INSTITUTO DE FÍSICA
Universidade Federal Fluminense

Charge conservation in initial conditions and relativistic hydrodynamics

(relativistic fluid dynamics at large net-charge densities)

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The VIth International Conference on the
INITIAL STAGES
OF HIGH-ENERGY NUCLEAR COLLISIONS

What you will see in this talk

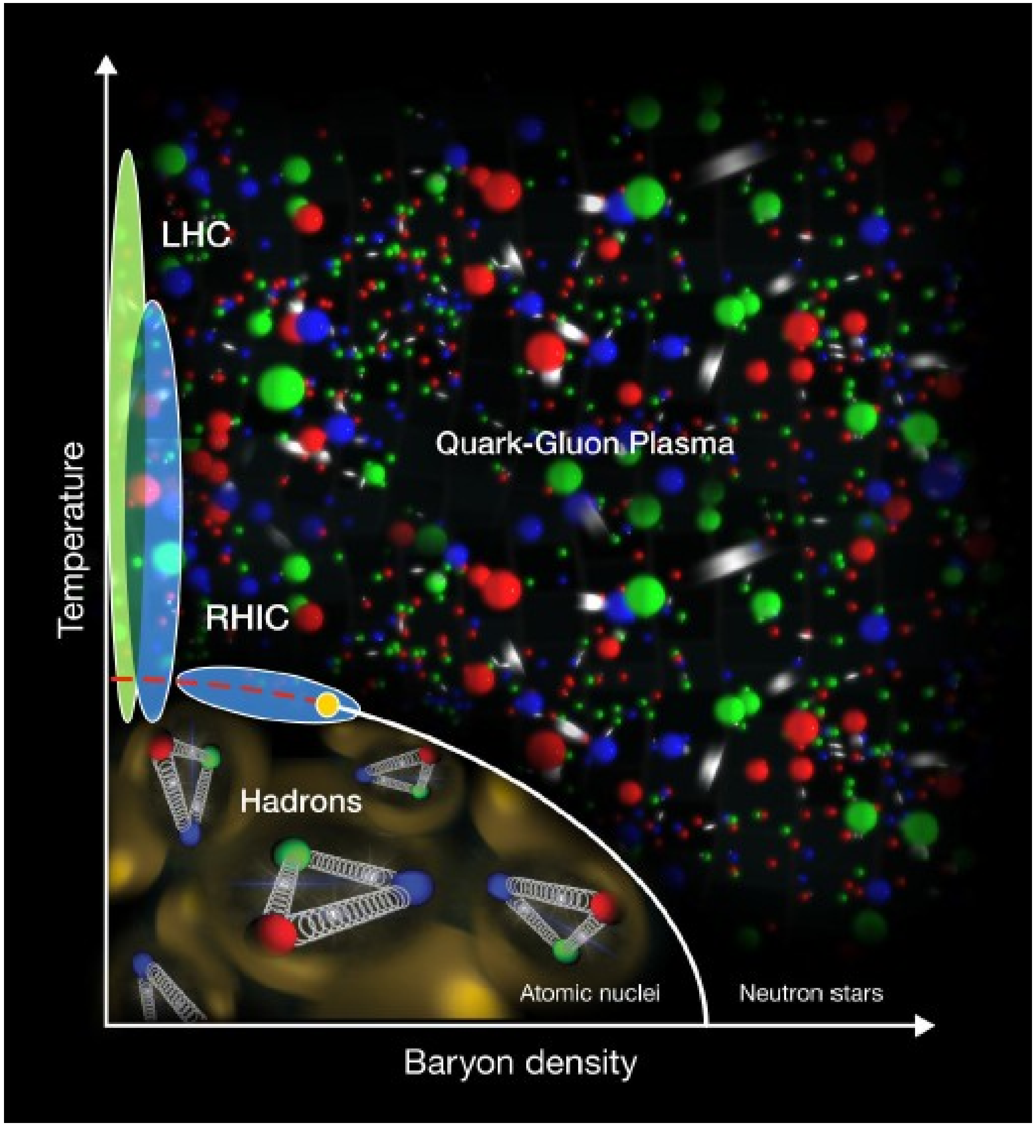
- ✔ Motivation

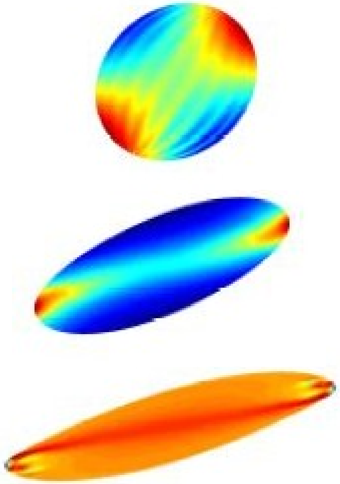
- ✔ Fluid-dynamical modeling of heavy-ion collisions

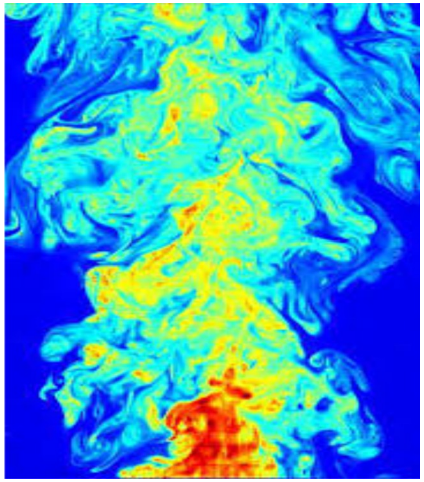
- ✔ Fluid dynamics at finite net-charge: some challenges

- ✔ Conclusions and perspectives

- *QCD phase diagram (thermodynamic properties)*
- *Non equilibrium phenomena (transport properties)*

