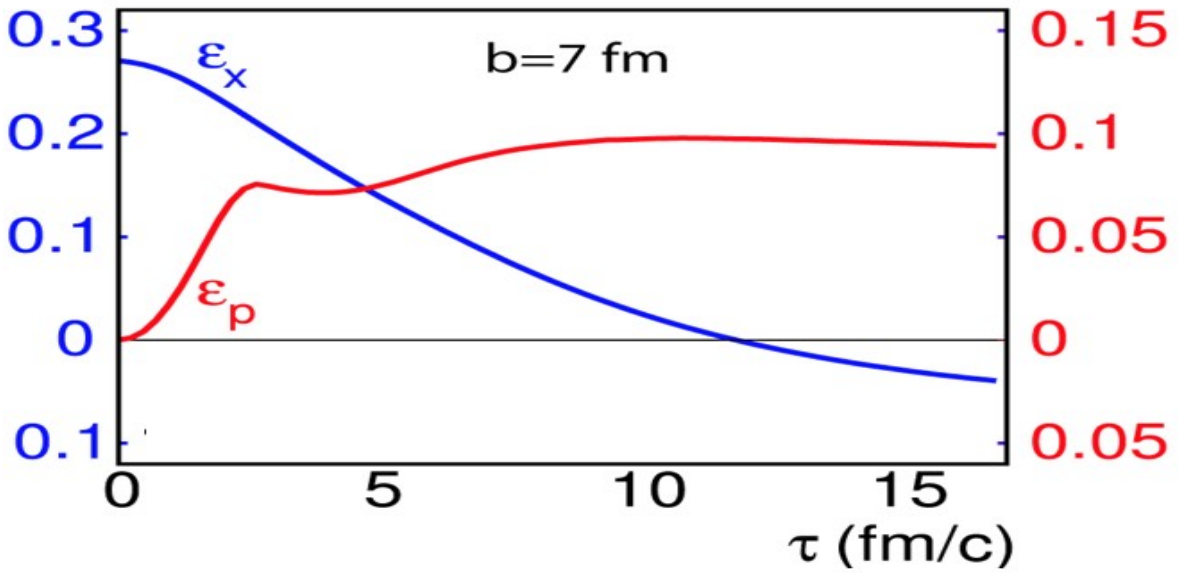
v_1 is directed flow, v_2 is elliptic flow, v_3 is triangular flow, etc.

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

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$





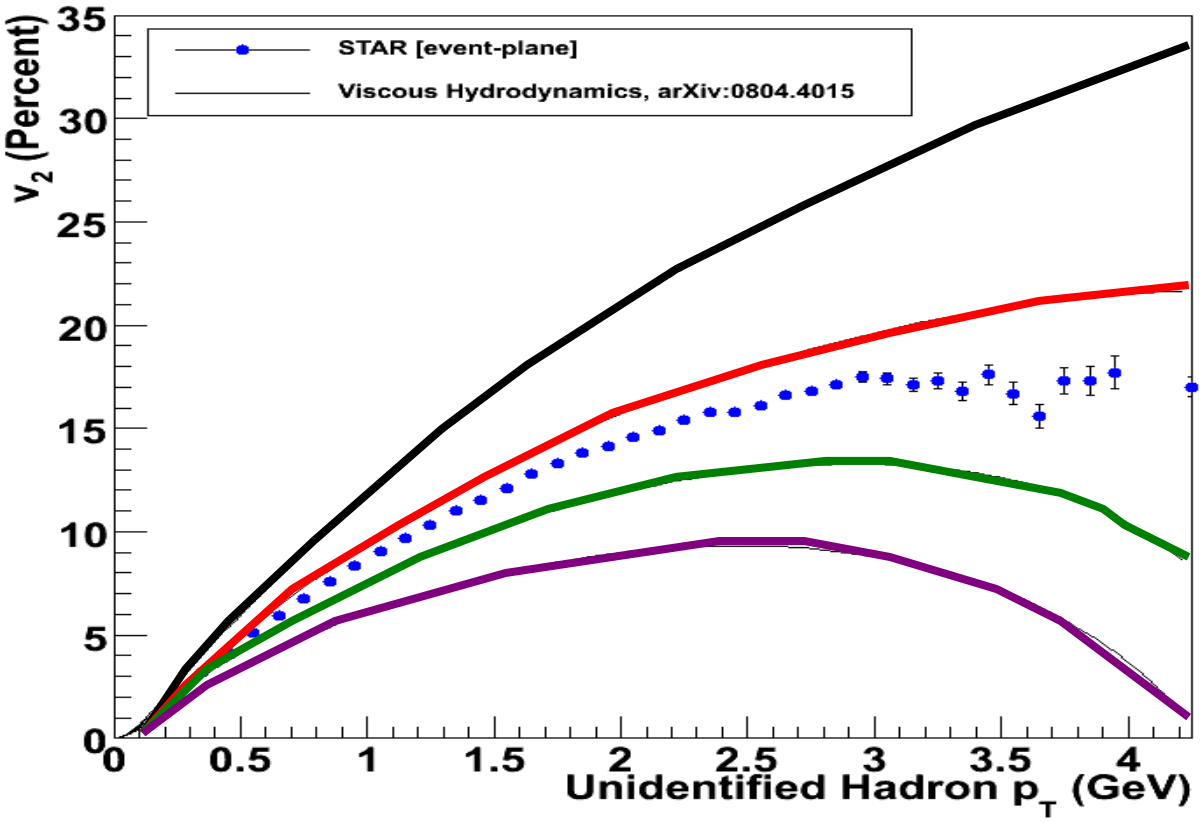
- The initial spatial anisotropy ε evolves (via interactions and density gradients) → Momentum-space azimuthal anisotropy v_2
- Pressure gradient is largest in the shortest direction of the ellipsoid.
- Signal is self-quenching with time

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle} \rightarrow v_2 = \langle \cos(2[\varphi - \Psi_R]) \rangle$$

2008 - Relativistic viscous hydrodynamics compared to data

Luzum, Romatschke, Phys. Rev. C78, 034915 (2008)

Lower Viscosity
↓
Less Dissipation
↓
More Flow
↓
Larger v_2



$\eta/s \sim 0$

$\eta/s = 1/4\pi$

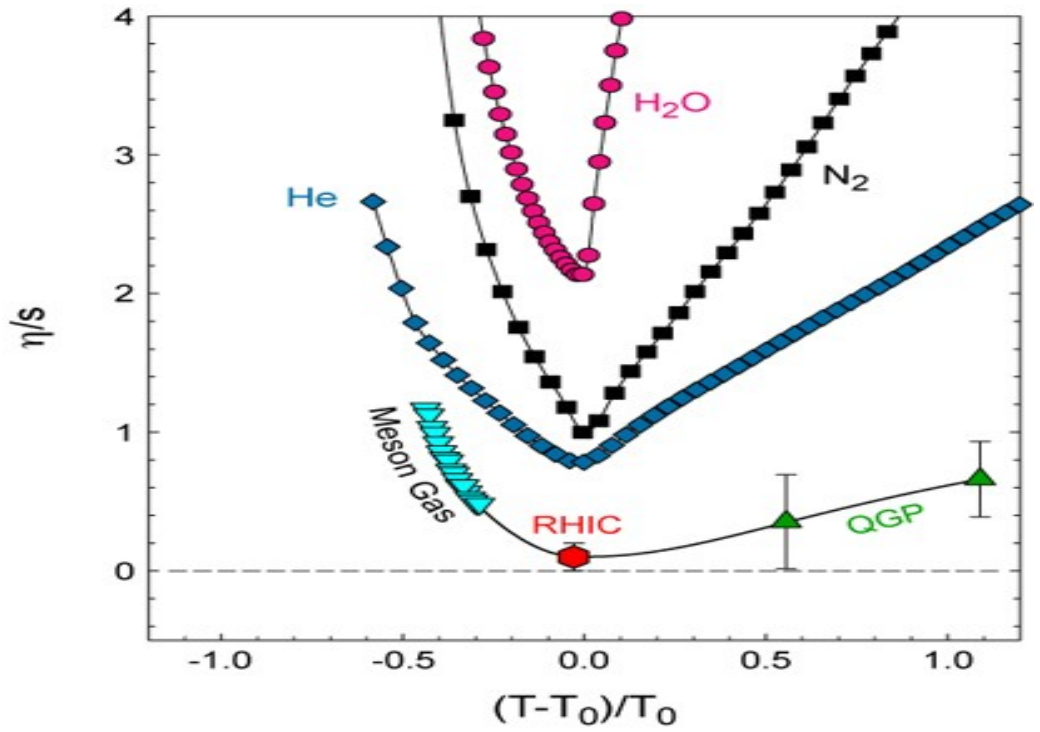
$\eta/s = 2 \times 1/4\pi$

$\eta/s = 3 \times 1/4\pi$

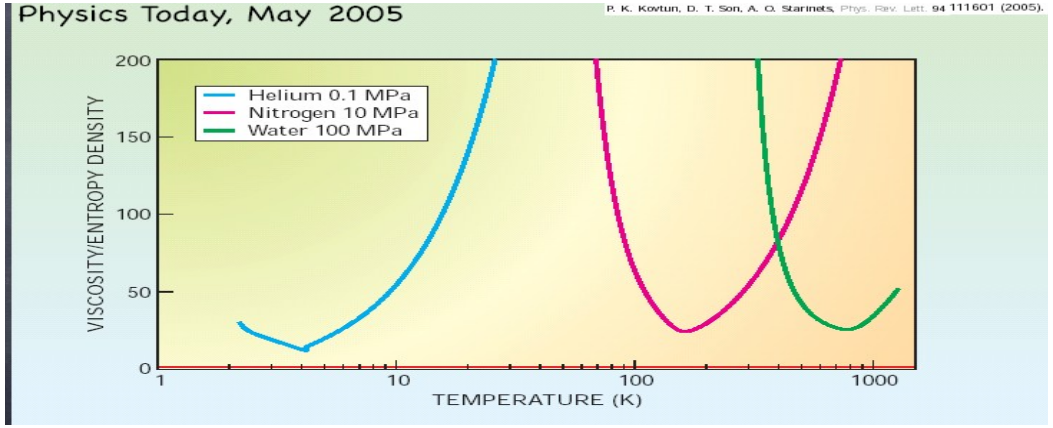
$$\left(\frac{\eta}{s}\right)\Big/\left(\frac{1}{4\pi}\right) = 1.3 \pm 1.3\,(\text{theory}) \pm 1.0\,(\text{experiment})$$

Change of paradigm

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



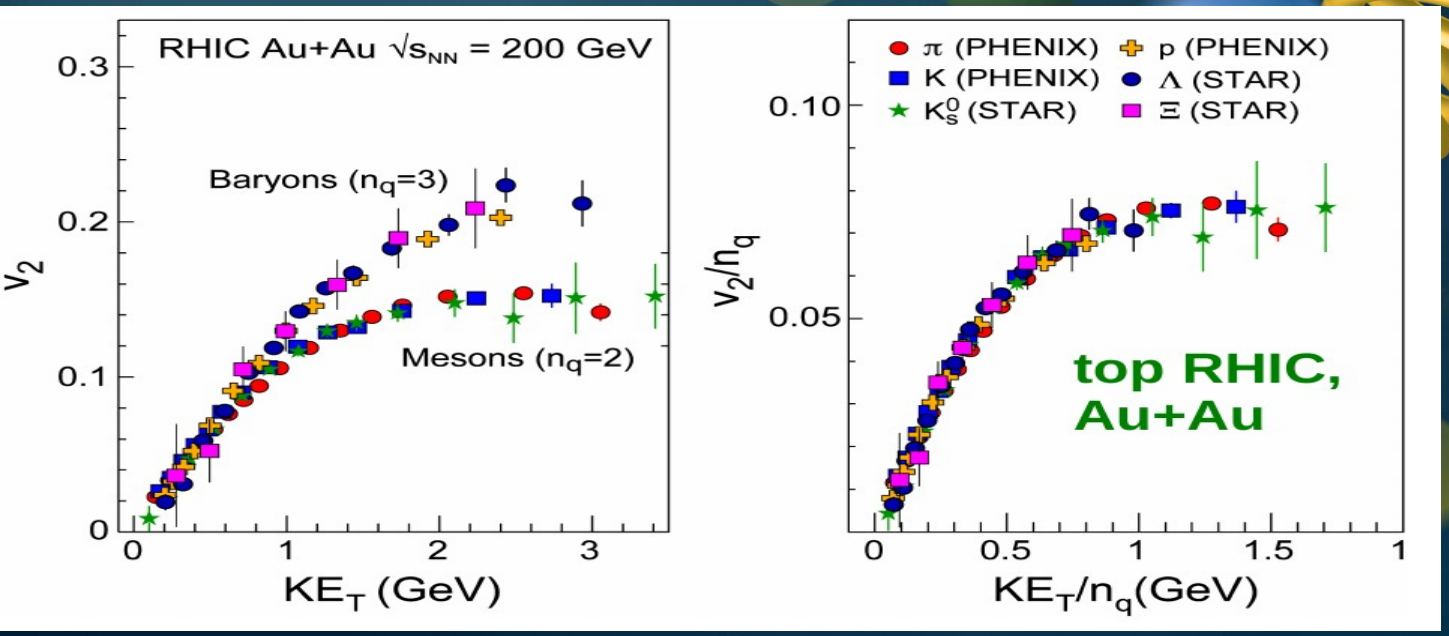




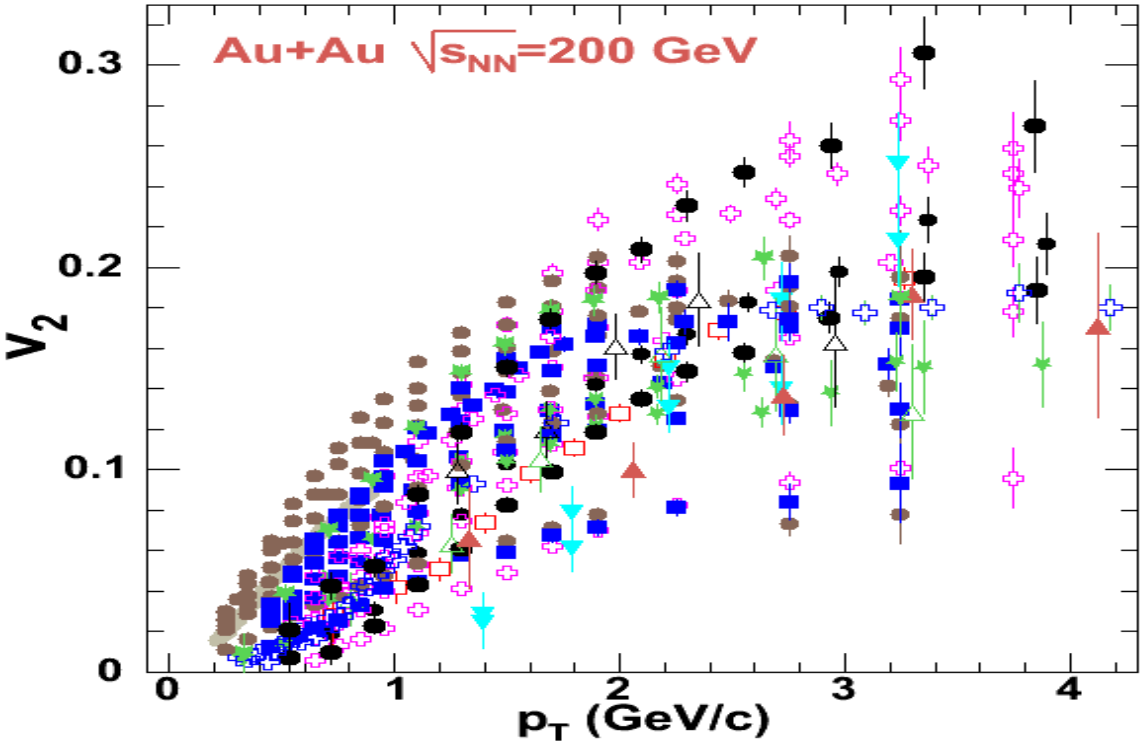
- Manifestation of strongly coupled QGP
- Not a gas of free quarks and gluons
- Instead, strongly coupled nearly perfect liquid reaching almost the minimum value of shear viscosity to entropy density ratio (η/s)

It's partons unchained?

Partonic degree of freedom at work ?



2006 - Anisotropic Flow at RHIC – partonic?



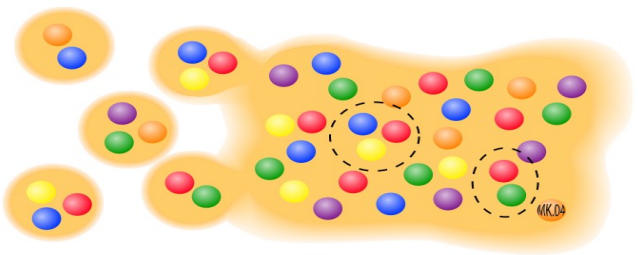
PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)

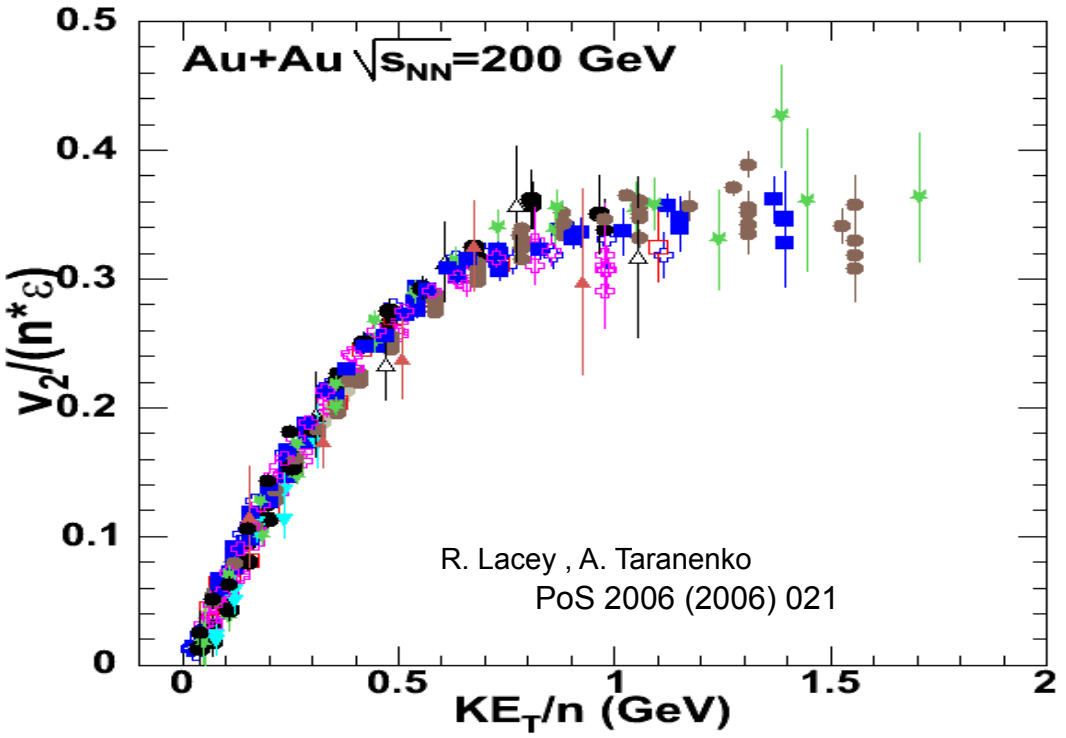
- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $p + \bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- d : min.bias, 10-50%
- ϕ : 20-60%

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

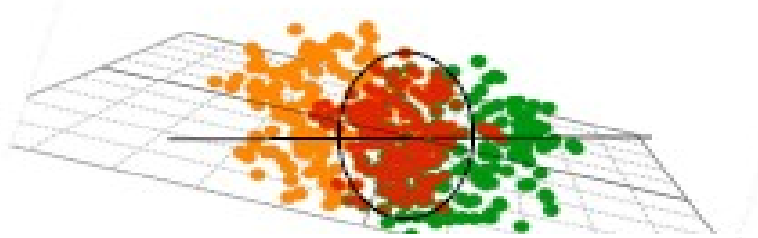
$$KE_T = m(\gamma_T - 1) = m_T - m$$

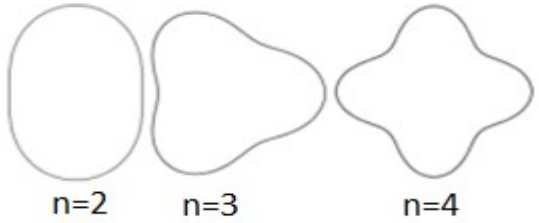




n=2 for mesons and
n=3 for baryons

Anisotropic Flow at RHIC-LHC



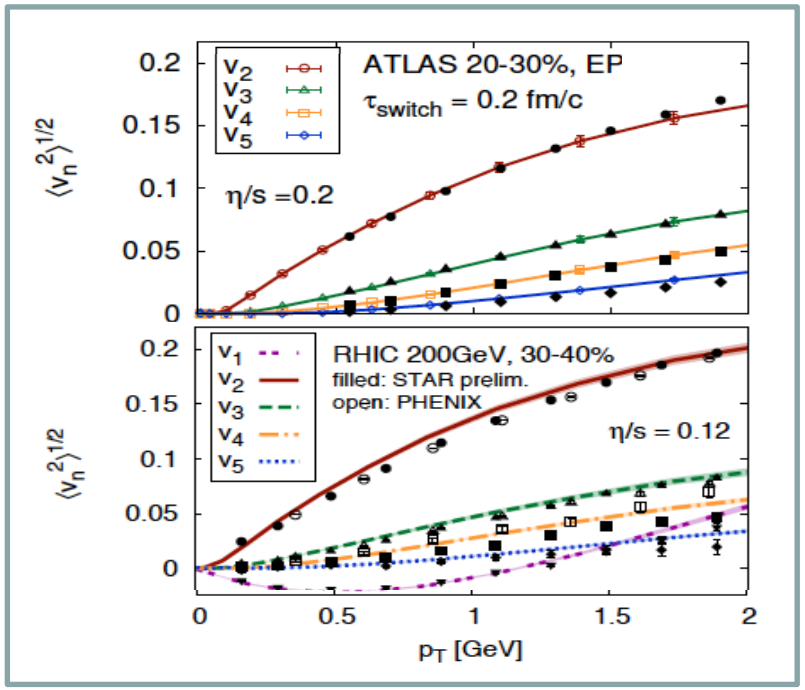


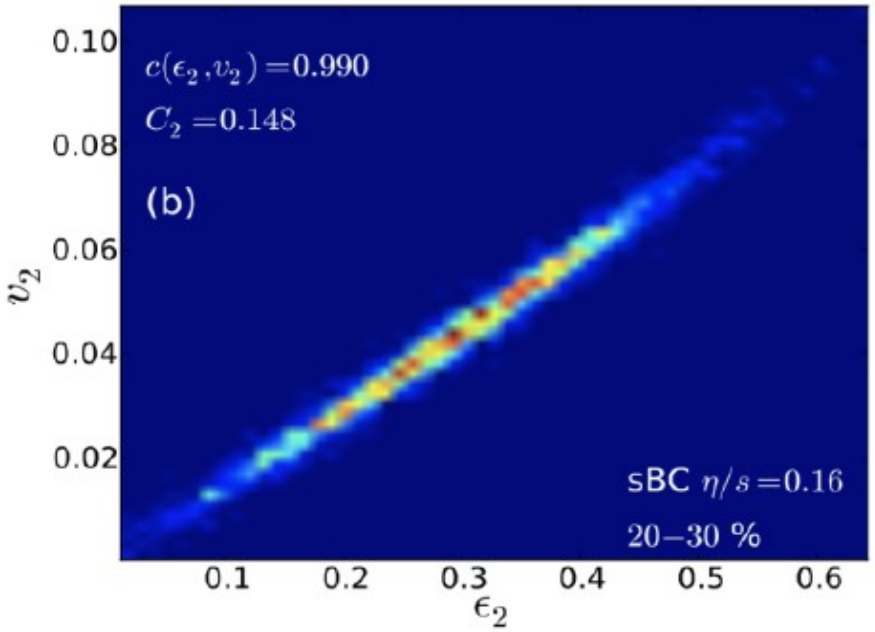
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

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

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

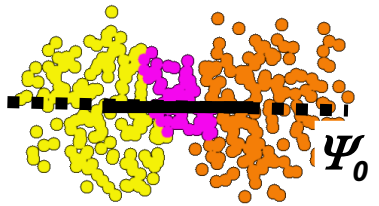
Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302

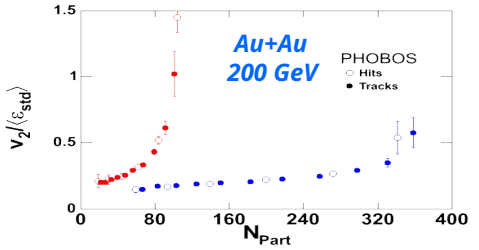




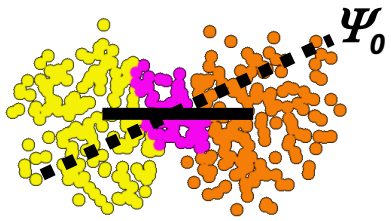
System size scan at top RHIC energy (= 200 GeV)

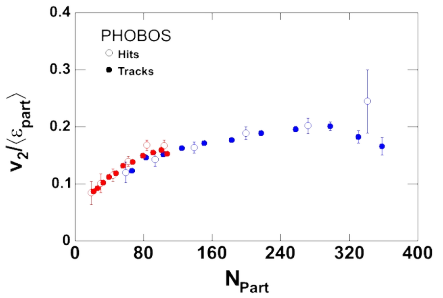
2001-2005 $\varepsilon_{\mathrm{std}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_x^2 + \sigma_y^2}$



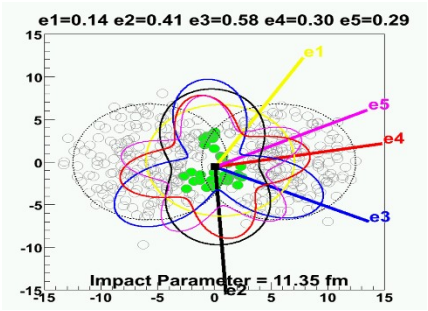


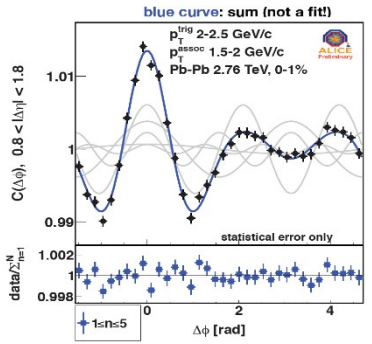
2005-2011 $\langle \epsilon_{\mathrm{part}} \rangle = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{(\sigma_y^2 + \sigma_x^2)}$





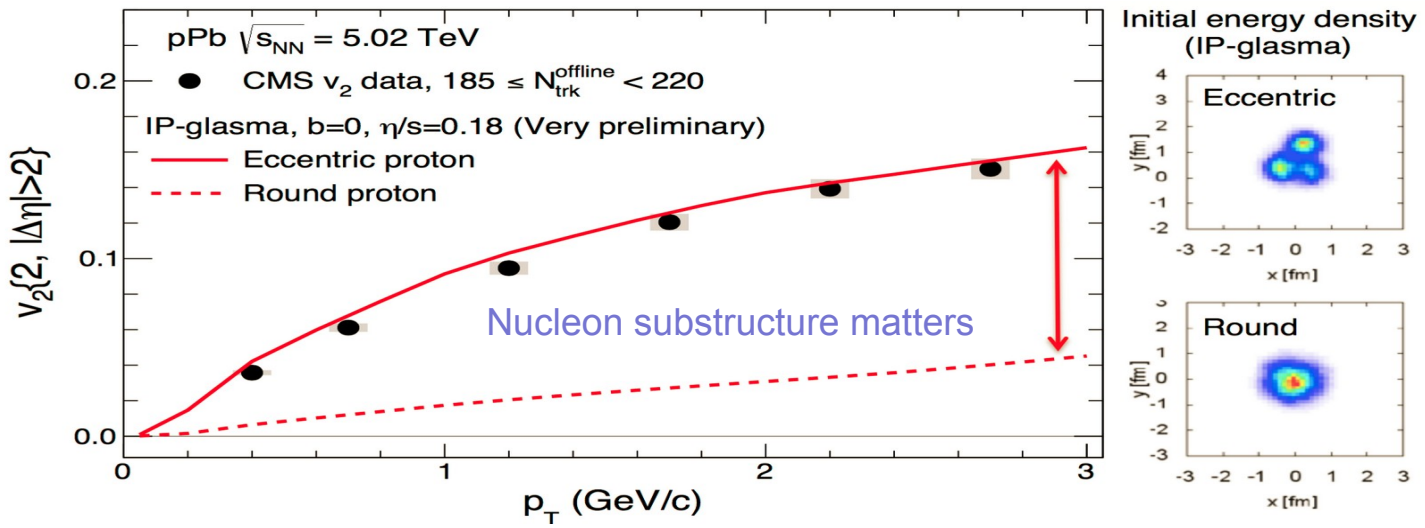
2011-2012 $\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$



