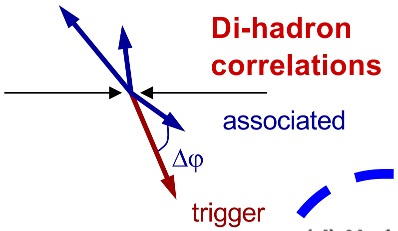
Small systems theory perspective: CGC, Transport, Hydro

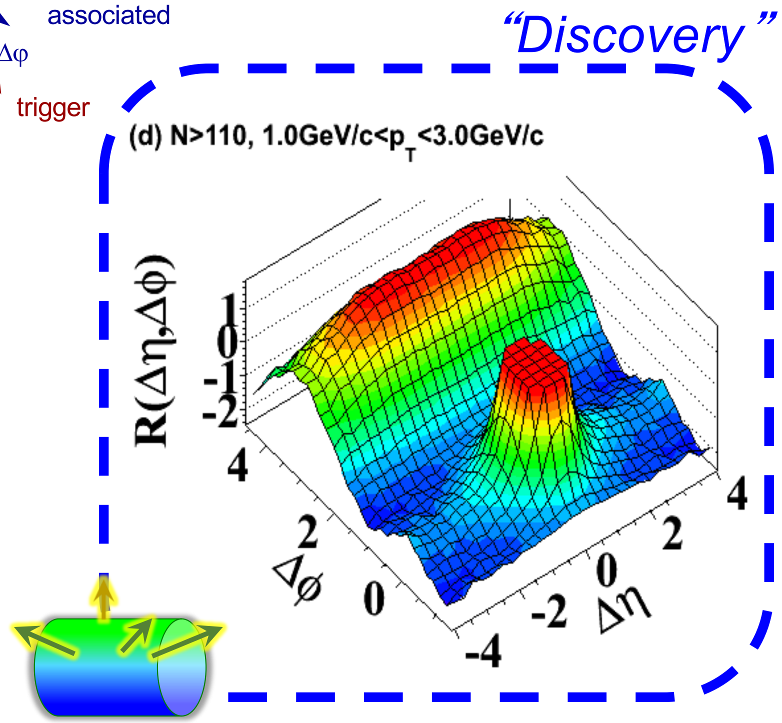
Raju Venugopalan

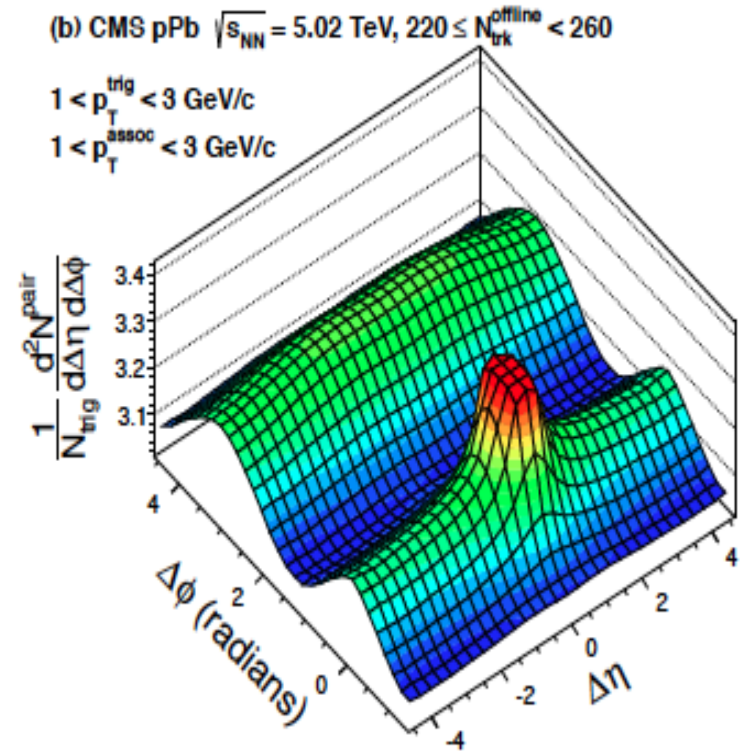
Brookhaven National Laboratory

Strange Quark Matter 2019

Discovery of the ridge in small systems







Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC
CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) *et al.).* **JHEP 1009 (2010) 091**

What’s the underlying QCD dynamics?

- Is it the initial state dynamics arising from rare configurations in the hadron wavefunctions?

- Or is it final state collective flow of the world’s smallest droplets?

- Or, is it some combination, where there is a smooth transition from one description to the other?

