Collective phenomena in large and small systems: status and perspectives from theory

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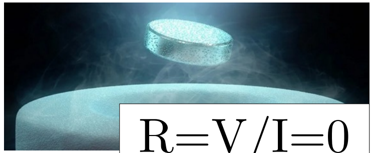
The physical world as an emergent phenomenon.

Describing interacting many-body systems through their emergent collective properties.

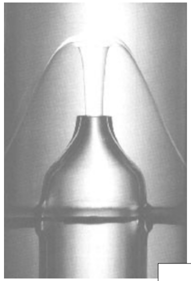
[Anderson, Science **177** no.4047, 393-396 (1972)]

Superconductivity



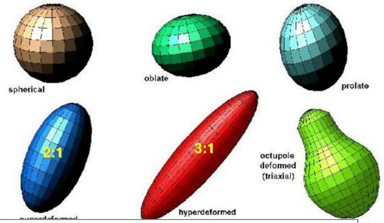
$R=V/I=0$

Superfluidity



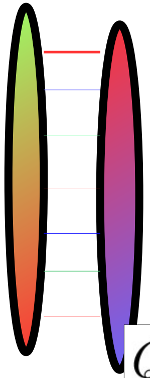
$\eta=0$

Nuclear deformations



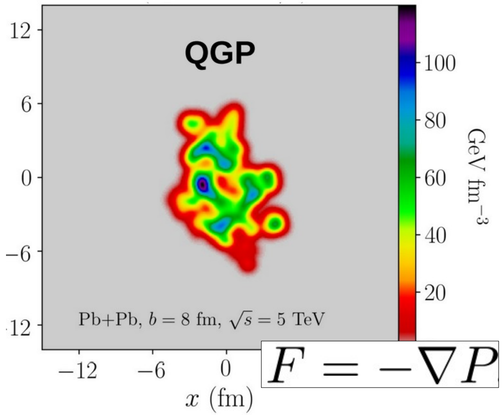
$$R = R_0\left(1+\sum_n \beta_n Y_n^0\right)$$

color glass condensate

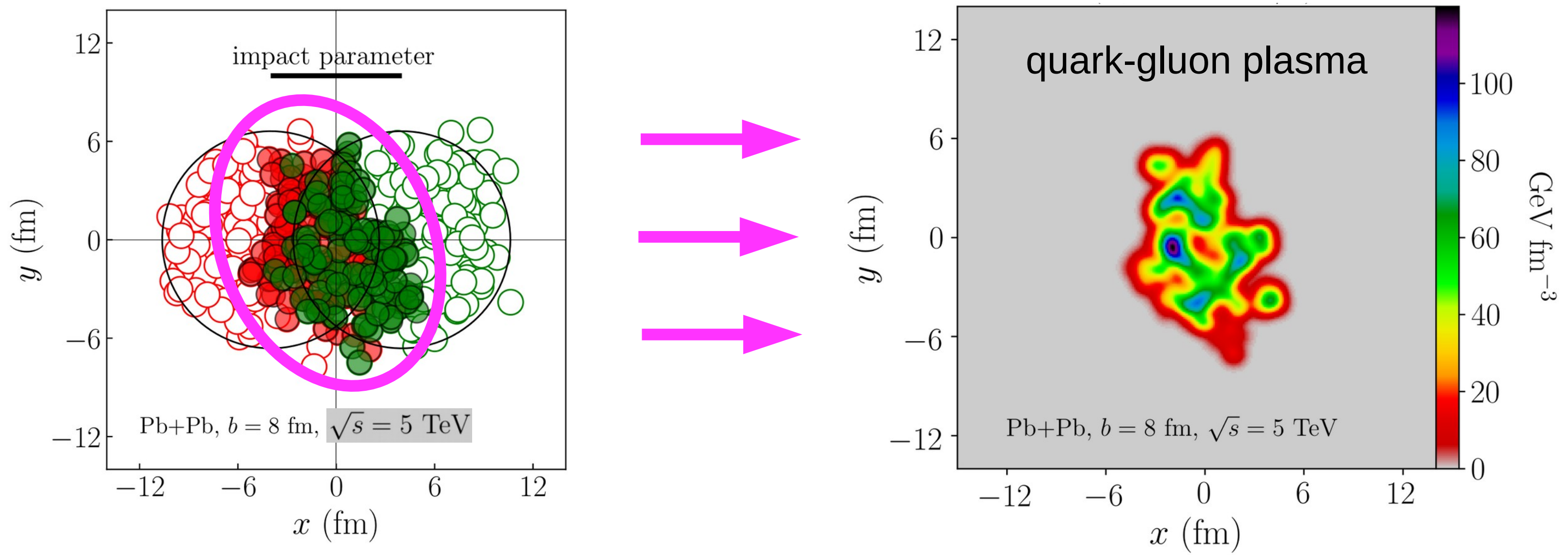


$Q_s^2(\mathbf{x})$

quark-gluon plasma



$F=-\nabla P$



THE HYDRODYNAMIC FRAMEWORK OF HIGH-ENERGY COLLISIONS

Fluctuation of energy density are driven by random nucleon positions.

[Miller, Snellings, nucl-ex/0312008] [Alver, Roland, PRC **81** (2010) 054905]

Effective fluid description: $T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu}$ [Romatschke & Romatschke, arXiv:1712.05815]

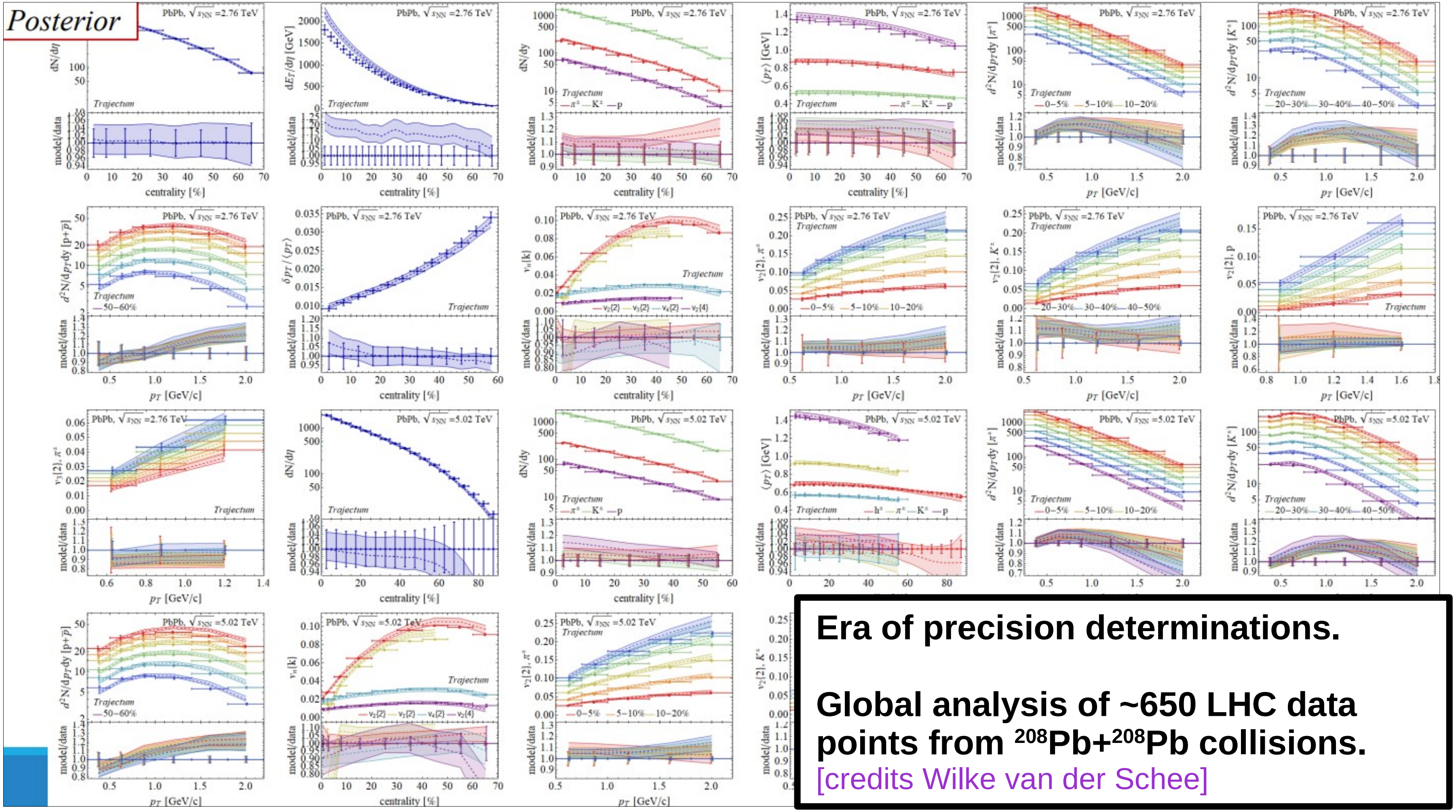
Equation of state from lattice QCD. [HoTQCD collaboration, PRD **90** (2014) 094503]
[Gardim, Giacalone, Luzum, Ollitrault, Nature Phys. **16** (2020) 6, 615-619]