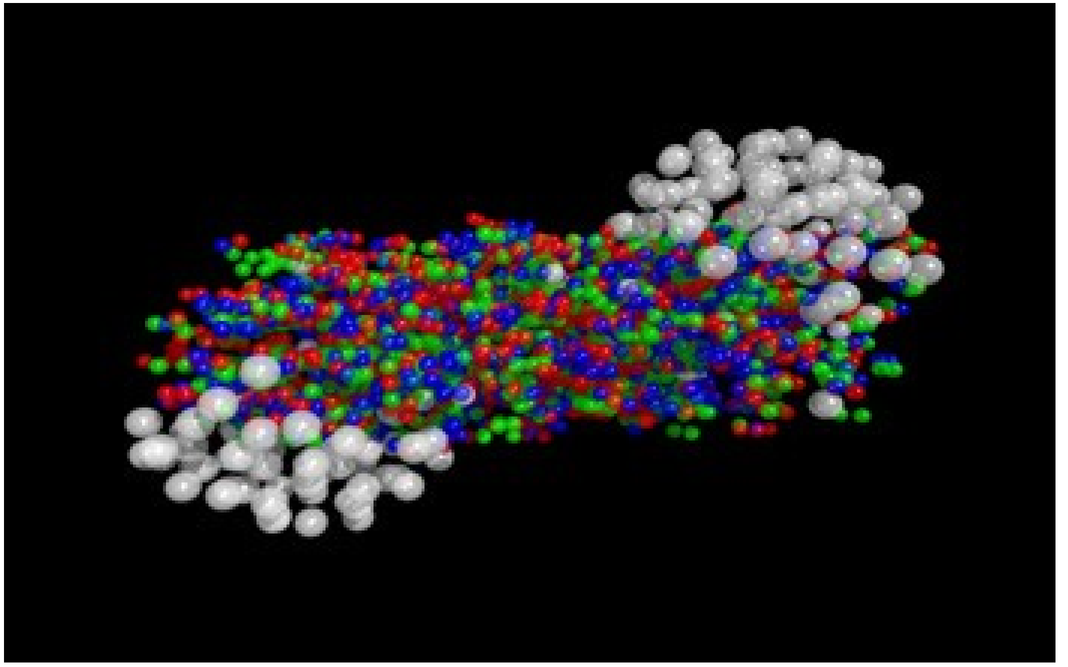




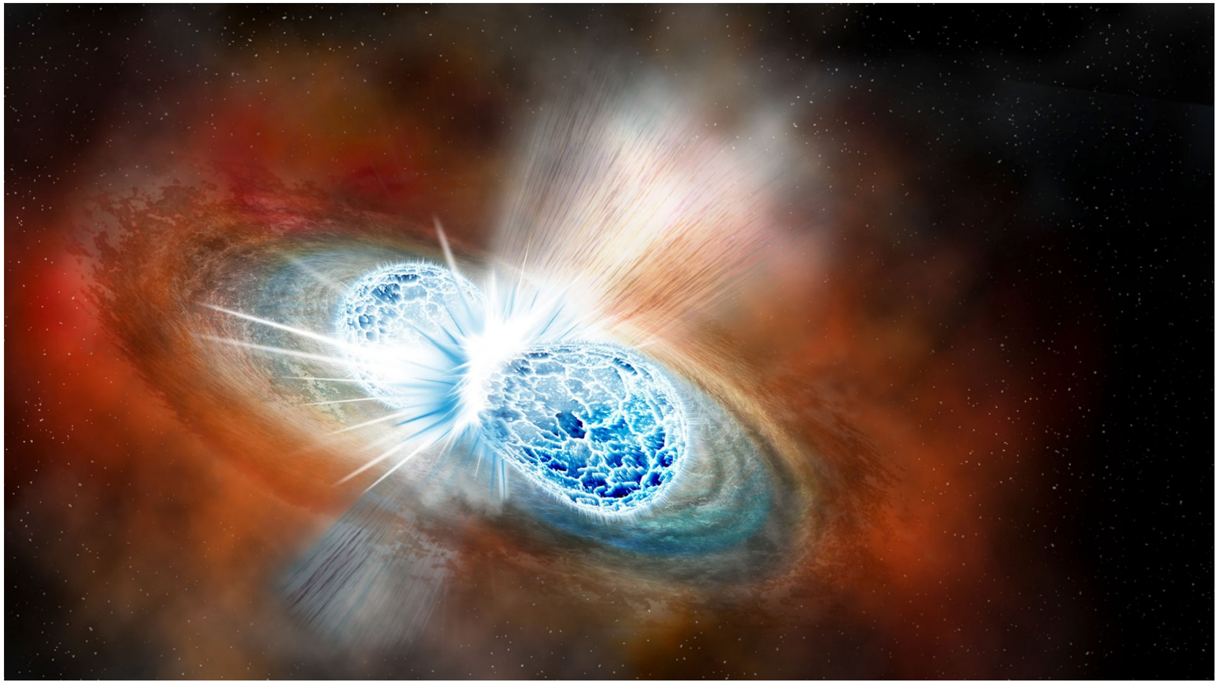


QCD matter at large densities

- *Heavy ion collisions:*



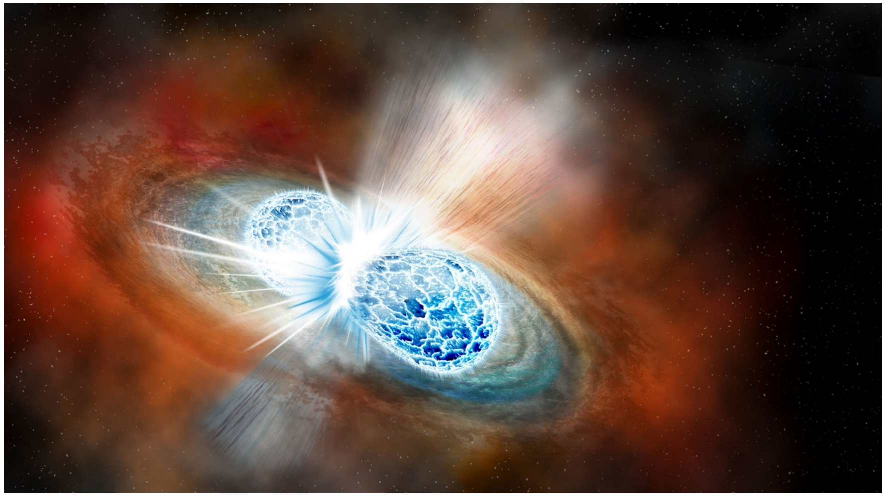
- *Neutron star merger:*



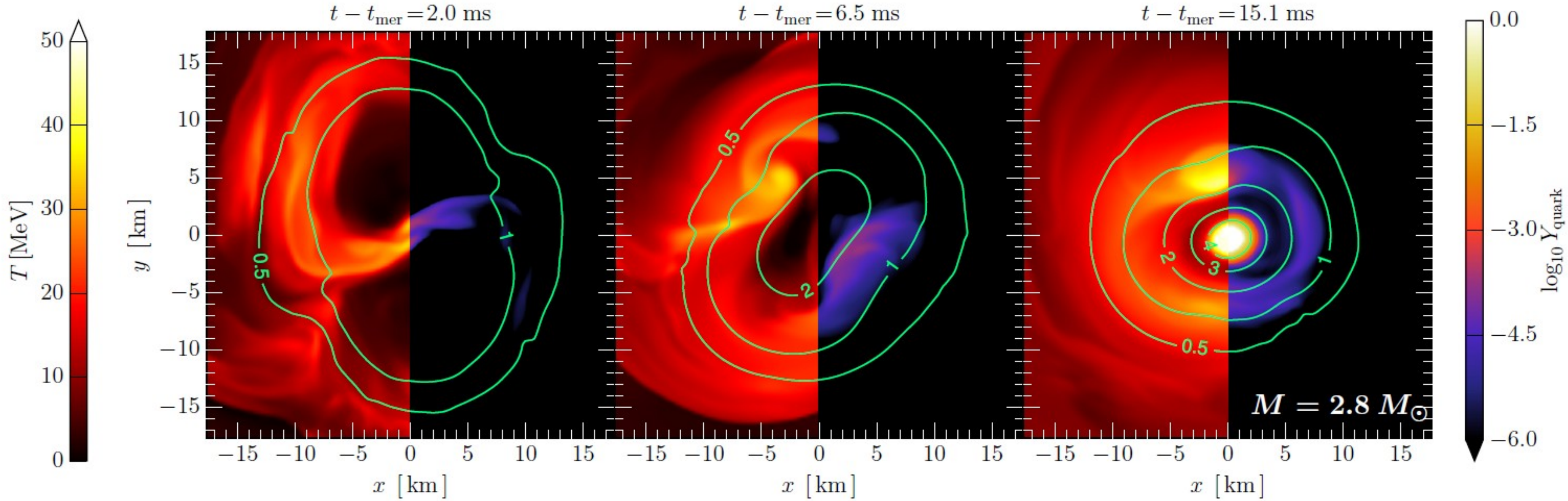
Neutron star mergers

- *High temperatures* are also achieved in these natural events

$T_{max} \sim 50$ MeV



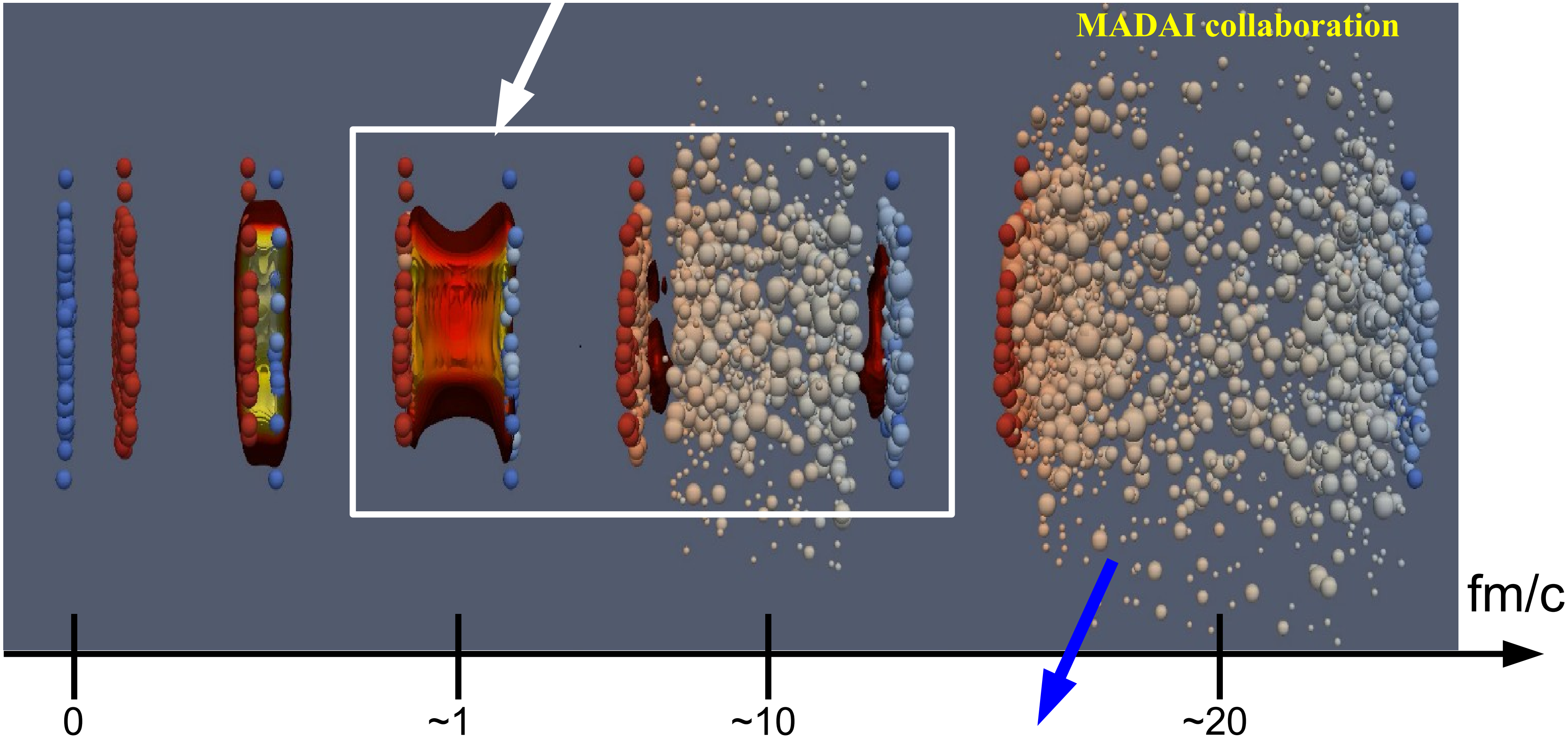
- *Simulations by Frankfurt group* *Phys.Rev.Lett. 122 (2019) 6, 061101*



Snapshot of temperature in equatorial plane at three different times