Option 1 stretches to the limit our understanding of the quark-gluon structure of the proton

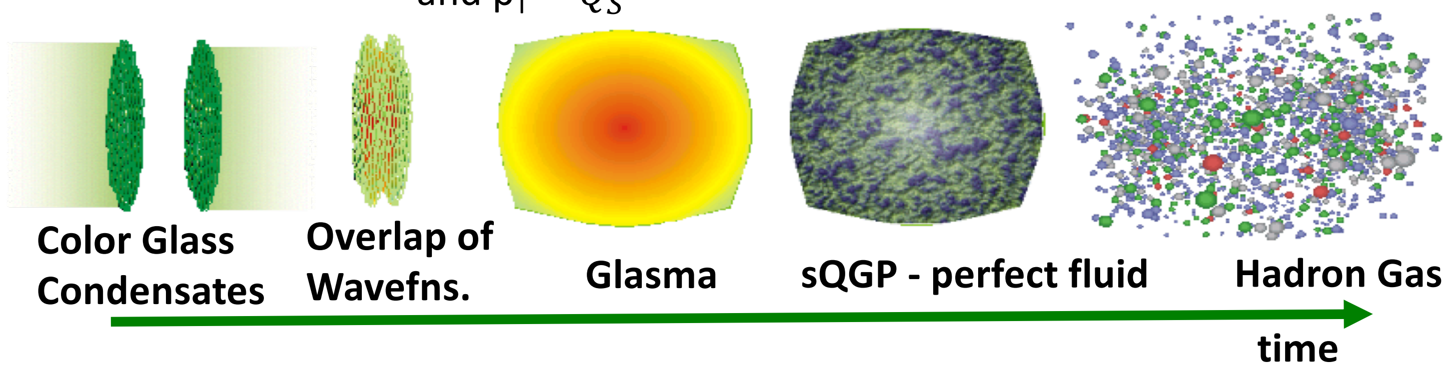
Option 2 stretches to the limit the applicability of thermodynamic and hydrodynamic concepts in high energy physics

From CGC to QGP in A+A collisions

Maximally occupied gluon states

Very dense matter: occupancy f ~ $1/\alpha_S$ and $p_T \sim Q_S$

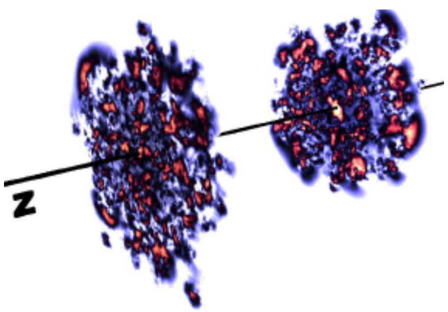
QGP has f ~ 1 and $p_T \sim T \ll Q_S$

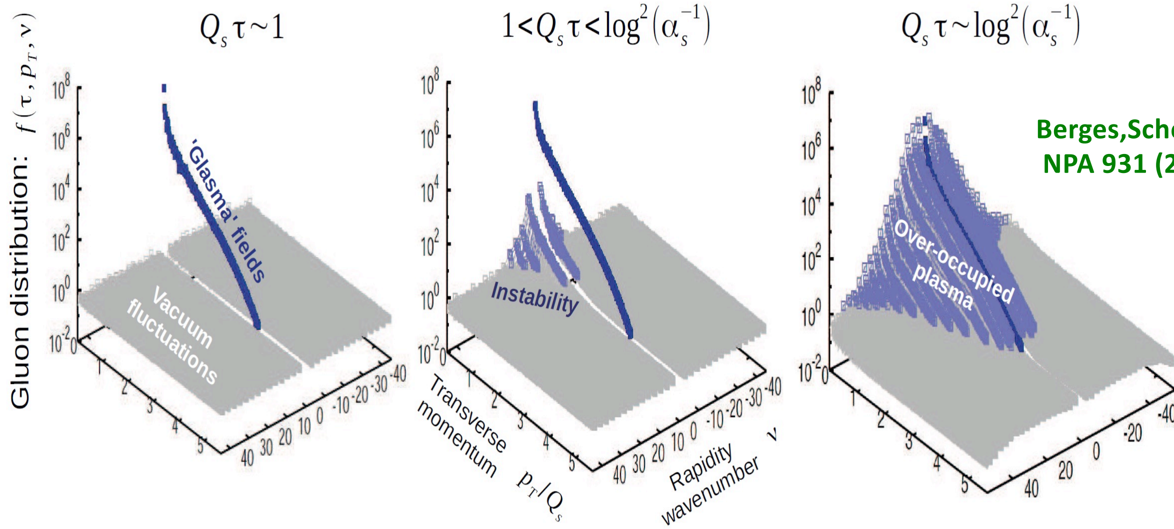


For weak coupling, α_S << 1 but α_S * f ~ 1 -- QCD matter is strongly interacting

