Heavy Ion Collisions and Elliptic Flow v_2 in QGP

HUGS 2024 Summer School Final Presentation

ALICE

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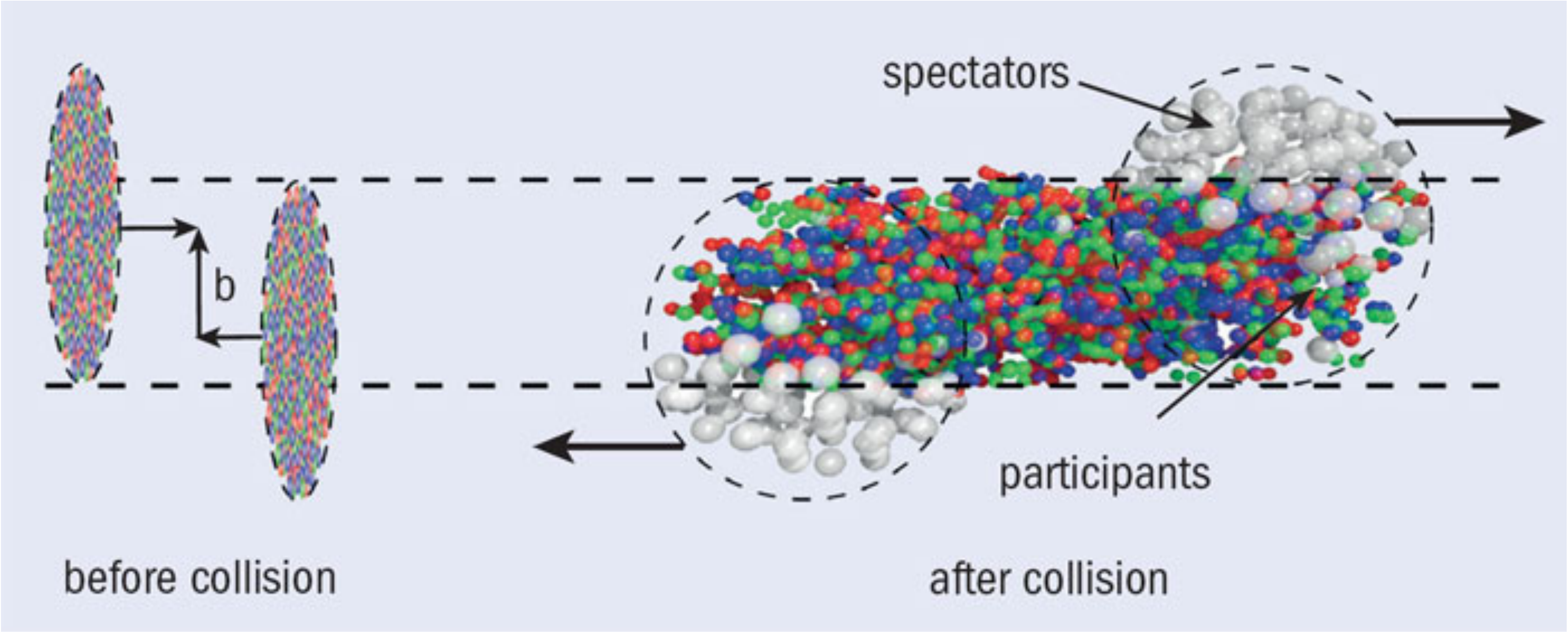
Outline

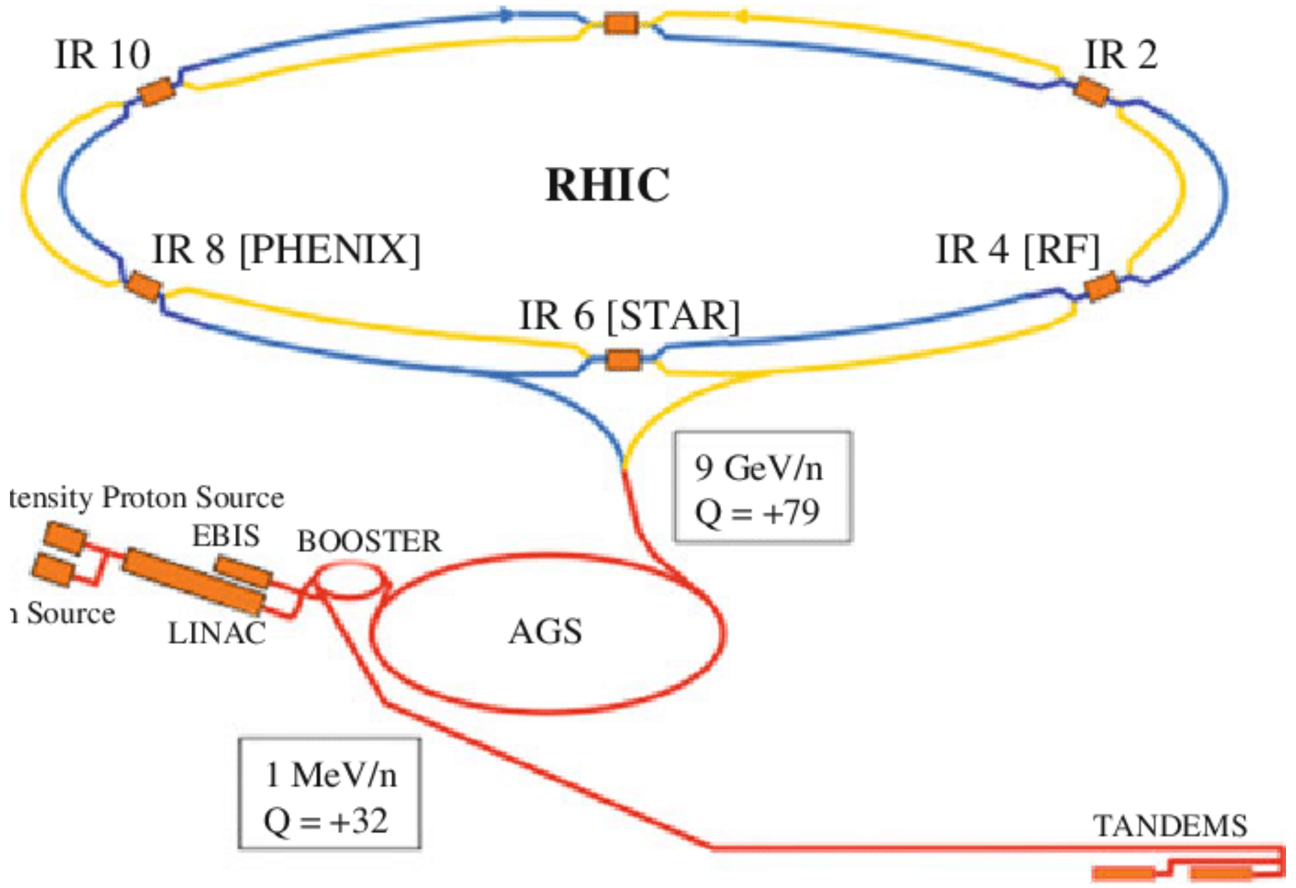
1. Heavy Ion Collisions
    - What they are and why we study them
    - Quark-Gluon Plasma
2. Anisotropic Flow
    - Definition
    - Elliptic flow