Heavy-Ion Collisions: *Produce* and *study* QCD matter near (local) equilibrium

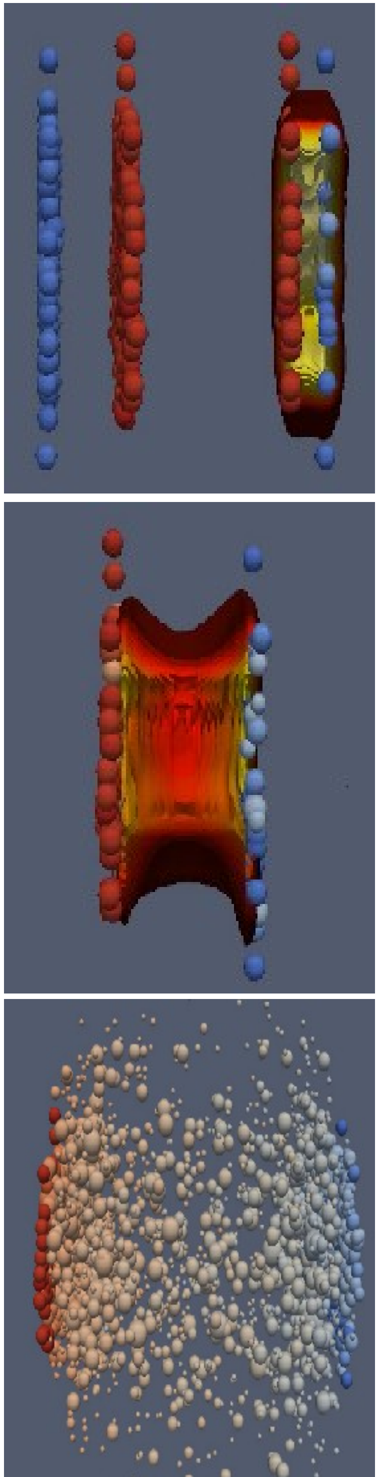
Assumption: *fluid-dynamical expansion (valid for BES?)*



measured: hadrons, leptons, and photons

Properties of matter must be reverse-engineered

Current theoretical description



1) Initial state and "pre-equilibrium" dynamics:

- description of early-time dynamics and "thermalization"
- initial condition for hydrodynamic evolution

(approach) thermalization (?)