Real time evolution described by an ensemble average of 3+1-D *classical-statistical* solutions of QCD Yang-Mills equations seeded by quantum fluctuations

From CGC to QGP in A+A collisions





Berges,Schenke,Schlichting,RV, NPA 931 (2014) 348

Classical-statistical evolution of energy-momentum tensor

$$\langle\langle T^{\mu\nu}\rangle\rangle_{\mathrm{LLx+Linst.}} = \int [D\rho_1][D\rho_2]\, W_{\mathrm{Y_{beam}-Y}}[\rho_1]\, W_{\mathrm{Y_{beam}+Y}}[\rho_2]$$

Distribution of color sources in the nuclei before the collision

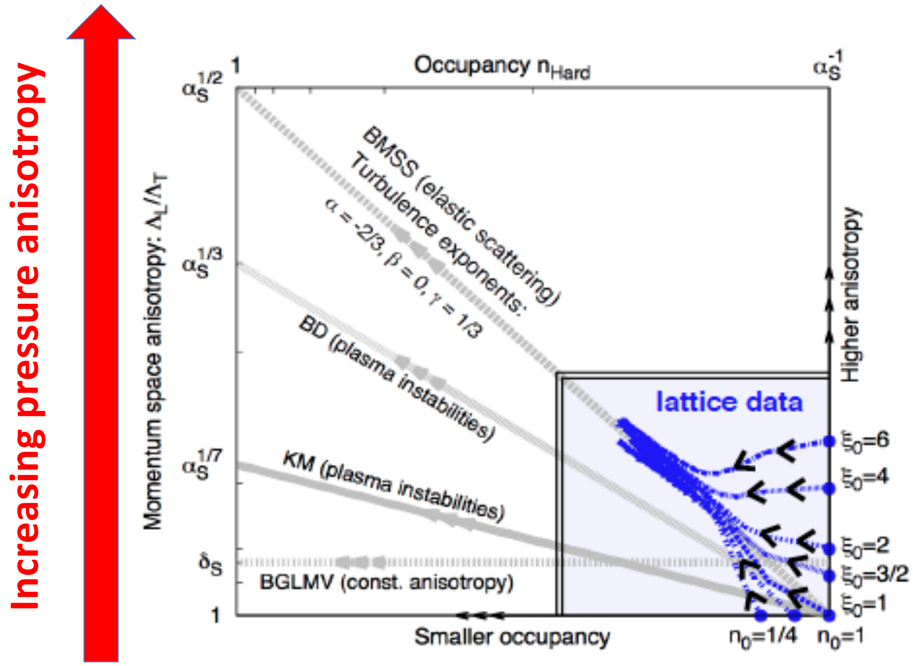
$$\times \int [da(u)]\; F_{\mathrm{init}}[a]\; T^{\mu\nu}_{\mathrm{LO}}[A_{\mathrm{cl}}(\rho_1,\rho_2) + a]$$

Distribution of quantum fluctuations immediately after collision

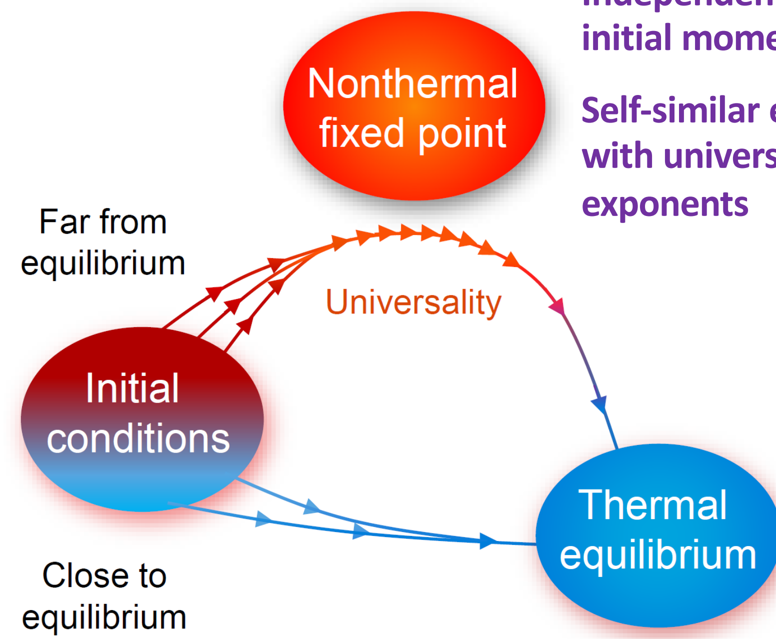
Path integral over multiple initializations of classical Yang-Mills trajectories $T^{\mu\nu}_{LO}$ leads to rapid quasi-ergodic "eigenstate thermalization"