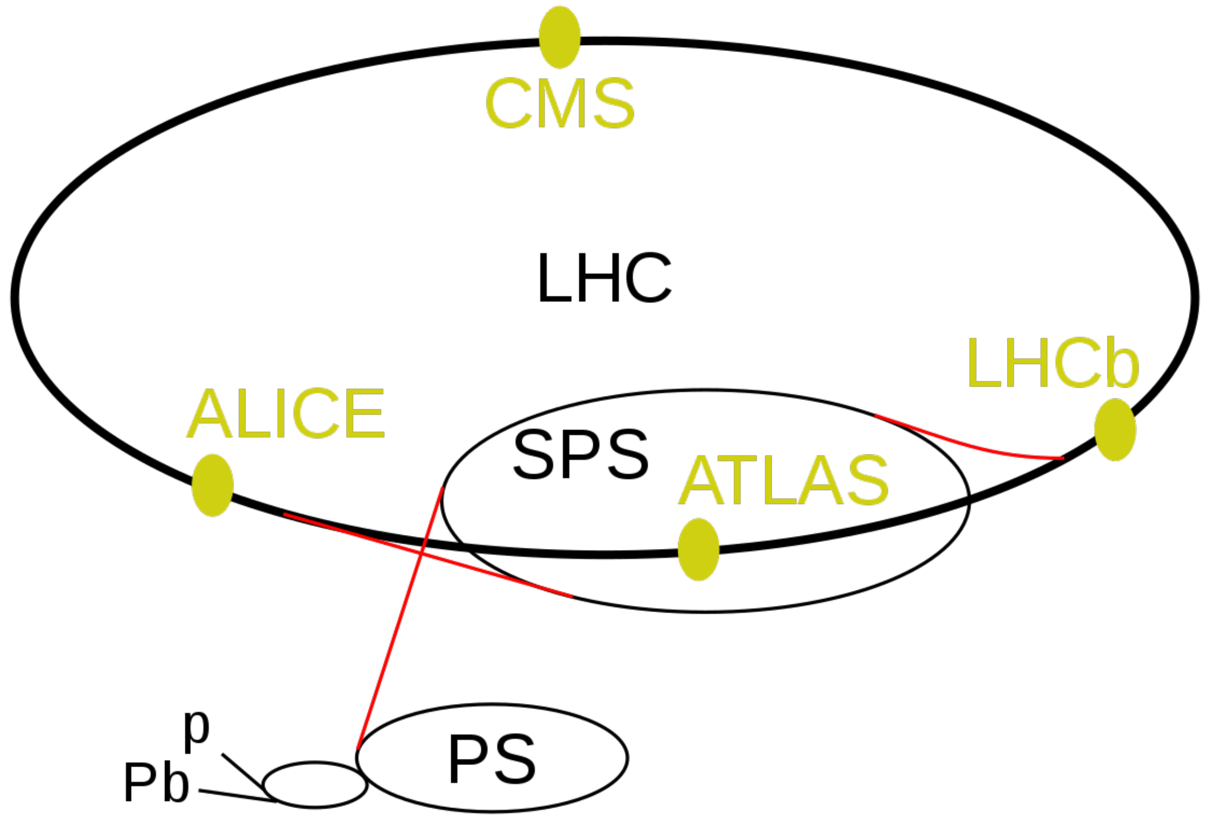
Heavy Ion Collisions



What are heavy ion collisions?

- Collisions of two large, Lorentz contracted, nuclei (typically Pb or Au) with each other at very high relative velocities (total collision energy)
- The impact parameter (b) determines the centrality of the collision
- The energy density in heavy-ion collisions is extremely high (> 12 GeV/fm³), creating conditions where quarks and gluons are deconfined and do not form individual hadrons



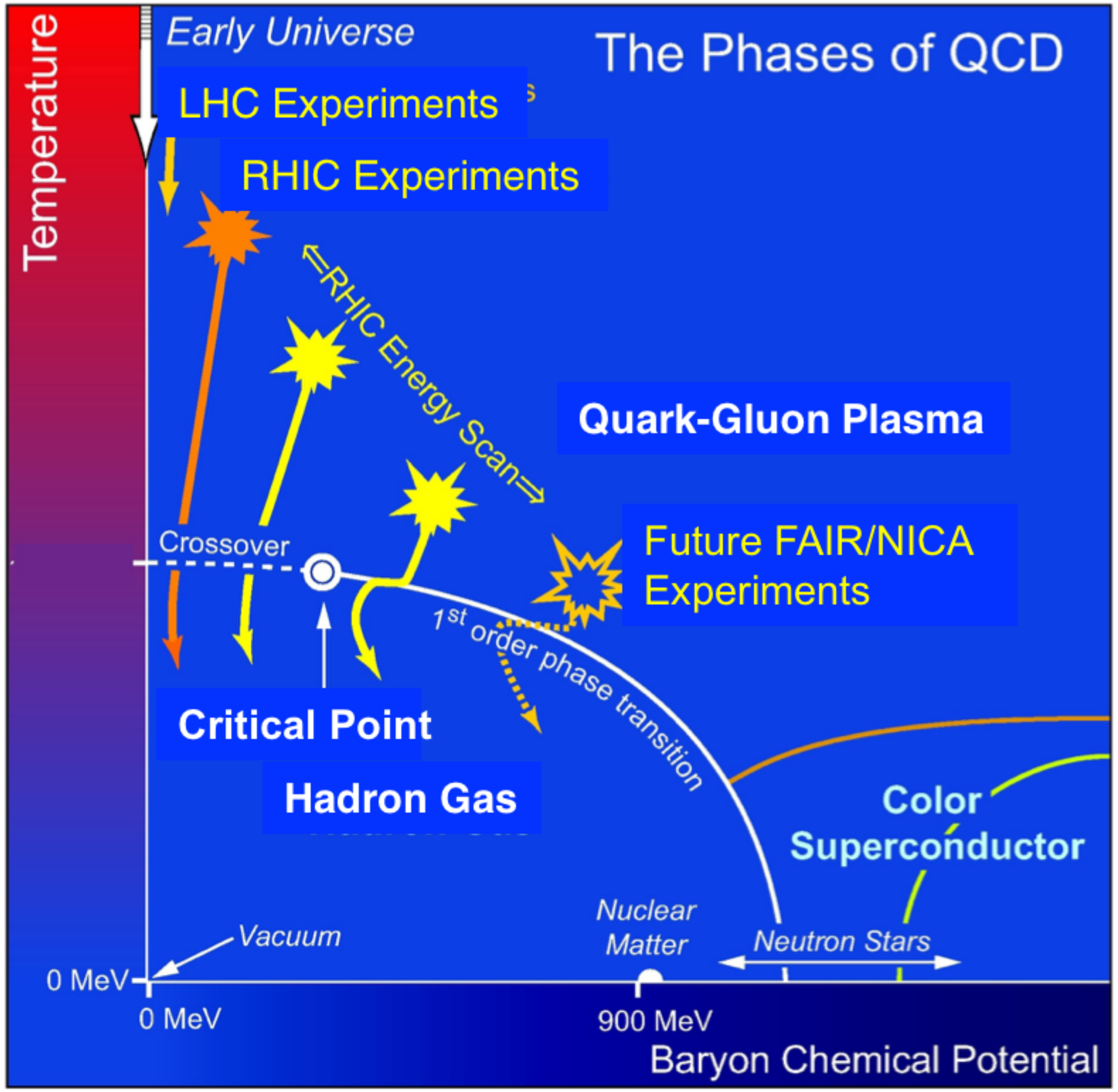


Heavy Ion Collisions

Why do we study them?