2) Fluid-dynamical expansion of QGP and Hadron Gas

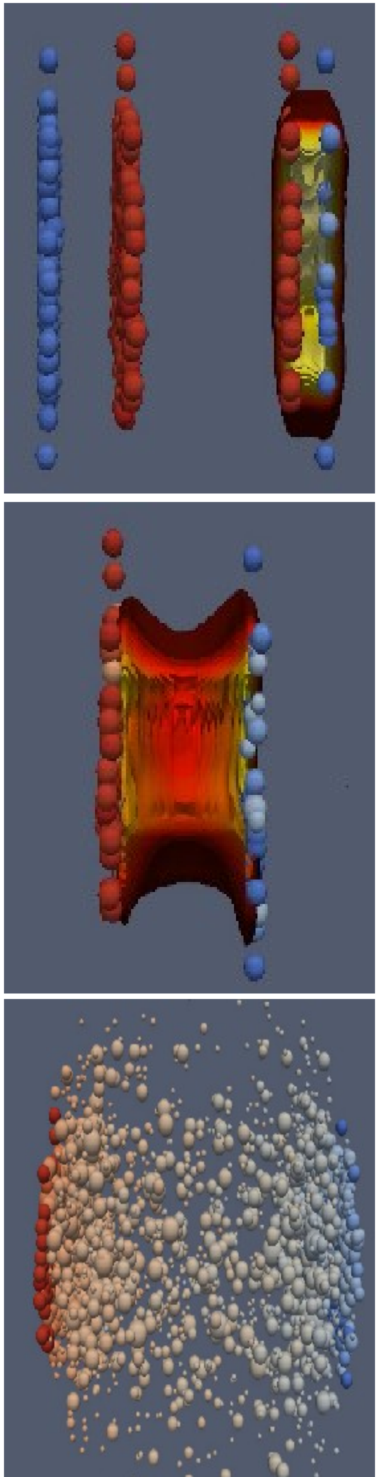
- Phase transition
- Matter described by EoS and transport coefficients

shear and bulk viscosity, charge diffusion, relaxation times ...

fluid elements converted to particles

3) Transport description of Hadron Gas

- Late stage description using the *hadron resonance gas* model – using cross sections and decay probabilities



During last 10 years, developed mostlyat $n_B=0$

- Focus has not been in extracting EoS
  - Extraction of transport properties (shear and bulk viscosities)
  - Understanding the initial state
- Fluid-dynamical models have evolved dramatically in the last 15 years:
  inclusion of dissipation (2006),
  event-by-event fluctuations (2010),
  sub-nucleonic fluctuations (2012), ...

Relativistic fluid dynamics

Effective theory describing the dynamics of a system over long-times and long-distances

Conservation laws
+
Equation of state
+
simple constitutive relations

Basics of fluid dynamics (Landau frame)

Conservation laws

energy-momentum conservation

$$\boxed{\partial_\mu T^{\mu\nu} = 0}$$

Net charge conservation

$$\boxed{\begin{aligned} \partial_\mu N_s^\mu &= 0 \\ \partial_\mu N_e^\mu &= 0 \\ \partial_\mu N_b^\mu &= 0 \end{aligned}}$$

strangeness

electric charge

Baryon number

Tensor decomposition

$$\boxed{\begin{aligned} N_q^\mu &= n_q u^\mu + n_q^\mu \\ T^{\mu\nu} &= \varepsilon u^\mu u^\nu - (P_0 + \Pi)\,\Delta^{\mu\nu} + \pi^{\mu\nu} \end{aligned}}$$

net-charge diffusion 4-current

Bulk viscous pressure

Shear stress tensor

Projection operator: $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$

Equation of state

Thermodynamic pressure: $P_0 = \underbrace{P_0\left(T, \mu_b, \mu_e, \mu_s\right)}_{\textit{not known!}}$

Taylor expansion up to 4th order:

$$\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{\chi^{B,Q,S}_{l,m,n}}{\underbrace{l!m!n!}_{\text{lQCD}}} \left(\frac{\mu_B}{T}\right)^l \left(\frac{\mu_Q}{T}\right)^m \left(\frac{\mu_S}{T}\right)^n$$

- matched to *hadron resonance gas* model at small T
- matched to Stefan-Boltzmann limit at large T

- Prescription employed by:

Monnai, Schenke, Shen, PRC 100, 024907 (2019)
Noronha-Hostler, Parotto, Ratti, Stafford, PRC 100, 064910 (2019)

Equation of state

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- matched to *hadron resonance gas* model at small T
- matched to Stefan-Boltzmann limit at large T

- Added a critical point:

Parotto *et al* Phys.Rev.C 101 (2020) 3, 034901

BEST COLLABORATION

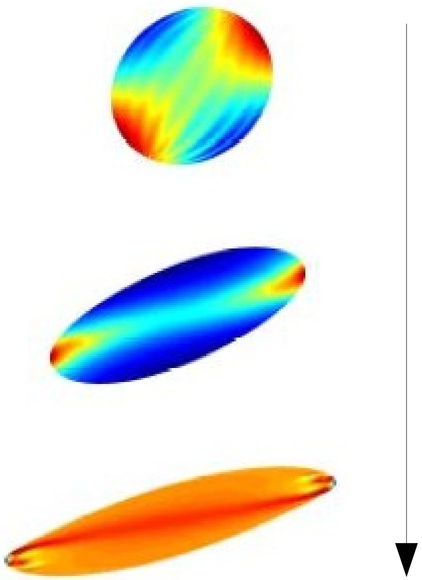
See Travis Dore's talk for the effects on hydro

Relativistic Navier-Stokes theory

Shear Viscosity

(Resistance to deformation)

$$\boxed{\pi^{\mu\nu} = 2\eta\nabla^{\langle\mu}u^{\nu\rangle}}$$



$$\eta\left(T,\mu_q\right)$$

Bulk Viscosity

(Resistance to expansion)

$$\boxed{\Pi = -\zeta\nabla_\mu u^\mu}$$

$$\zeta\left(T,\mu_q\right)$$

Net-Charge Diffusion

$$\boxed{n_q^\mu = \kappa_q\nabla^\mu\frac{\mu_q}{T}}$$

$$\kappa_q\left(T,\mu_q\right)$$

Relativistic Navier-Stokes theory

Shear Viscosity

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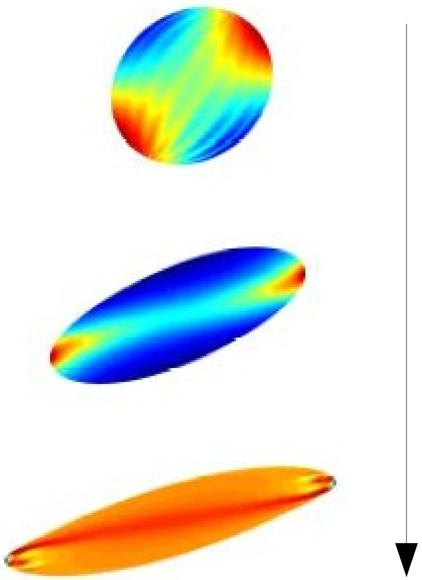

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Net-Charge Diffusion

$$n_q^\mu = \kappa_q\nabla^\mu\frac{\mu_q}{T}$$

$$\kappa_q\left(T,\mu_q\right)$$

How does the critical point affect these coefficients?