Fluid is viscous (η/s **,** ζ/s **, ...).** [Bernhard, Moreland, Bass, Nature Phys. **15** (2019) 11, 1113-1117]

LARGE SYSTEMS

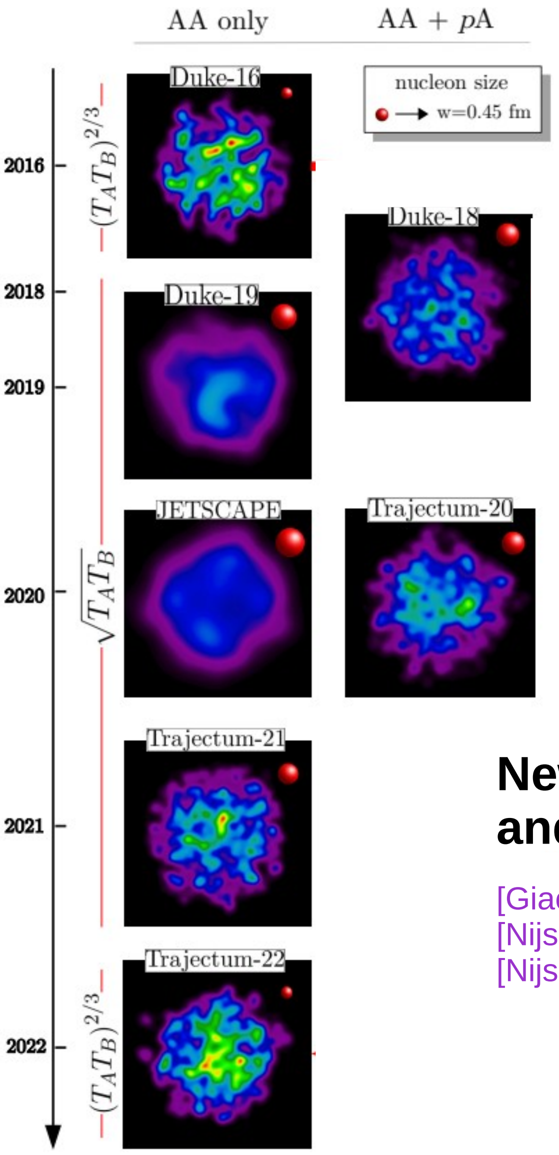
(refining the picture)

20 years later: hydrodynamic model constrained via global statistical analyses.



Era of precision determinations.

Global analysis of ~650 LHC data points from $^{208}Pb+^{208}Pb$ collisions.
[credits Wilke van der Schee]



Energy deposition in Bayesian analyses

[Giacalone, arXiv:2208.06839]

2016 "breakthrough": $dS/dy \propto (T_A\ T_B)^{1/2}$

2018-20: $dE/dy \propto (T_A\ T_B)^{1/2}$

2020 crisis: the QGP has lost all of its structure!

2022-23: restoring "sanity".

New insights about the role of the nucleon size and the total hadronic cross section.

[Giacalone, Schenke, Shen, PRL **128** (2022) 4, 042301]
[Nijs, van der Schee, PRL **129** (2022) 23, 232301]
[Nijs, van der Schee, arXiv:2304.06191]

$dE/dy \propto (T_A\ T_B)^{q/2}$ → q=4/3 from LHC data

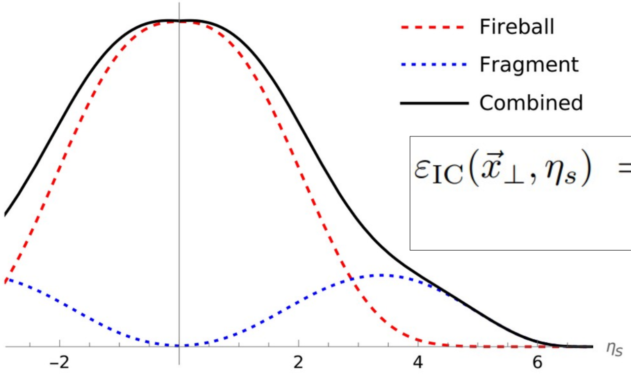
... AND BACK AGAIN!

Three-dimensional initial conditions and dynamics

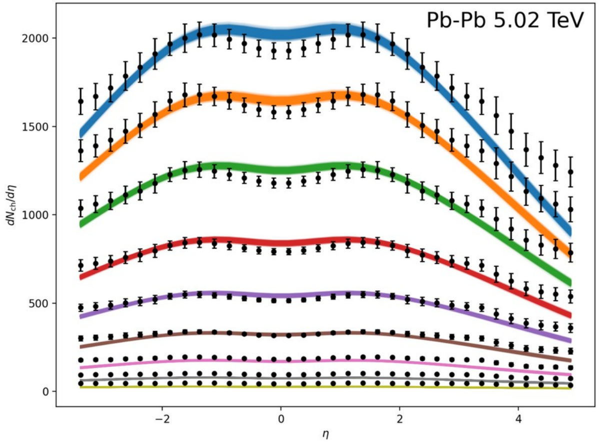
– Dynamical 3D Glauber Monte Carlo for multi-purpose studies.

[Shen, Schenke, PRC **105** (2022) 6, 064905]

– TRENTo 3D model. [Soeder *et al.*, arXiv:2306.08665]

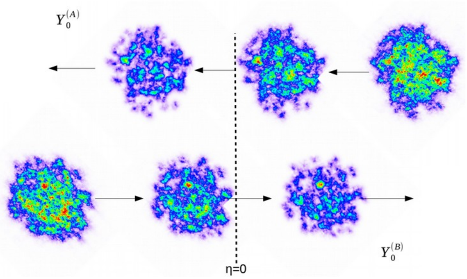


$$\varepsilon_{\mathrm{IC}}(\vec{x}_\perp, \eta_s) = \varepsilon_{\mathrm{fb}}(\vec{x}_\perp, \eta_s) + \varepsilon_{\mathrm{frag},A}(\vec{x}_\perp, \eta_s) + \varepsilon_{\mathrm{frag},B}(\vec{x}_\perp, \eta_s)$$



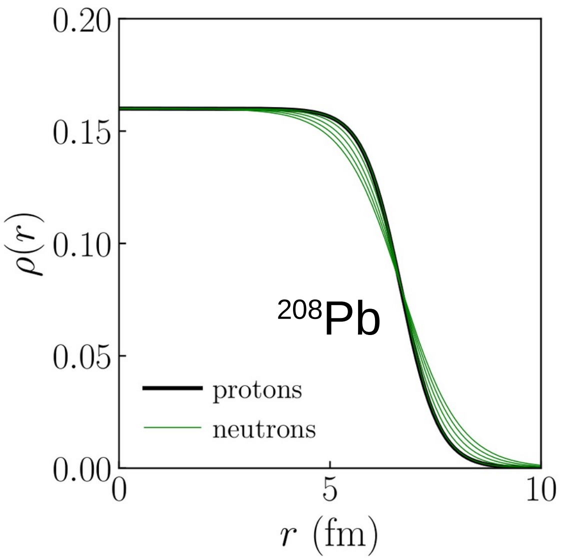
– Progress in 3+1D Glasma/IP-Glasma simulations.