We want to know: What happens to matter at extreme temperatures and densities?

- QCD in Cosmology: Recreate droplets of matter that filled the universe microseconds after the Big Bang! Understand the core of a neutron star!
- Phase diagram of QCD
- Understand the properties of Quark Gluon Plasma (QGP)



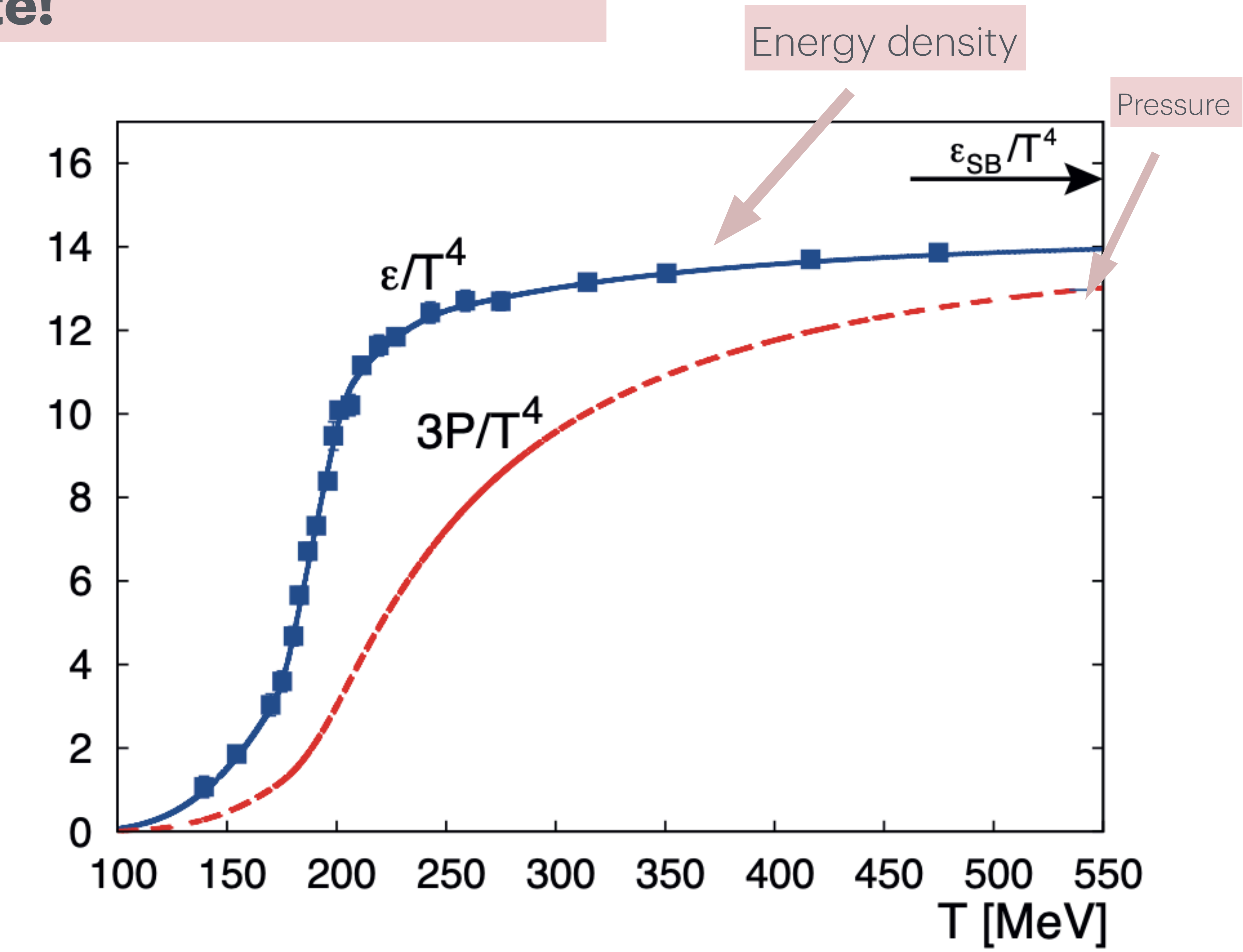
Quark Gluon Plasma (QGP)

QGP is a state of matter where quarks and gluons are in a deconfined state!

Lattice QCD calculations show a rapid increase in energy density around T = 190 MeV, indicating the transition to a **deconfined state**