First calculations with viscosity (2015)

UrQMD + Hydro + UrQMD

Karpenko *et al*, PRC91 (2015) 6, 064901

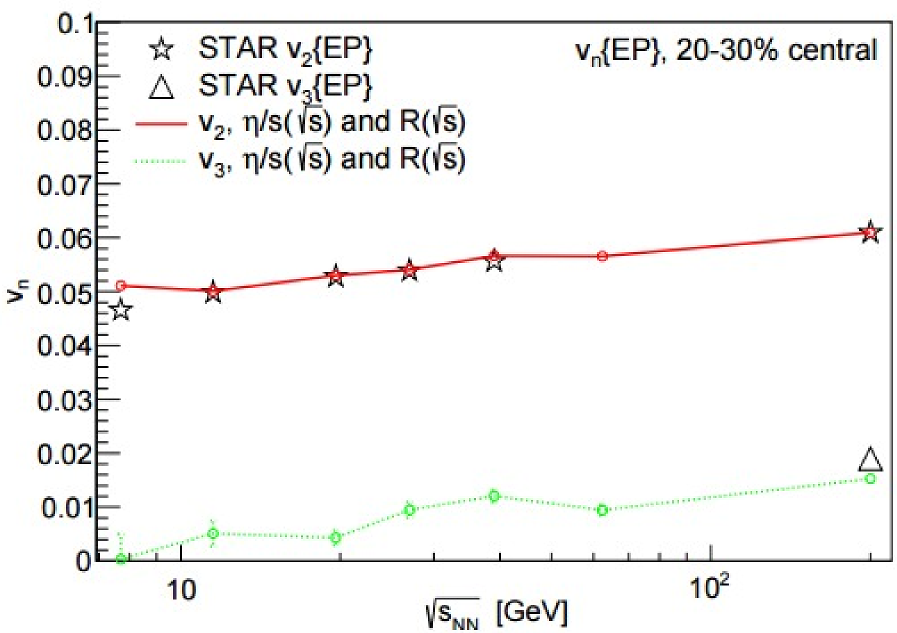
Finite baryon number, isospin, and electric charge must be included

Effective EoS is employed

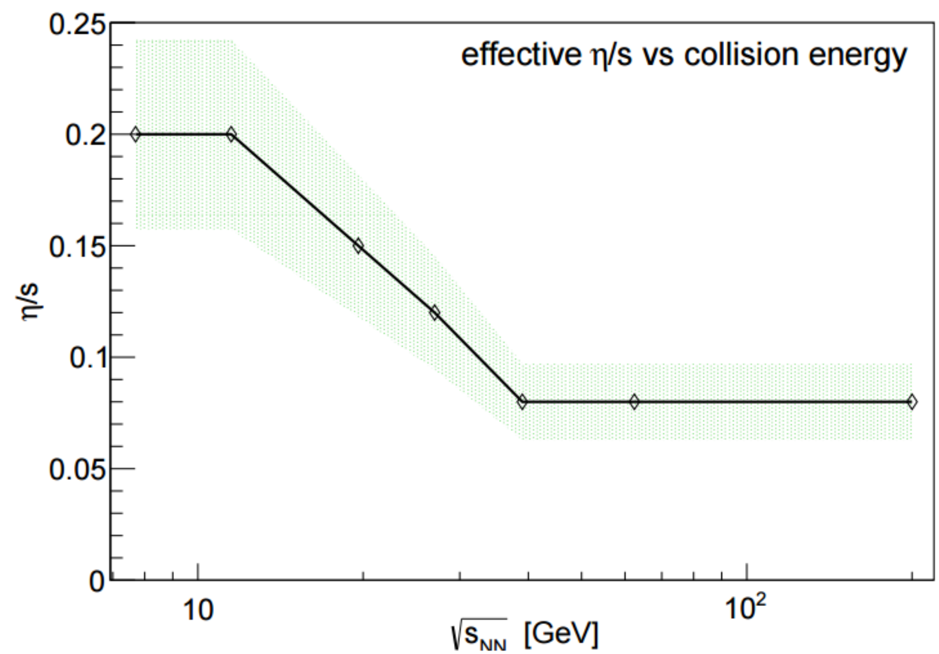
Steinheimer&Schramm&Stocker, J. Phys. G 38, 035001 (2011).