[McDonald, Jeon, Gale, arXiv:2306.04896]
[The McDIPPER model, O. Garcia-Montero, Initial Stages 2023]
[Ipp *et al.*, PRD **104** (2021) 11, 114040]

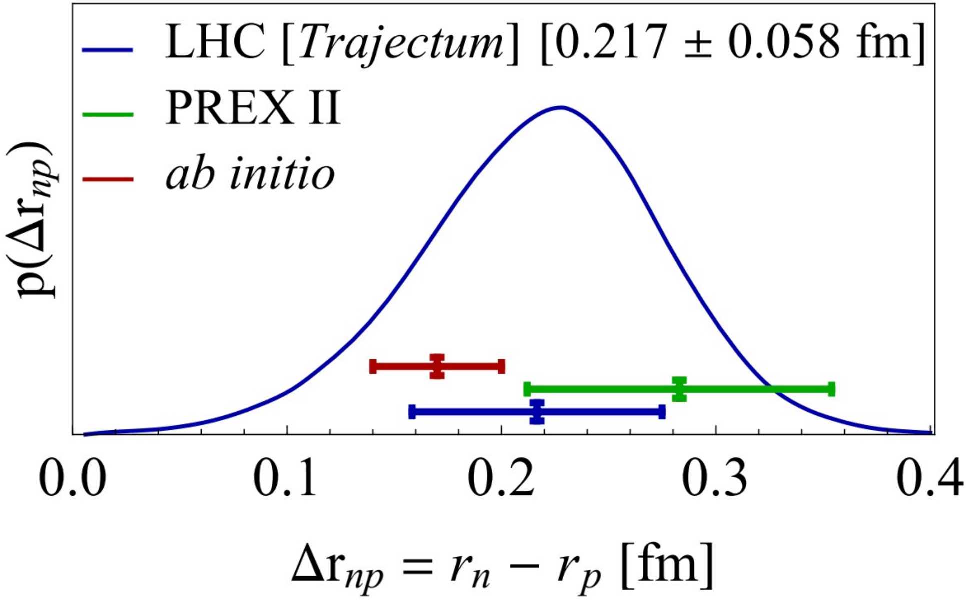


Nuclear structure in the hydrodynamic framework

First attempt, extracting the neutron profile of ^{208}Pb from LHC data.



[Giacalone, Nijs, van der Schee, arXiv:2305.00015]



Consistency between high-energy data and low-energy expectations.

Promising result: more sophisticated features of the nuclei can be included.

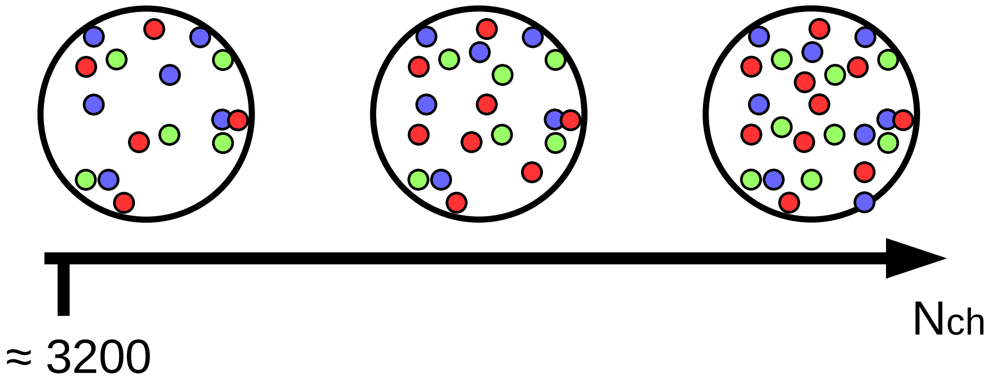
[see also Cheng *et al.* PRC **107** (2023) 6, 064909]

TALK BY YOU ZHOU

Thermalization and EOS in ultra-central collisions

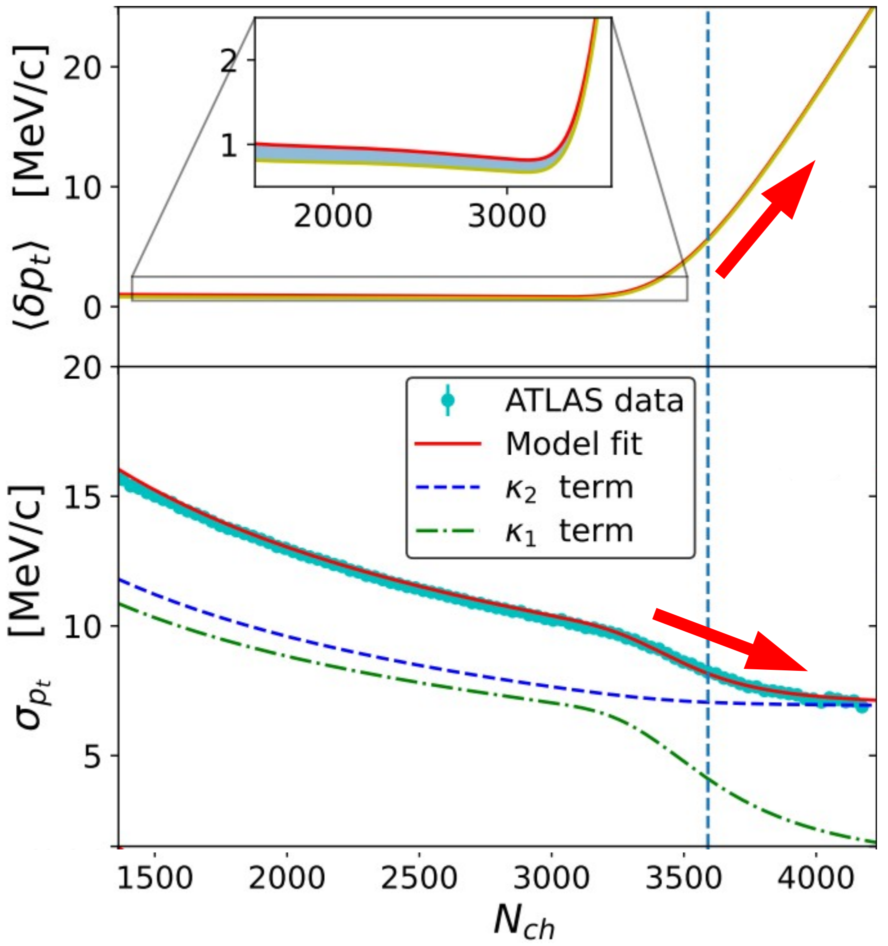
In UCC the "volume" becomes fixed.

Stuffing more and more matter in the same volume.



Increase in density leads to increase in <p_T>.

Phenomenon depends entirely on EOS.



[Samanta, Bhatta, Jia, Luzum, Ollitrault, arXiv:2303.15323]
[Samanta, Picchetti, Luzum, Ollitrault, arXiv:2306.09294]

TALK BY SOMADUTTA BHATTA

Tansport coefficients

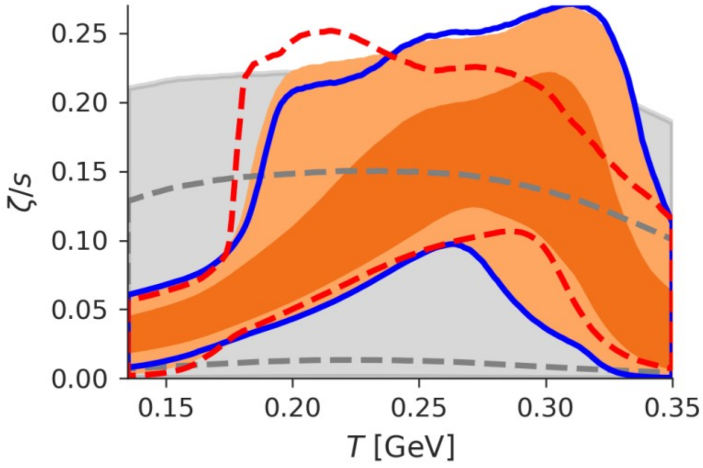
– Bayesian analysis with Viscous Anisotropic Hydrodynamics equations.