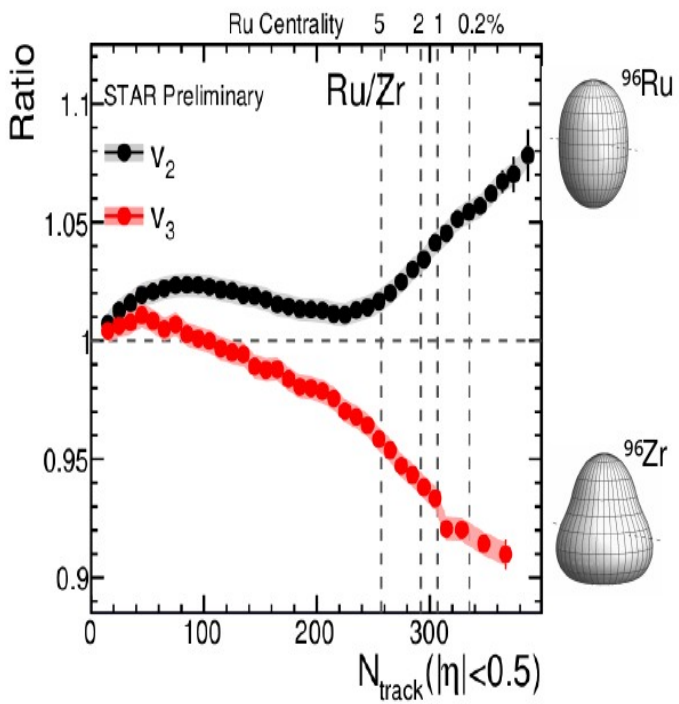


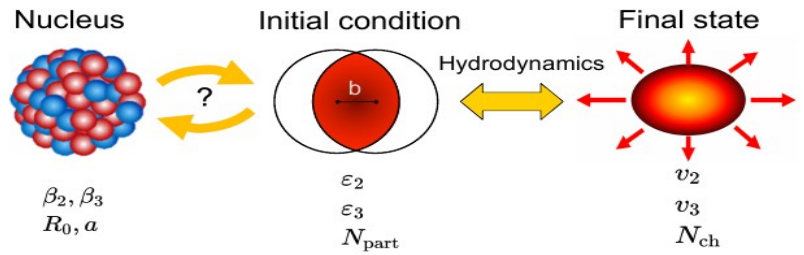
For "lumpy" *profile* $\varphi \neq \varphi + \pi$ Odd harmonics ≠ 0

2011-2016



2020-2025







Nuclear imaging in HIC

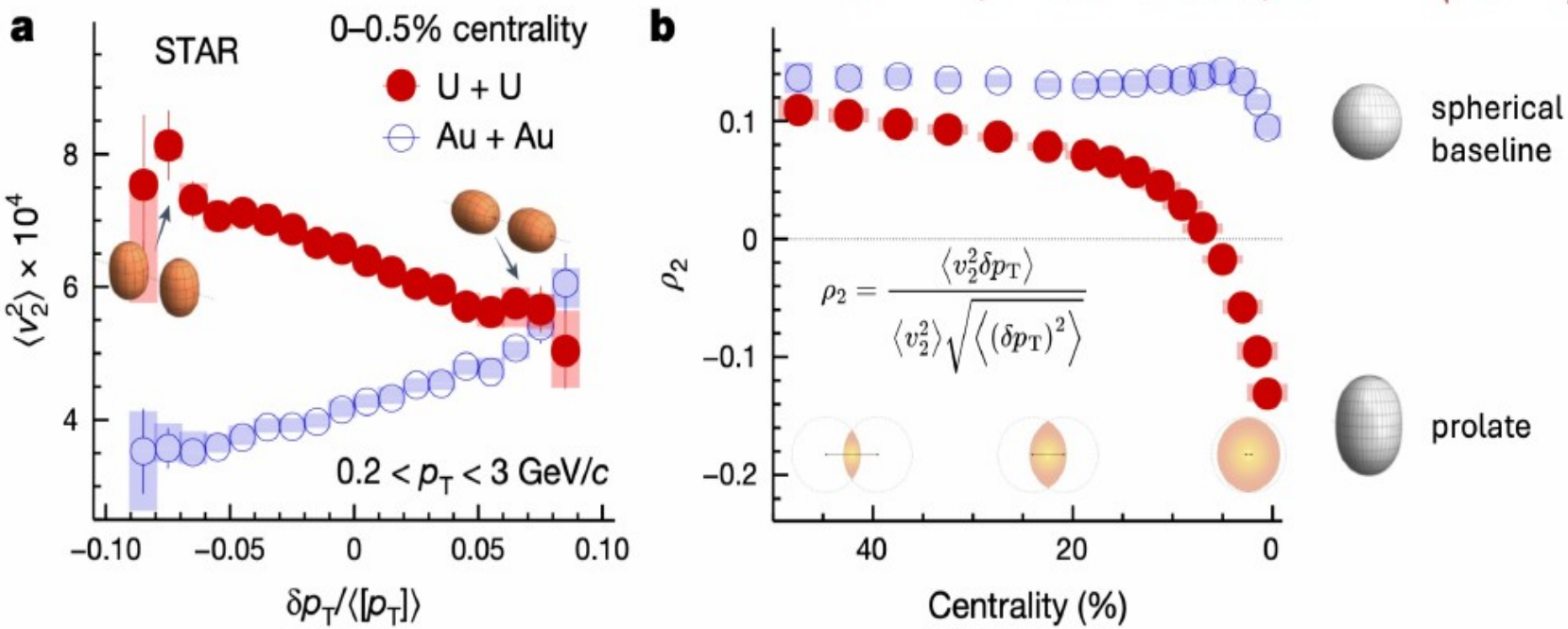
- Nuclear structure leaves imprints on v_n and v_n - p_T correlations.
- Compare similar-sized systems U+U, Au+Au to gain insights on nuclear structure.

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

$$R(\theta,\phi) = R_0(1+\beta_2[\cos\gamma Y_{2,0}(\theta,\phi) + \sin\gamma Y_{2,2}(\theta,\phi)] + \beta_3 Y_{3,0}(\theta,\phi))$$

β_2 → quadrupole deformation
β_3 → octupole deformation
γ → triaxiality
a_0 → surface diffuseness
R_0 → nuclear size

STAR, Nature 635, 67-72 (2024)



$$\langle v_2^2 \rangle = a_1 + b_1\beta_2^2$$
$$\langle (\delta p_T)^2 \rangle = a_2 + b_2\beta_2^2$$
$$\langle v_2^2 \delta p_T \rangle = a_3 - b_3\beta_2^3\cos(3\gamma)$$

Nuclear imaging in HIC

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

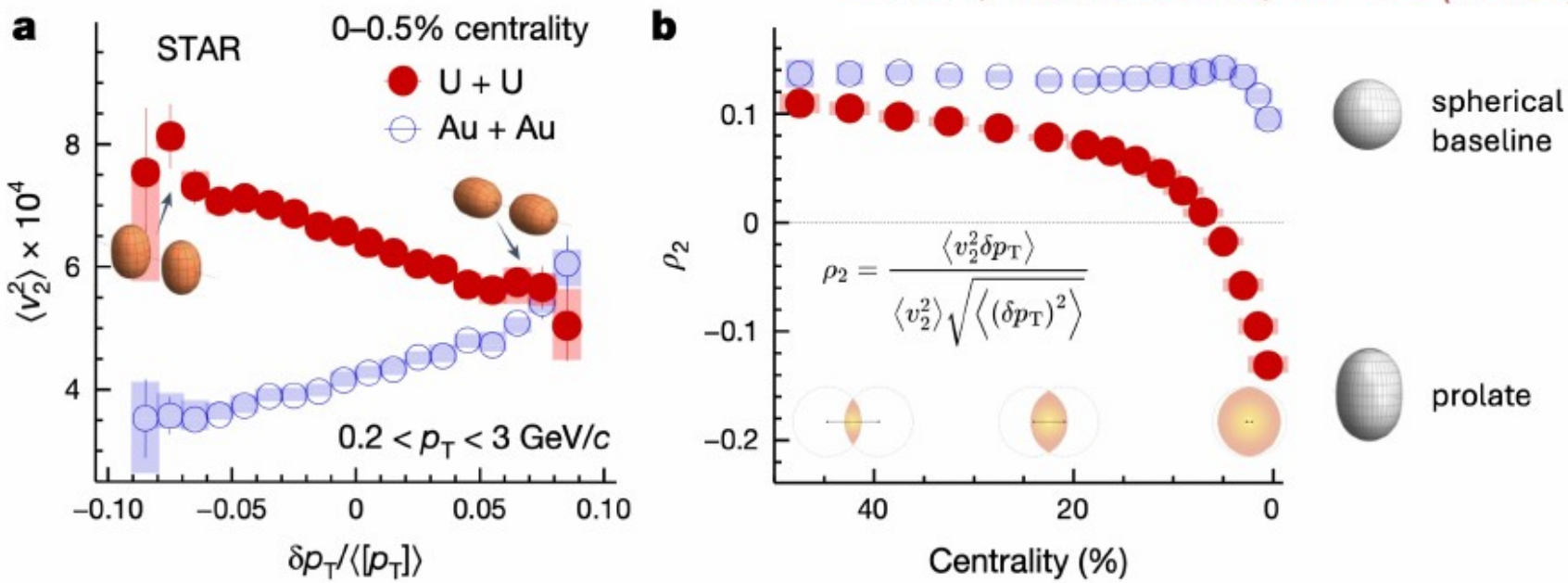
$$R(\theta,\phi) = R_0(1+\beta_2[\cos\gamma Y_{2,0}(\theta,\phi)+\sin\gamma Y_{2,2}(\theta,\phi)]+\beta_3 Y_{3,0}(\theta,\phi))$$

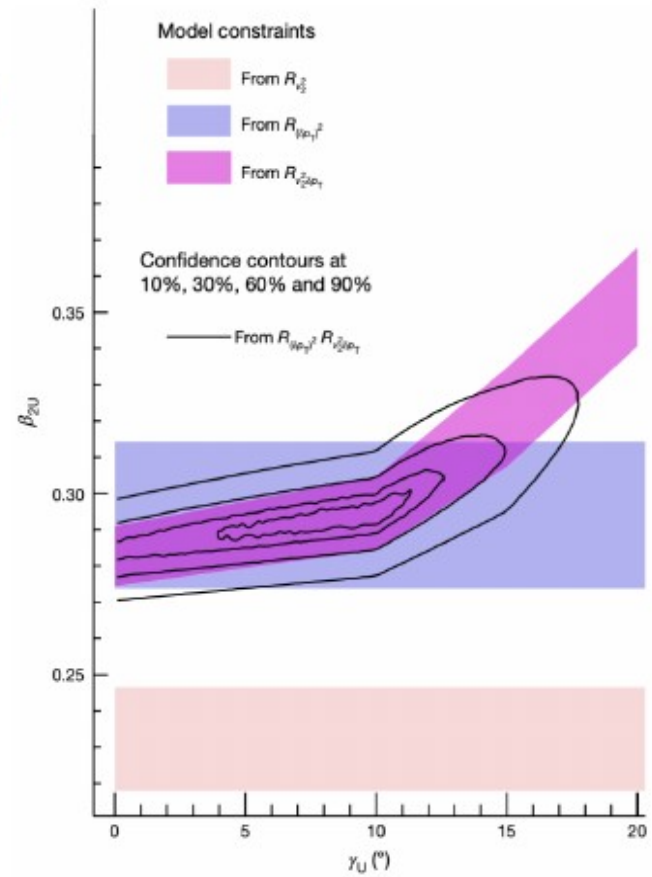
- Nuclear structure leaves imprints on v_n and v_n - p_T correlations.
- Extract U+U shape parameters β_2 and γ:
  - Large quadrupole deformation, consistent with low-energy measurements and indication of small triaxiality in U+U ground state.

$$\beta_{2U} = 0.297 \pm 0.015$$

$$\gamma_U = 8.5^\circ \pm 4.8^\circ$$

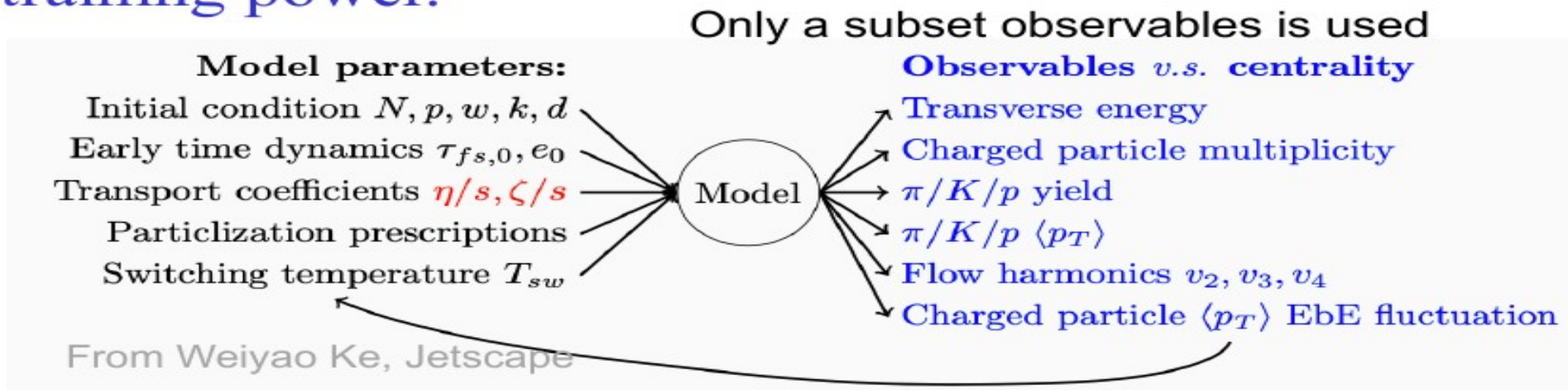
STAR, Nature 635, 67-72 (2024)



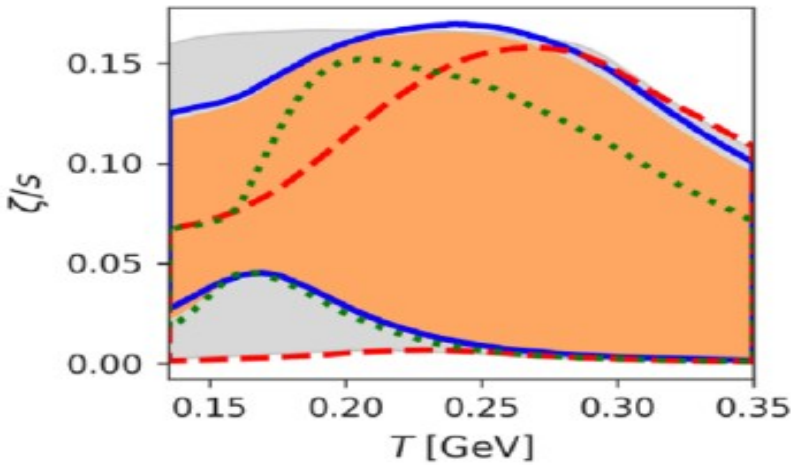


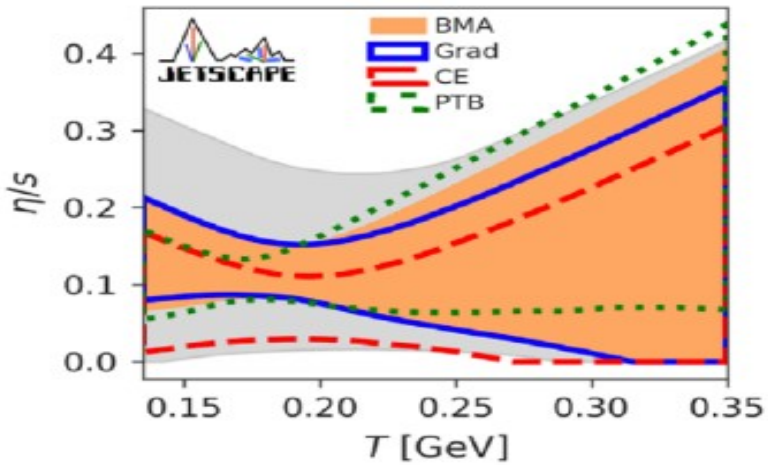
State-of-the-art modeling of HI collisions

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



- Detailed temperature dependence of viscosity!

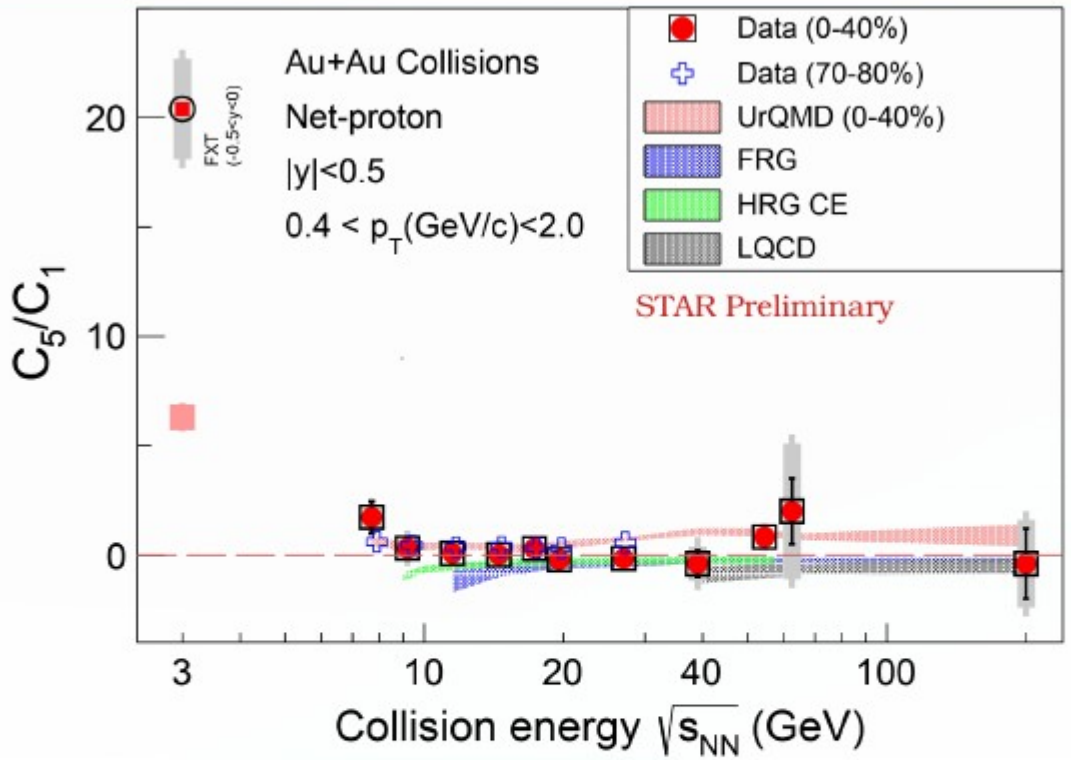


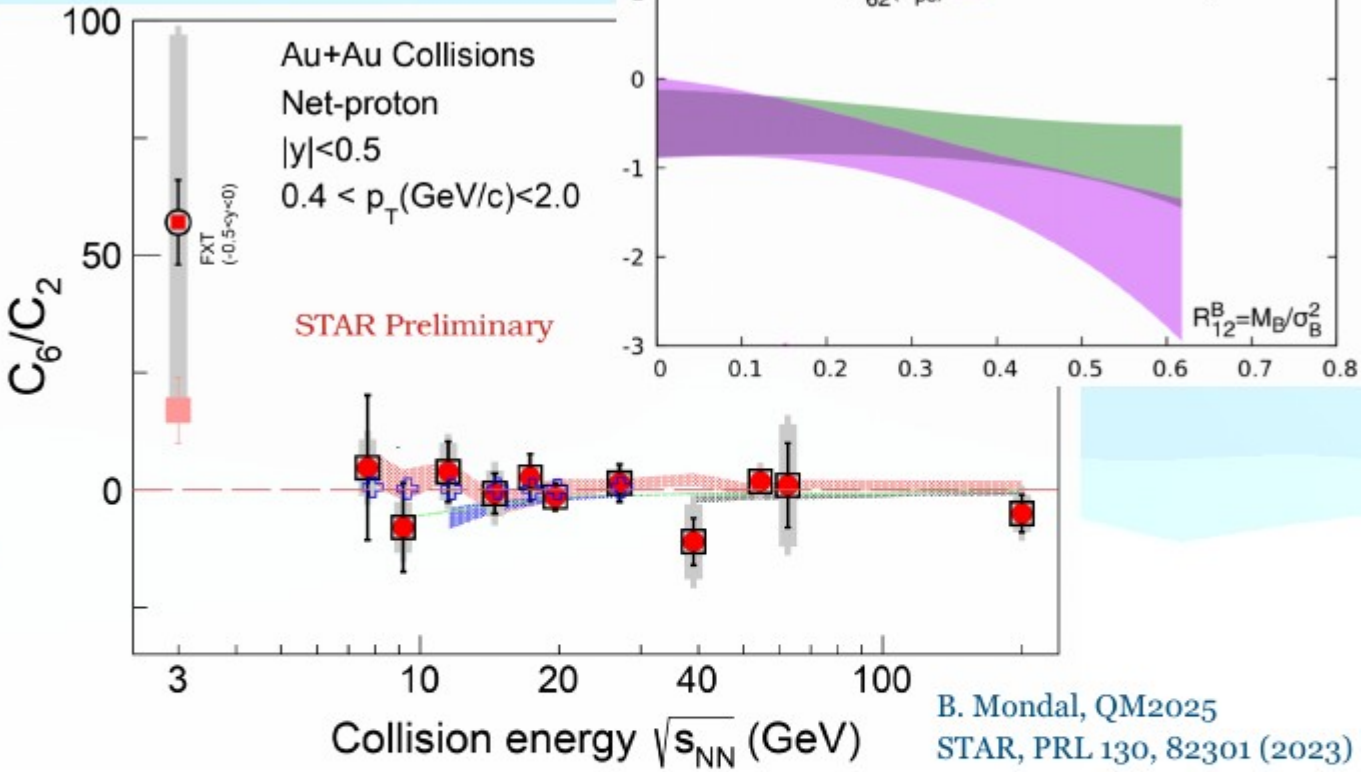


Jetscape PRL.126.242301
Trjactum PRL.126.202301

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

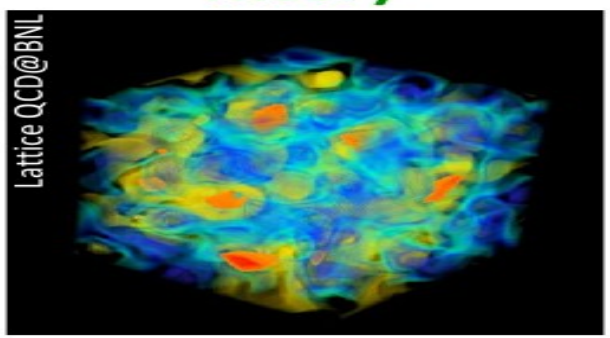
Translation

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

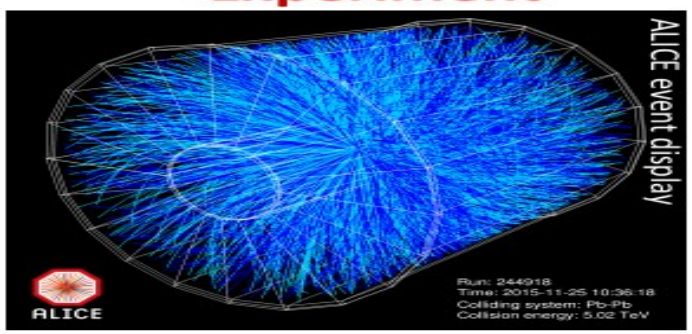
$\kappa_n \rightarrow$ cumulants of $\Delta N_B = N_B - N_{\bar{B}}$

Bridge experimental data to LQCD calculations

Theory



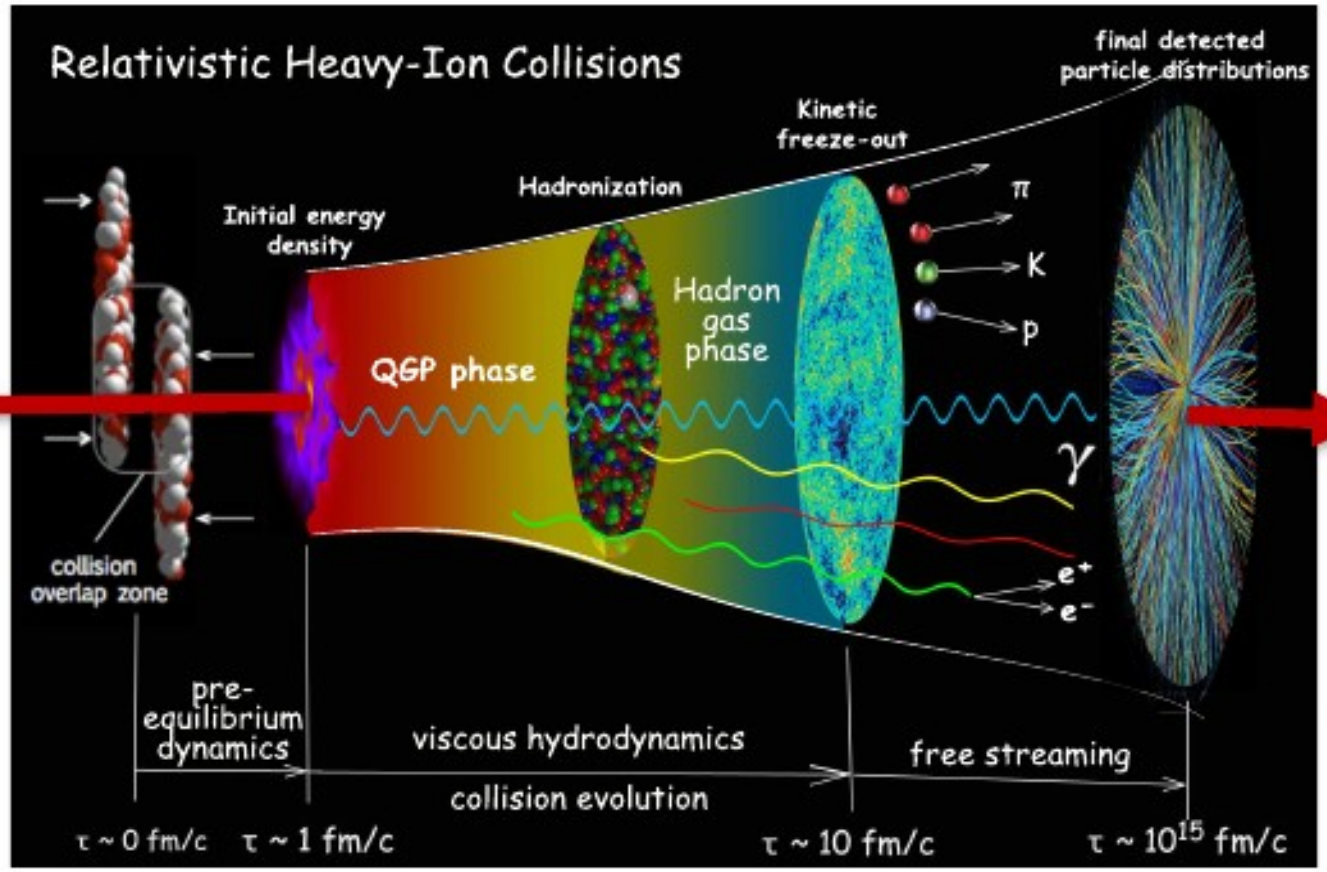
Experiment



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 ...