Constant η/s is extracted separately for each collision energy

- proxy for temperature and chemical potential dependencies



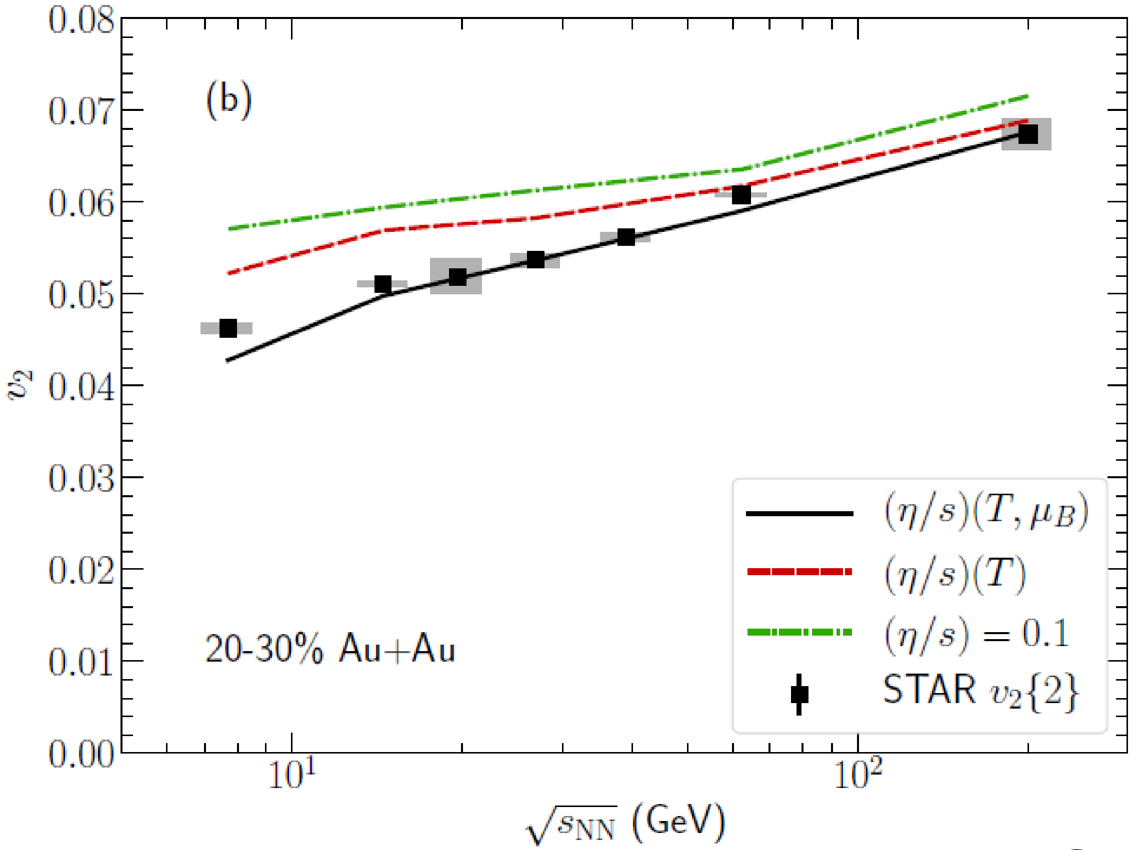
v_2 as a function of energy described



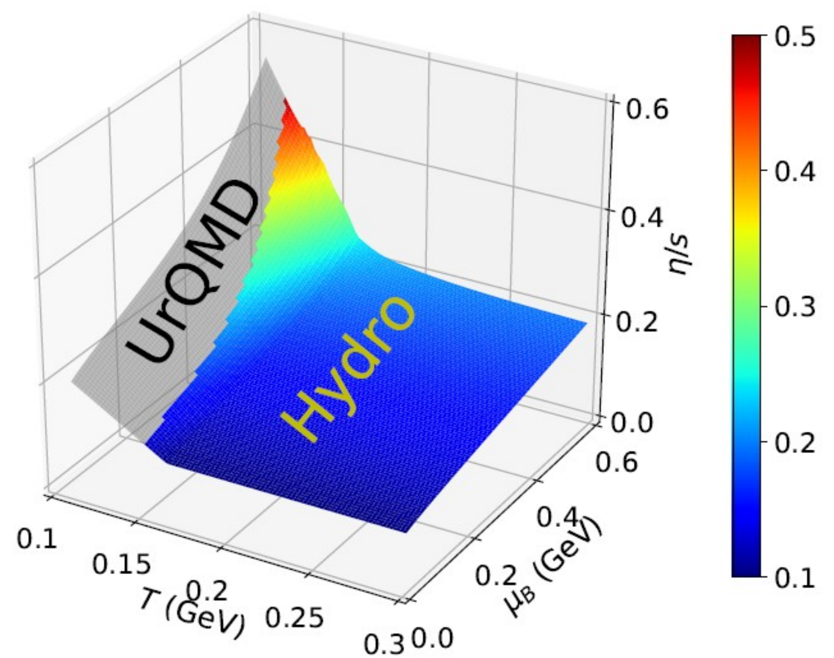
η/s estimated

Recent calculation with $\eta/s(T,\mu_B)$:

C. Shen and S. Alzhrani, PRC 102 (2020) 1, 014909



$$\frac{\eta}{s}(T,\mu_B) = \left(\frac{\eta}{s}\right)_0 f_T(T) \left(\frac{e+P}{Ts}\right) f_{\mu_B}(\mu_B)$$



See poster by Sahr Alzhrani

First calculation with diffusion: GSD, Gale, Jeon, Monnai, Schenke, Shen, PRC 98 (2018) no.3, 034916

Must include **Net-Charge Diffusion**

$$\boxed{j_q^\mu = \kappa_q \nabla^\mu \alpha_q}$$

Denicol *et al*, PRC98 (2018) no.3, 034916

$\alpha = \mu/T$

thermal potential

Our systems have at least *3 conserved charges:*
baryon number, strangeness, electric charge

The diffusion currents are coupled!

$$\begin{pmatrix} j_B^\mu \\ j_Q^\mu \\ j_S^\mu \end{pmatrix} = \begin{pmatrix} \kappa_{BB} & \kappa_{BQ} & \kappa_{BS} \\ \kappa_{QB} & \kappa_{QQ} & \kappa_{QS} \\ \kappa_{SB} & \kappa_{SQ} & \kappa_{SS} \end{pmatrix} \cdot \begin{pmatrix} \nabla^\mu \alpha_B \\ \nabla^\mu \alpha_Q \\ \nabla^\mu \alpha_S \end{pmatrix}$$

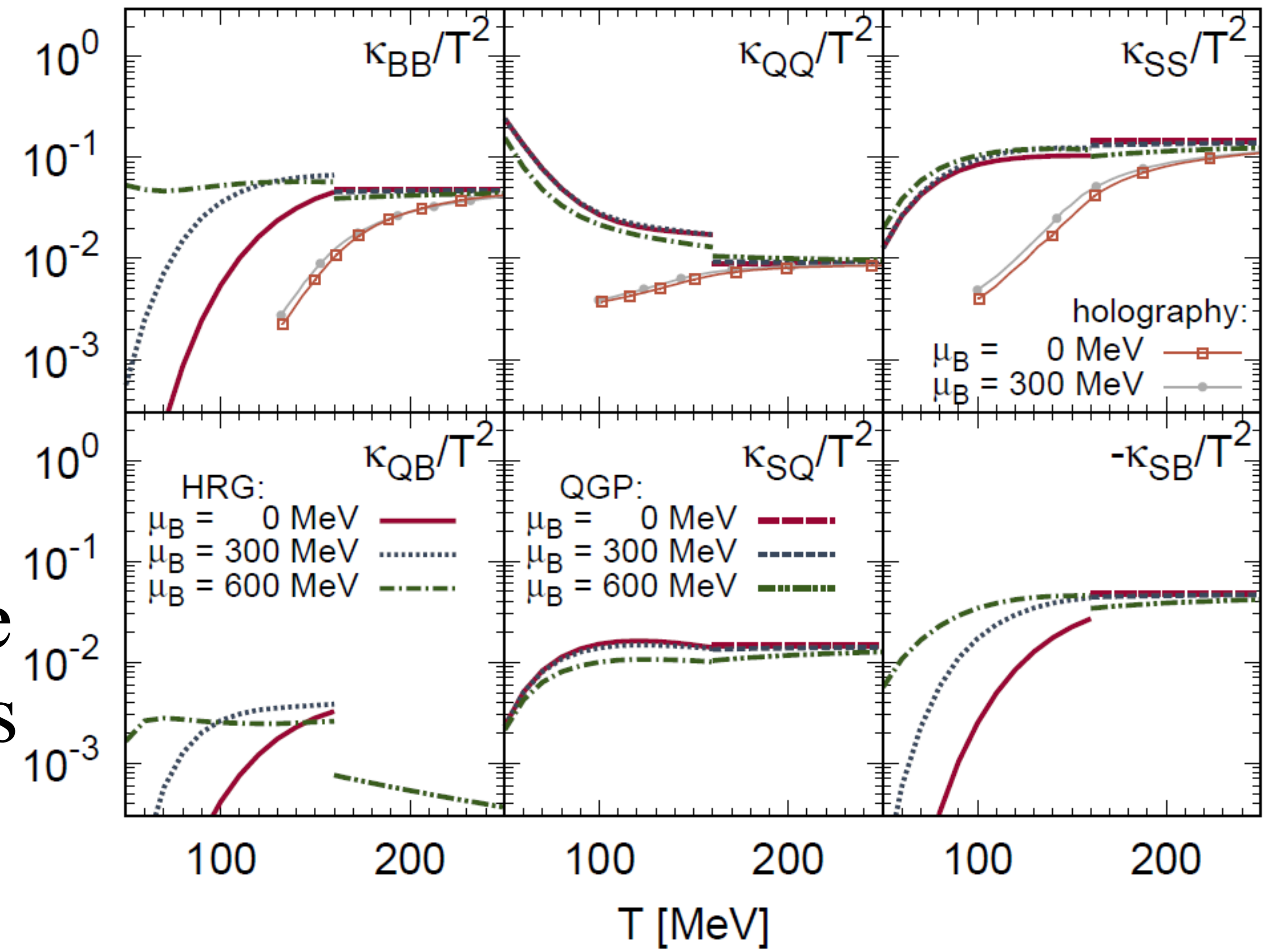
M. Greif *et al*, PRL 120 (2018) no.24, 242301

Our systems have at least <u>*3 conserved charges:*</u> baryon number, strangeness, electric charge