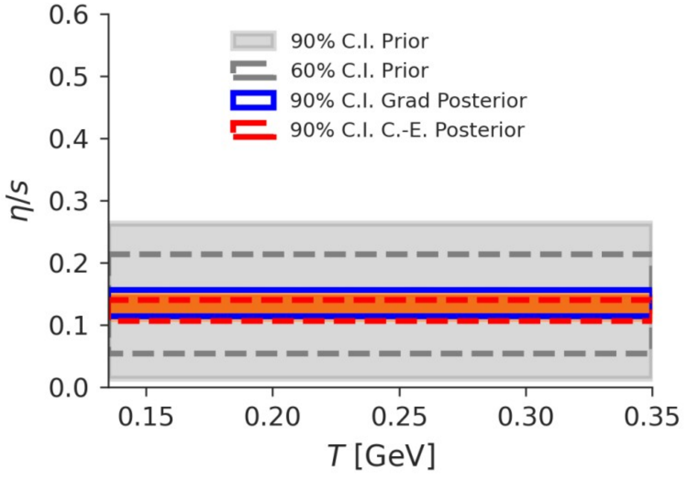
$$T^{\mu\nu} = \epsilon u^\mu u^\nu + P_L z^\mu z^\nu - P_\perp \Xi^{\mu\nu} + 2W^{(\mu}_{\perp z} z^{\nu)} + \pi^{\mu\nu}_\perp$$

[Liyanage *et al.*, arXiv:2302.14184]

– First Bayesian analysis with 2D IP-Glasma initial conditions!
Seemingly excellent constraint on η/s.

[Heffernan *et al.*, arXiv:2302.09478]
[Heffernan *et al.*, arXiv:2306.09619]

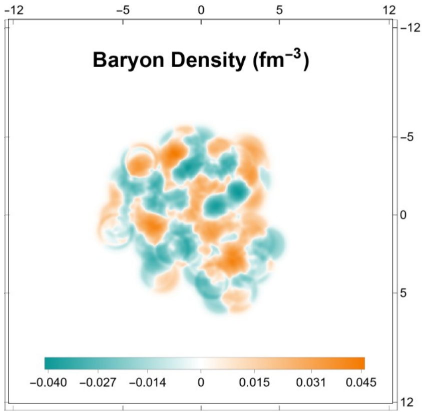


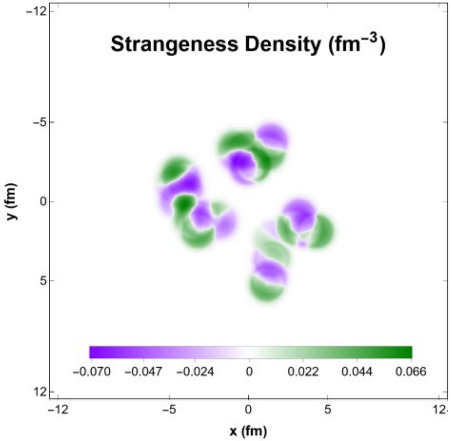


Hydro with conserved charges

– Non-equilibrium Green's function for conserved charges in KøMPøST.

[Carzon *et al.*, arXiv:2301.04572]





– Heavy quark diffusion coefficient from QCD kinetic theory.

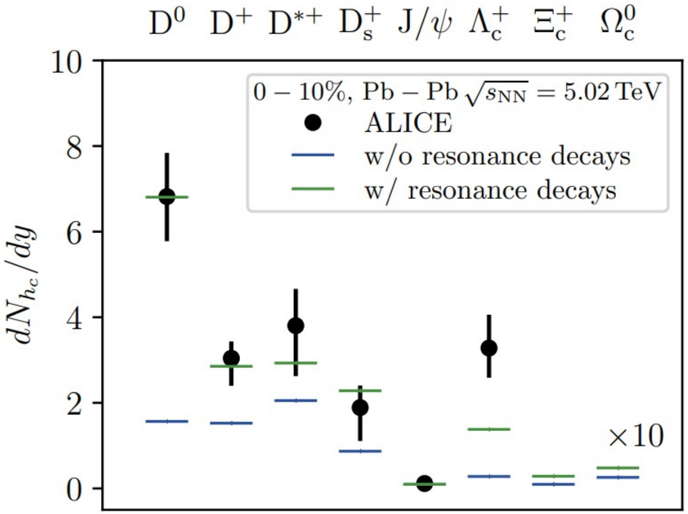
[Boguslavski *et al.*, arXiv:2303.12520]

– Initialize charm density and solve for respective current (conserved=no thermal charm production).

$$n_{\rm hard}^{Q\overline{Q}}(\tau_0, \vec{x}_\perp, y=0) = \frac{1}{\tau_0} n_{\rm coll}(\vec{x}_\perp) \frac{1}{\sigma^{\rm in}} \frac{d\sigma^{Q\bar{Q}}}{dy}$$

$$\nabla_\mu N^\mu = 0$$

[Capellino *et al.*, arXiv:2307.14449]
[Capellino *et al.*, PRD **106** (2022) 3, 034021]



SMALL SYSTEMS

(understanding the picture)

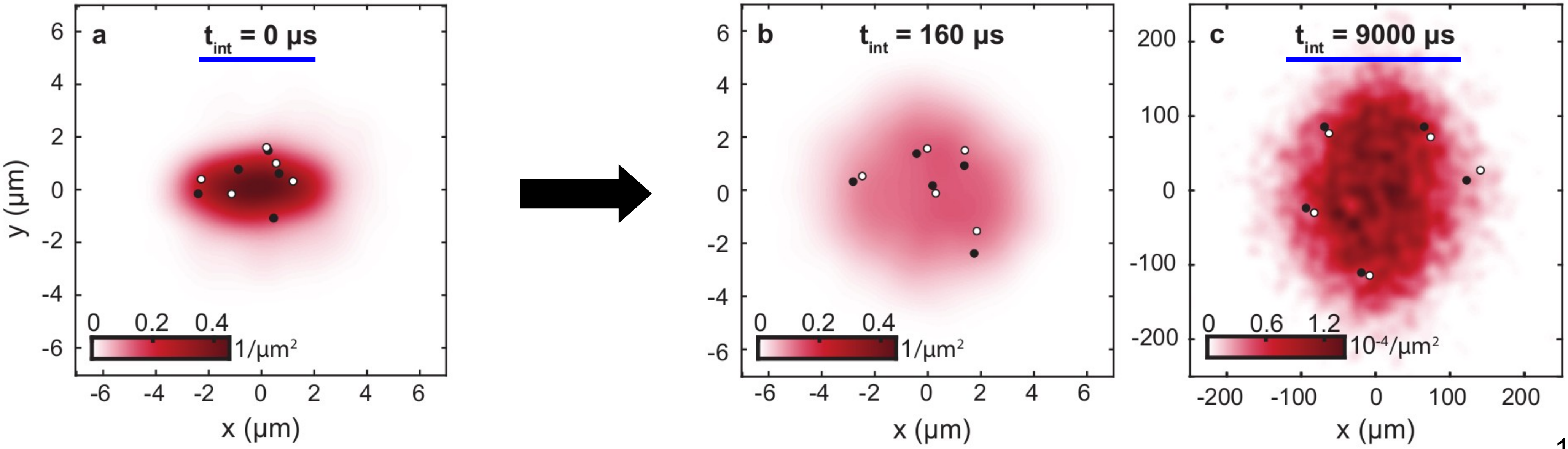
“Small system question” from a new angle. [Brandstetter *et al.*, arXiv:2308.09699] [Flörchinger *et al.*, PRC **105** (2022) 4, 044908]

Strongly-interacting ^{6}Li atoms in a trap. Imaging the expansion driven by interactions.

No separation of scales in the initial system: system size = interparticle spacing.