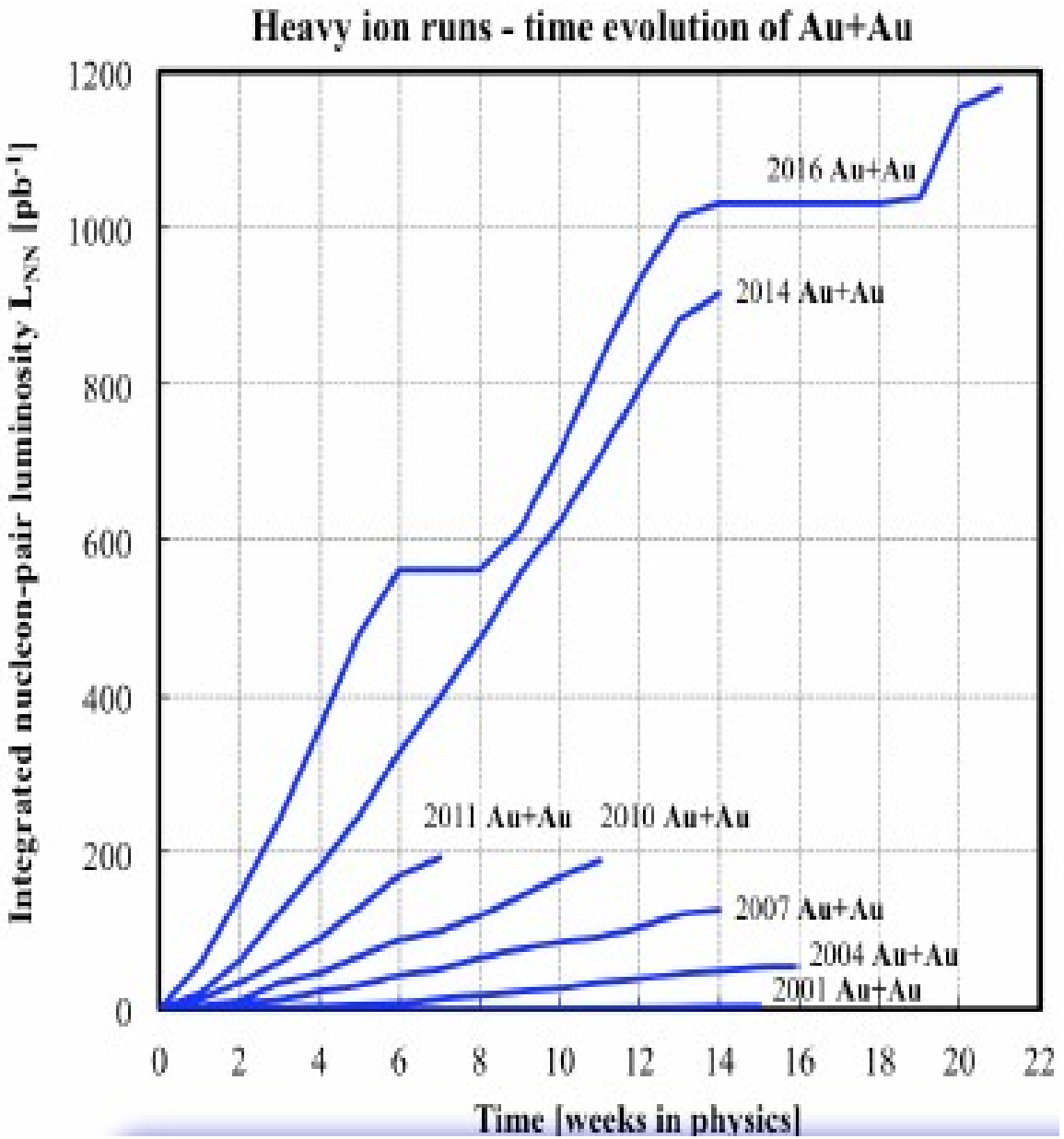


"Psychoanalysis" of Matter

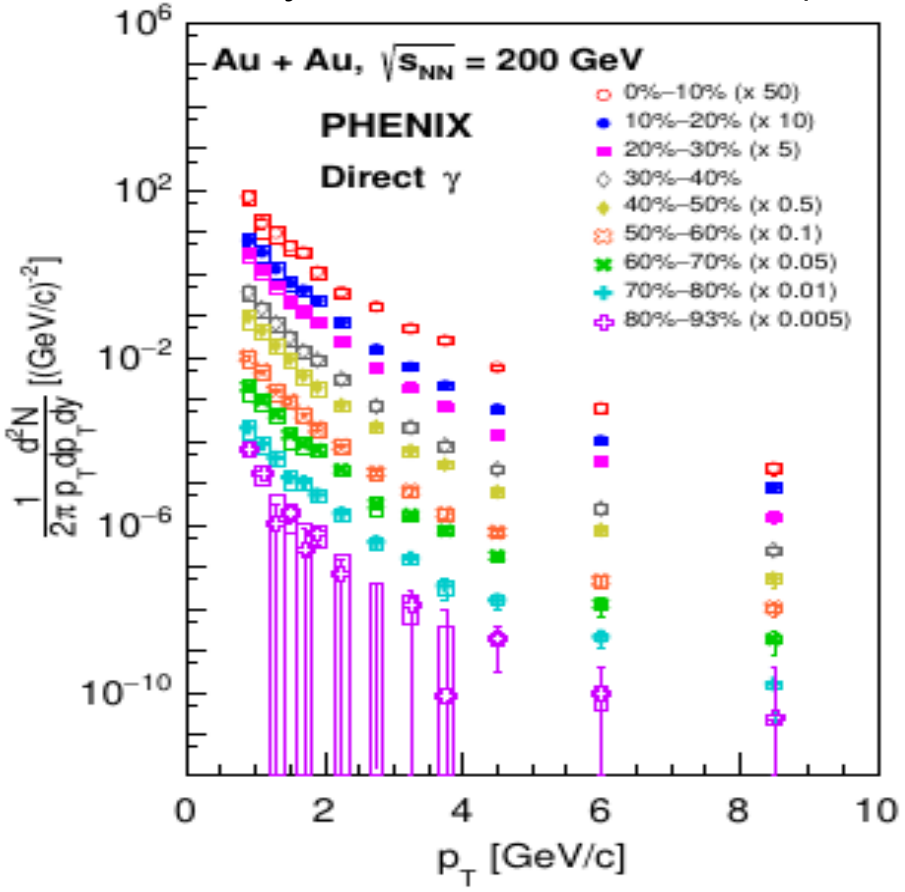
~200+200 nucleons in 10^{-22} seconds = 1000-30000 hadrons

Understanding RHIC/LHC is hard. Many-body physics across many scales; strongly interacting, relativistic, and very, very small

Heavy-Ion runs in PHENIX

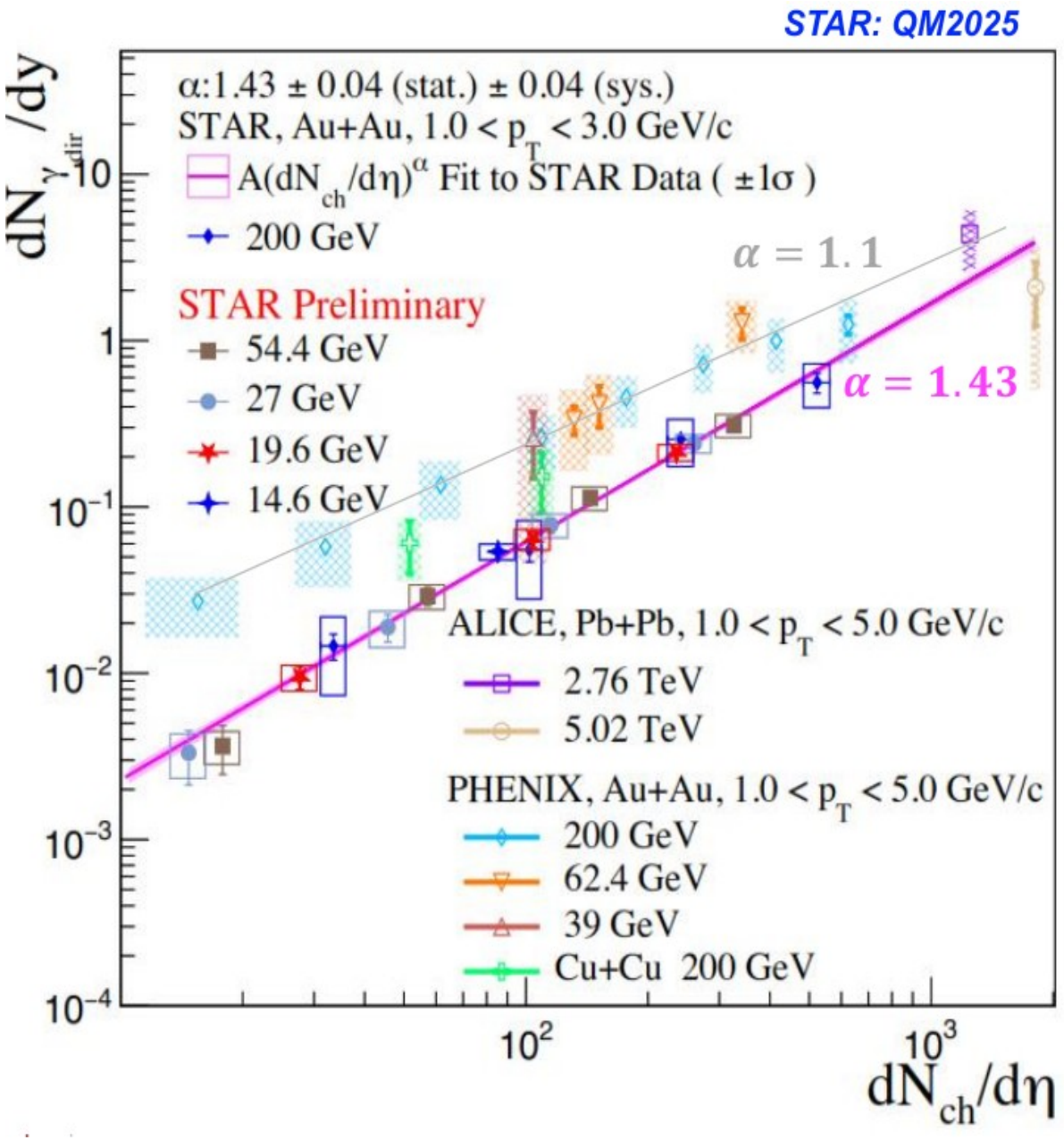


Phys. Rev. C 109, 044912 (2024)



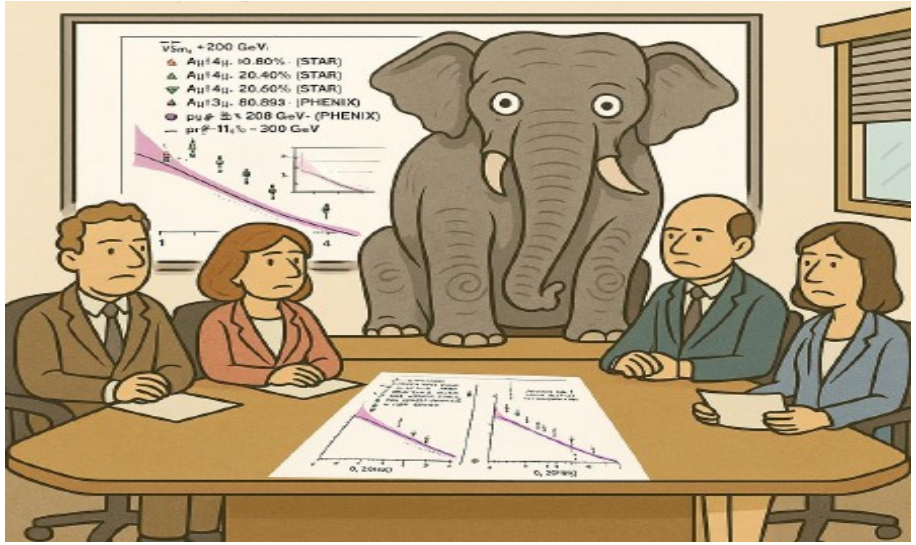
In 2014, a total of 19 billion Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV were recorded by the PHENIX detector at the Relativistic Heavy Ion Collider (RHIC) with a minimum-bias (MB) trigger, based on the response of two beam-beam counters (BBC) [25]. The BBCs are located

Direct-Photon Production at RHIC: STAR vs PHENIX



- **STAR results:**
  - Virtual photon analysis $\gamma^* \rightarrow e^+e^-$ for Au+Au at 14.6, 19.6, 27, 54.4, 200 GeV
  - Self consistent analyses & results across energies
  - Direct photon yield scales with $N_\gamma^{dir} \sim \left(\frac{dN_{ch}}{d\eta}\right)^\alpha$ with $\alpha \sim 1.43$

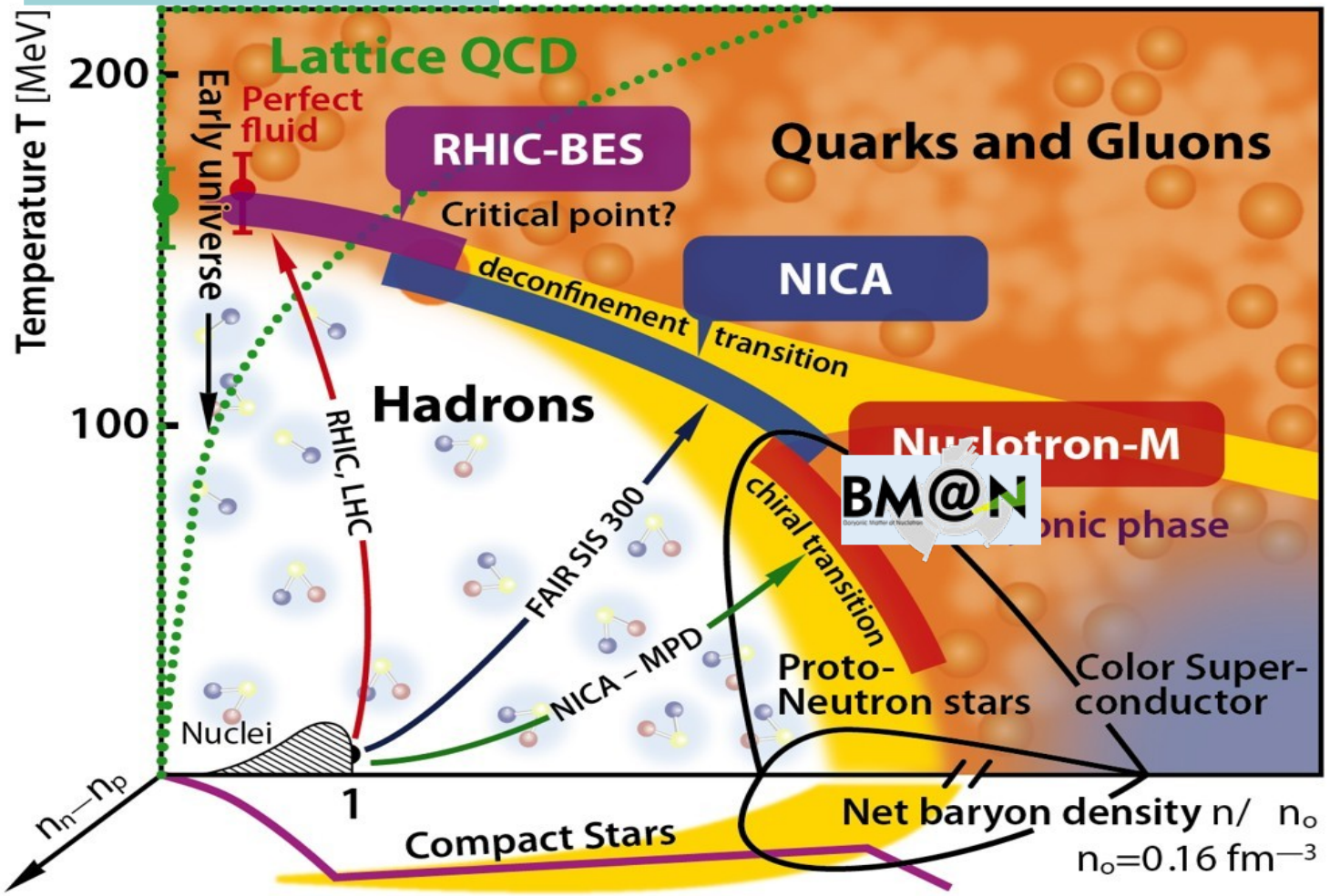
- **Compared to PHENIX results:**
  - STAR yield a factor of 3-5 below PHENIX
  - $\alpha \sim 1.43$ versus $\alpha \sim 1.1$ for PHENIX

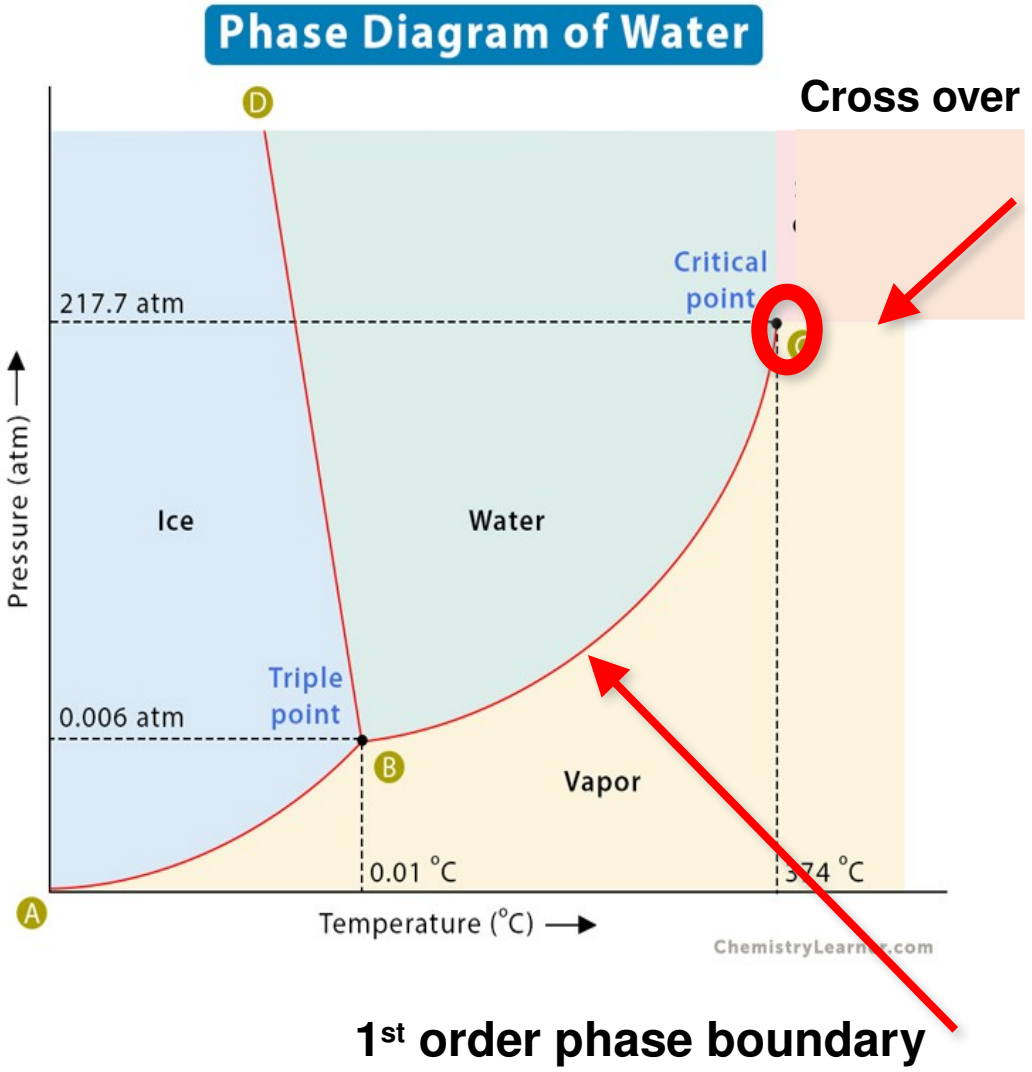


Relativistic Heavy-Ion Collisions and QCD Phase Diagram

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

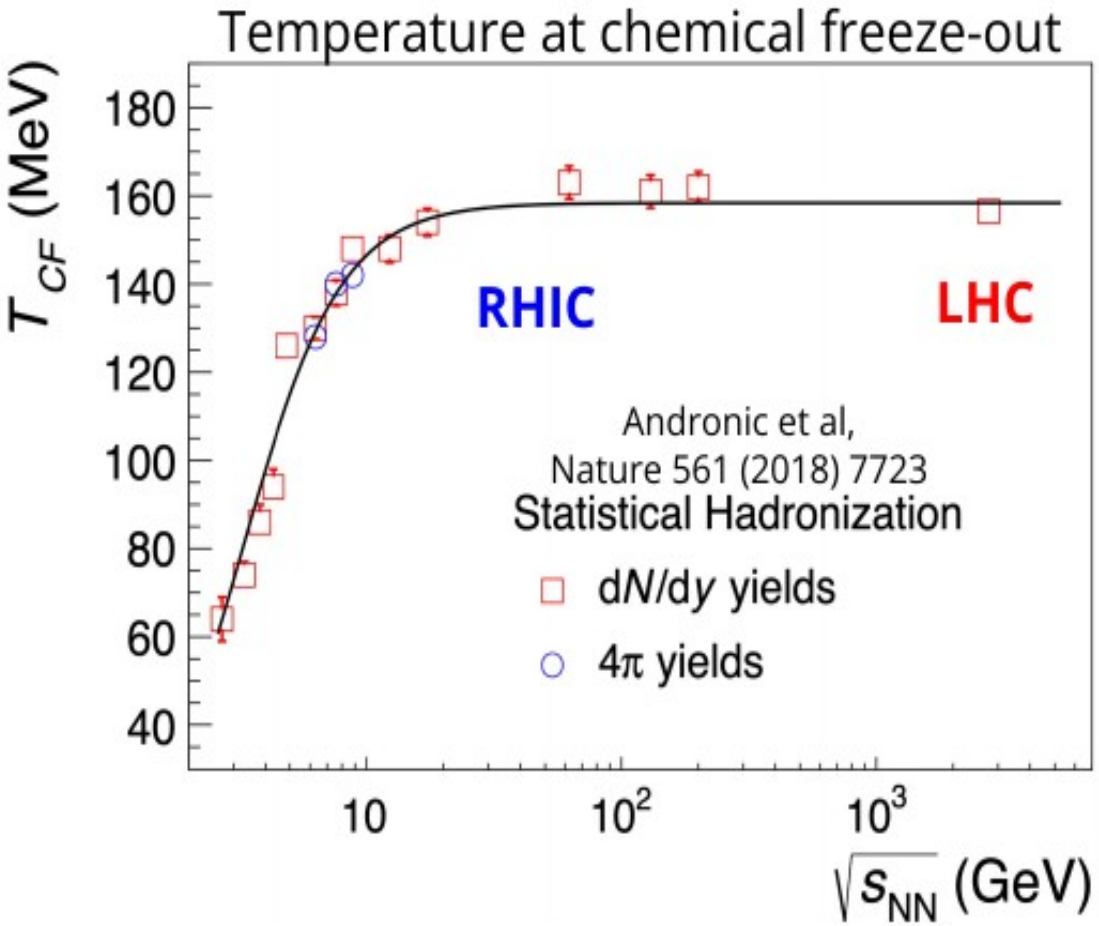
[PRD 90 094503 (2014)]

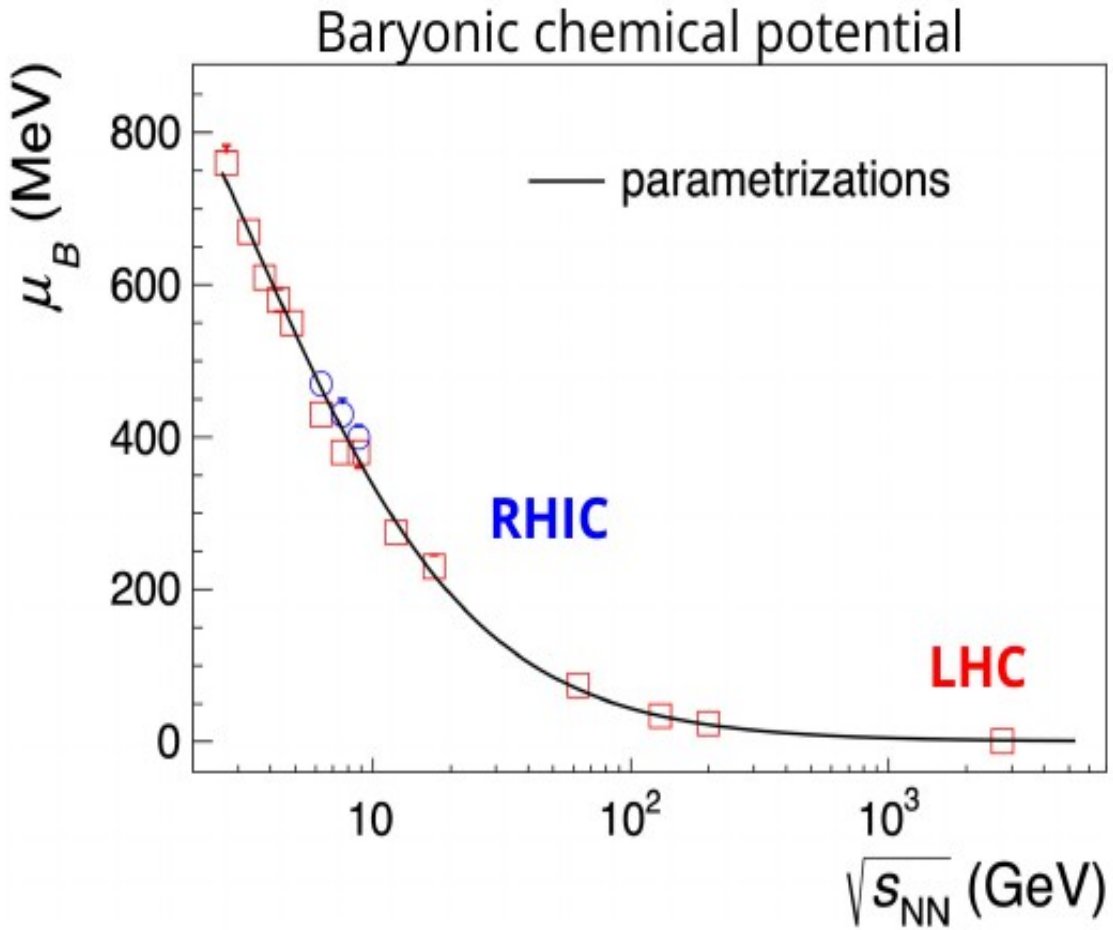




Smooth *transition from hadronic degrees of freedom to quark-gluon degrees of freedom at zero baryonic density*