- <u>*first estimates from kinetic theory*</u>
- provide information on *effective* degrees of freedom of QCD
- off-diagonal terms are related to conductivities

Rose *et al*, Phys.Rev.D 101 (2020) 11, 114028

M. Greif *et al*, PRL 120 (2018) no.24, 242301

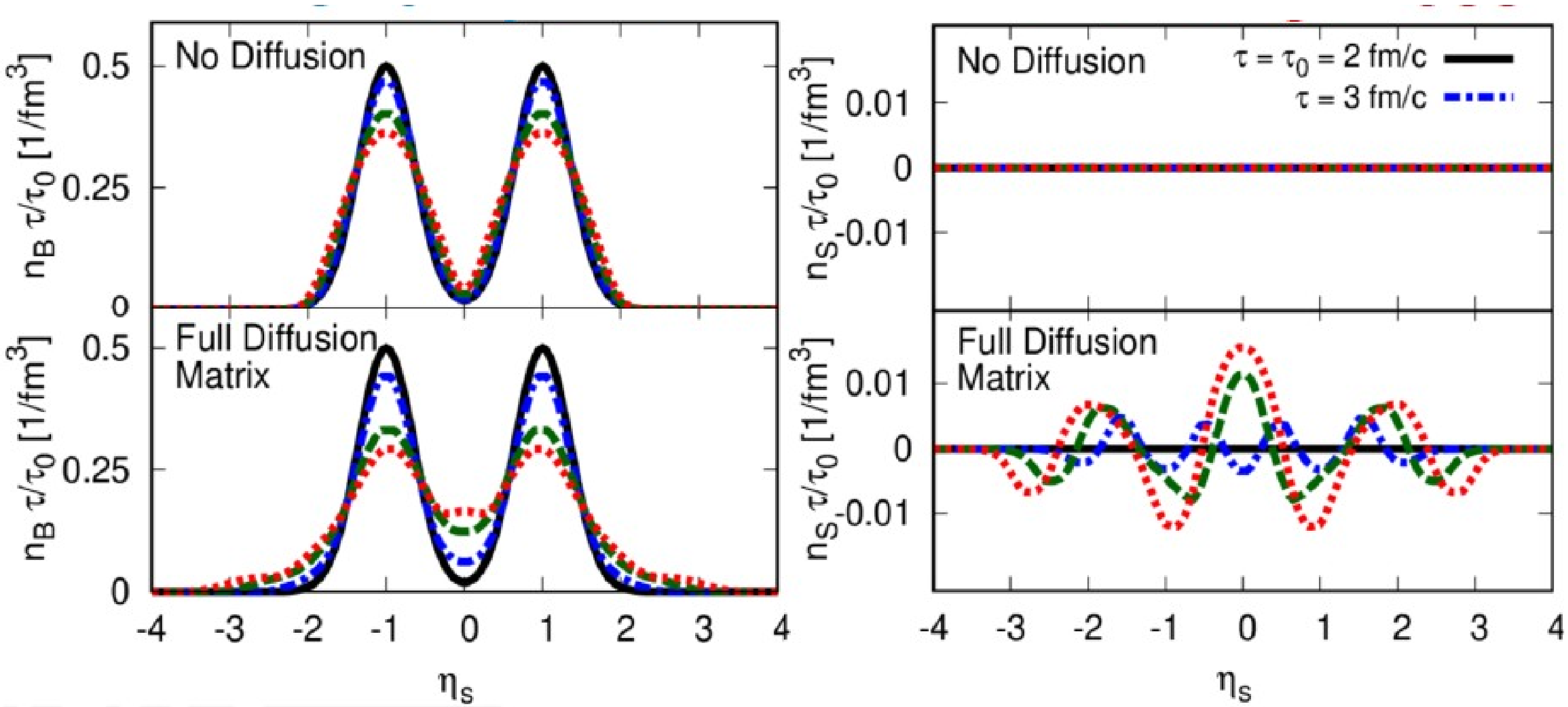


Our systems have at least *3 conserved charges:* baryon number, strangeness, electric charge

Effects explored in 1+1D simulations

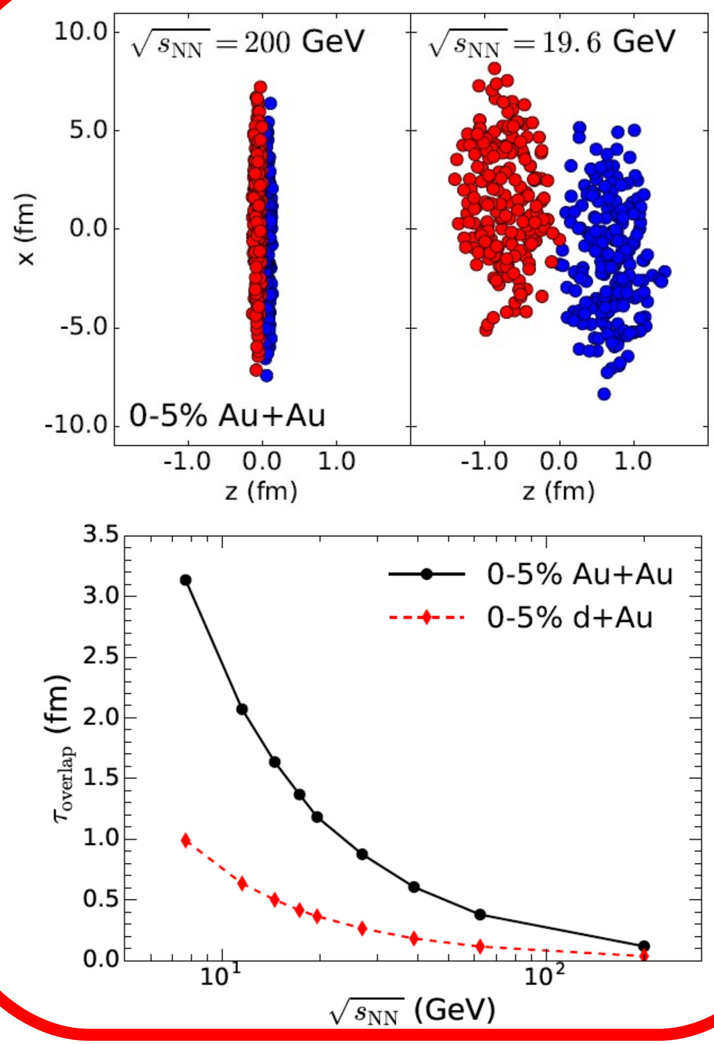
J. Fotakis *et al*, PRD 101 (2020) 7, 076007

Net baryon number **Net strangeness**



Initial Condition - sources

- Interpenetration time of the two nuclei is not negligible
- medium created: *freshly produced unthermalized particles*
  \+ *dissipative fluid*