TEXTBOOK FLUID DYNAMICS DOES NOT APPLY …

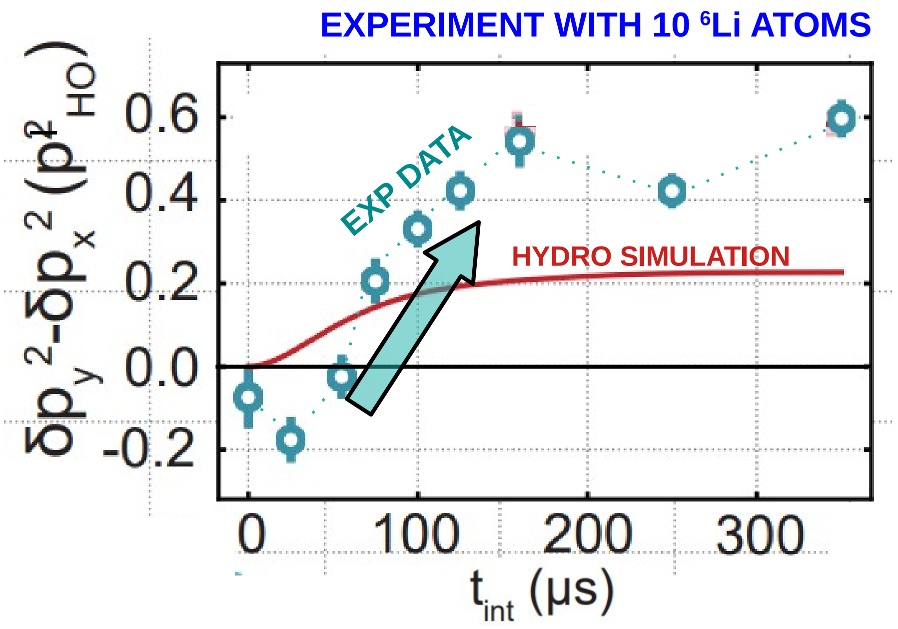
… but shape inversion is observed!

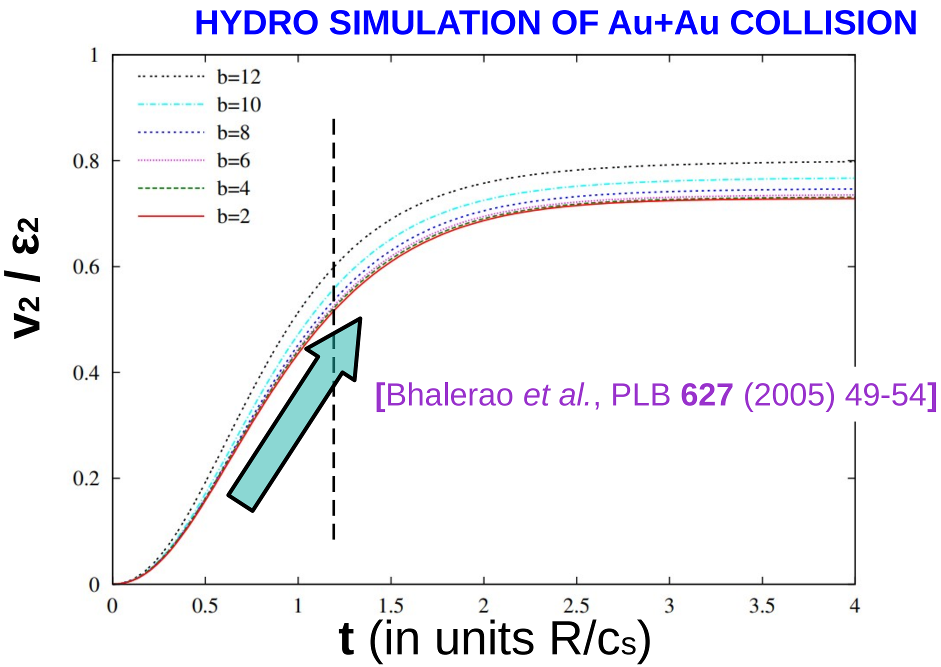


Real time imaging of the emergence of elliptic flow (momentum space).

From data alone it behaves in all respects like a fluid.

New “small system question” outside of the field of high-energy collisions.

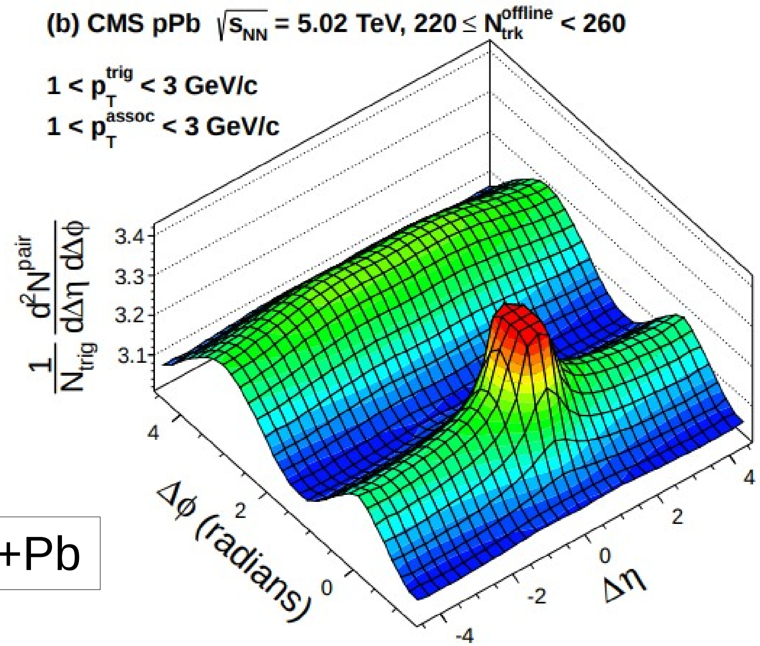




NB: Hydro calculation based on corresponding many-body EOS does not work.

Similar situation in small system collisions.

Collective behavior is observed.



p+Pb

[CMS collaboration, PLB **724** (2013) 213-240]

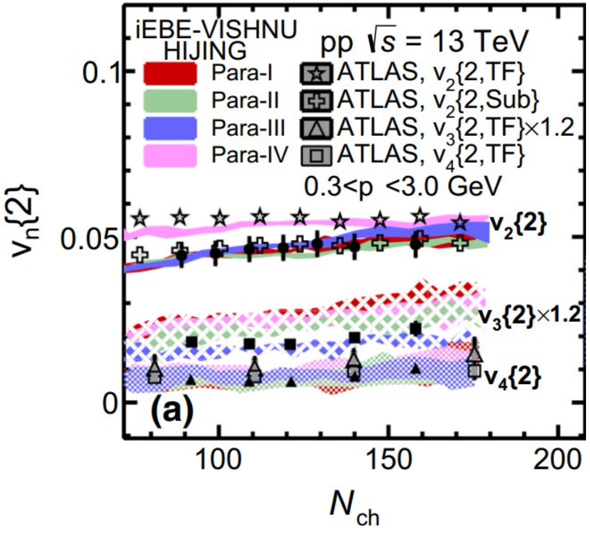
$$v_2\{2,4,6,8\} \quad v_3\{2,4\} \quad v_4\{2\}$$

$$\langle v_2^2 v_3^2 \rangle \quad \langle v_2^2 v_4^2 \rangle$$

$$\langle V_2^2 V_4^* \rangle$$

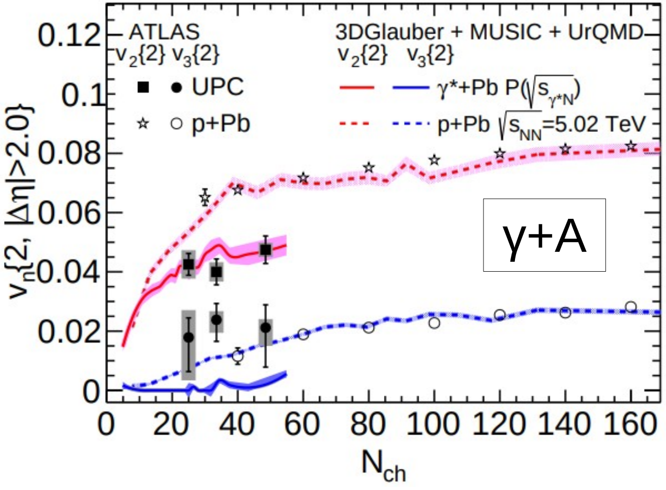
$$\langle v_2^2 \langle p_t \rangle \rangle \quad \langle v_3^2 \langle p_t \rangle \rangle$$