Energy dependence of chemical freeze-out parameters

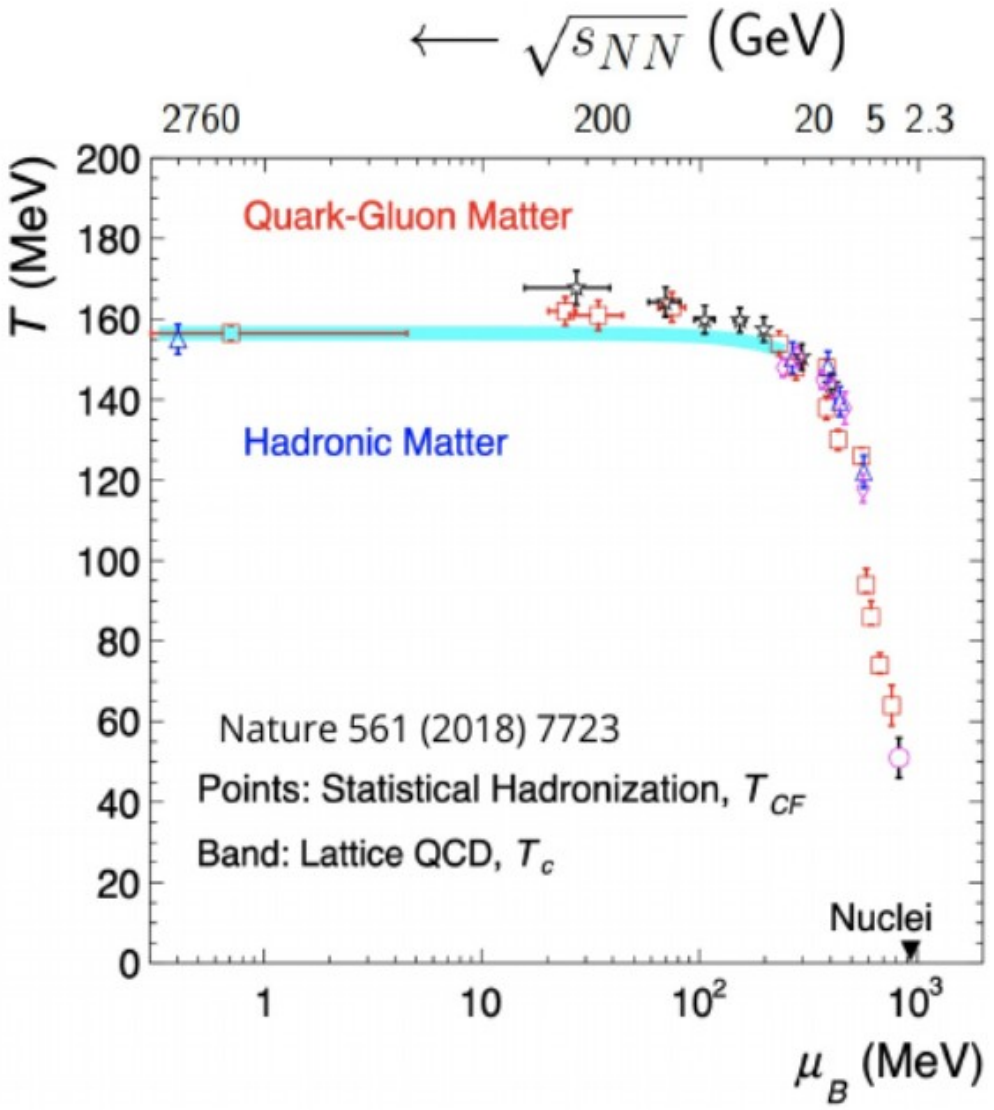




Smooth evolution of T_{CF} and μ_B with beam energy:

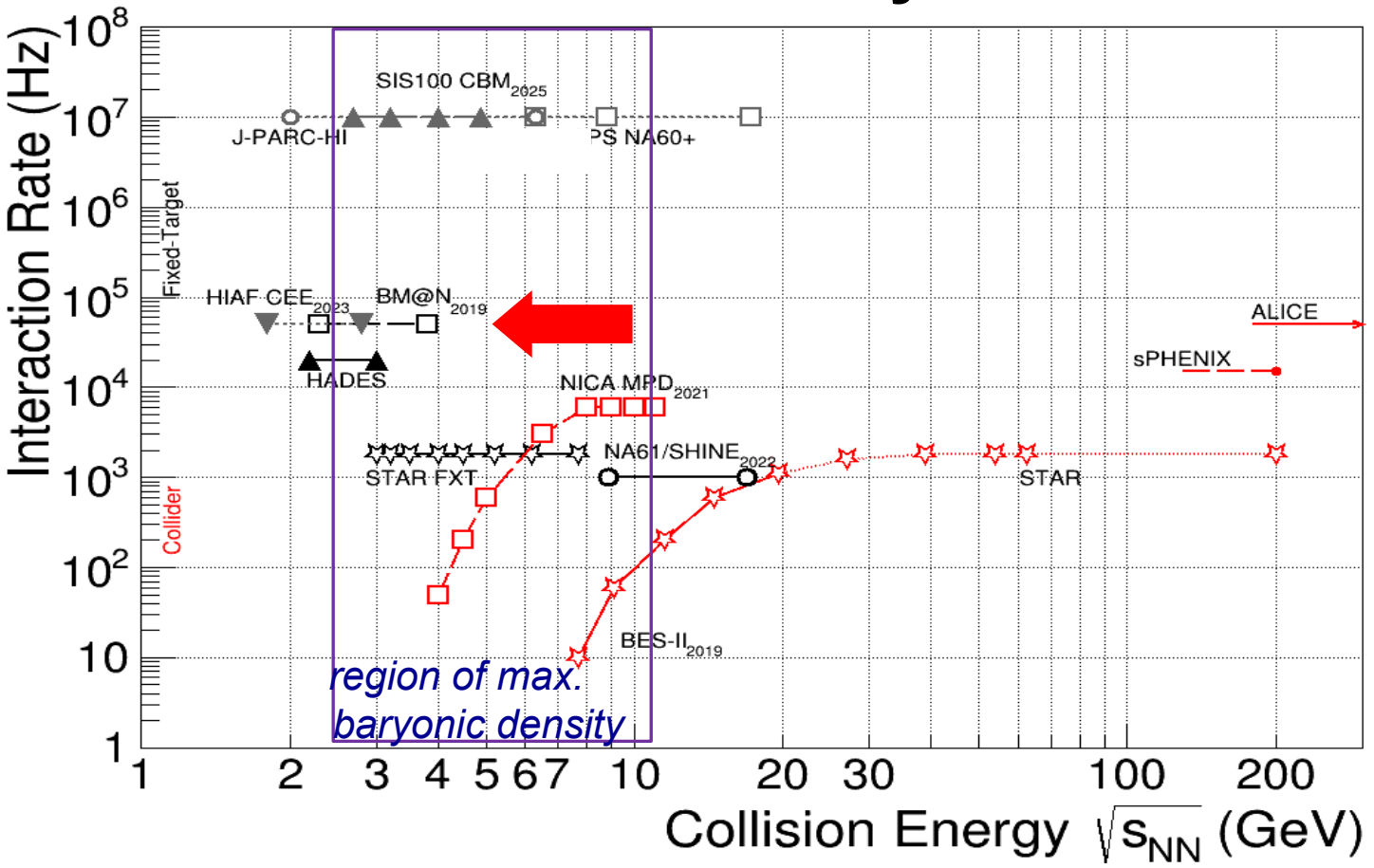
→ T_{CF} reaches limiting value close to pseudo-critical temperature.

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).

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:

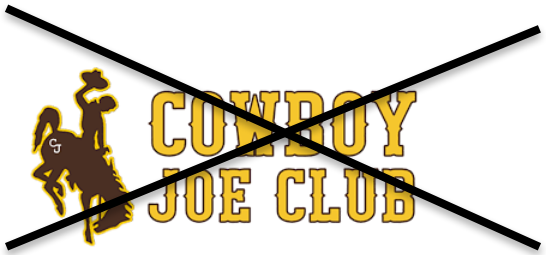
HIAF/CEE (China) 2.1-4.5 GeV (2026-?)
FAIR/CBM (Germany) 2.4-4.9 GeV (2029-?)
JPARC-HI (Japan) 2-5 GeV (2030-?)
NA60+(CERN) 6.1-16.4 GeV (2029-?)

BM@N: = 2.3 - 3.3 GeV
MPD: = 4 - 11 GeV

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**

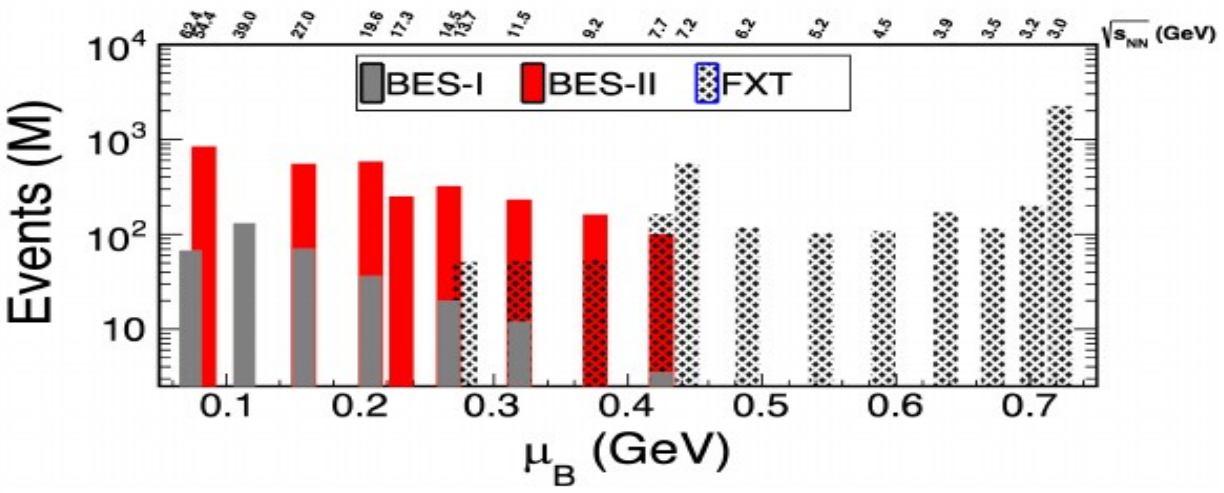
$(\mu_c, T_c) = (495 - 654, 100 - 119)$ MeV ➡ $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

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



Beam Energy Scan programs

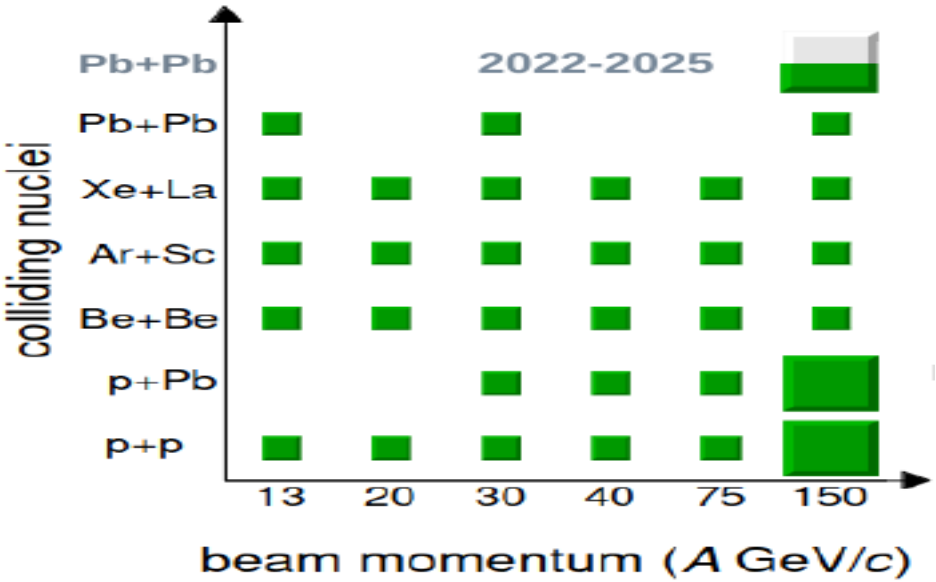
STAR at RHIC: $3 < \sqrt{s_{NN}} < 200$ GeV ($750 < \mu_B < 25$ MeV)

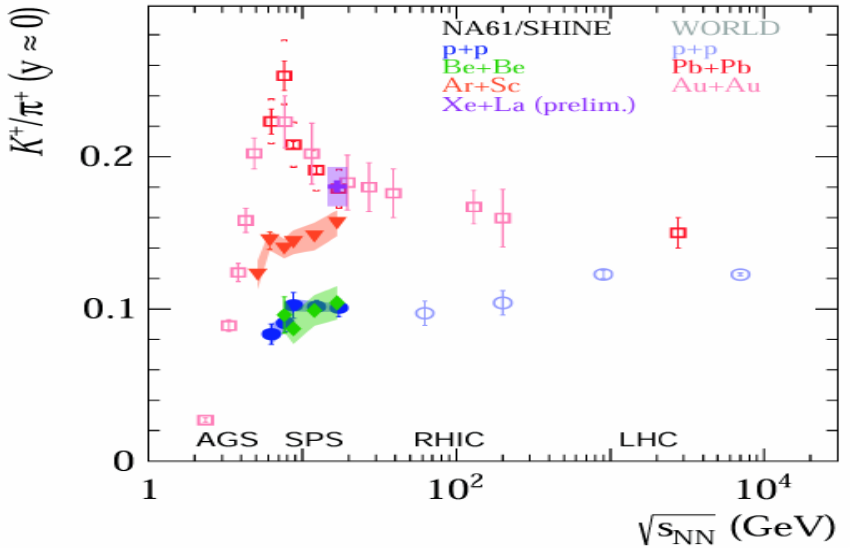


Au+Au Collisions at RHIC

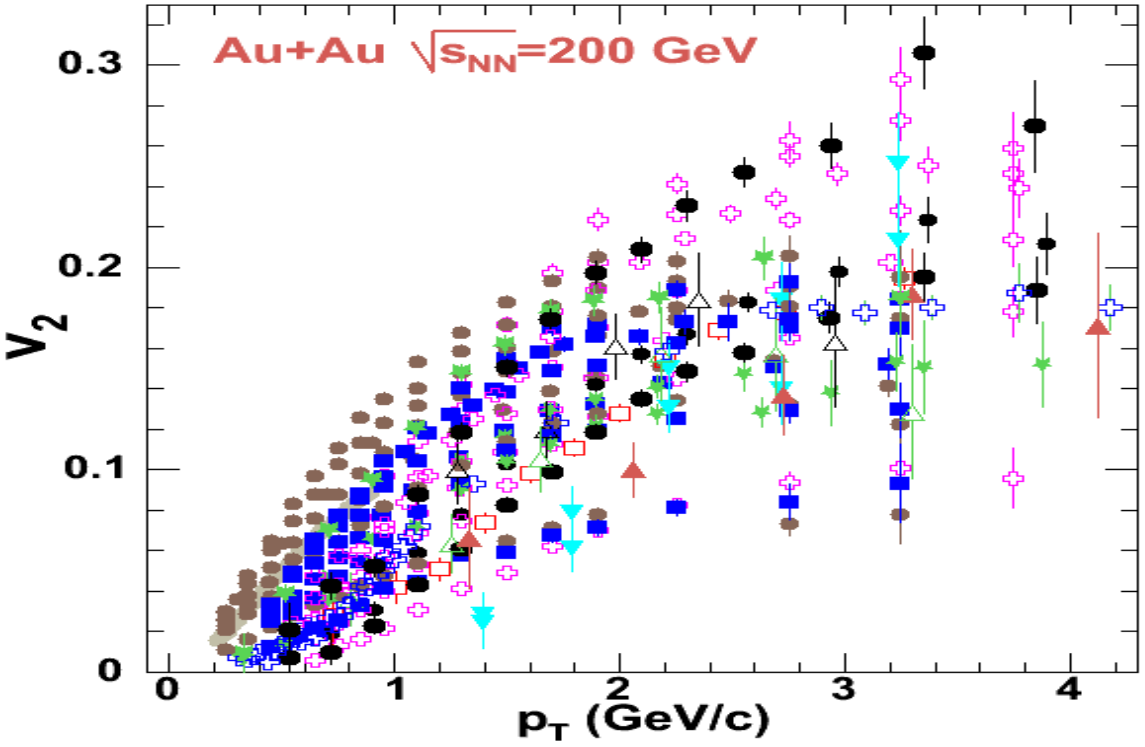
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	200	380 M	25 MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	157 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	3.0 (3.85)	2000 M	750 MeV	-1.05	Run-18, 21

NA61SINE at SPS: $5.1 < \sqrt{s_{NN}} < 17$ (27) GeV





Anisotropic Flow at RHIC – partonic?



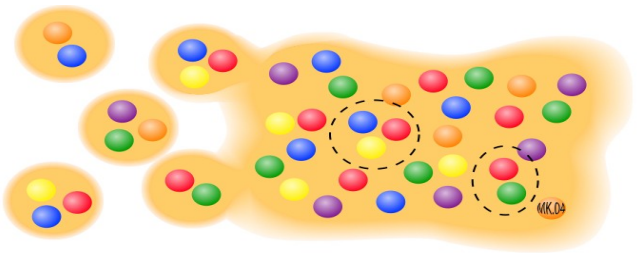
PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)

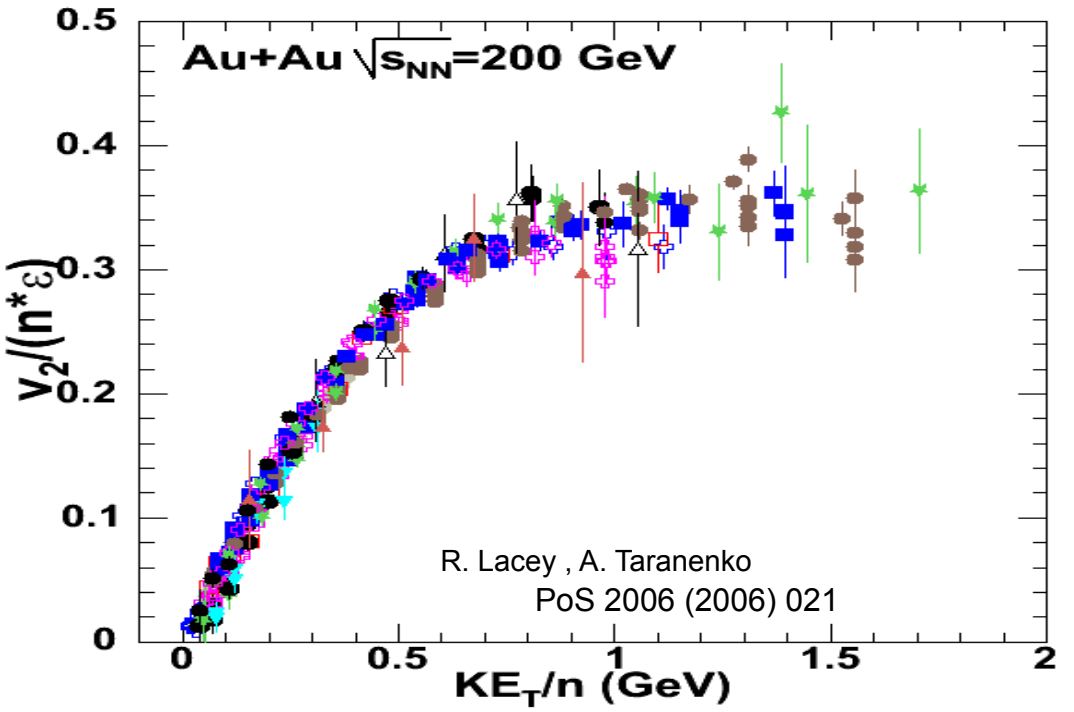
- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $p + \bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- d : min.bias, 10-50%
- ϕ : 20-60%

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

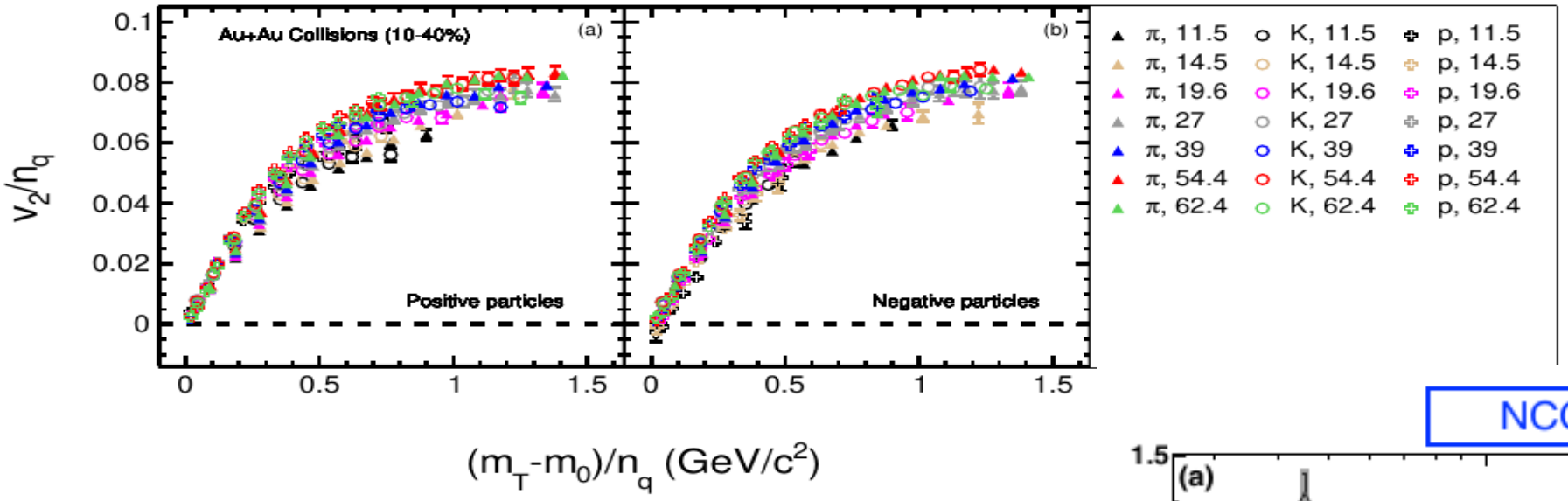
$$KE_T = m\,(\gamma_T - 1) = m_T - m$$

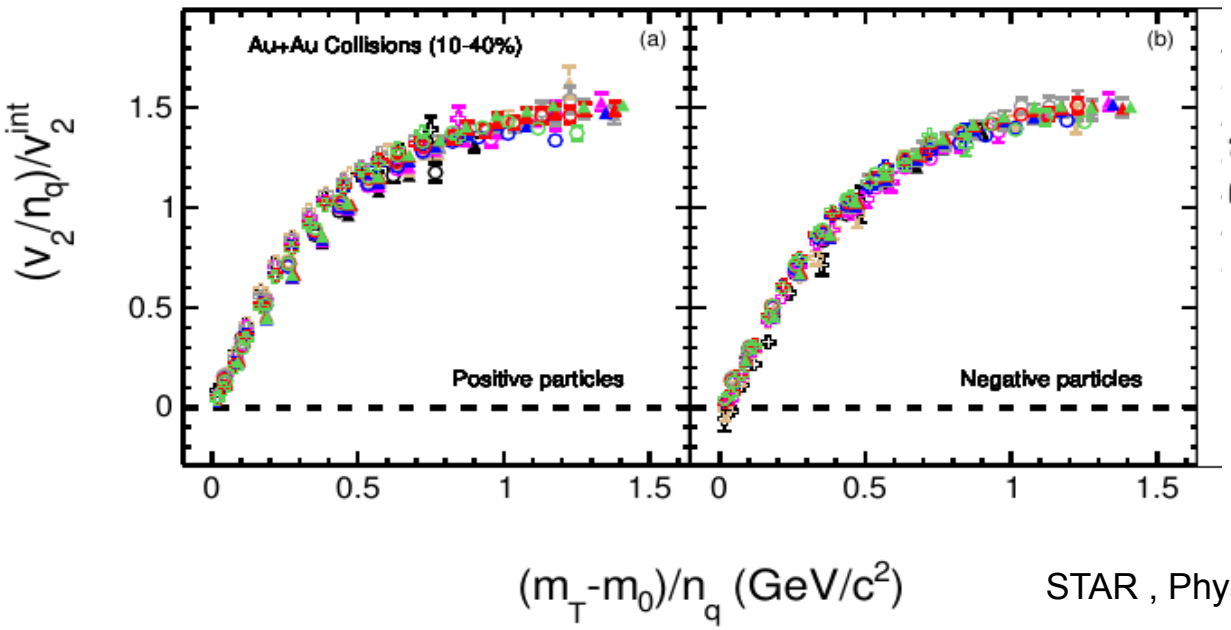




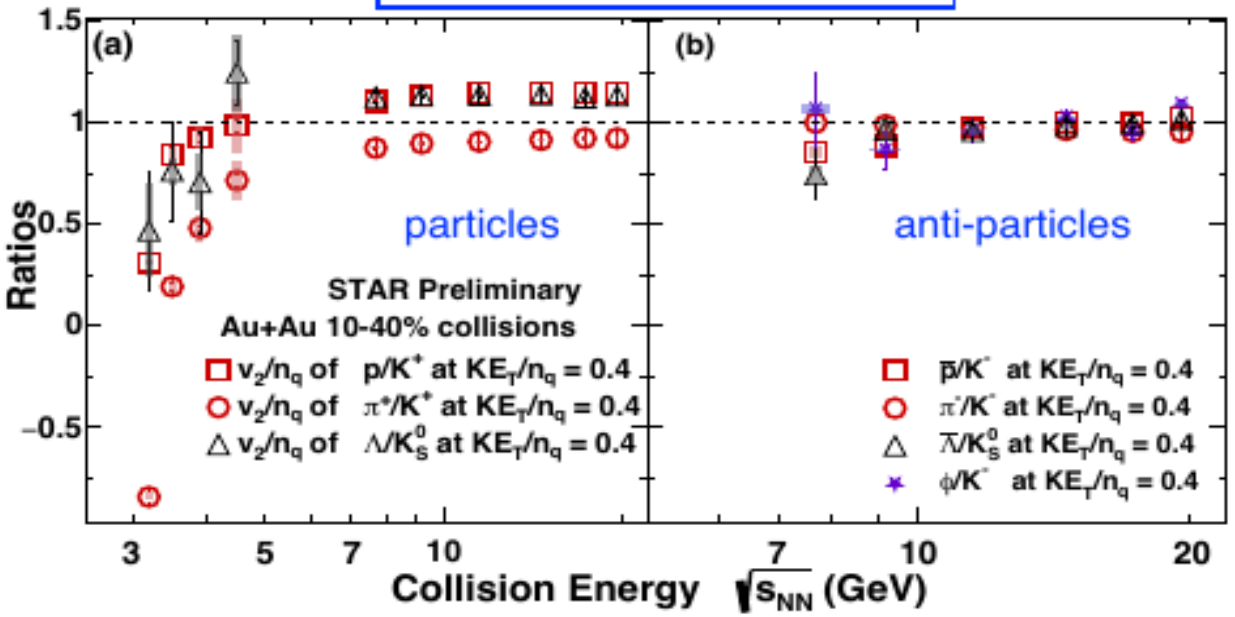
n=2 for mesons and
n=3 for baryons

Elliptic flow from STAR BES program





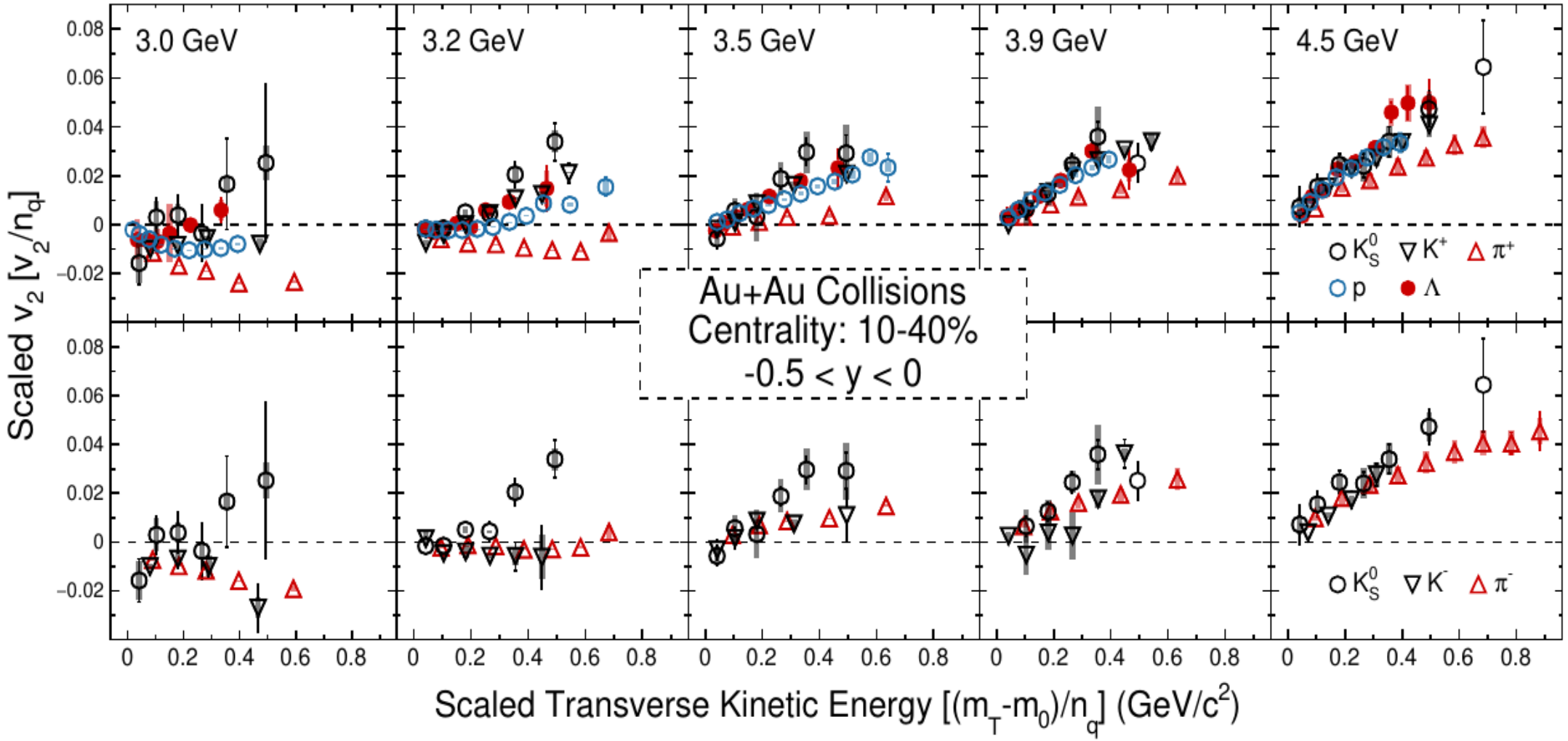
NCQ scaled v_2 ratios



STAR , Phys Rev C93, 14907 (2016)