Conservation laws are suplemented by source terms

$$\partial_\mu T^{\mu\nu} = J^{\nu}_{\mathrm{source}}$$

$$\partial_\mu J^{\mu} = \rho_{\mathrm{source}}$$

M. Okai, K. Kawaguchi, Y. Tachibana, and T. Hirano, PRC95, 054914 (2017)

C. Shen and B. Schenke, PRC97 (2018) 024907

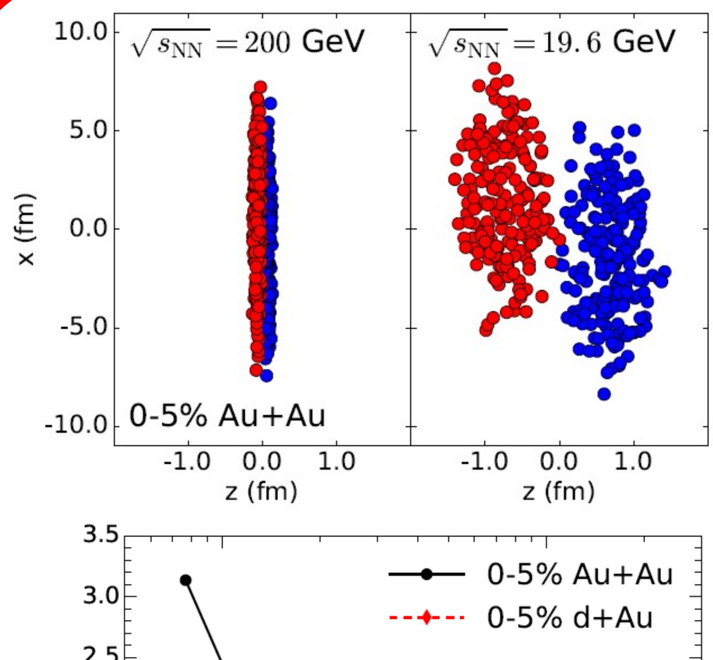
L. Du, U. Heinz and G. Vujanovic, NPA982 (2019) 407

<u>See Chun Shen's talk for more</u>

<u>See Lipei Du's talk for more</u>

Initial Condition - sources

- Interpenetration time of the two nuclei is not negligible
- medium created: *freshly produced unthermalized particles* + *dissipative fluid*



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M. Okai, K. Kawaguchi, Y. Tachibana, and T. Hirano, PRC95,

Challenges in the description of pre-equilibrium dynamics ...

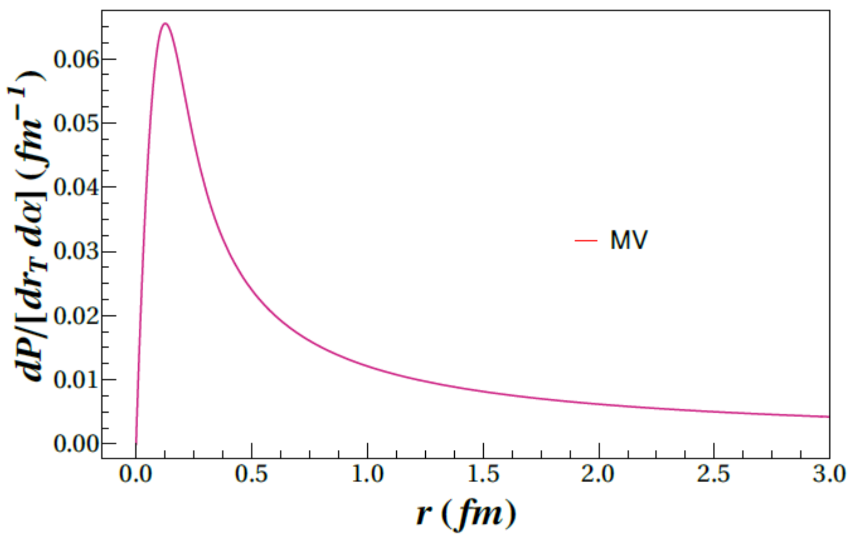
<u>See Sangwook Ryu's poster for an study with SMASH</u>

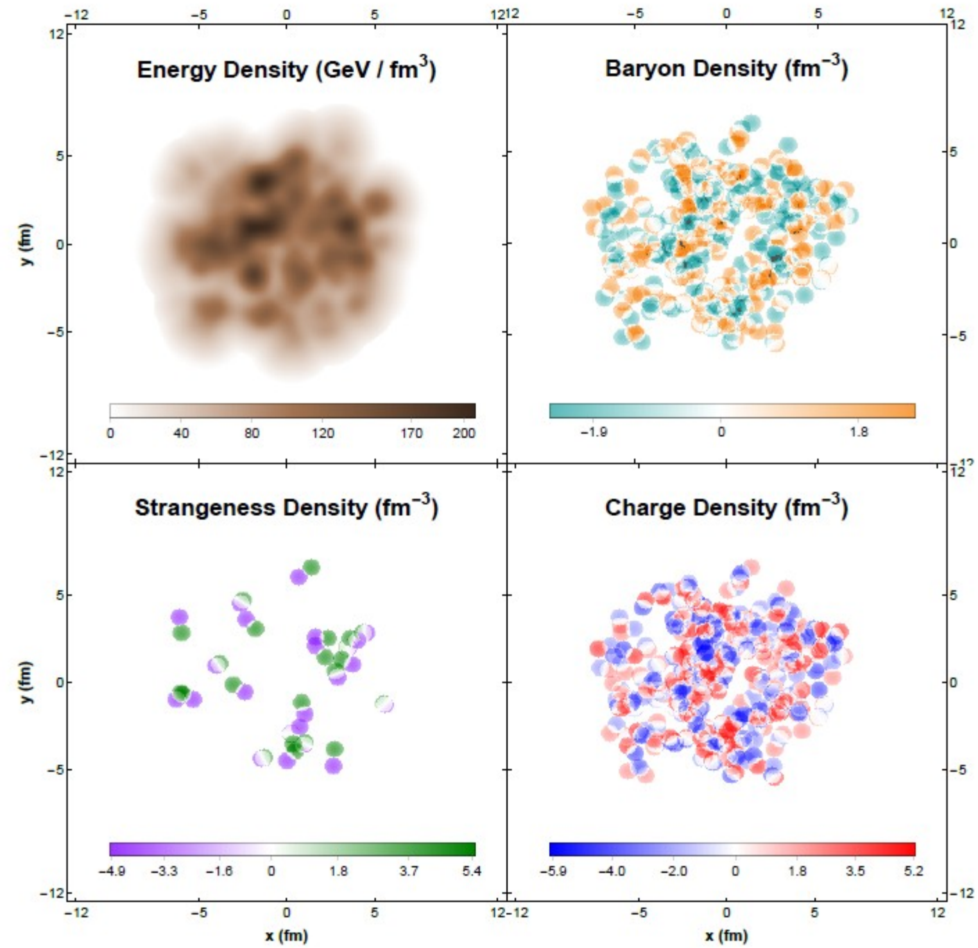
<u>See Xiaojian Du's poster for a study of attractors at finite μ</u>

net-charge fluctuations in *high energy* collisions

Global net-charge may be small, but may still fluctuate

Sea quarks distribution due to gluon splitting $g \to q\bar{q}$





Iccing See Patrick Carzon's poster for more

- May also expect some effects at large rapidity

Conclusions and outlook

Fluid-dynamical models that describe low energy heavy ion collisions are under construction – but appear to be able to fit the data

- Equation of state is not understood. What are its effects on the data? Can it really be extracted?

- Many transport coefficients appear at finite μ_B. Very difficult to include and extract them...

but they may be crucial in identifying a phase transition

Hydrodynamics near critical point? New theories may be required ... inclusion of fluctuations.