GREAT EXPERIMENTAL PROGRAM



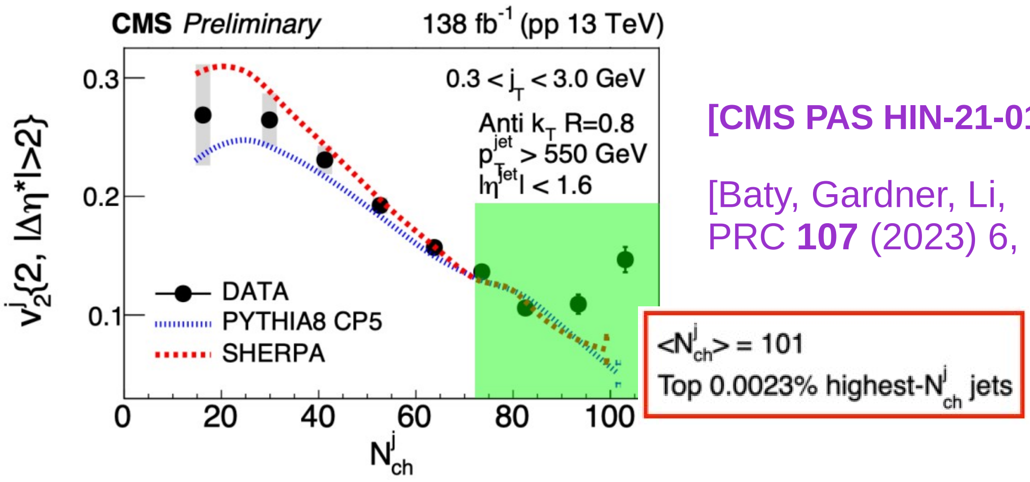
p+p

[Zhao *et al.*, EPJC **80** (2020) 9, 846]



γ+A

[Zhao, Shen, Schenke, PRL **129** (2022) 25, 252302]



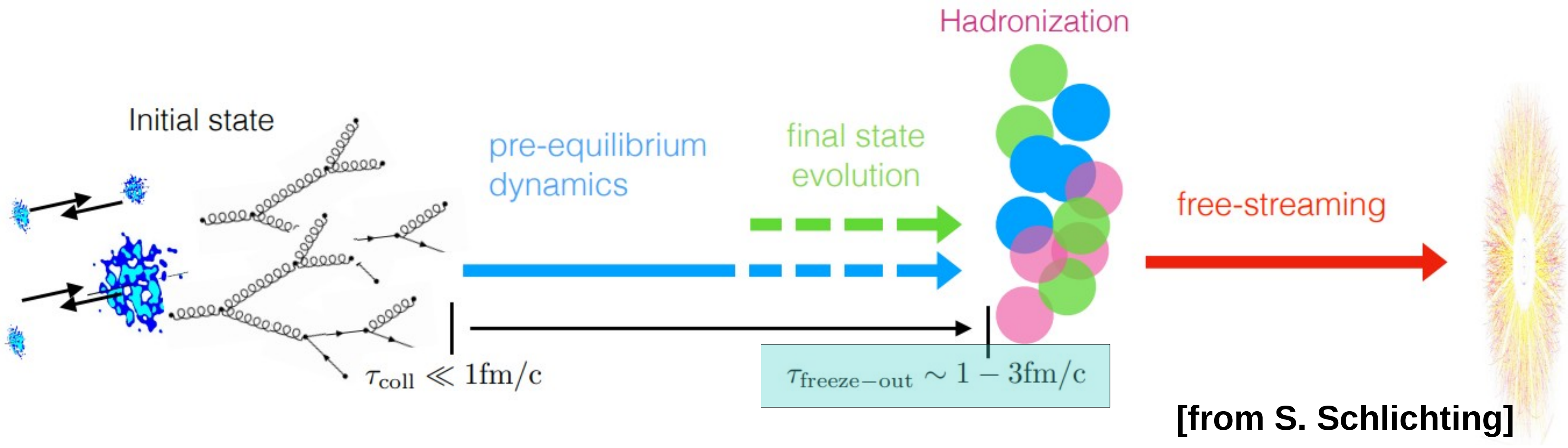
[CMS PAS HIN-21-013]

[Baty, Gardner, Li,
PRC **107** (2023) 6, 064908]

“Extreme” collective behavior driven by QCD.

Hydrodynamic interpretation?

Issue with a hydrodynamic interpretation: collective behavior occurs out of equilibrium!



[from S. Schlichting]

– Existence and imprints of the hydrodynamic attractor.

[e.g. Soloviev, EPJC **82** (2022) 4, 319]

– Numerical advances for realistic equilibration with transverse expansion.

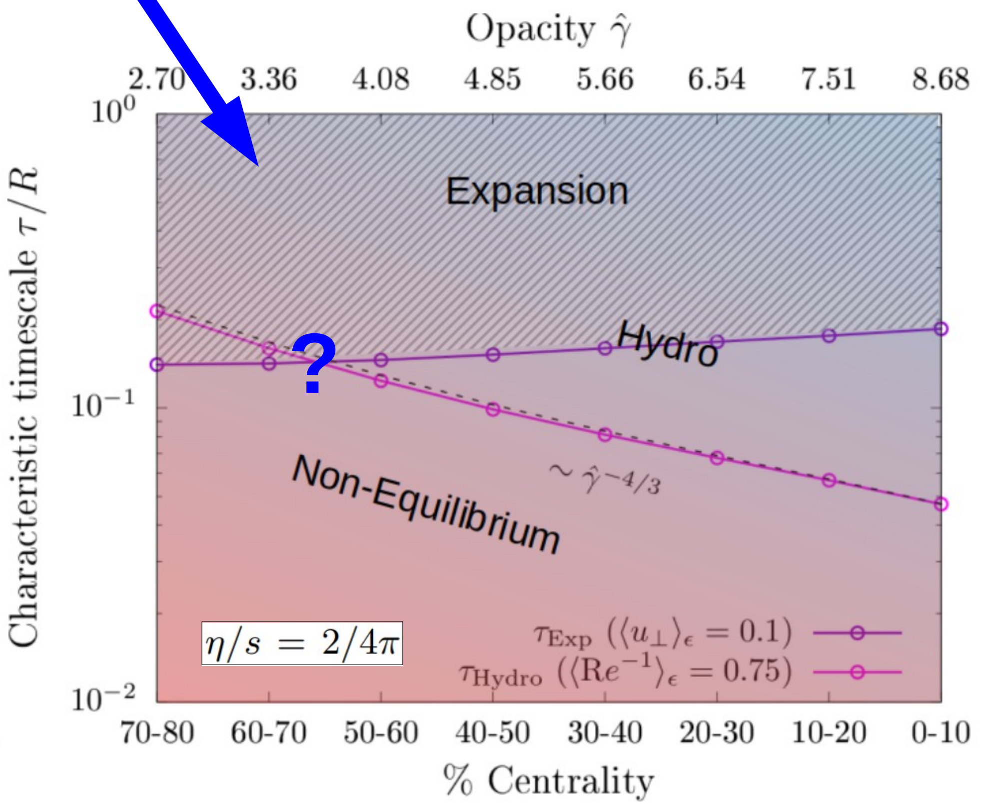
[Kurkela et al., PLB **811** (2020) 135901]
[Kurkela, Mazeliauskas, Törnkvist, JHEP **11** (2021) 216]
[Ambrus, Schlichting, Werthmann, PRD **105** (2022) 1, 014031]
[Ambrus, Schlichting, Werthmann, PRD **107** (2023) 9, 094013]
[Ambrus, Schlichting, Werthmann, PRL **130** (2023) 15, 152301]

EXAMPLE: Boltzmann equation in the relaxation time approximation (RTA):

$$p^\mu \partial_\mu f(x,p) = -\frac{u^\mu(x) p_\mu}{\tau_R(x)} \left[f(x,p) - f_{\rm eq}(x,p) \right] \qquad \hat{\gamma} = \frac{1}{5\eta/s} \left(\frac{R}{\pi a} \frac{dE_\perp^0}{d\eta} \right)^{1/4}$$

[Ambrus, Schlichting, Werthmann, PRD **105** (2022) 1, 014031]
[Ambrus, Schlichting, Werthmann, PRD **107** (2023) 9, 094013]
[Ambrus, Schlichting, Werthmann, PRL **130** (2023) 15, 152301]

^{16}O-^{16}O
p-^{208}Pb



Reliable criteria to establish the applicability of hydrodynamics in high-energy collisions.