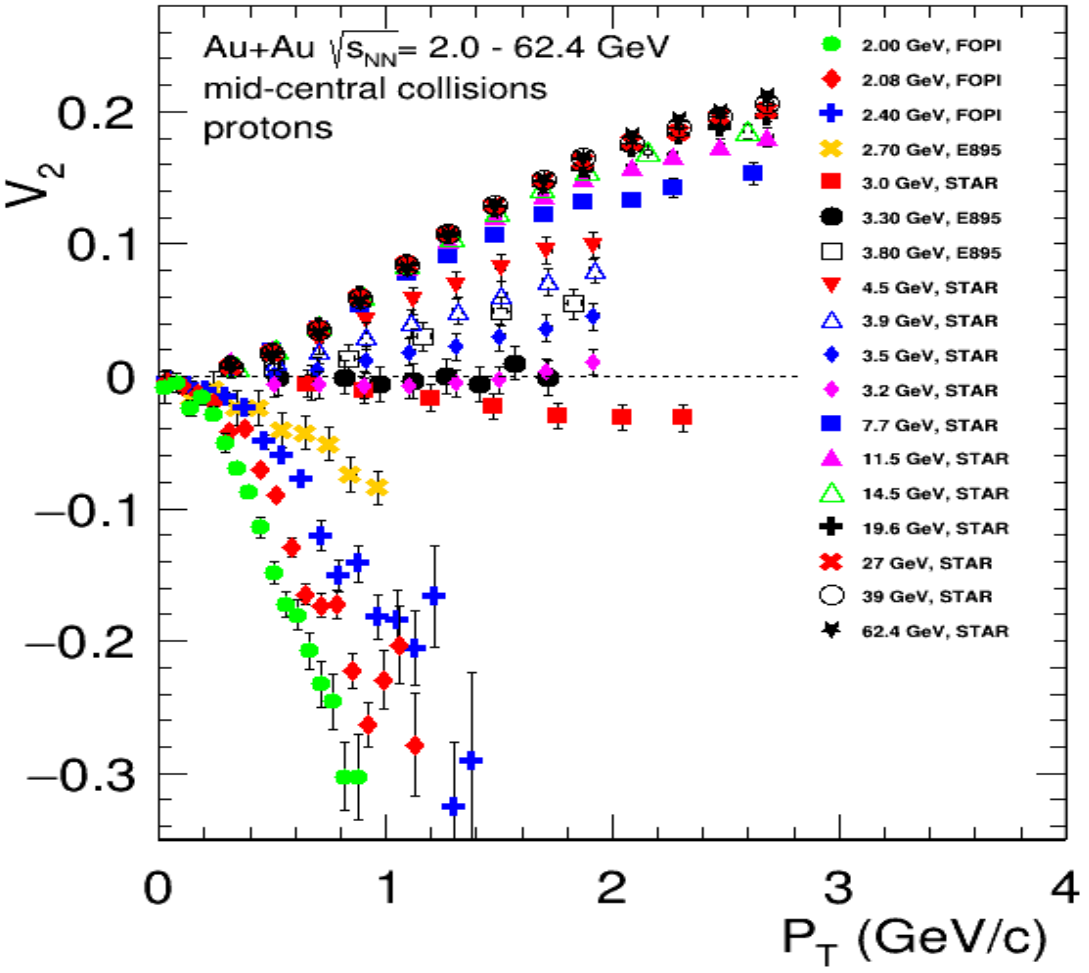
Anisotropic Flow at RHIC BES

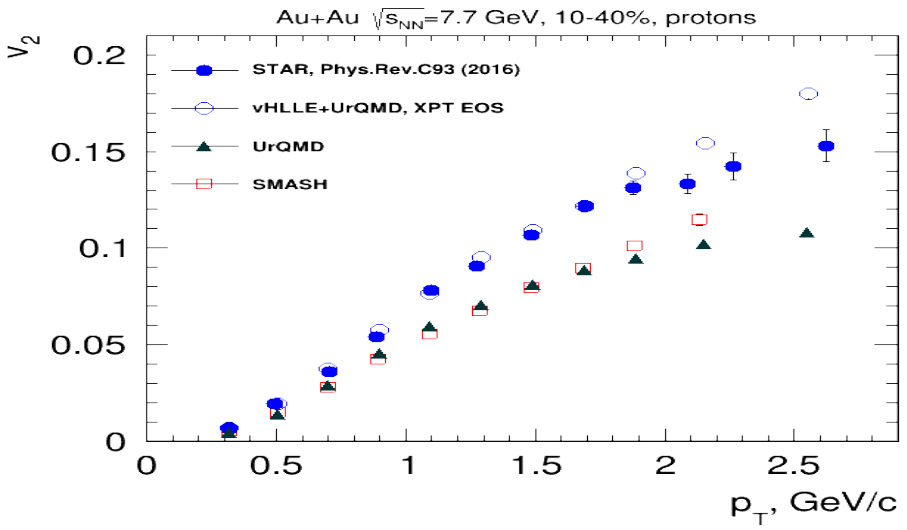
Li-Ke Liu (CCNU), STAR Collaboration, CPOD 2024

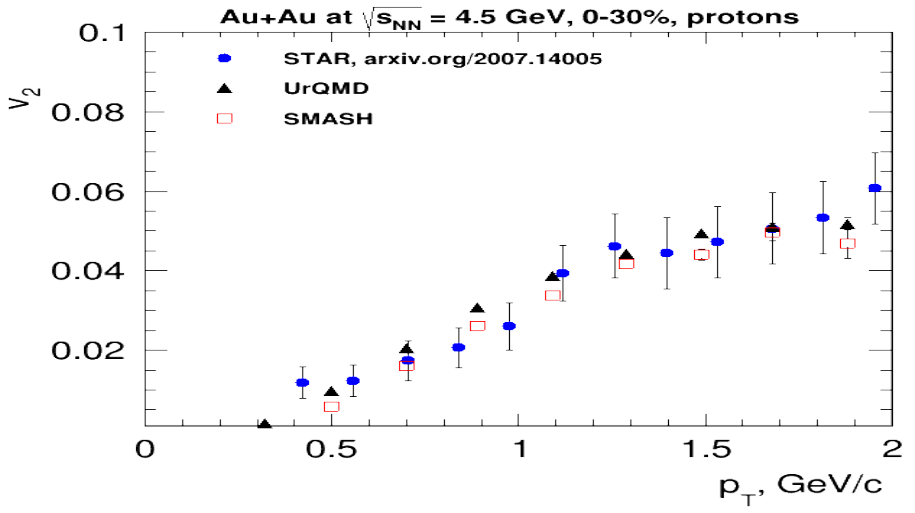


At high energies, data follows NCQ scaling, indicating partonic collectivity???
NCQ scaling for v2 breaks completely at 3.5 GeV and below,

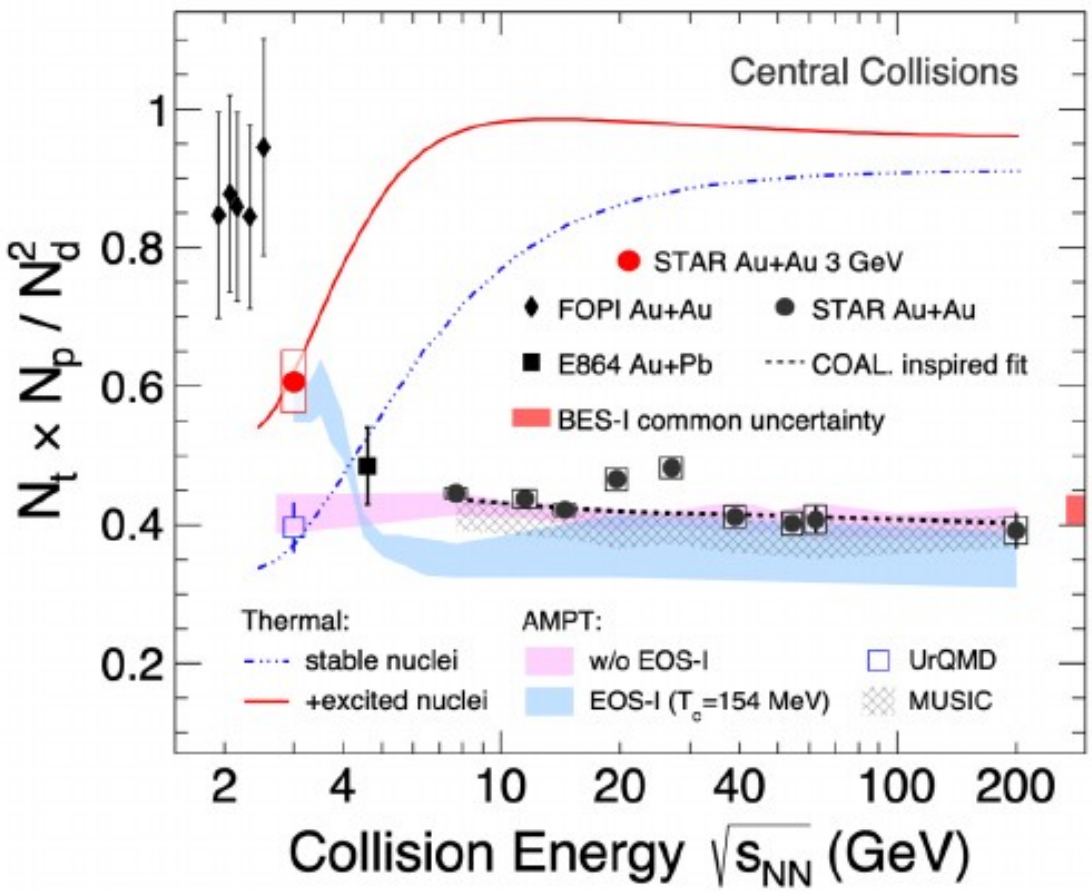
Beam Energy Dependence of Elliptic Flow (v_2)







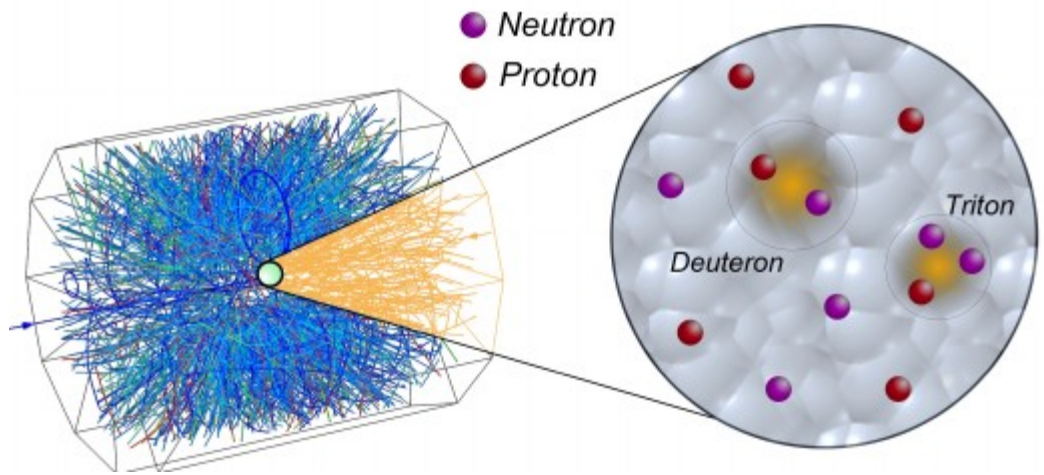
- Strong energy dependence of v_2 at $\sqrt{s_{NN}}$ = 2.4-7 GeV



Phys. Rev. Lett. 130 (2023) 202301
Phys.Rev.C 110 (2024) 5, 054911

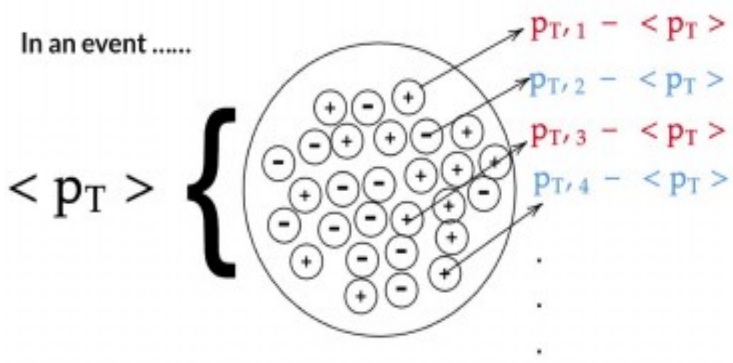
$$\frac{t \times p}{d^2} = g(1 + \Delta n)$$

Δn : Neutron Density Fluctuation

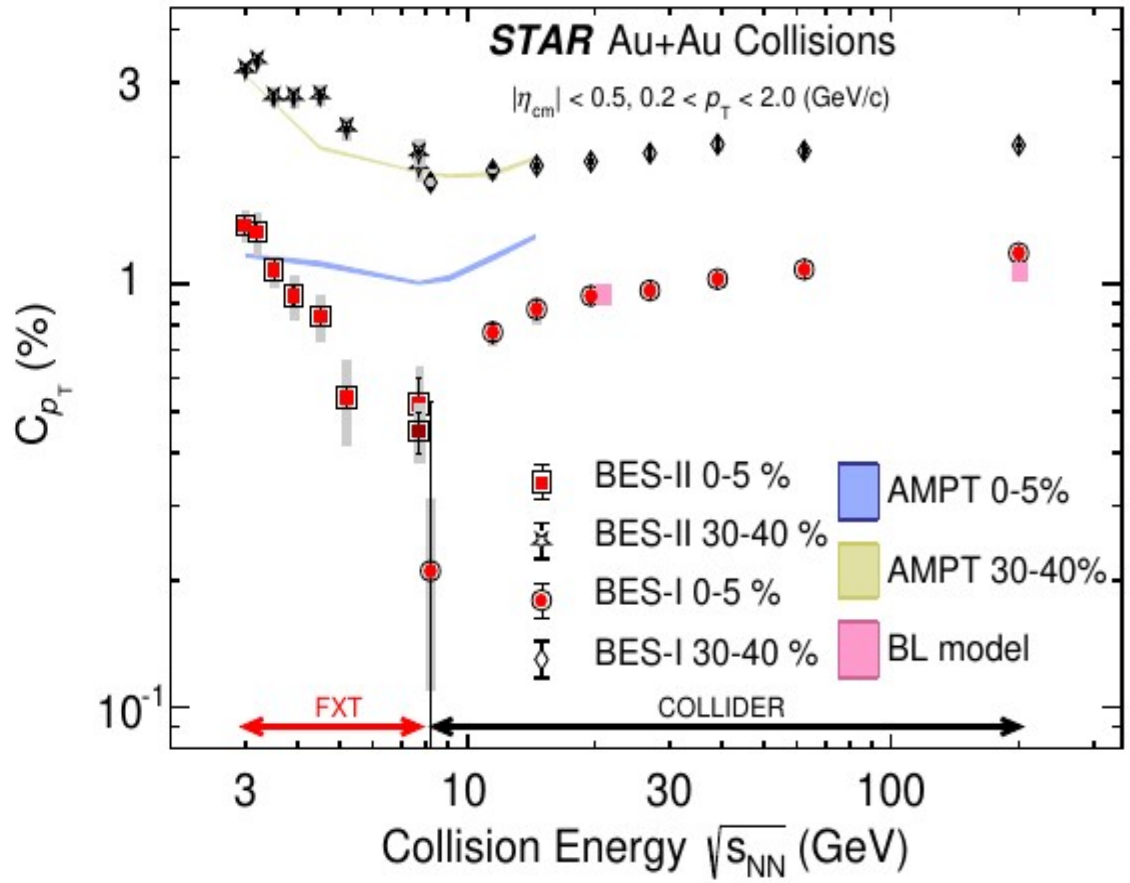


- Yield ratios is sensitive to neutron density fluctuations
- In central collisions, non-monotonic behavior around 19.6 and 27 GeV observed
- $\sqrt{s_{NN}}$ =3.2-27 GeV compound ratio from STAR BES-II is in progress.

p_T Correlations at 3–200 GeV



S. Gavin, PRL 92, 162301 (2004)
V. Kovalenko, V. Vechernin, arXiv:1502.01758
B. Schenke et al., PRC 102, 034905 (2020)
L.-M. Liu et al., arXiv:2511.11094



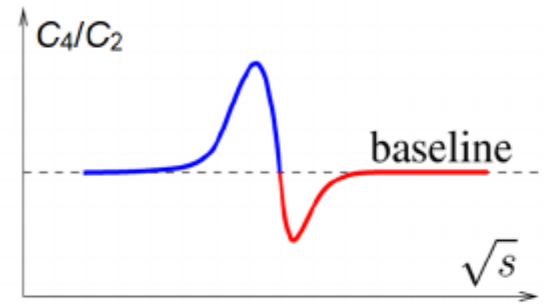
- $\langle p_T \rangle$ correlator $C_{p_T} = \sqrt{\langle \Delta p_{T,i} \Delta p_{T,j} \rangle} \Big/ \langle\langle p_T \rangle\rangle$
- Robust against volume fluctuations
- Sensitive to CP signatures
  - Temperature fluctuations, partonic dynamic correlations…

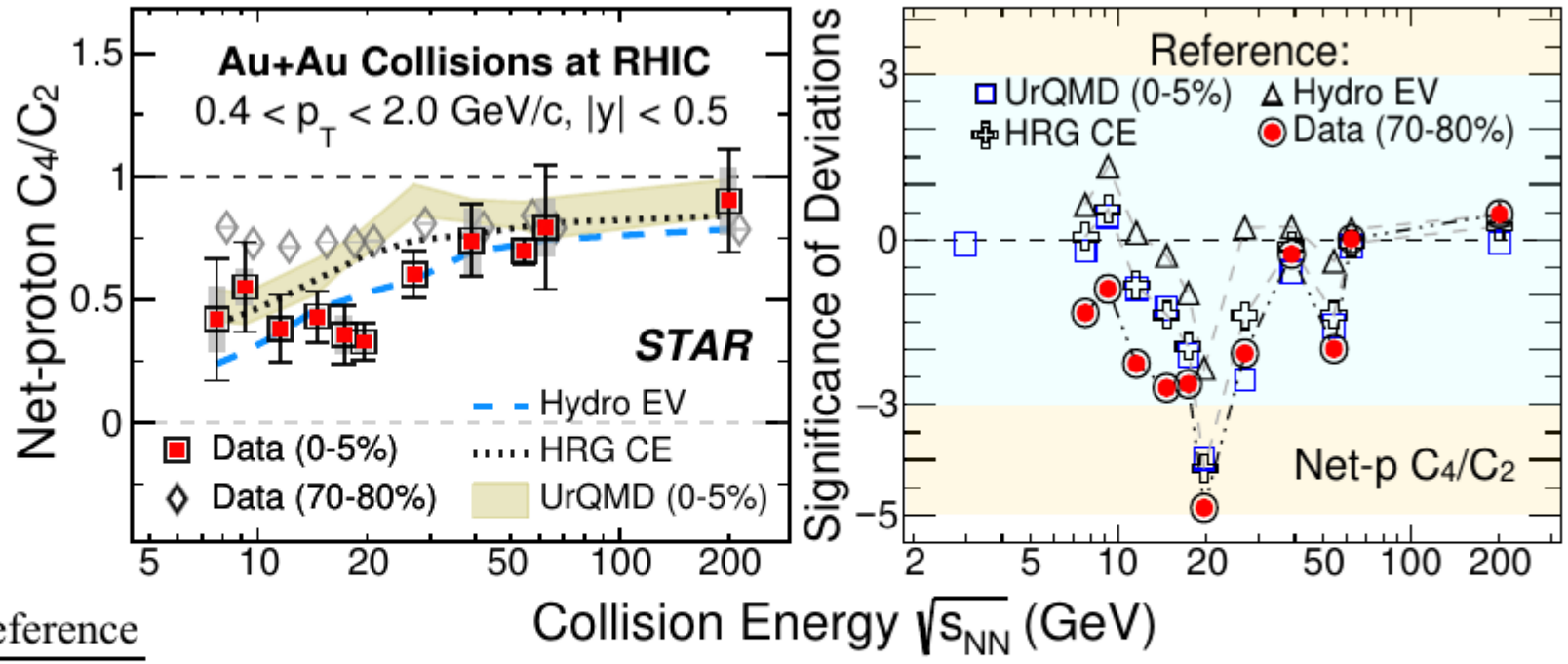
STAR, arXiv:2604.06434

- Clear non-monotonic energy dependence in central collisions

(Net-)Proton Fluctuations at 7.7–27 GeV (I)

M. A. Stephanov, PRL 107, 052301 (2011)





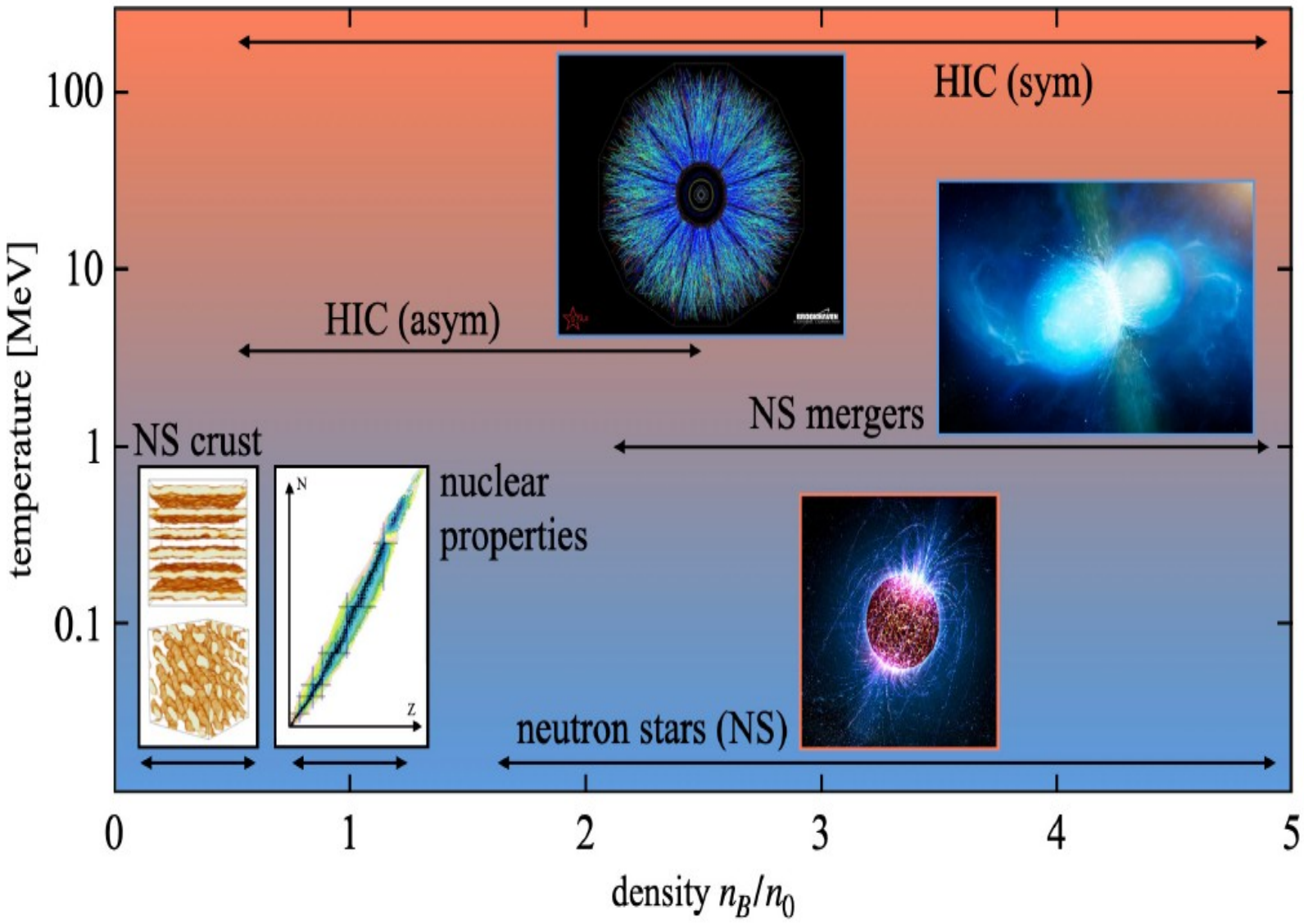
- C_n: nth-order cumulant
- $\text{Significance} = \dfrac{\text{0–5\% data} - \text{reference}}{\sqrt{\sigma^2_{\text{0–5\% data}} + \sigma^2_{\text{reference}}}}$

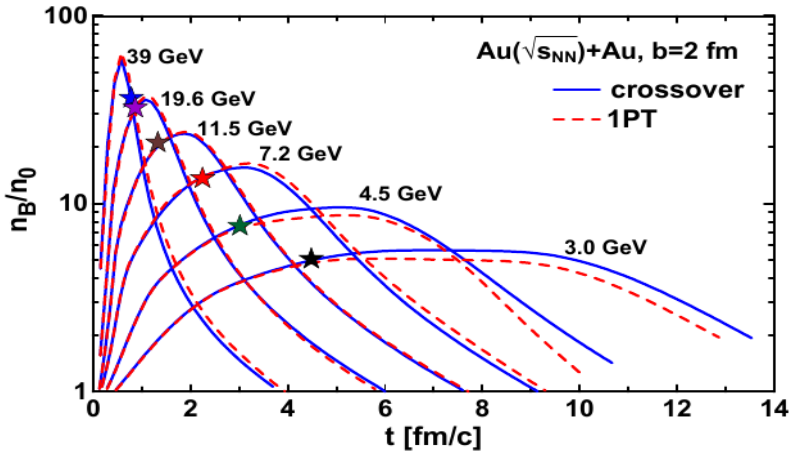
STAR, PRL 135, 142301 (2025)

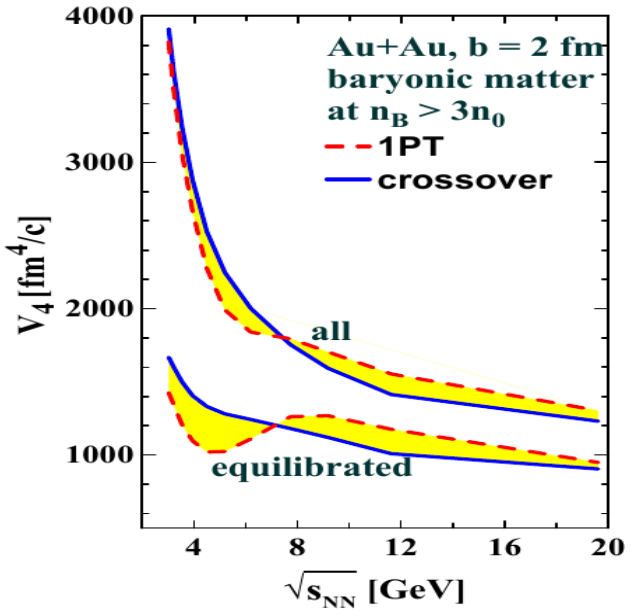
- Precision measurement of (net-)proton fluctuations in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 7.7$–$27$ GeV
- Central C_4/C_2 shows a maximum deviation of 2–5σ from non-CP references (models and peripheral data) at 19.6 GeV