Berry; Srednicki; Rigol et al.; …

From CGC to QGP in A+A collisions



Berges,Boguslavski,Schlichting,RV (2014)



Independent of initial momentum dist.

Self-similar evolution with universal scaling exponents

After some evolution when $1 < f < 1/\alpha_S$ a dual description is feasible either in terms of kinetic theory or classical-statistical dynamics … A.H. Mueller,D. Son (2002); S. Jeon (2005)

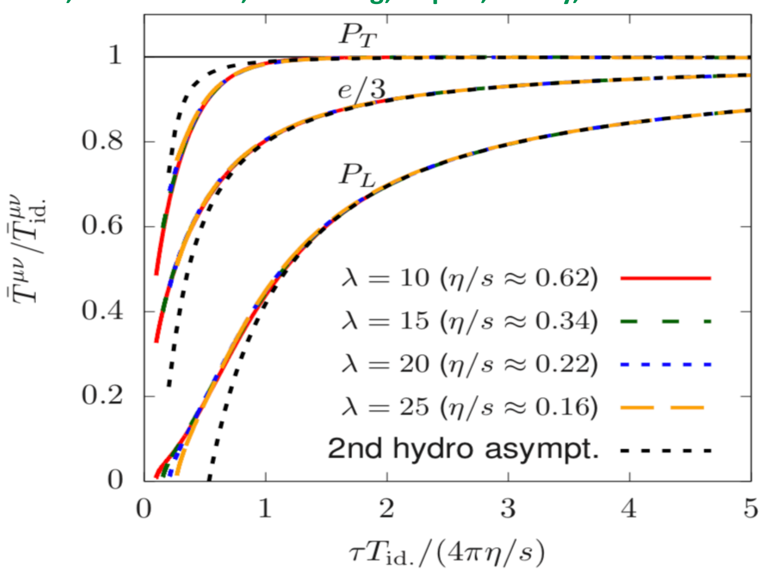
Numerical simulations pick out kinetic "bottom-up" thermalization scenario

CGC naturally leads to thermalization: $\tau_{therm} \to 0$ as $Q_S \to \infty$

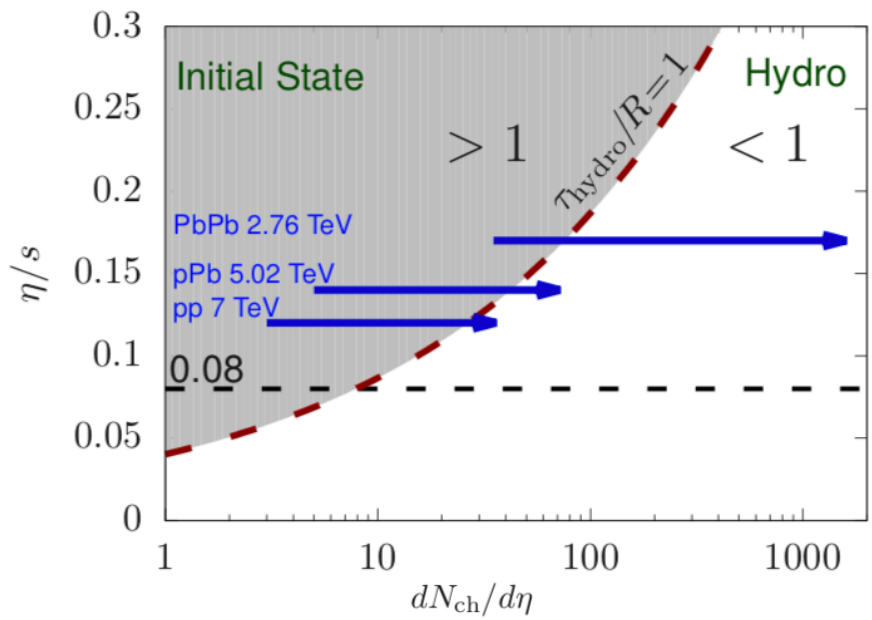
Baier,Mueller,Schiff,Son (2001)