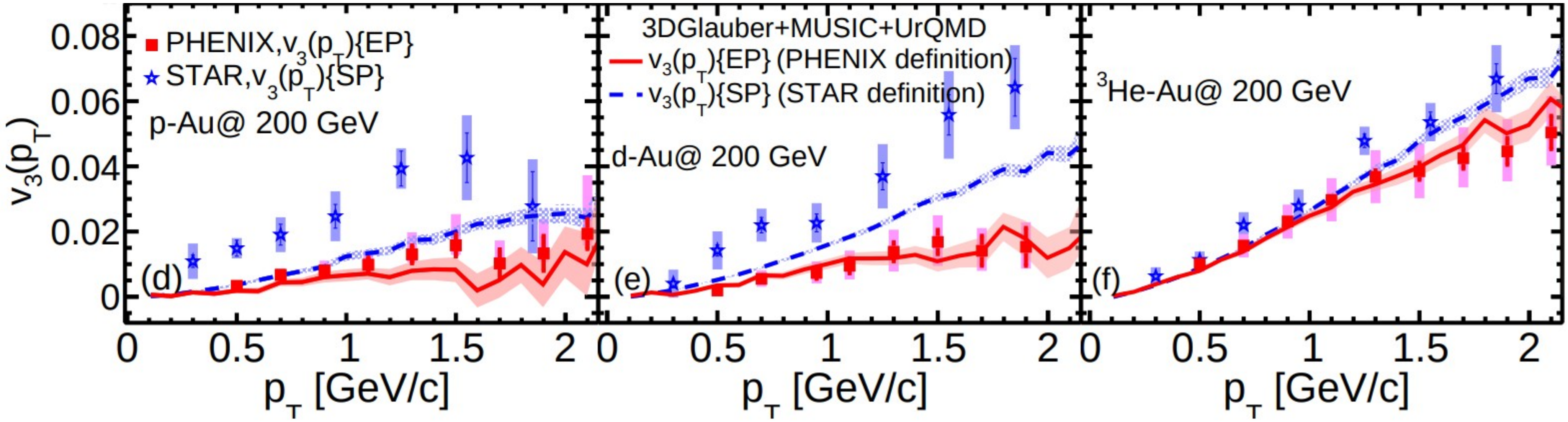
PROSPECTS:

QCD collision kernel.

Exploiting theoretical advances?

Small system collectivity in p-A collisions.

[PHENIX Collaboration, Nature Phys. **15** (2019) 3, 214-220]
[STAR collaboration, PRL **130** (2023) 242301]



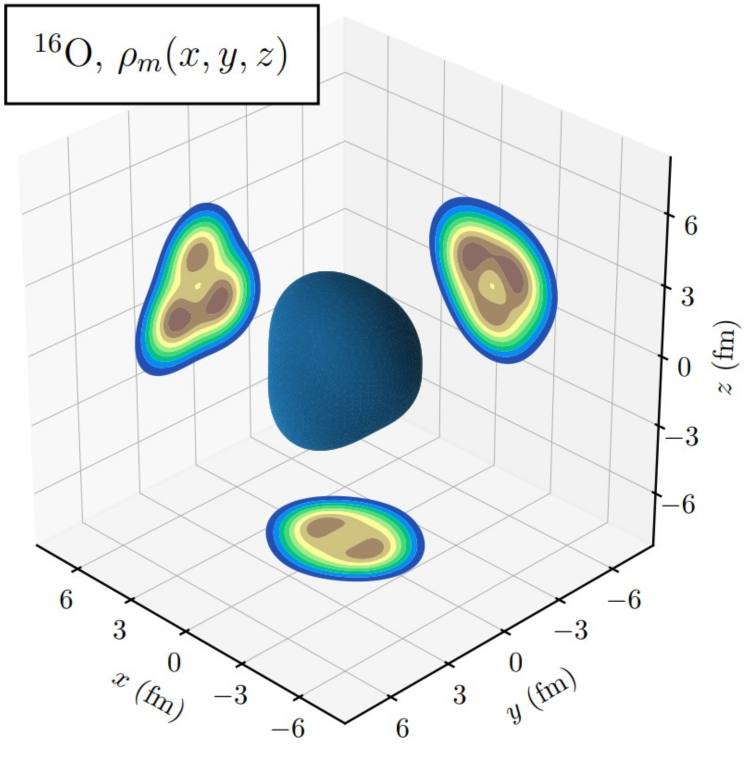
[Zhao, Ryu, Shen, Schenke, PRC **107** (2023) 1, 014904]

Full 3D modeling + sub-nucleon structure are essential!

Quantitative understanding of data seems out of reach?

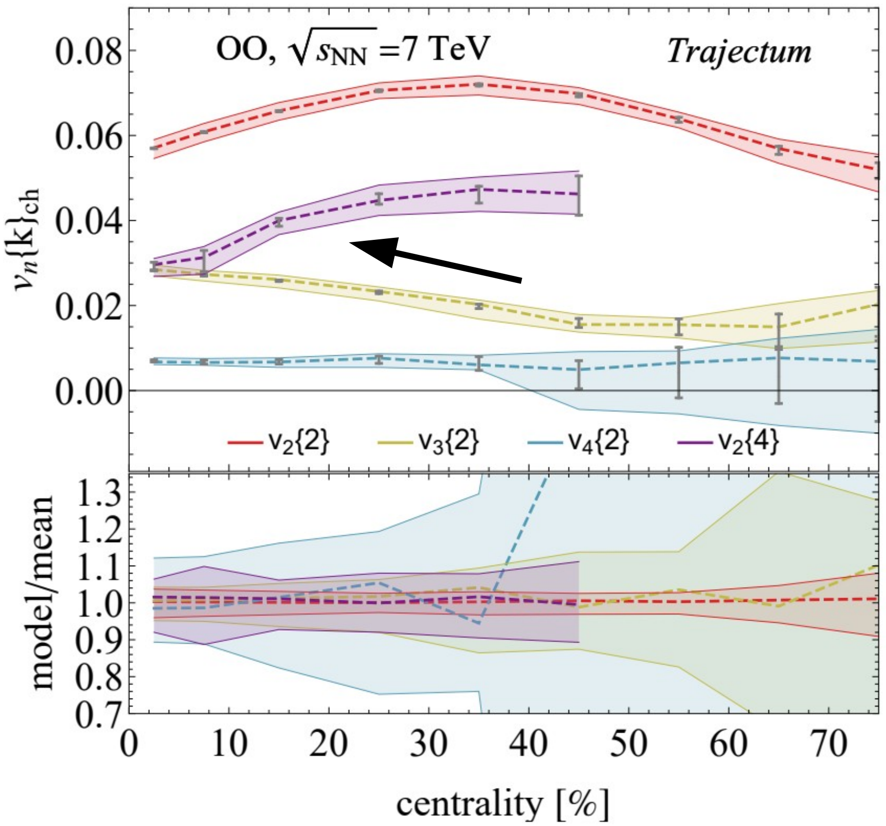
Away from the p-A baseline: prospects with light nuclei.

Same multiplicities, better controlled geometries.



