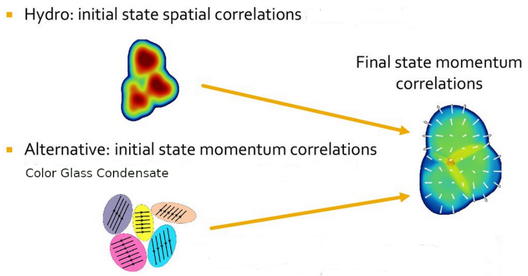
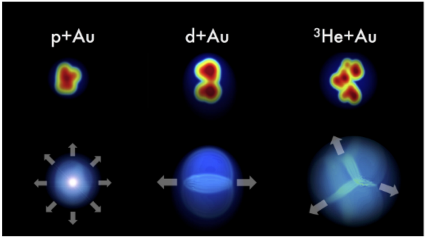
Lecture 27
Small systems (fim)



In this lecture, we continue our survey of data in small systems that are compatible with collectivity. We present explanations hydro-based or not (CGC, parton transport) and discuss the suggestion that hydro may be applicable out-of-equilibrium.

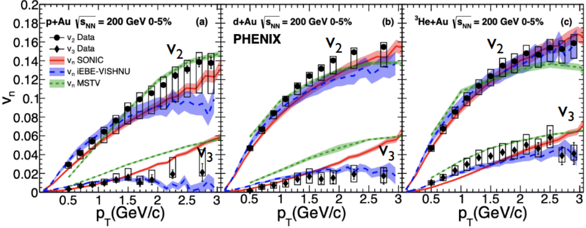
Small System Scan at RHIC

Changing the geometry (p, d or He) should lead to different v_2 and v_3.



This is indeed seen and well reproduced by hydro

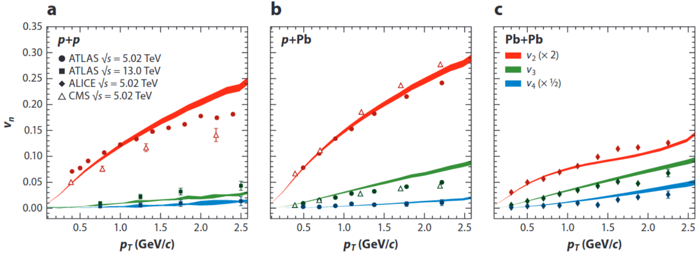
Nature Physics 15, 214 (2019)



MSTV is a CGC calculation that turned out to be wrong (see below)

Proton substructure fluctuations are crucial as shown in the superSONIC hydro calculation ain previous slide and below

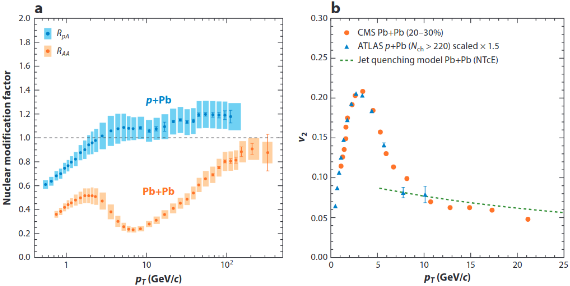
proton=3 valence quarks with gluon cloud around each



Weller and Romatschke "One fluid to rule them all" PLB 774 (2017) 351

How about jet suppression?

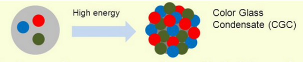
• In A + A collisions, an important confirmation of the heavy ion standard model comes from jet quenching (for exemple $R_{AA}(p_\perp) < 1$ at large $p_\perp$) but it is not observed in p+A.
In small systems with high multiplicity, the medium created is smaller, so the average path is expected to be significantly shorter and jet quenching must be smaller. The figure above is for minimum bias (= all collisions).



• However, there is elliptic flow with the same pattern in p+Pb than in Pb+Pb. If there is no jet quenching, how can this happen?

Alternative 1: Color Glass Condensate

• CGC is a description for the initial conditions in hadronic collisions and nuclear collisions at high energy



- **Color** gluons have color
- **Glass** gluons do not change their positions quickly
- **Condensate** gluons with small momentum fraction (x«1) are so numerous (because a large x gluon is likely to split into smaller x gluons) that their density may saturate

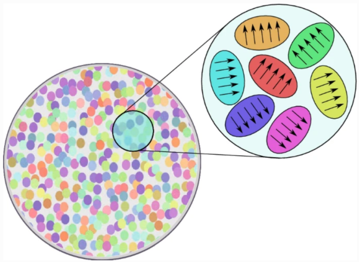
Simple properties of the CGC follow from first principles of QCD.

• CGC is not the same as Glasma.

When two sheets of Color Glass Condensate collide in a high energy heavy ion collision, they form matter with very high energy densities called the Glasma. The Glasma can later thermalize into the the sQGP.