Dense Nuclear Matter

Yuri B. Ivanov, PRC 113 (2026), 6







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

The Nuclear Equation of State (EOS)

$$E/A(n,\delta) = E/A(n,0) + S(n)\delta^2 + ... \quad \text{with}$$

isospin asymmetry $\delta=(n_p-n_n)/n$

baryon density

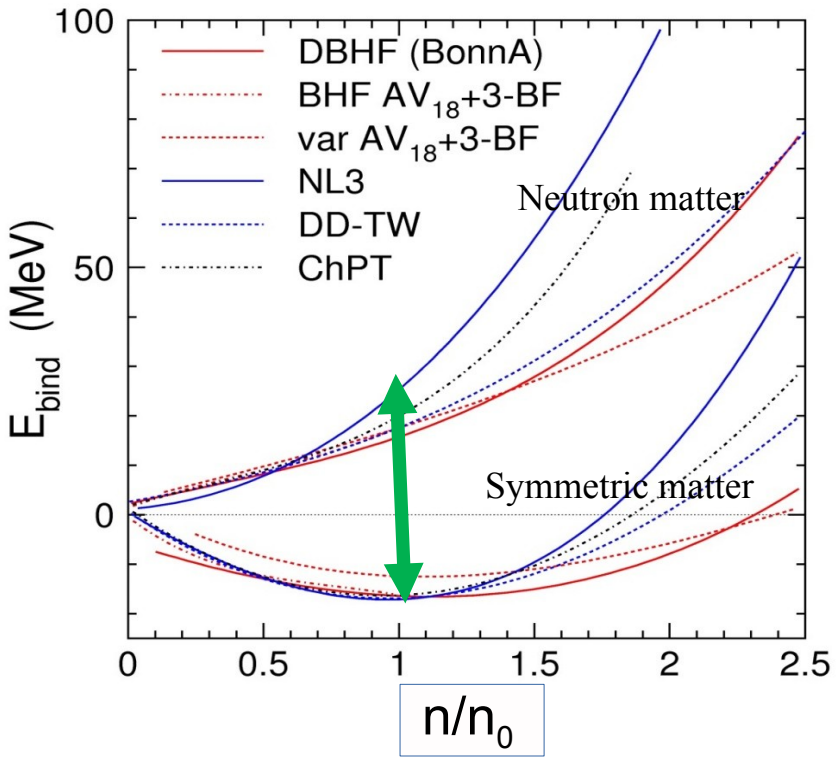
energy of symmetric nuclear matter

$$E/A(n,0) = E_0/A + \frac{1}{18}K_0\ \varepsilon^2 + ...$$

$$\varepsilon = \frac{n-n_0}{n_0}$$

symmetry energy

$$S(n) = S_0 + \frac{1}{3}L\varepsilon + \frac{1}{18}K_{sym}\ \varepsilon^2 + ...$$



$$n_0 = 0.16 \pm 0.01\ \text{fm}^{-3}$$

$$E_0/A = -16 \pm 1.0\ \text{MeV}$$

binding energy per nucleon at saturation density n_0

$$S_0 \equiv \frac{1}{2}\left(\frac{\partial^2 (E/A)(n,\delta)}{\partial \delta^2}\right)_{n=n_0,\delta=0}$$

symmetry energy at n_0

$$L \equiv 3n_0\left(\frac{\partial S(n)}{\partial n}\right)_{n=n_0}$$

$$K_0 \equiv 9n_0^2\left(\frac{\partial^2 (E/A)(n,\delta)}{\partial n^2}\right)_{n=n_0,\delta=0}$$

incompressibility at n_0

$$K_{sym} \equiv 9n_0^2\left(\frac{\partial^2 S(n)}{\partial n^2}\right)_{n=n_0}$$

EOS describes the relation between density (n), pressure (P), temperature (T), energy (E), and isospin asymmetry $\delta=(n_p-n_n)/n$

Relativistic Heavy-Ion Collisions: Constraints on Nuclear Equation of State

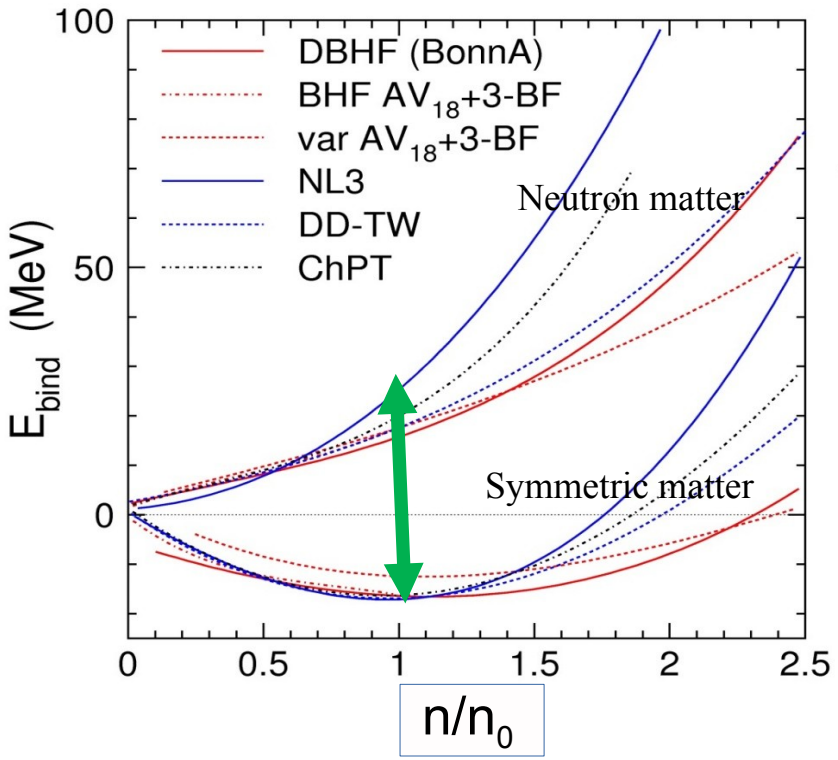
$$E/A(n,\delta) = E/A(n,0) + S(n)\delta^2 + ... \quad \text{with}$$

baryon density

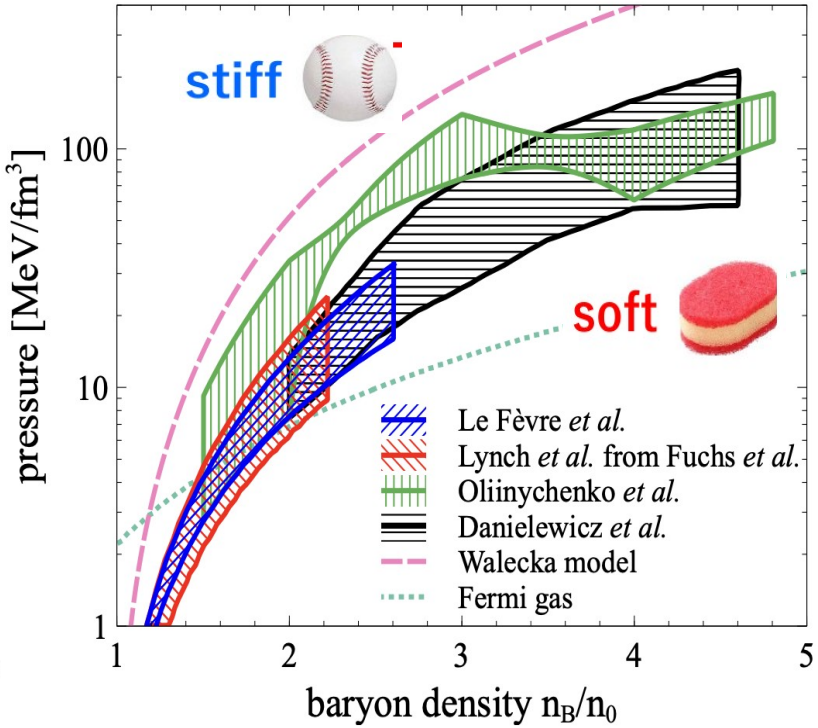
isospin asymmetry $\delta=(n_p-n_n)/n$

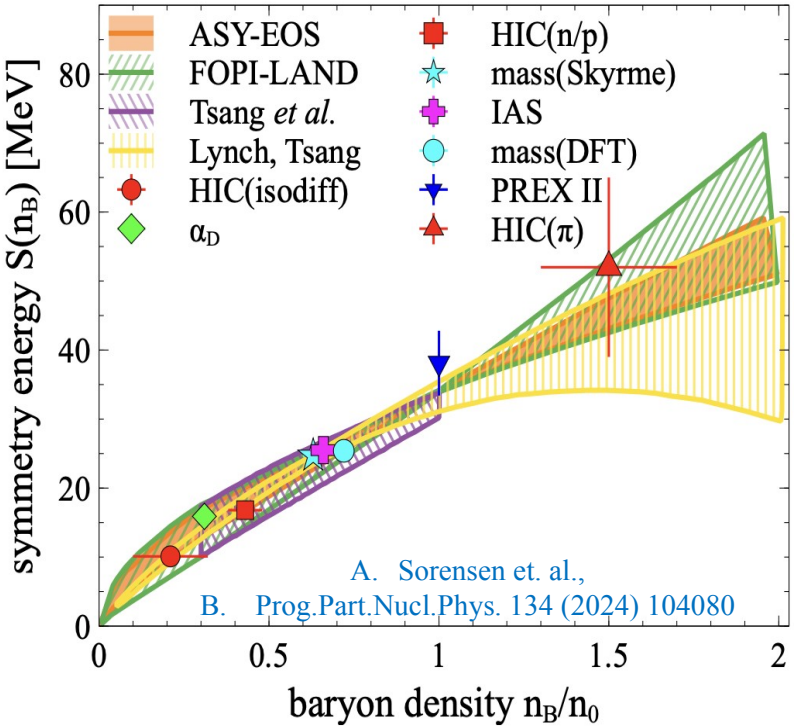
Symmetric nuclear matter

Symmetry energy



Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

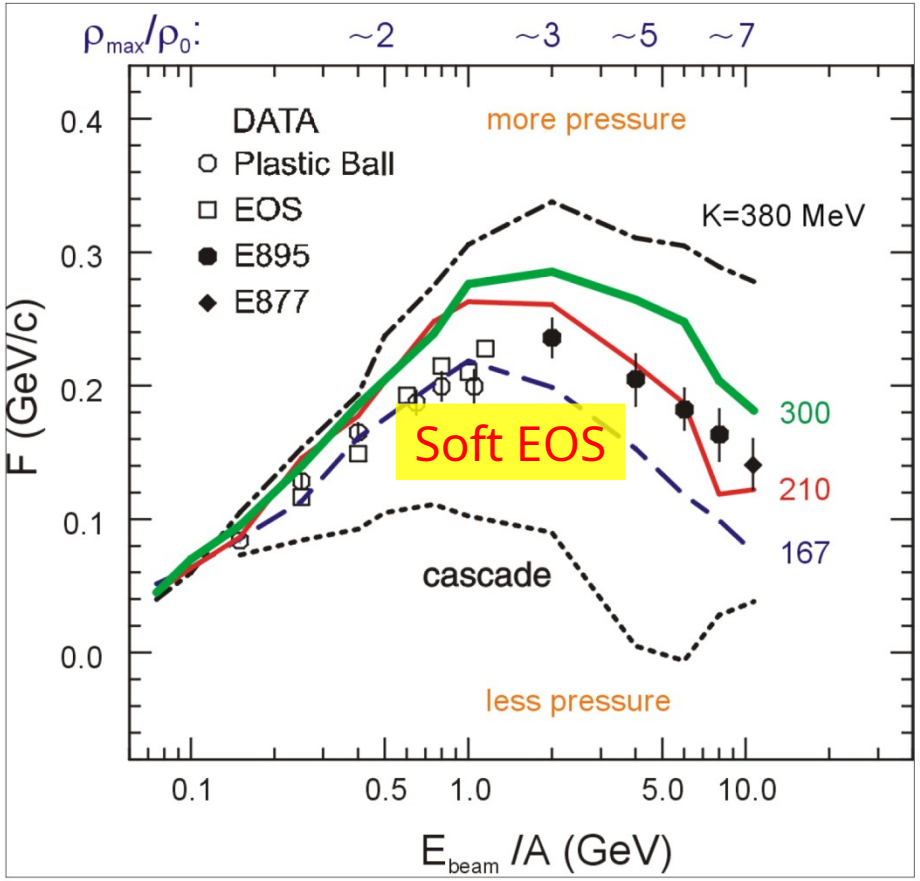


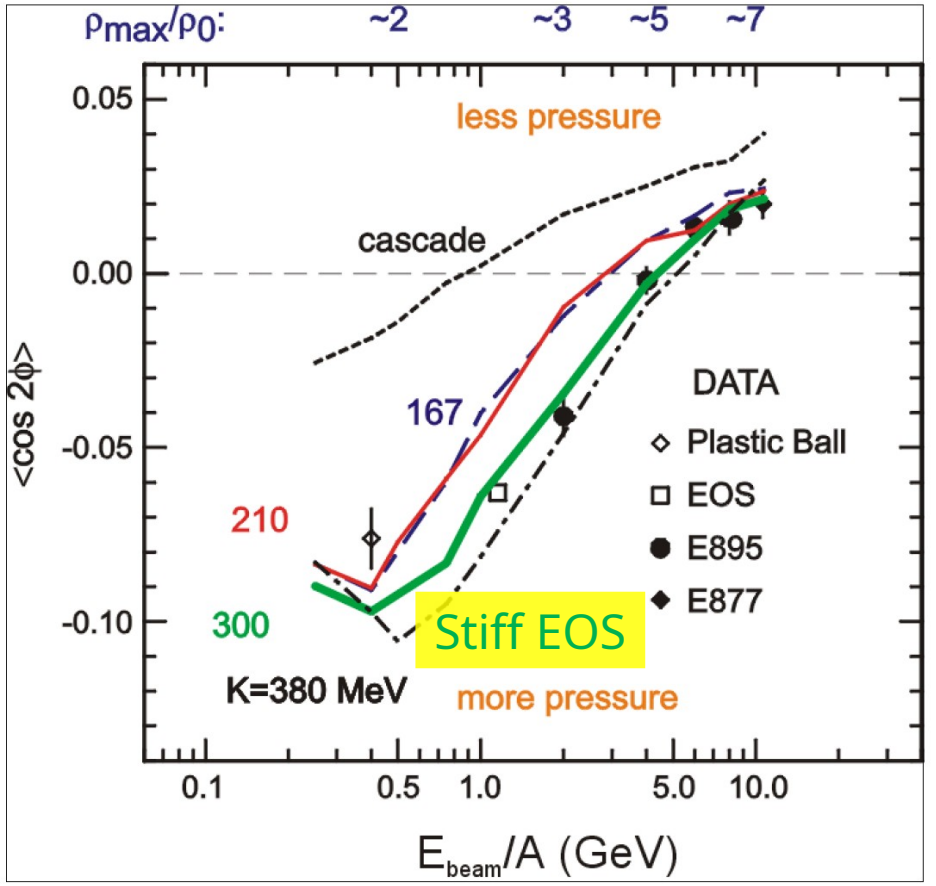


EOS describes the relation between density (n), pressure (P), temperature (T), energy (E), and isospin asymmetry $\delta=(n_p-n_n)/n$

Nuclear incompressibility from collective proton flow

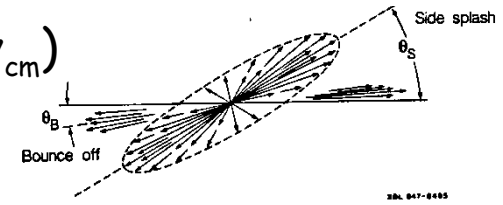
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



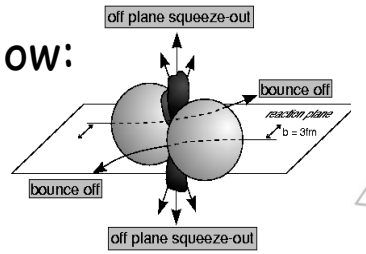


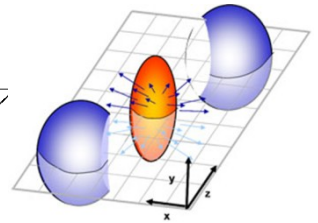
Transverse in-plane flow:

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



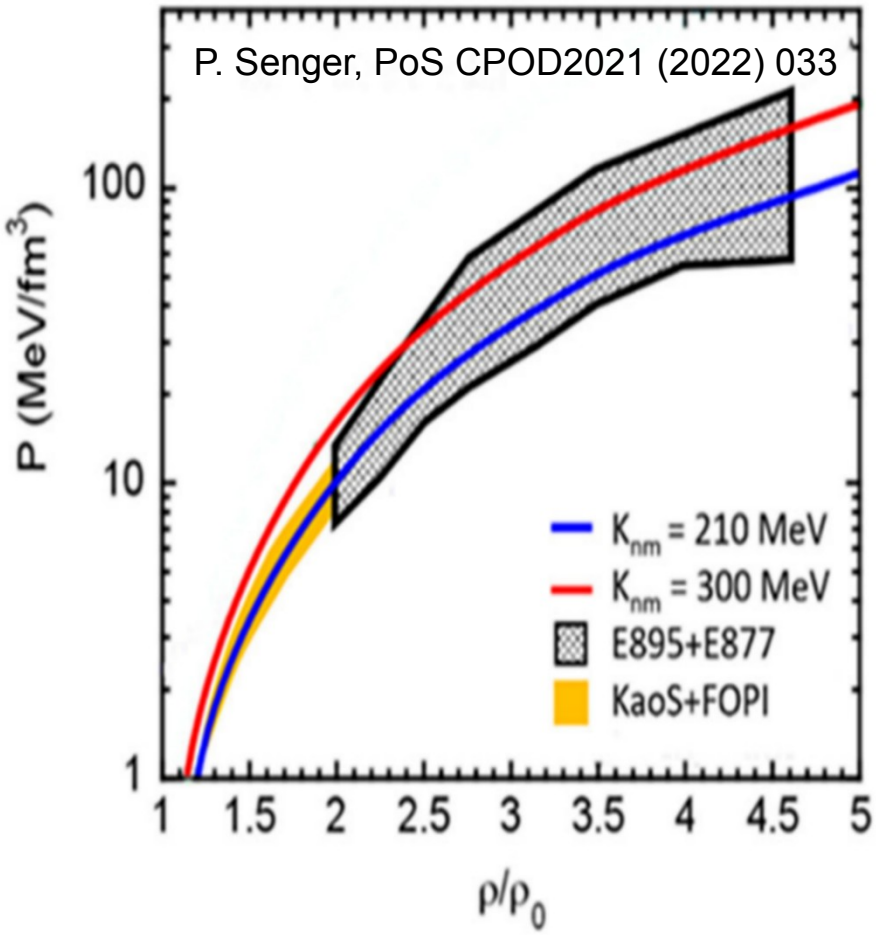
Elliptic flow:

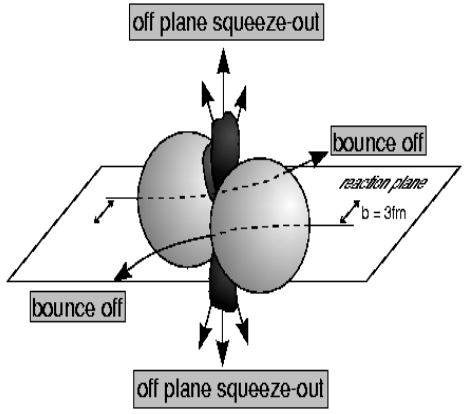


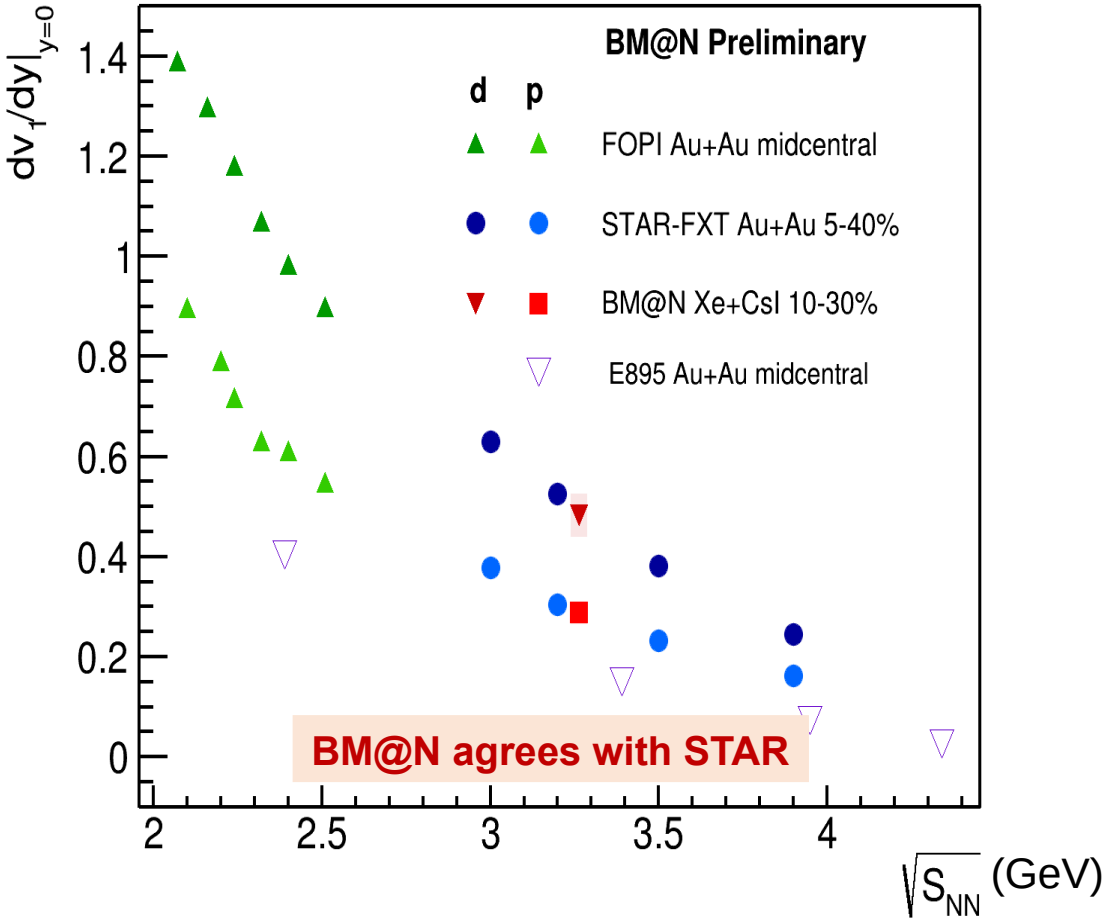


$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

Directed flow of protons and EOS of symmetric matter





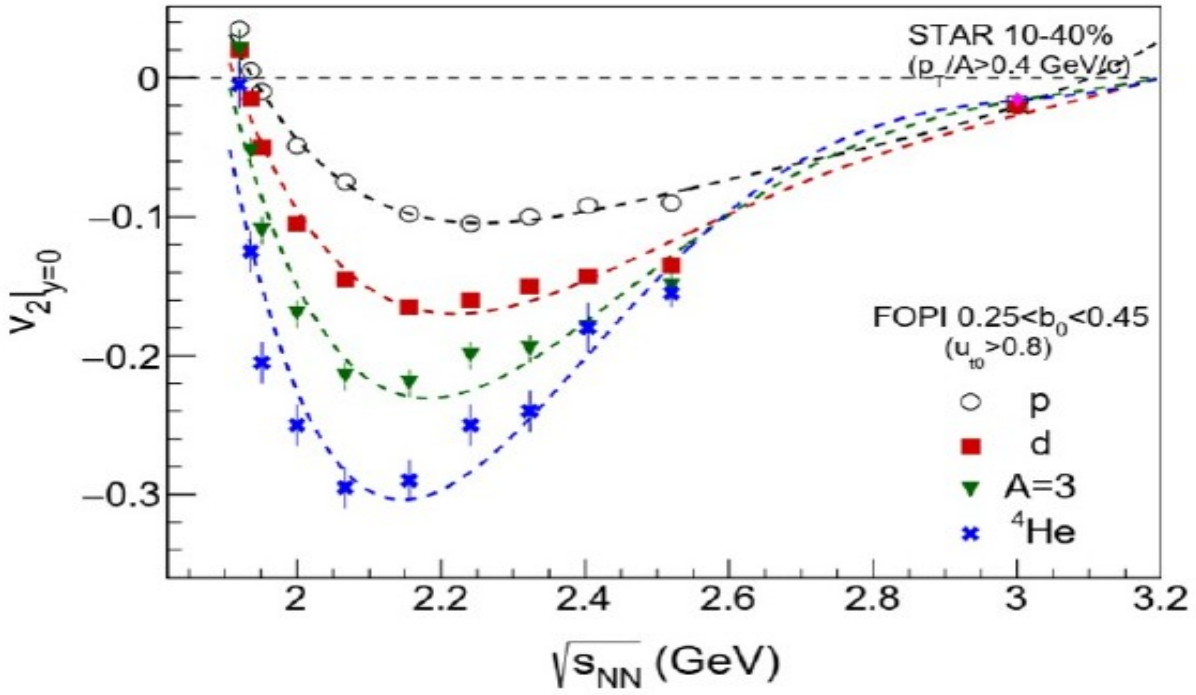


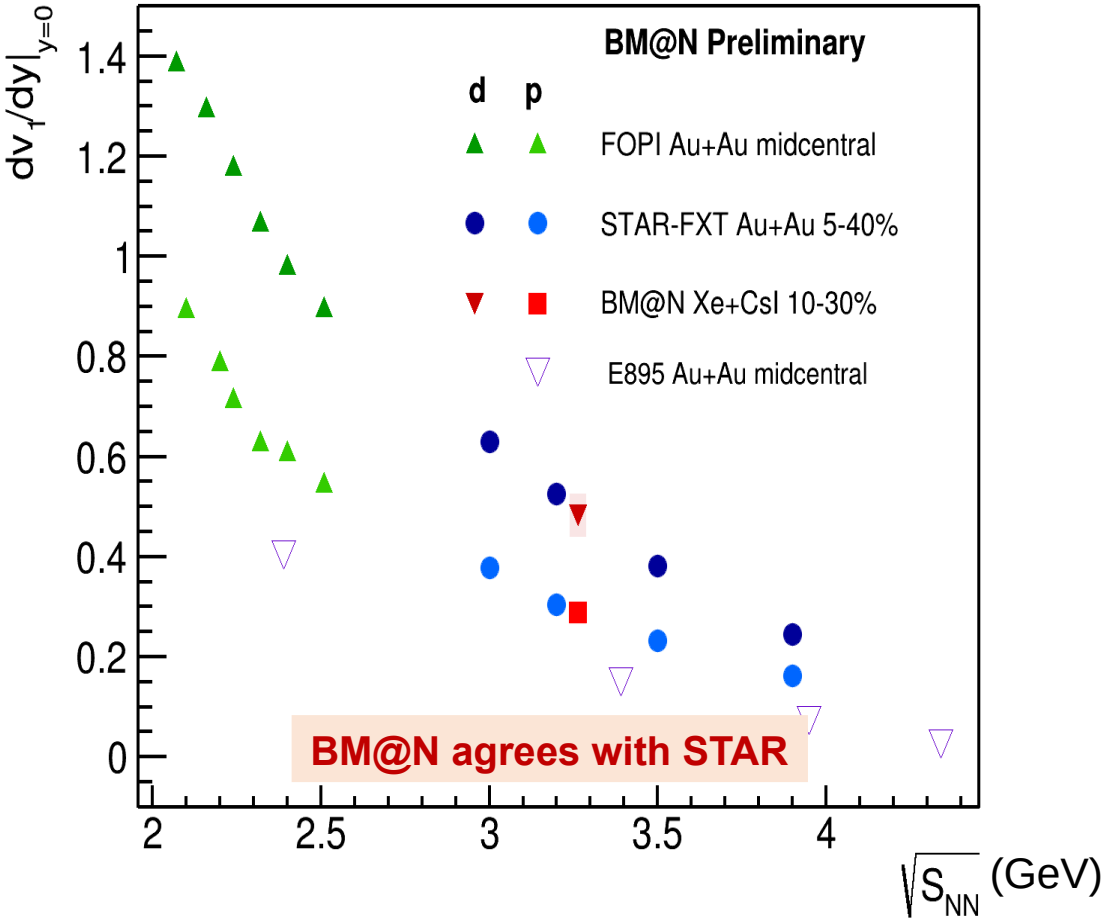
Nuclear incompressibility from collective proton flow