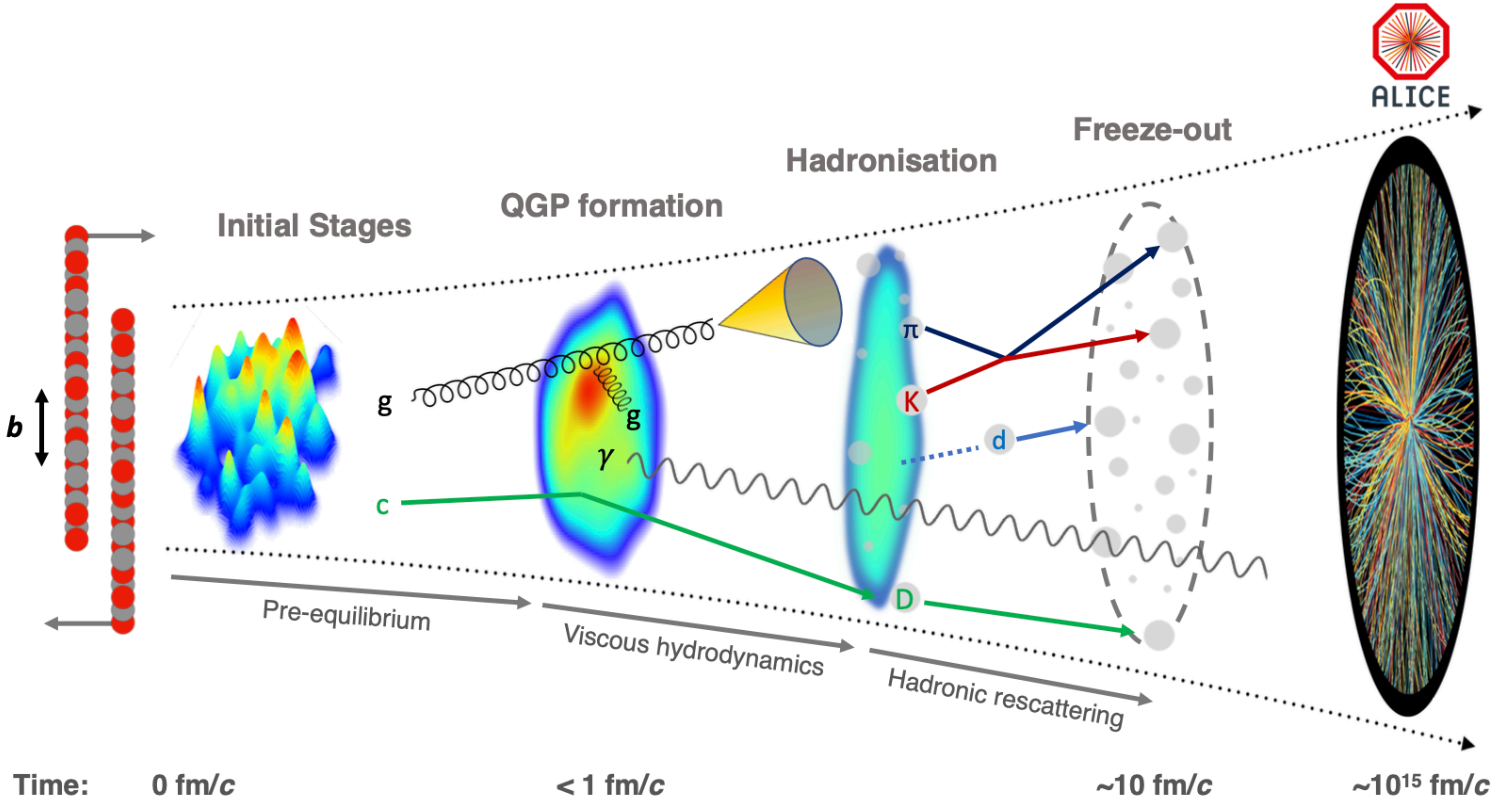
QGP behaves like an almost **ideal fluid** with very low viscosity $$\frac{\eta}{s} \approx \frac{\hbar}{4\pi k_B}$$

The low viscosity and strong coupling lead to hydrodynamic flow, making QGP a nearly perfect liquid



arXiv:1102.3010v2

Heavy Ion Collisions Evolution



ALICE Detector

The detector covers full azimuth and the psuedorapidity region $|\eta| < 0.9$

$$\eta = -ln[tan\ \theta/2]$$

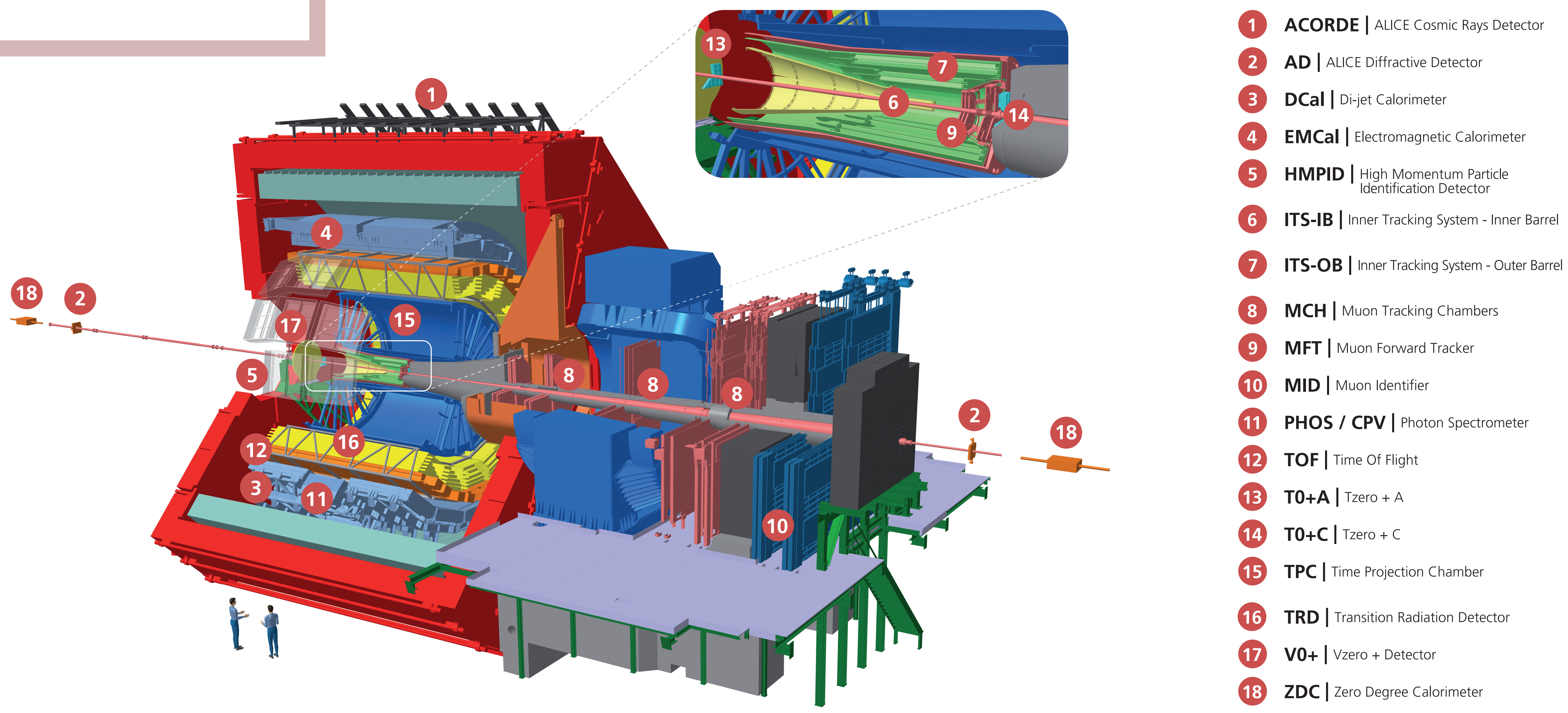
The highest center of mass energy per nucleon pair ($\sqrt{s_{NN}}$) achieved has been 5.36 TeV in Pb-Pb

Key Features

Time Projection Chamber (TPC): tracking and particle identification

Zero Degree Calorimeter (ZDC): detects spectator particles

V0, FT0: determines particle centrality and multiplicity



Anisotropic Flow in Heavy Ion Collisions

Anisotropic flow is the collective expansion of QGP created during the collision

Result of a directional dependence to these pressure gradients. This occurs if spatial anisotropies in the initial state, which may arise if the collision zone is almond shaped (at $b > 0$ fm)

Why do we care about anisotropic flow?