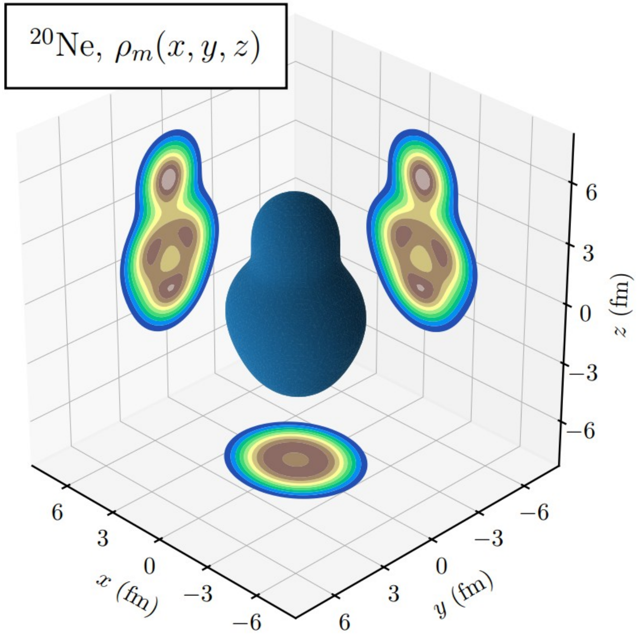
[Bally *et al.*, in preparation]

[Nijs, van der Schee, PRC **106** (2022) 4, 044903]

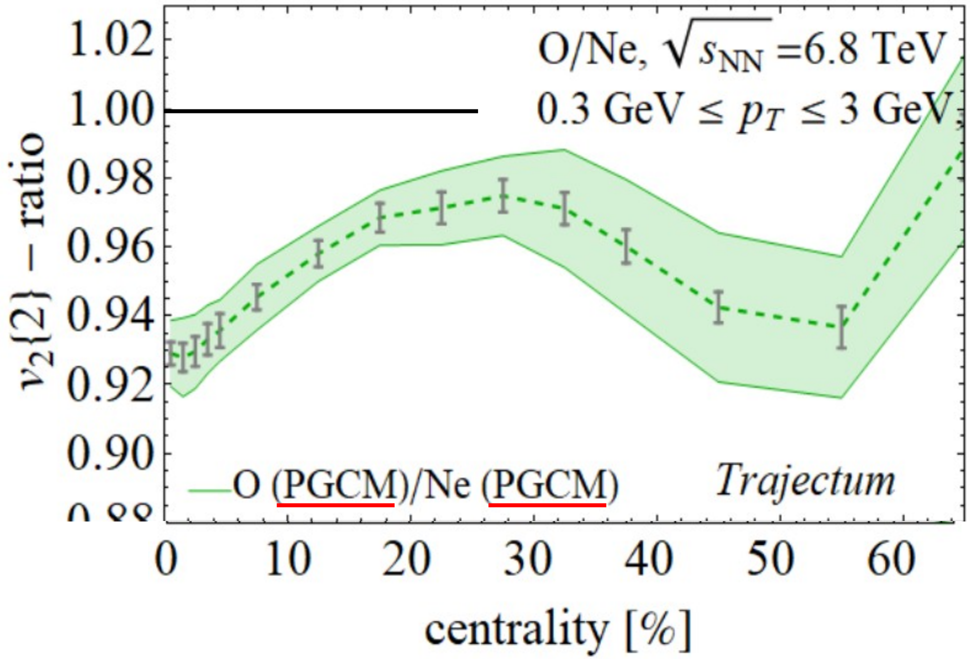


Much more robust results by complementing ^{16}O with an additional light ion.

Natural choice is ^{20}Ne.



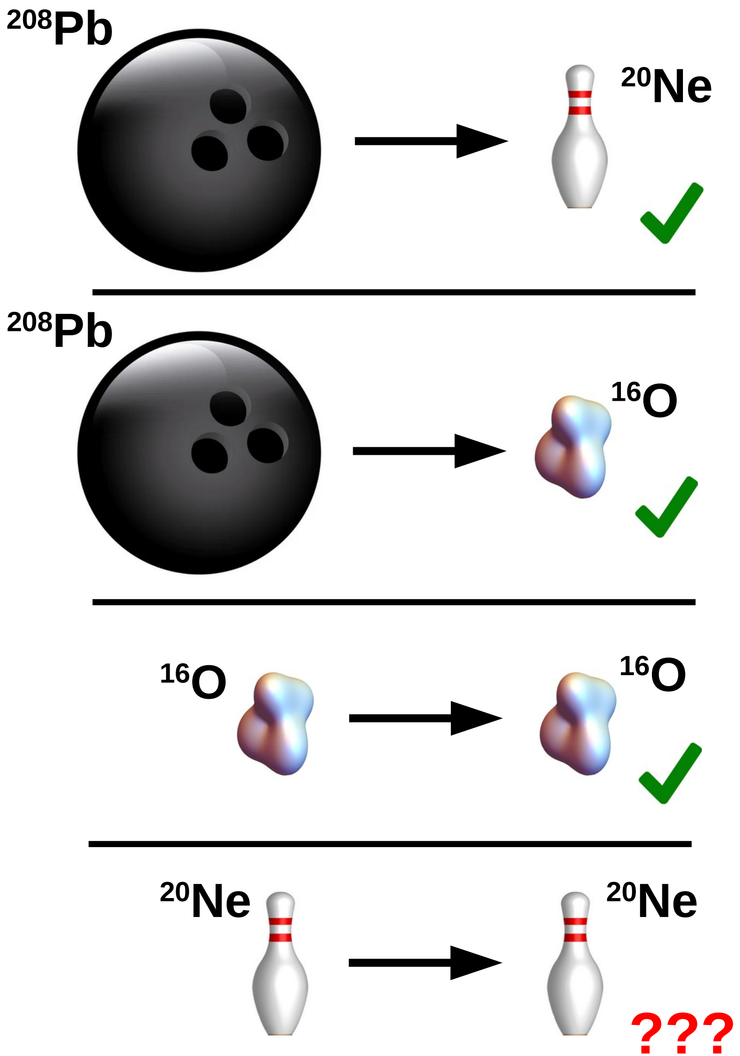
[Bally *et al.*, in preparation]



$$\frac{v_2\,[\mathrm{O}+\mathrm{O}]}{v_2\,[\mathrm{Ne}+\mathrm{Ne}]} = 0.93 \pm 0.01$$

Theory uncertainties cancel.
Quantitative predictions!

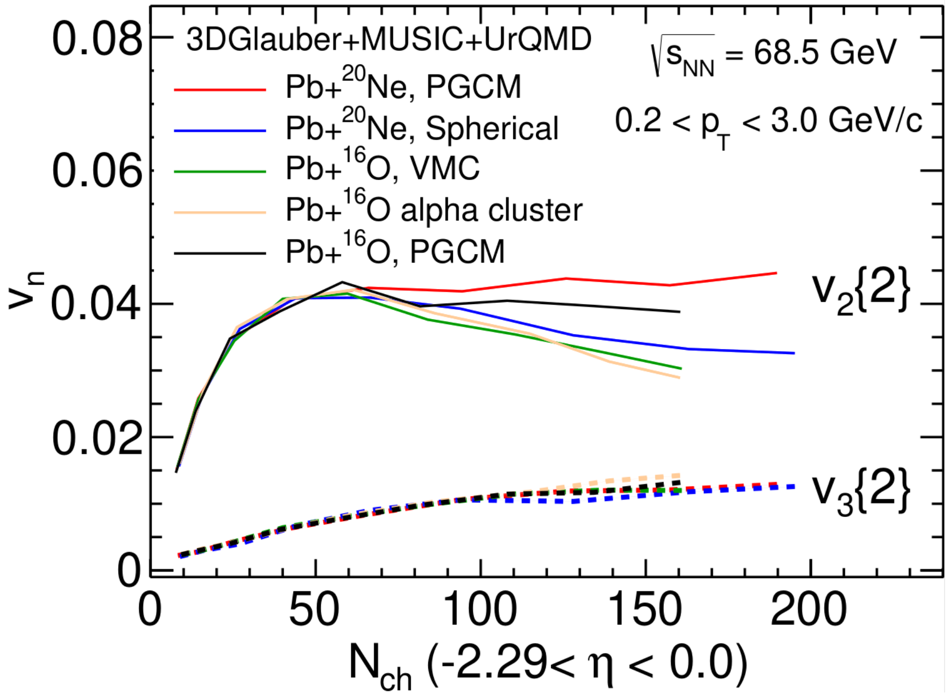
NB: Synergy with LHCb SMOG program.



[LHCb Collaboration, JINST **17** (2022) 05, P05009]

3D Hydro predictions.

[W. Zhao *et al.*, in preparation]



SUMMARY

LARGE SYSTEMS

- Refinement of well-established hydrodynamic picture (energy deposition, longitudinal dynamics, nuclear structure, transport coefficients, …).

SMALL SYSTEMS

- **Novel "small system question" with flow of ultracold atoms:** Few strongly-interacting particles without a separation of scales display fluid-like behavior.

- Much work and progress in understanding hydro-like behavior out of equilibrium.

- Light nuclei enable more quantitative studies around dN/dy≈100.
  Great potential of ^{16}O+^{16}O + LHCb SMOG + ^{20}Ne+^{20}Ne collisions.

THANK YOU!