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

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

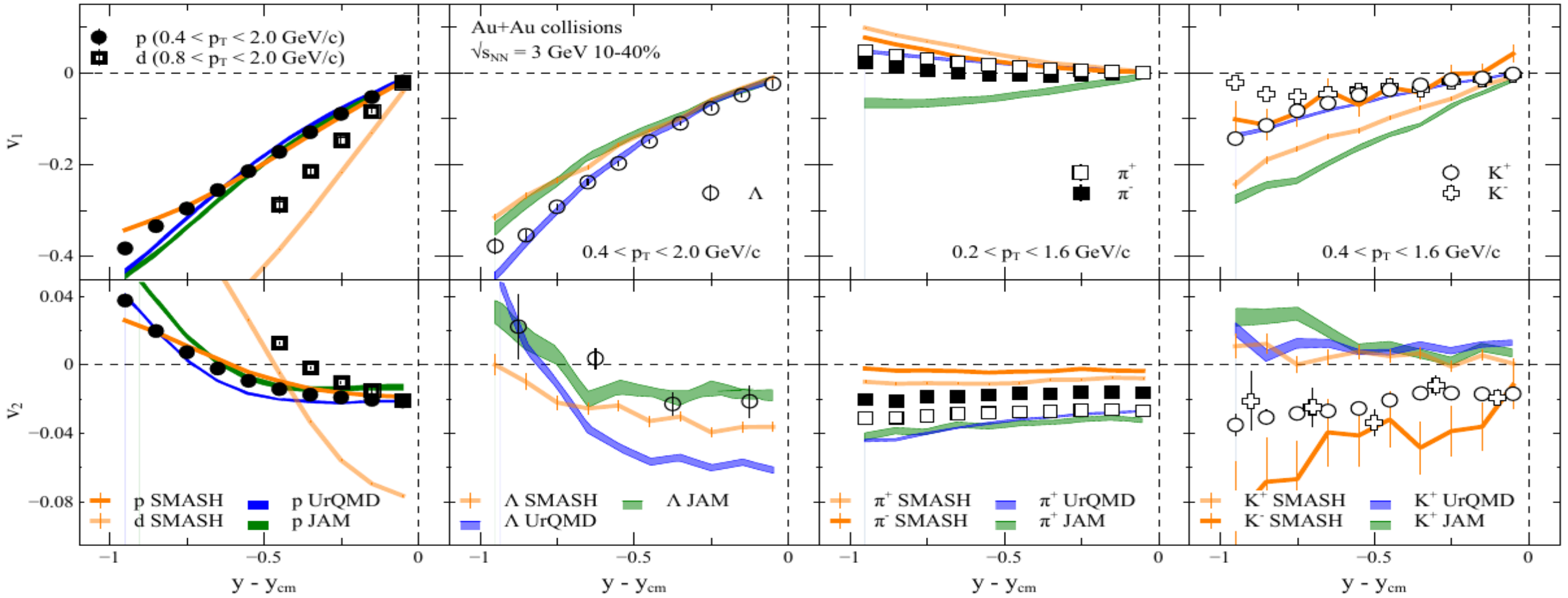
Directed and elliptic flow and EOS of symmetric matter





Describing proton flow is not enough

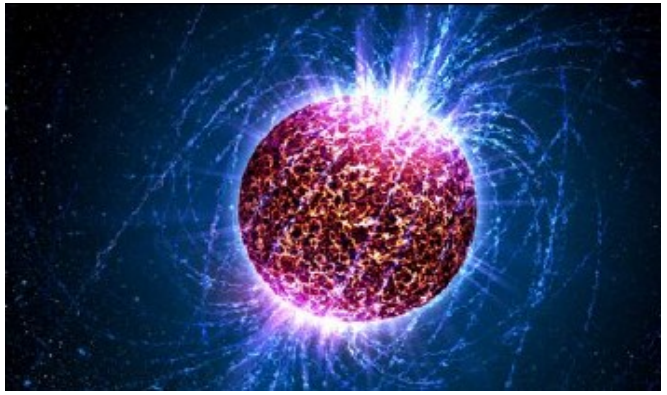
Prog.Part.Nucl.Phys. 134 (2024) 104080



Strange baryons are not well described
— the results may depend on:
• nucleon-hyperon and hyperon-hyperon interactions
• in-medium modifications of interactions

Pions and kaons NOT described!
Not very surprising: UrQMD, JAM, and SMASH don't have mean-fields for mesons

Neutron Stars and Big Questions



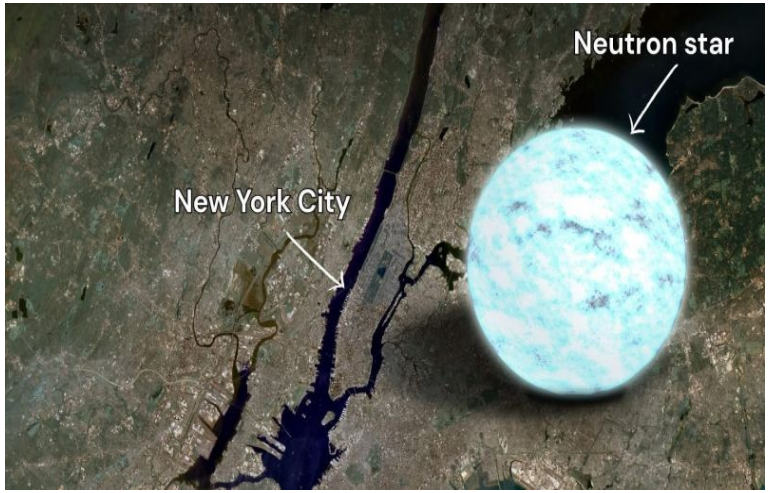
Nature of matter at extreme density?



Origin of cosmic explosions?

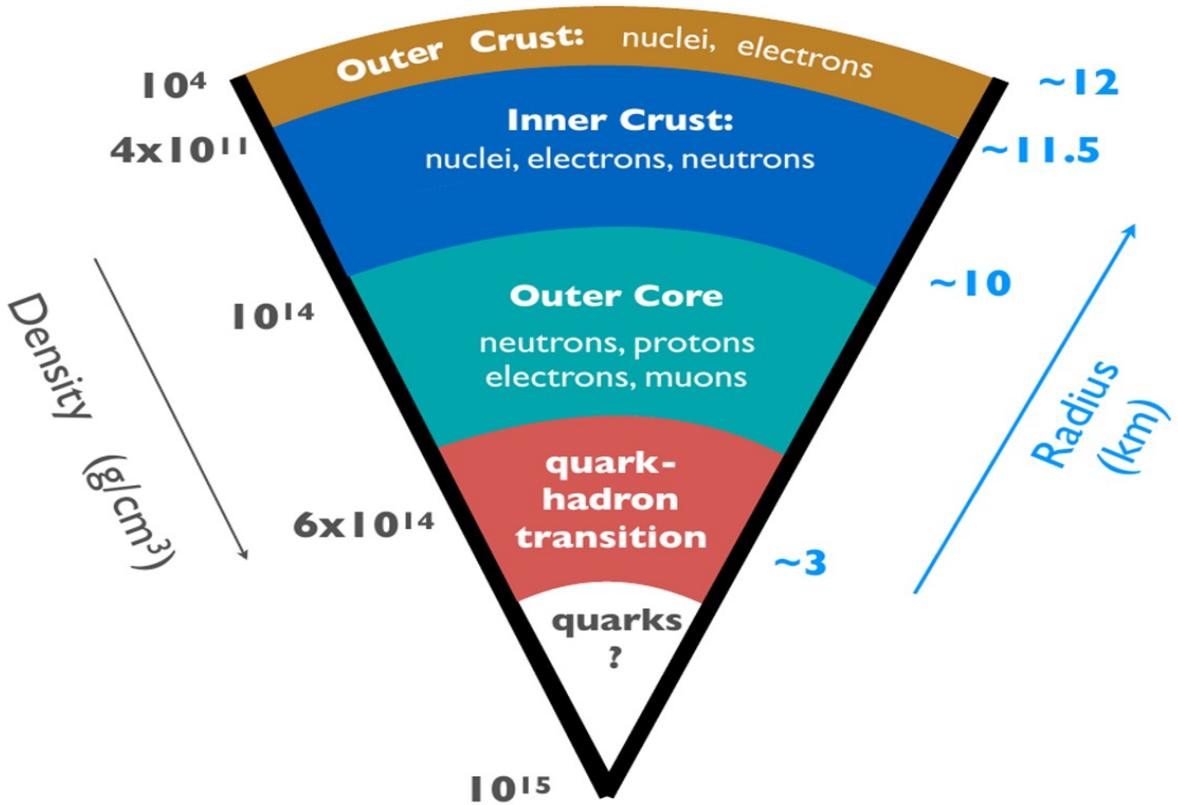


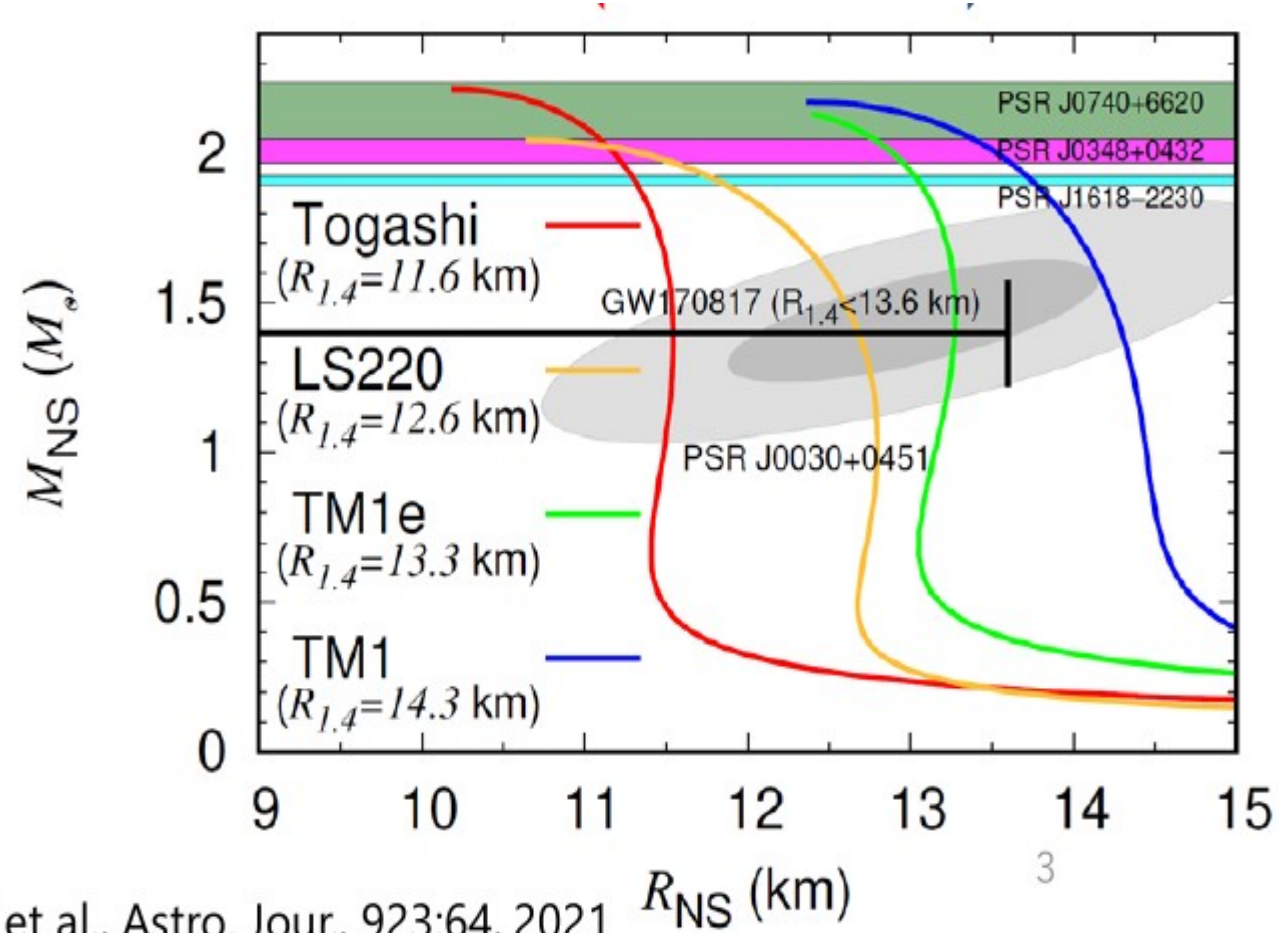
Synthesis of heavy elements?



- usually refer to compact objects with $M \approx 1\text{-}2\ M_\odot$ and $R \approx 10\text{-}12$ Km
- produced in core collapse supernova explosions, usually observed as pulsars
- extreme densities up to $5\text{-}10\ \rho_0$ ($n_0 = 0.16$ fm^{-3} => $\rho_0 = 3 \cdot 10^{14}$ g/cm^3)

Neutron Stars (NS): Mass and Radius



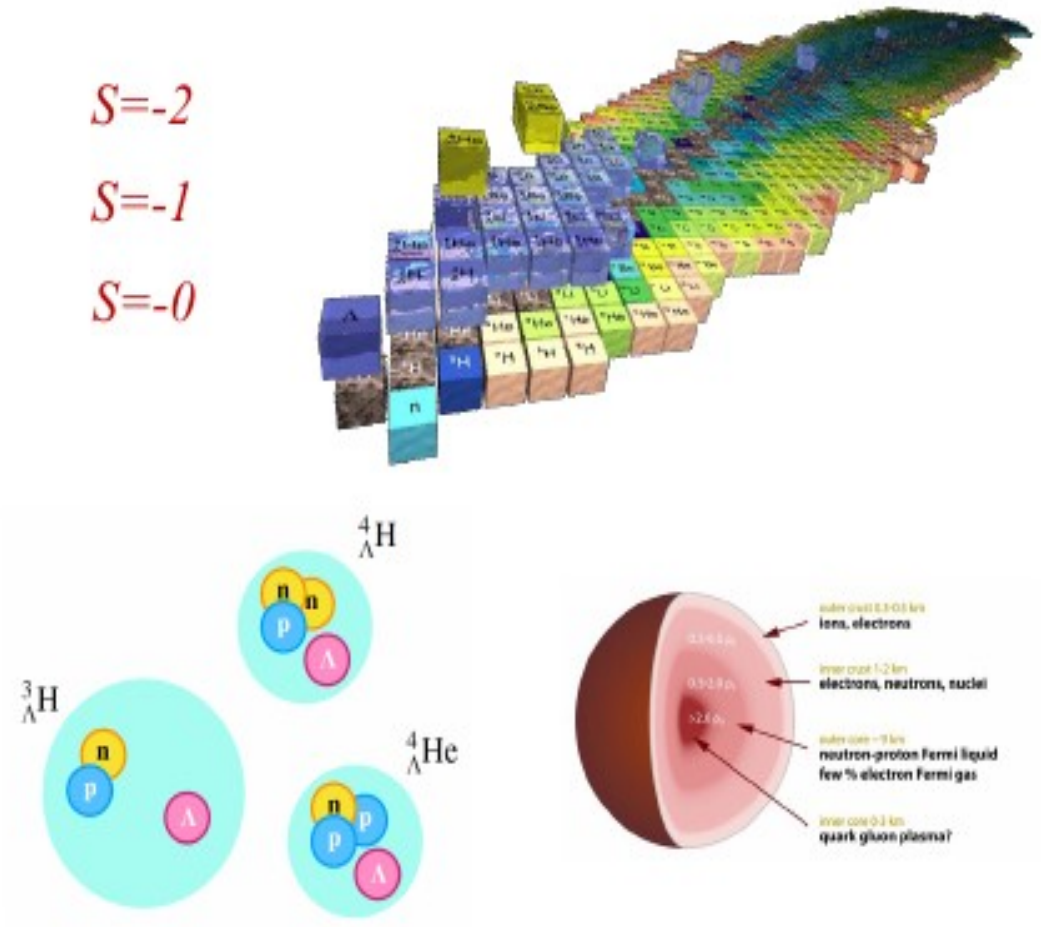


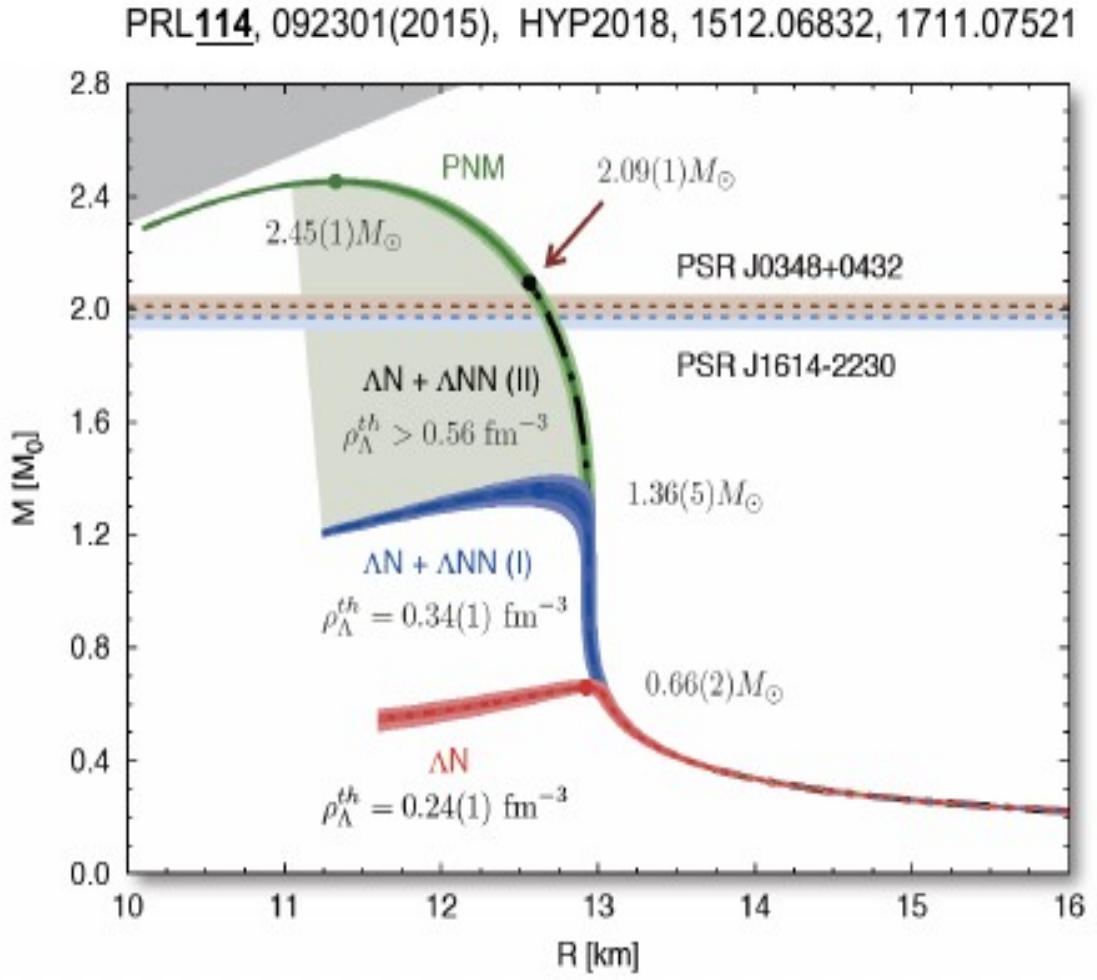
Dohi et al., Astro. Jour., 923:64, 2021

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

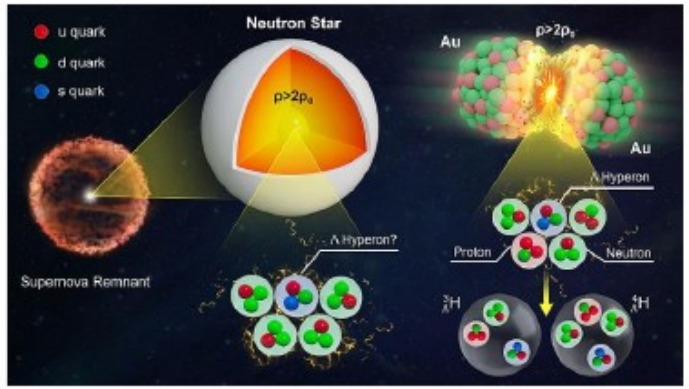
Hyperon and Hyper-Nuclei Production in Heavy-Ion Collisions and Neutron Stars





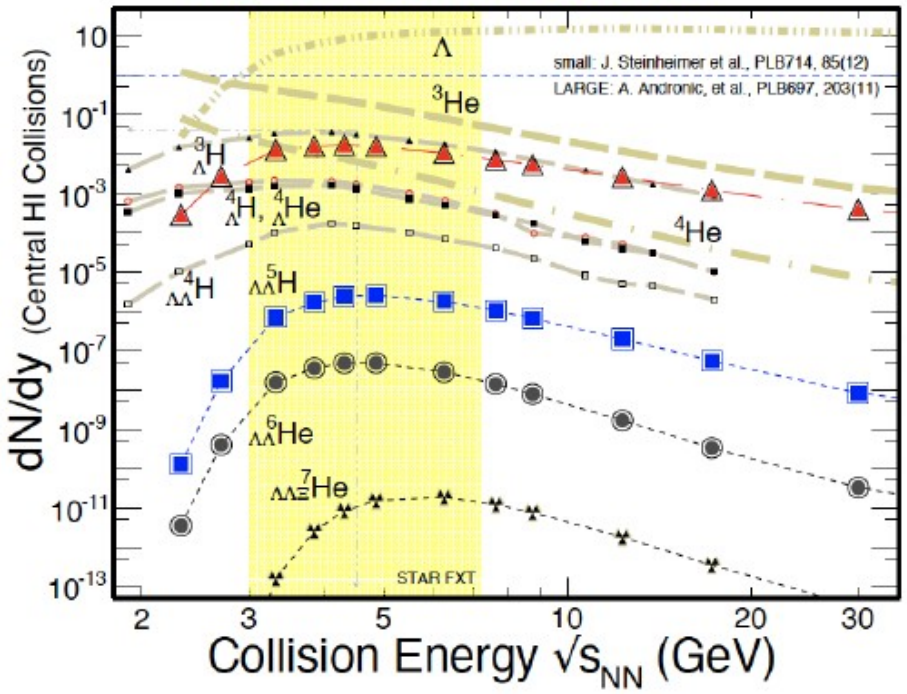
Hyperon and Hyper-Nuclei production provide access to the hyperon–nucleon interactions: NY, YNN, : key to understand the EoS at high baryon density and inner structure of neutron star.

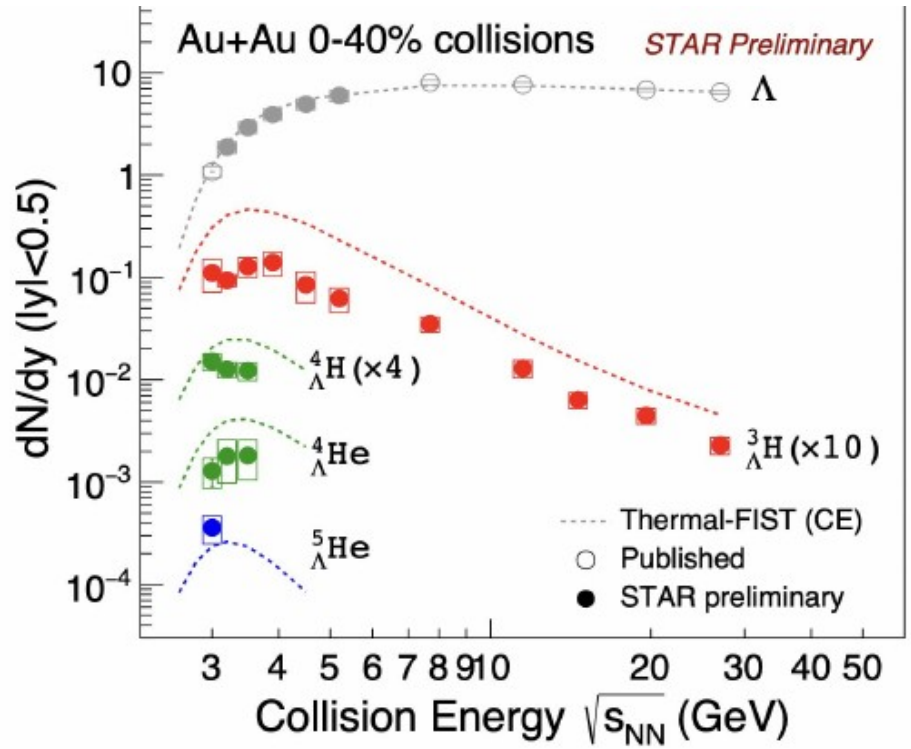
Bonus: hypernuclei production

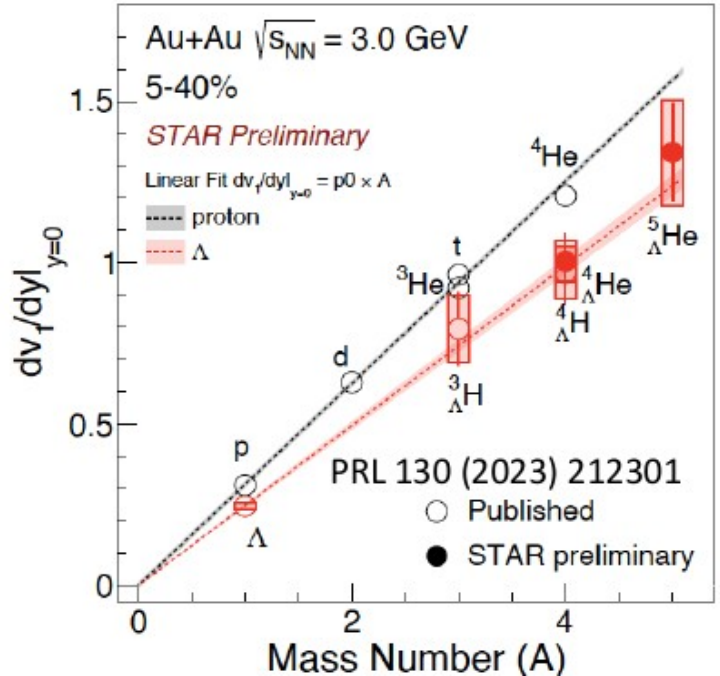


Picture credit:
BNL news article
https://www.bnl.gov/newsroom/news.php?a=121192

Hypernuclei Production





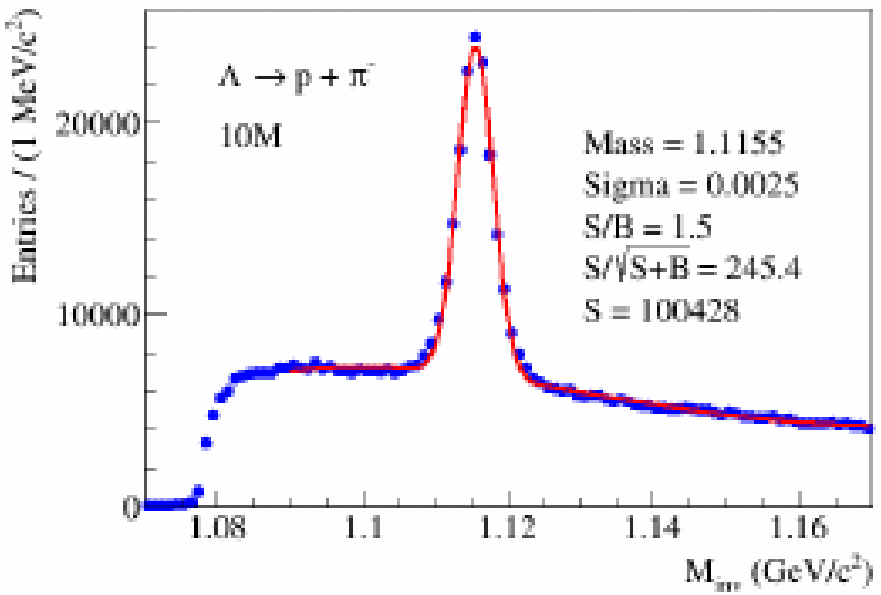


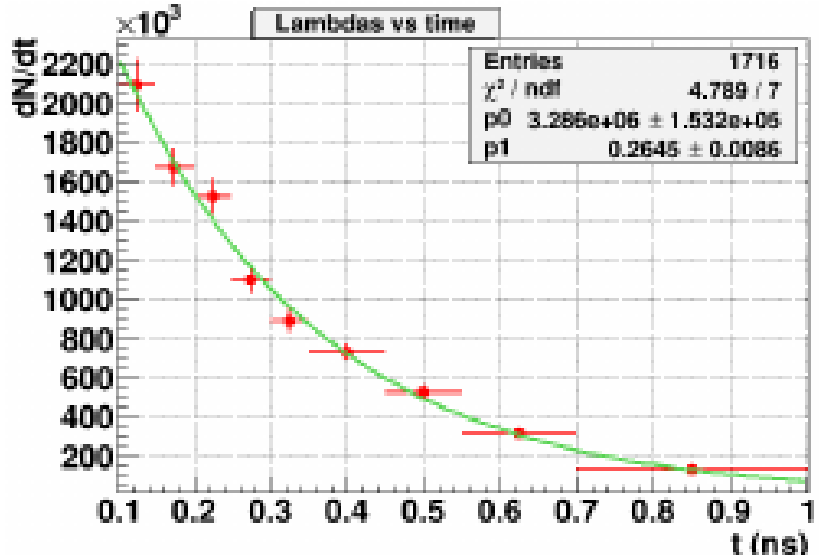
Midrapidity v_1 slopes follow baryon number scaling, implying that coalescence is the dominant production mechanism