- It is a physical observable that provides information on the equation of state and transport properties of QGP!
- Flow is extremely sensitive to the early stages of the collision (at this stage, QGP is the main player)

Are we sure flow even exists?

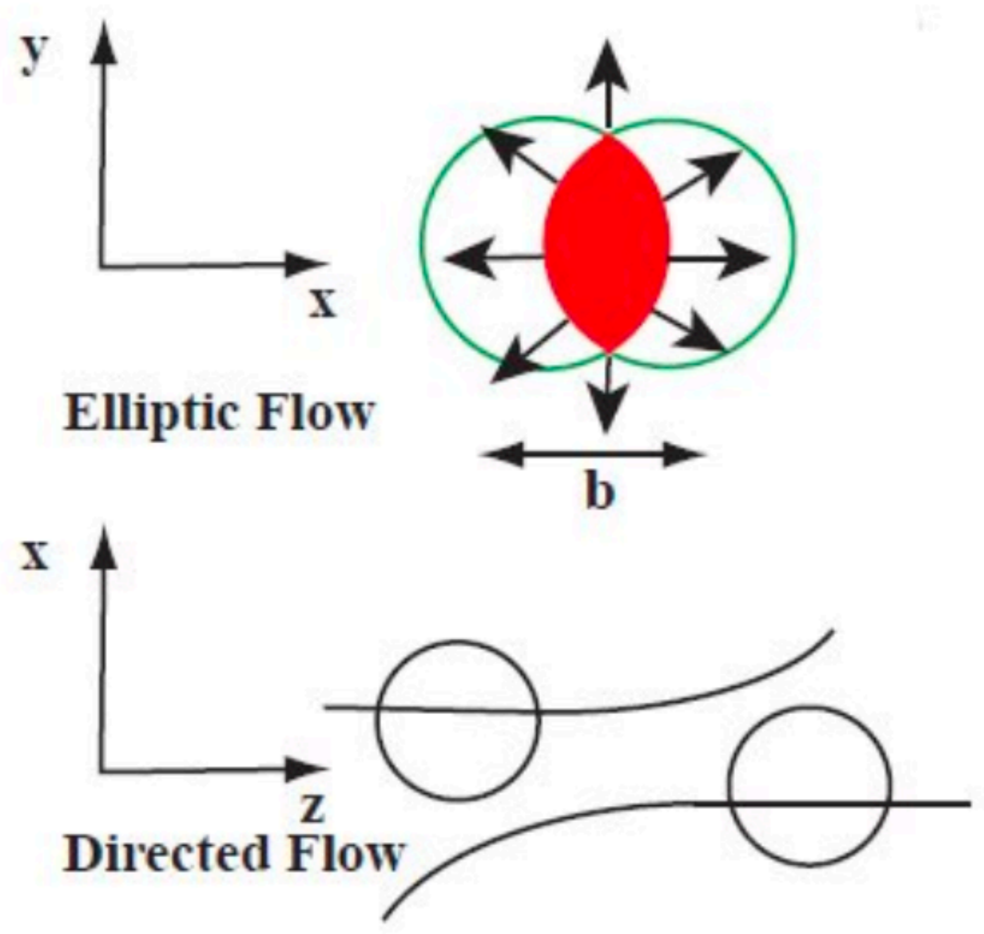
- Yes! Azimuthal anisotropy in production of particles is the clearest signature of collective flow
- Caused by initial asymmetries in the collision geometry

Anisotropic Flow in Heavy Ion Collisions

To define flow, we can begin by expanding a Fourier series of the particle azimuthal distribution

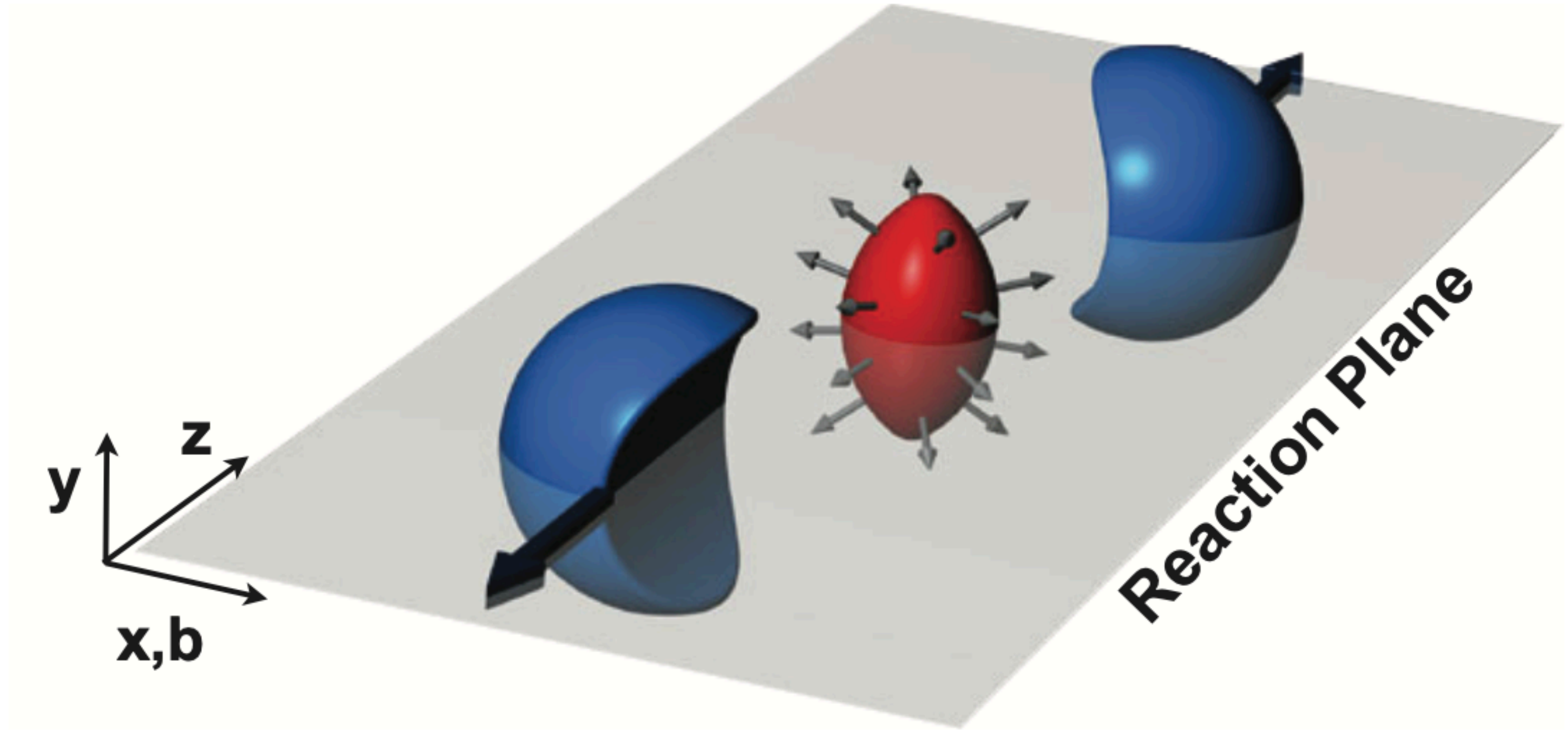
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi} + \frac{d^2N}{p_T dp_T dy}(1 + \sum_{n=1}^{\infty} 2v_n\, cos(n(\phi - \Psi_{RP})))$$

Event anisotropy is characterized by the coefficients: $v_n = \langle cos[n(\phi_i - \Psi_{RP})]\rangle$



v_2 = elliptic flow

v_1 = directed flow



Experimental Methods

How do we measure flow?