• Only gluon saturation has a reasonable experimental evidence, CGC, and even more so Glasma, are still hypothetical.

How can anisotropic flow be created from the CGC?



Picture of the chromoelectric fields inside the target

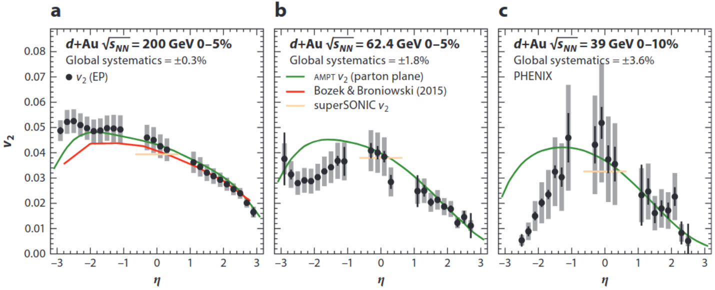
- When a parton coming from the projectile wave function hits the target it scatters in one of these domains and pick up a momentum proportional to the chromoelectric field inside.
- Angular correlation appears when two partons scatter in the same chromoelectric domain.
- A perhaps naive expectation is that $v_2(d + Au) < v_2(p + Au)$ (contrary to data).

At present, no CGC-based model is able to fully describe the existing experimental data.

The search for observables that may discriminate initial momentum anisotropy (CGC) and initial space anisotropy+hydro continues

Alternative 2: Parton Transport models

- Exemples are the AMPT (A Multi-Phase Transport) model and BAMPS (Boltzmann Approach to Multi-Parton Scatterings)
- There are scatterings for partons (quarks and antiquarks for AMPT and gluons for BAMPS). For AMPT, there is hadronization and scatterings between hadrons and it leads to reasonable agreement for example for v_2 in d+Au at various energies. However there still are unphysical assumptions and many parameters.



A change of paradigm: Out-of-equilibrium Hydrodynamics

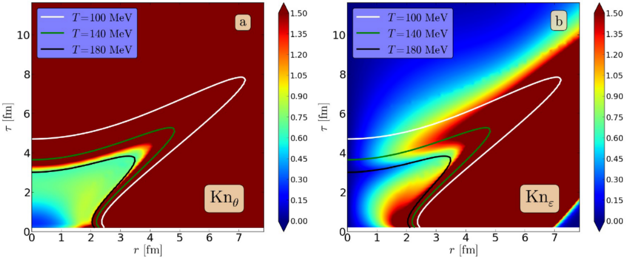
Is it reasonable that hydrodynamics works so well even in small systems where not so many partciles are created?

• The usual expectation for hydrodynamics to apply is that the Knudsen number

$$\boxed{Kn \equiv l/R << 1}$$

where l is the typical microscopic length/time scale and R the largest.

• Typical estimates indicate that it might be the case in A+A but not p+A



Niemi and Denicol 1404.7327: p+Pb at LHC for $dN_{ch}/d\eta$=270, with $l = \tau_\pi$ and two possibilities for R

Towards out-of-equilibrium system

• The first order relativistic hydrodynamics (Navier-Stokes) can be constructed adding to the ideal fluid momentum-energy tensor small terms in the gradients $\nabla_\mu ln\epsilon$ and $\nabla_\mu u_\nu$ (∇_μ covariant derivative).

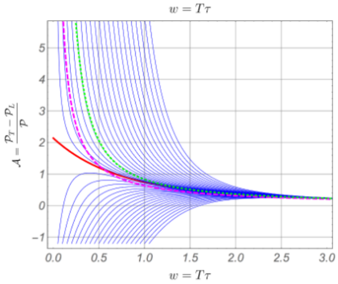
• Similarly the second order relativistic hydrodynamics adding terms with two derivatives $\nabla_\mu \nabla_\nu ln\epsilon$, etc.

• Up two now, it was implicit that these gradients were small so as to maintain the system near thermodynamic equilibrium.

• It is in fact possible to resum non small gradients (Borel resummation) in the form $T^{\mu\nu}_{Borel} = T^{\mu\nu}_{hydro} + T^{\mu\nu}_{non-hydro}$

Solutions of the **hydrodynamic** evolution equations with different initial conditions evolve to the same late time behavior, which is called the hydrodynamic attractor (represented by $T^{\mu\nu}_{hydro}$)

Ex. A strongly-coupled systems in the figure exhibits relaxation to a universal attractor for τ > 0.7 / T



Hydrodynamics behavior $\not\Rightarrow$ thermalization

Other references on this topic

- J.L.Nagle and W.A.Zajc “Small System Collectivity in Relativistic Hadronic and Nuclear Collisions” Annual Review of Nuclear and Particle Science 68 (2018) 211) (very clear and interesting)
- Romatschke and Romatschke arXiv:1712.05815 (tip: concentrate on hydro in §2.1 a 2.5)