Constrain hyperon – nucleon and hyperon-hyperon interaction

Connection to neutron stars

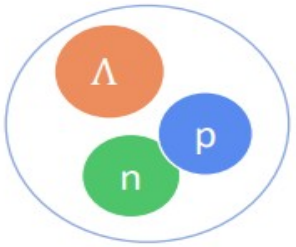
Hyperons and Hyper-Nuclei Production in Xe+Cs(I) at 3.8 AGeV (BM@N)



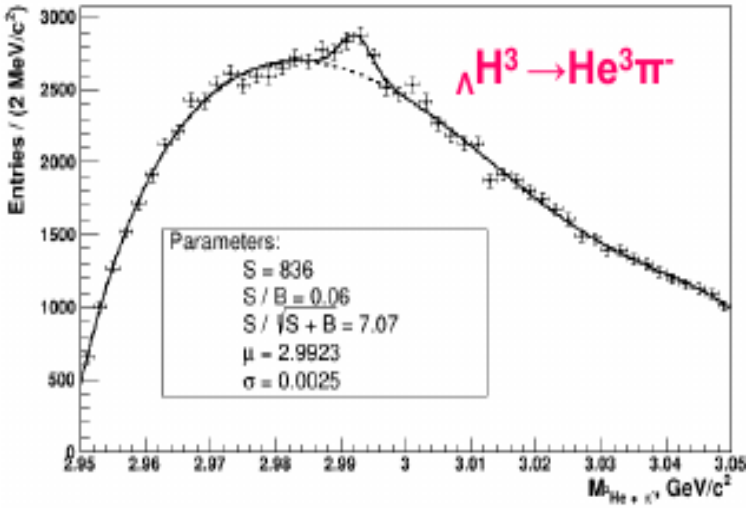




Λ

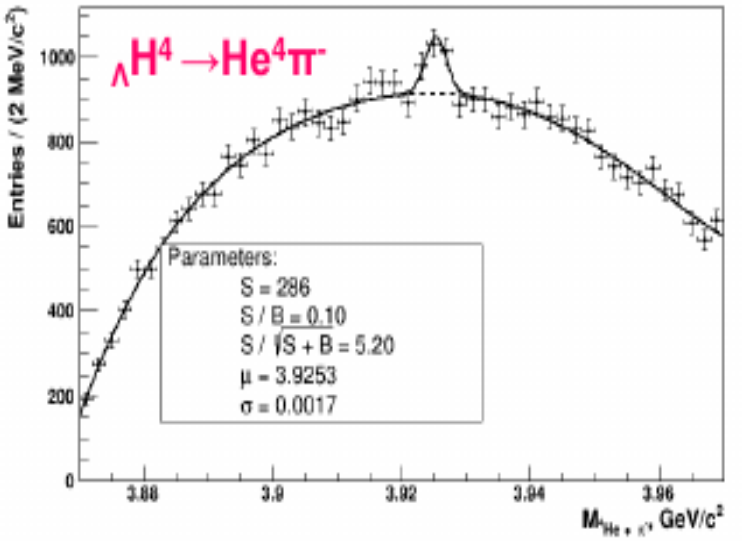


$^{3}_{\Lambda}H$





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



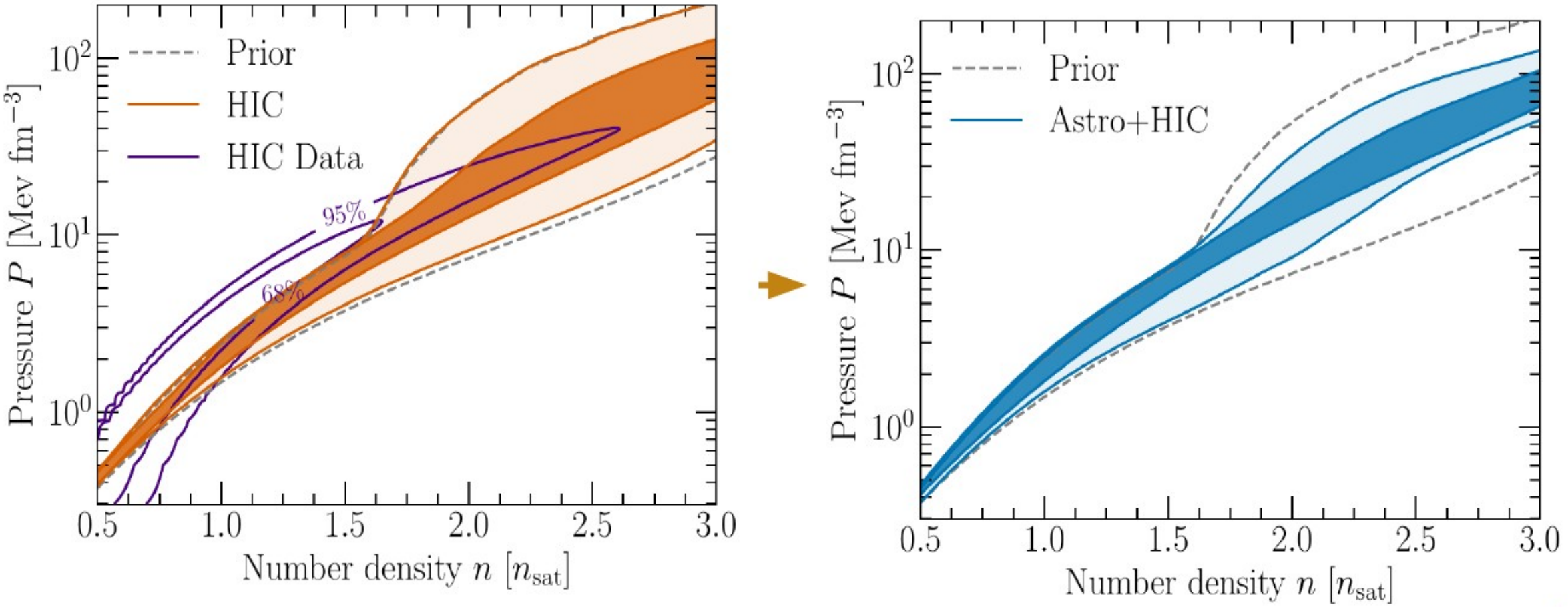
Constraining neutron-star matter with microscopic and macroscopic collisions

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

HIC experiments:

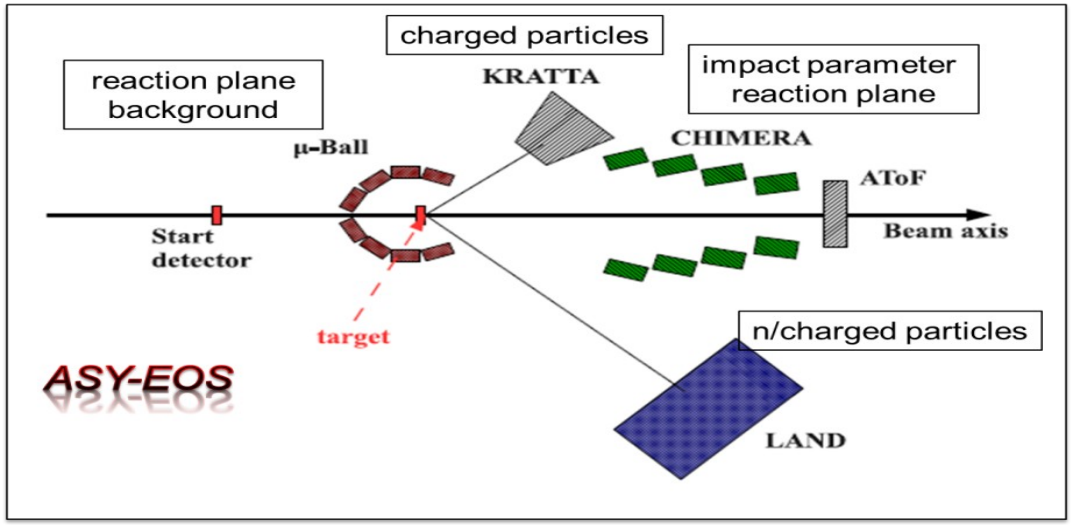
Bayesian combinations

HIC and Astro combined:



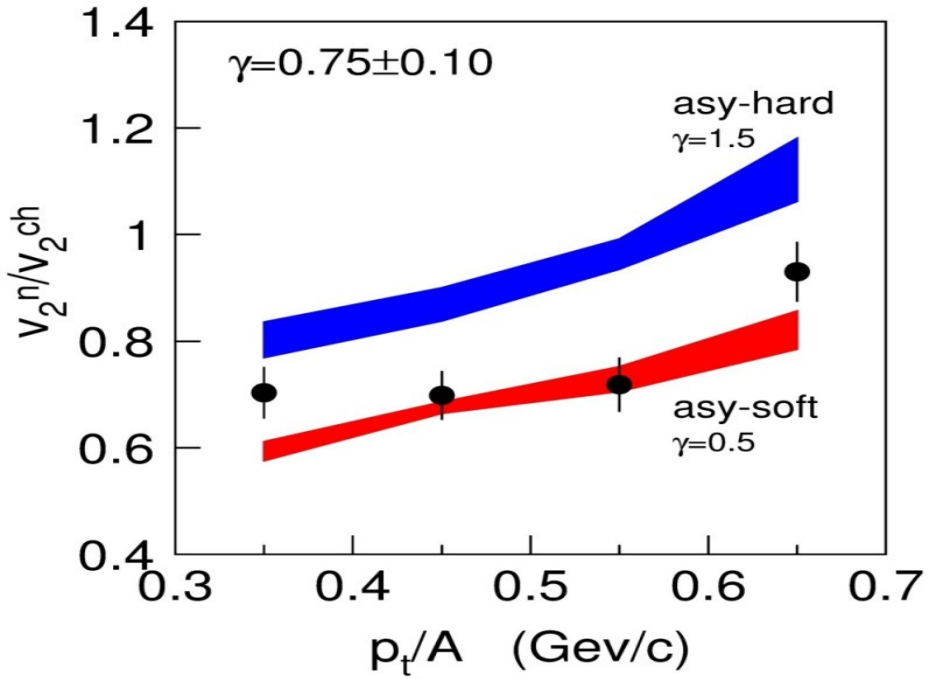
Astrophysical observations narrow constraints above 2 n_{sat}

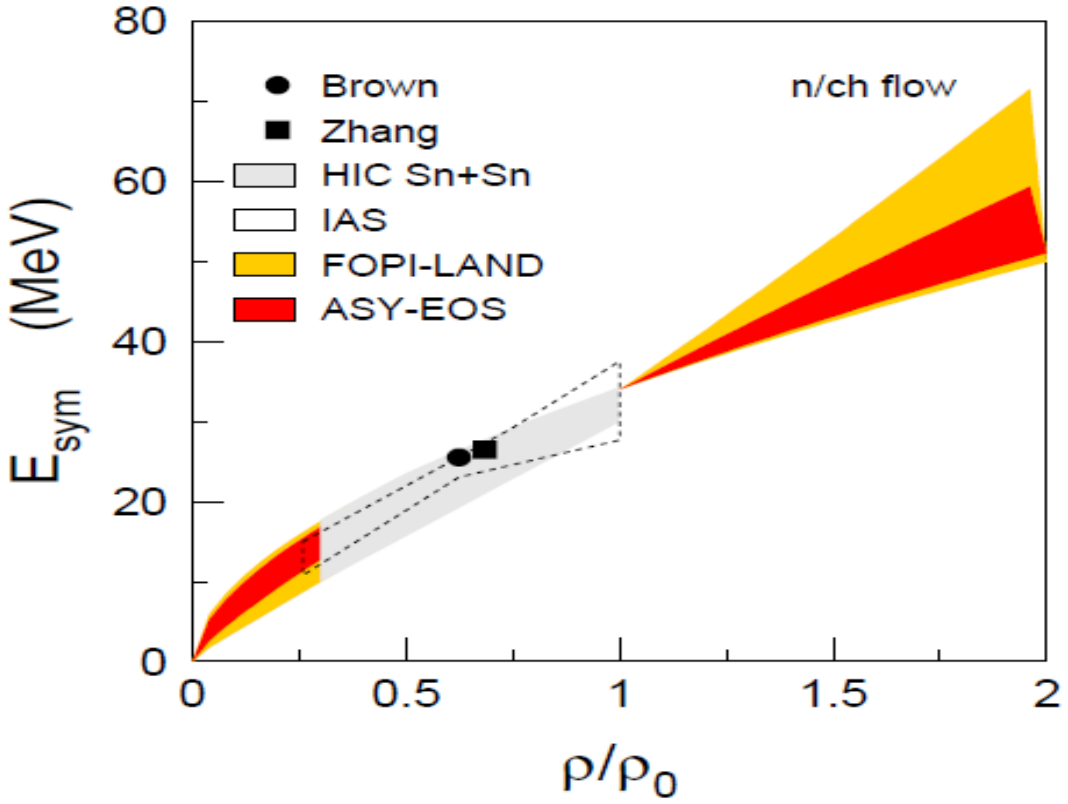
The ASY-EOS experiment at GSI:
The symmetry energy up to densities of $2\rho_0$



P. Russotto et al.,
Phys. Rev. C 94, 034608 (2016)

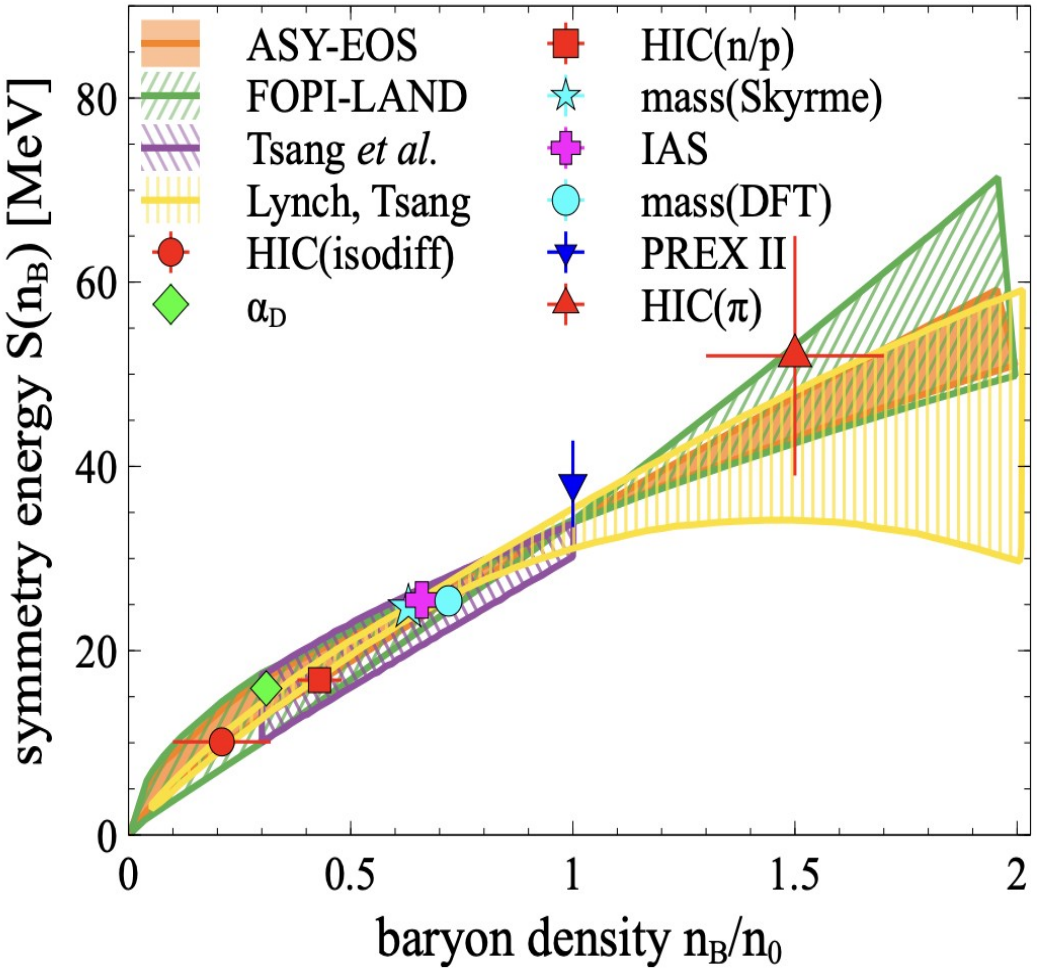
Measuring the elliptic flow of charged particles and neutrons in Au+Au collisions at 400A MeV



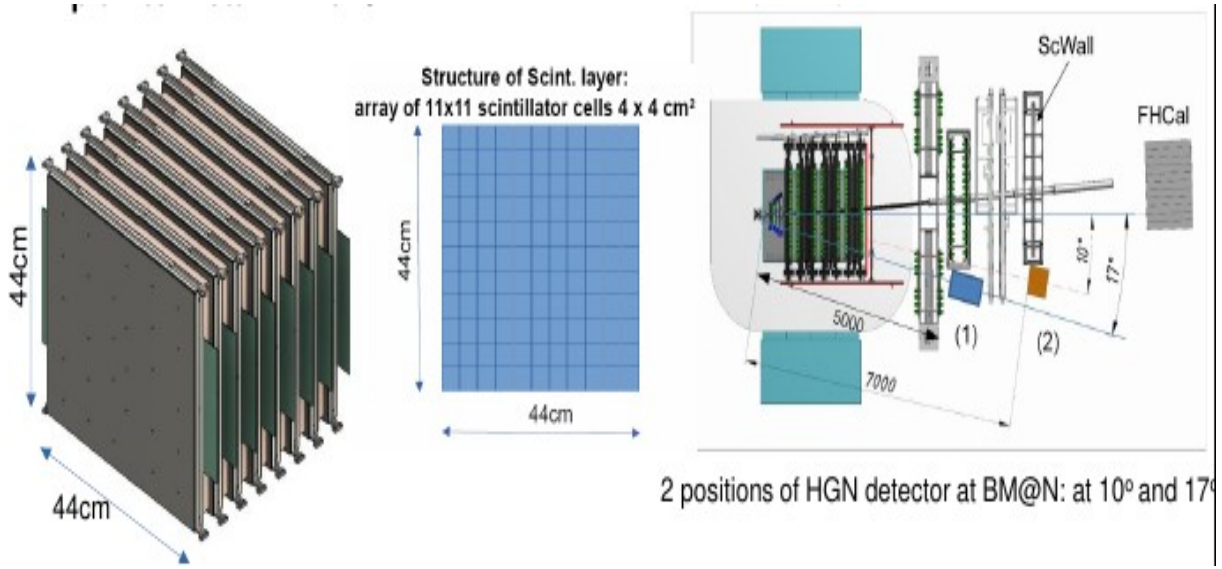


Observables to study symmetry energy (EoS)

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



BM@N Neutron Detector (2027-)

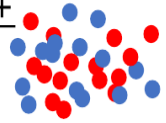


The Highly-Granular time-of-flight Neutron Detector for the BM@N experiment, Nucl. Instrum. Meth. A 1072 (2025) 170152

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^+

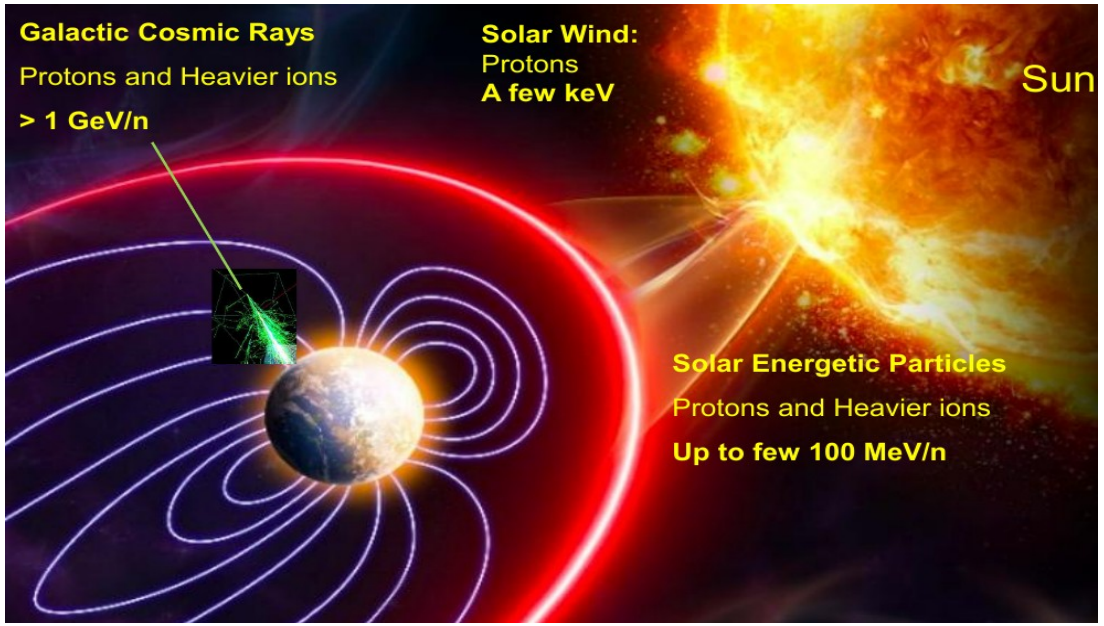


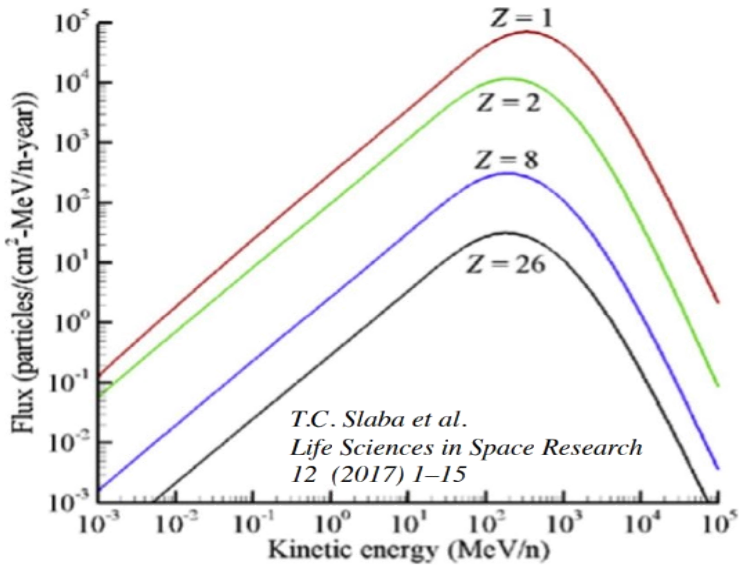
Nuclotron-NICA density region: $2 < n_B/n_0 < 8$

Symmetry energy E_{sym} has strong density dependence

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



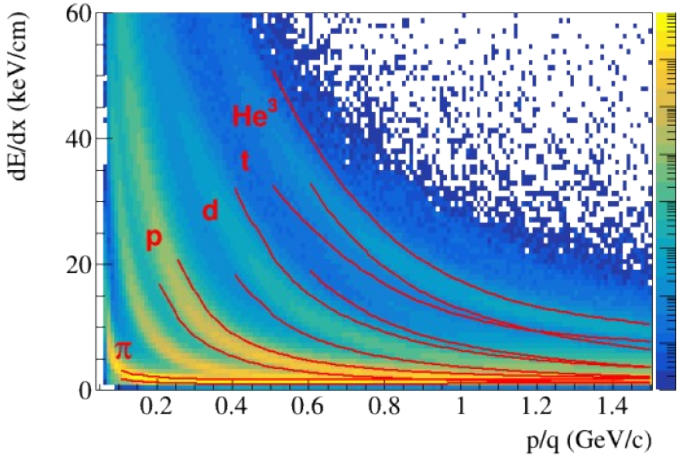


- Cosmic rays are a serious concern to astronauts, electronics, and spacecraft.
- The damage is proportional to Z^2, therefore the component due to ions is important
- Damage from secondary production of p, d, t, ^{3}He, and ^{4}He is also significant
- Need input information for transport codes for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

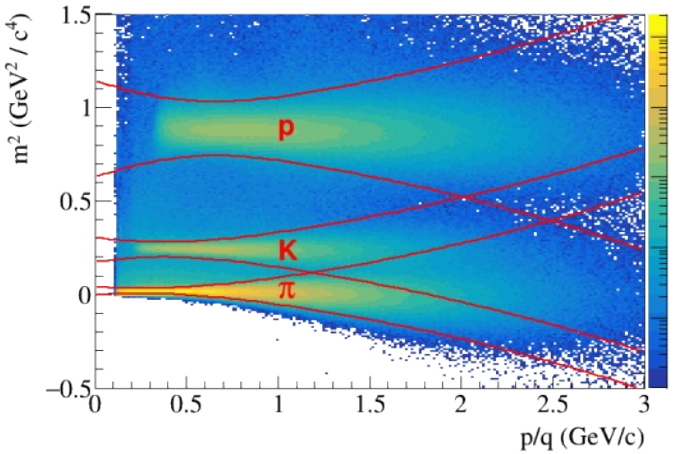
High energy heavy ion reaction data

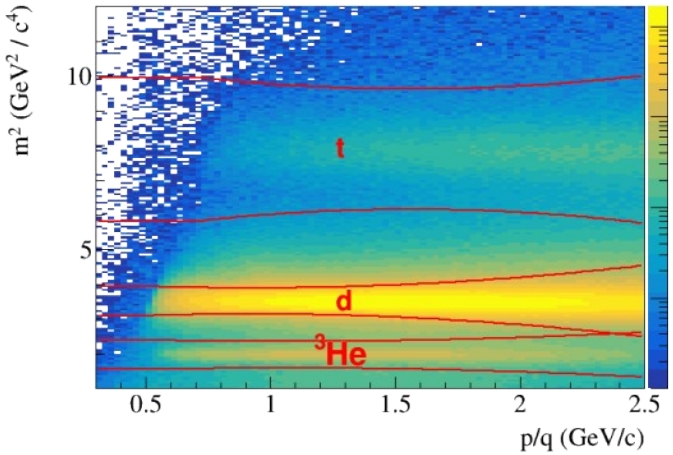
- NICA can deliver different ion beam species and energies:
  - ✓ Targets of interest (C = astronaut, Si = electronics, Al = spacecraft) + He, C, O, Si, Fe, etc.
- No data exist for projectile energies > 3 GeV/n

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

Conclusion and outlook:

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

Physics at High Baryon Density

Critical point and phase boundary;
Nuclear matter EOS at high baryon density;
Y-N interactions, inner structure of compact stars.

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



MPD: ~500 participants - 38 institutes, 12 countries