Event Plane Method

Estimates the azimuthal angle of the reaction plane from observed event plane angle

$$Q_{n,x} = \sum_i w_i cos(n\phi_i) \qquad Q_{n,y} = \sum_i w_i sin(n\phi_i)$$

$$\Psi_n = arctan2(Q_{n,y}/Q_{n,x})/n$$

Two Particle Correlations

Estimates anisotropic flow using two observed particle azimuthal correlations

$$\langle cos(n(\phi_1 - \phi_2)) \rangle = \langle e^{in(\phi_1 - \phi_2)} \rangle = \langle v_n^2 \rangle + \delta_n$$

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★ Difficult to estimate this angle experimentally

Two Particle Correlations

Estimates anisotropic flow using two observed particle azimuthal correlations

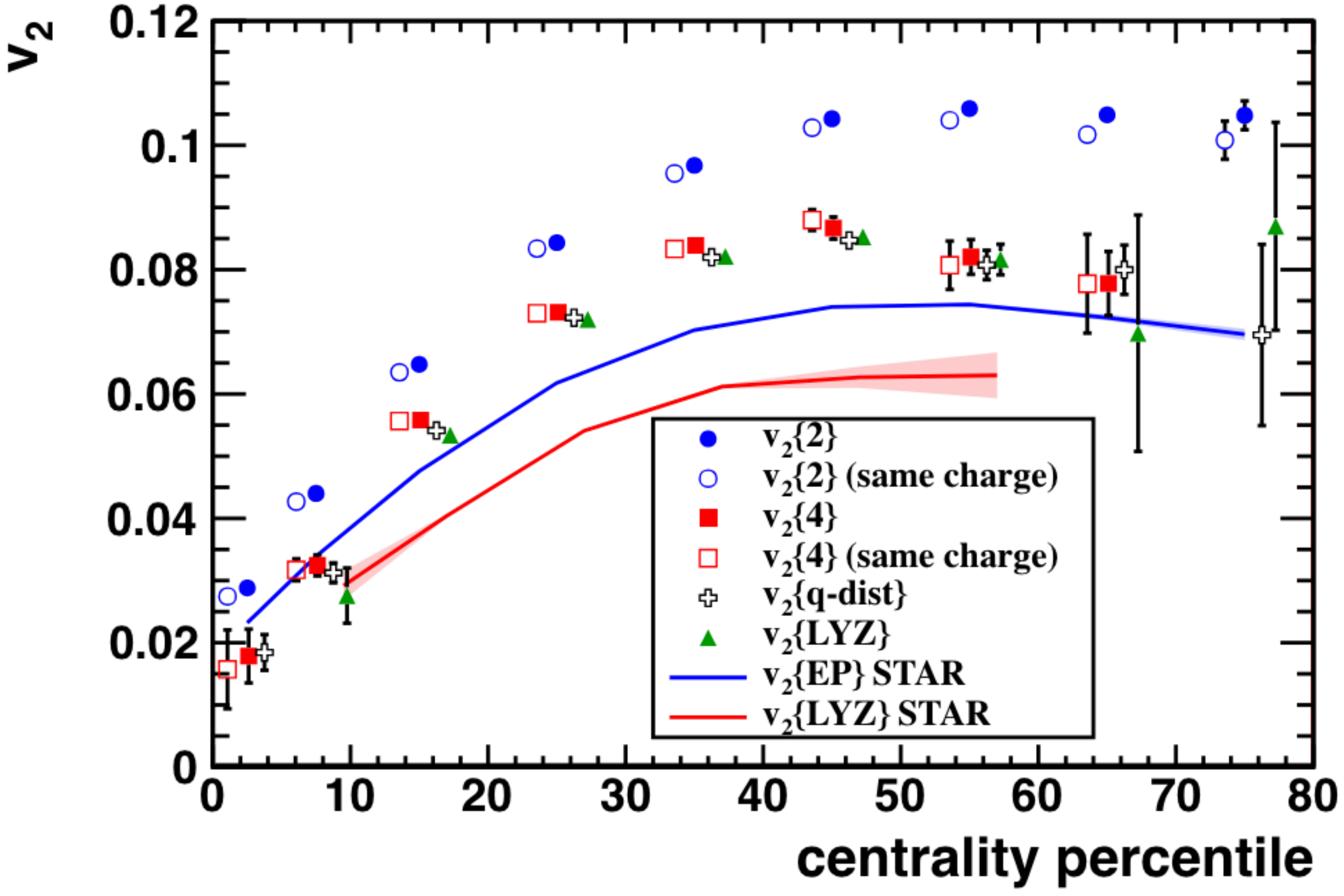
$$\langle cos(n(\phi_1 - \phi_2))\rangle = \langle e^{in(\phi_1 - \phi_2)}\rangle = \langle v_n^2\rangle + \delta_n$$

★ Must account for non-flow effects

Published Results

ALICE Pb – Pb $\sqrt{s_{NN}} = 2.76$ TeV, STAR Au – Au $\sqrt{s_{NN}} = 200$ GeV

arXiv:1011.3914v3



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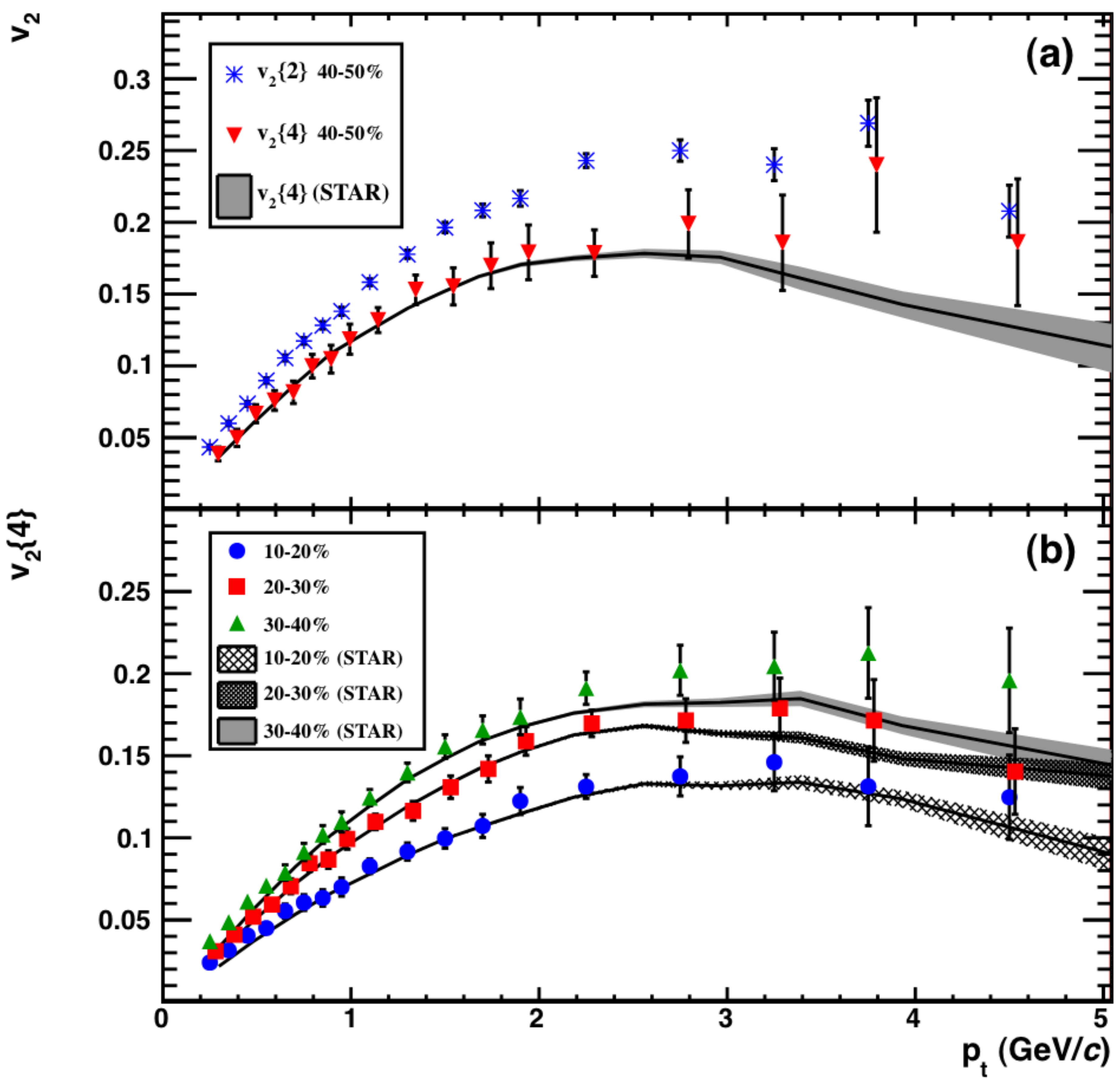
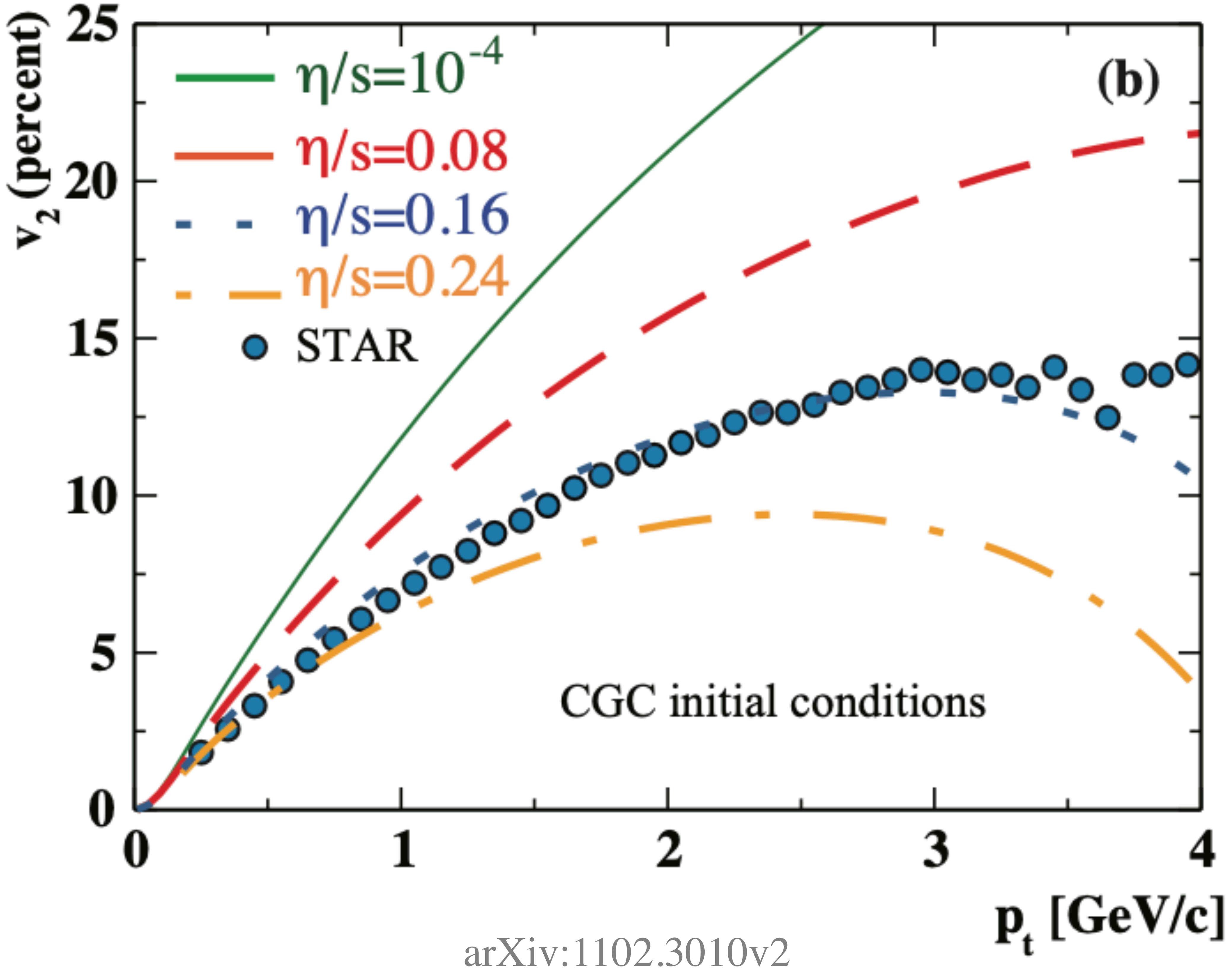


Published Results

Comparing to models, we see evidence for strongly interacting matter that behaves like a perfect liquid



arXiv:1102.3010v2

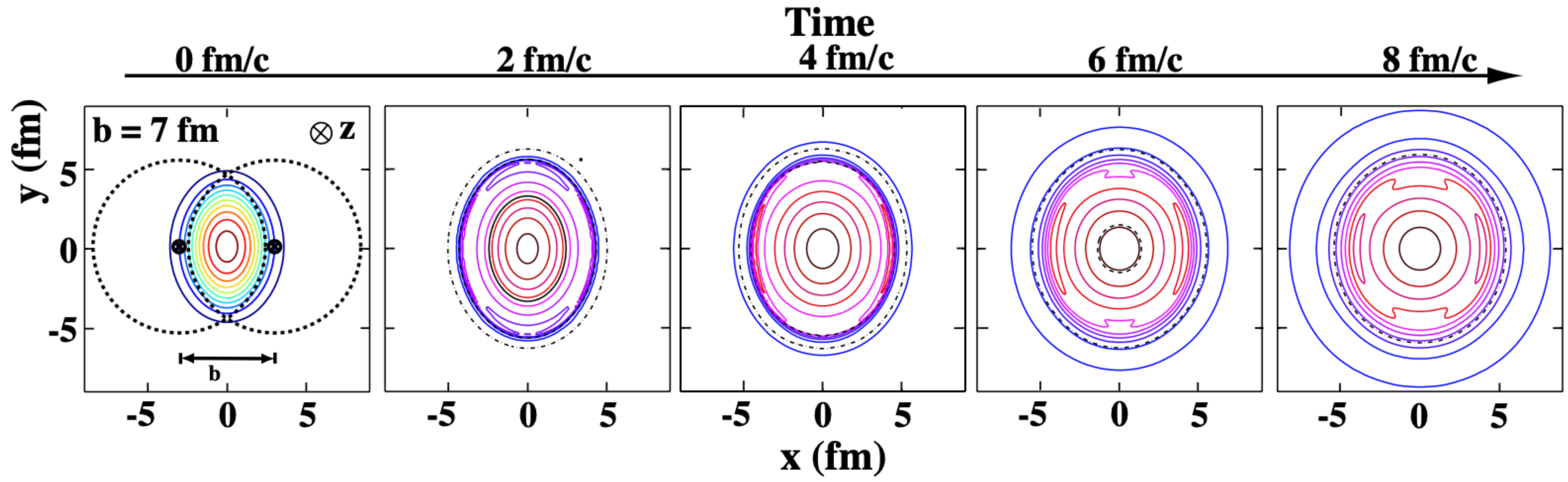
Summary and Outlook

- Elliptic flow has shown to be a good probe for understanding QGP: its evolution and medium properties
- ALICE is currently planning to run oxygen-oxygen collisions in 2025
  - Interesting flow can be observed in small systems!
- Measuring v2 flow with spectator particles to eliminate non-flow effects
- Measuring the neutron skin
  - Creating a model to relate v2 to the neutron skin
  - Understand the structure of neutron stars

Thank you!

Backup

Evolution of interaction (elliptic flow)

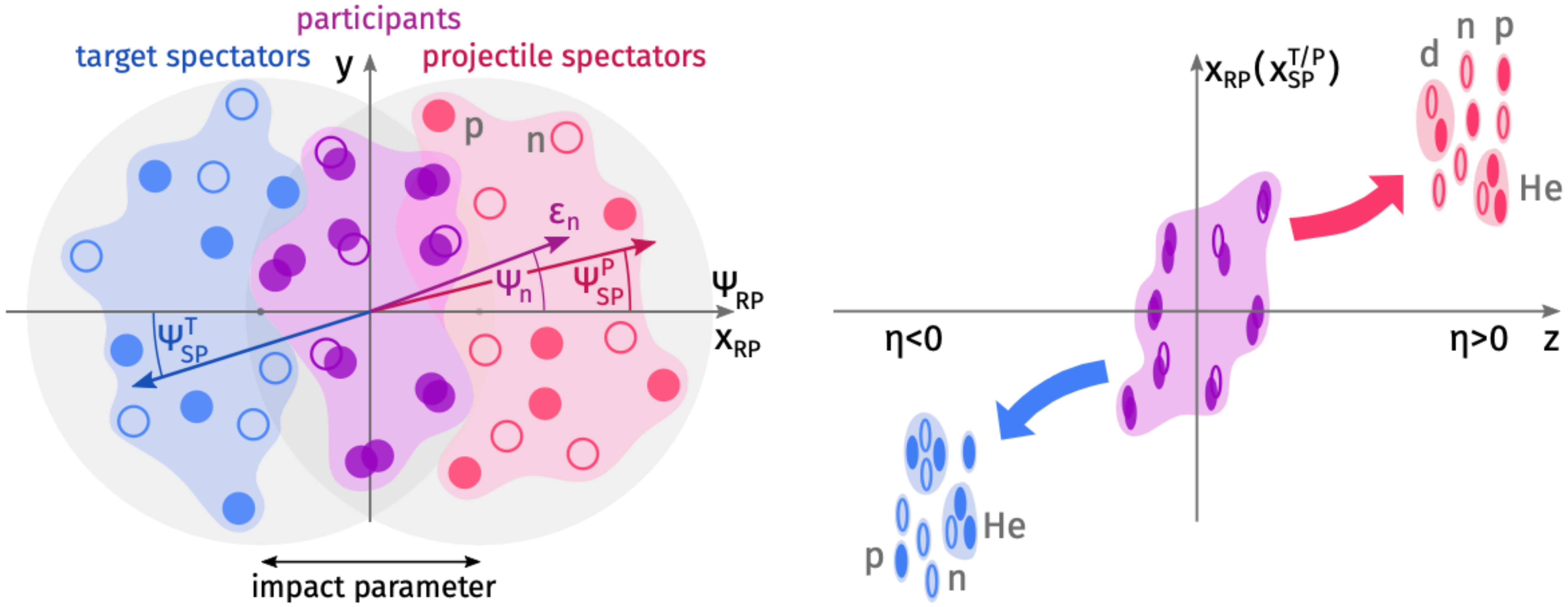


The colored contours indicate energy density profile

Goes from an almond shaped region -> nearly symmetric

Measuring Elliptic Flow using Spectators

- Spectators are particles that do not participate in the collision
- The direction that the spectators are deflected are strongly correlated to the reaction plane
- We use the scalar product (mixed harmonics) method when calculating elliptic flow with a far forward detector, the ZDC



(a) transverse view (b) longitudinal view

Measuring Elliptic Flow using Spectators

$$q_n^K = x_n^K + iy_n^K = \sum_{j\in K} (w_j)^p e^{in\varphi_j} \bigg/ \sum_{j\in K} (w_j)^p$$

$$v_2\{\Psi_{\mathrm{SP}}\} = \frac{2}{3}\left(\frac{\langle x_2^T x_1^A x_1^C\rangle}{\langle x_1^A x_1^C\rangle} - \frac{\langle x_2^T y_1^A y_1^C\rangle}{\langle y_1^A y_1^C\rangle} + \sqrt{\frac{\langle y_2^T x_1^A y_1^C\rangle\langle y_2^T y_1^A x_1^C\rangle}{\langle x_1^A x_1^C\rangle\langle y_1^A y_1^C\rangle}}\right)$$

Zero Degree Calorimeters (ZDC)