CGC to QGP in A+A: nuts to soup

Kurkela,Mazeliauskas,Schlichting,Paquet,Teaney,arXiv:1805.00961



Mazeliauskas, arXiv:1807.05586



Kinetic theory results when plotted as function of scaled "hydrodynamization" variable match smoothly to viscous hydro even when system is quite anisotropic

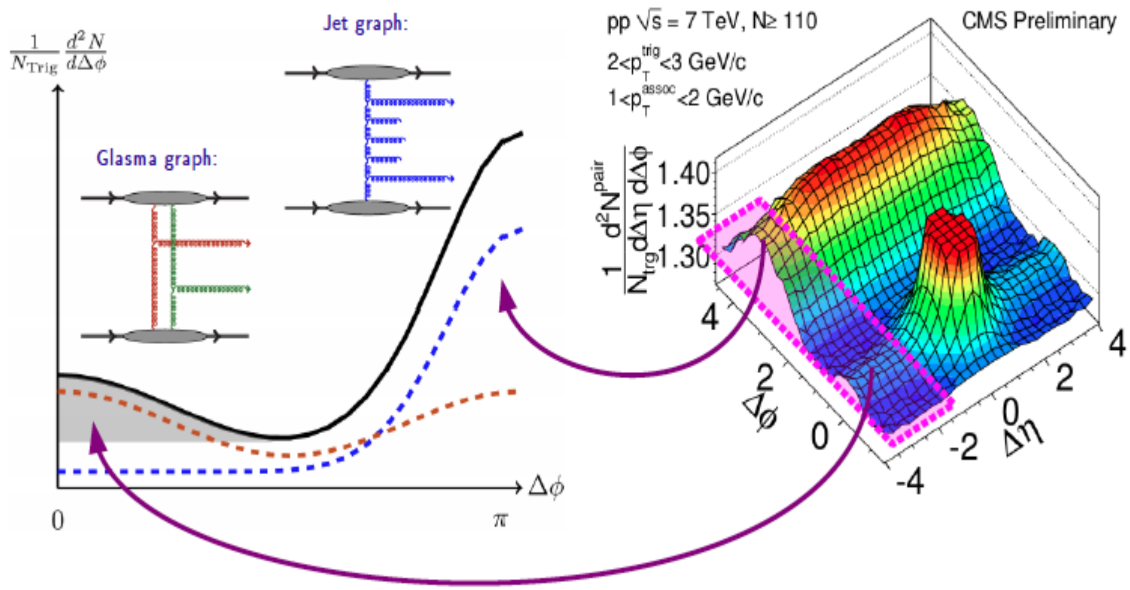
Note however from kinetic theory analysis that regime of validity of hydro is limited for small systems: large v_n coefficients already seen for quite low multiplicities

Heller,Kurkela,Spalinski,Svensson,arXiv:1609.04803
Bazow,Heinz,Martinez, arXiv:1507.06595
Romatschke, arXiv:1704.08699
Strickland,Noronha,Denicol,arXiv:1709.06644

Recent analysis with similar conclusions, Kurkela,Wiedemann,Wu, arXiv:1905.05139

From A+A to small systems: can the initial state alone describe v_n data?

Dumitru et al., arXiv:5295
Dusling, RV, arXiv:1302.7018



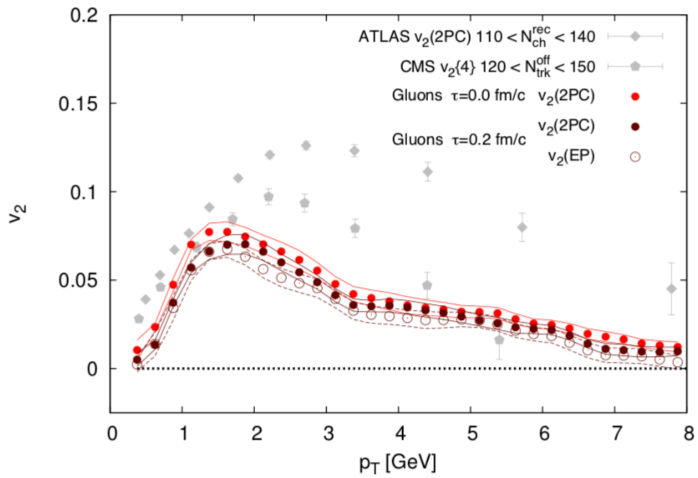
Basic idea: Bose and HBT enhancement of Glasma graphs (relative to mini-jet) in high multiplicity collisions

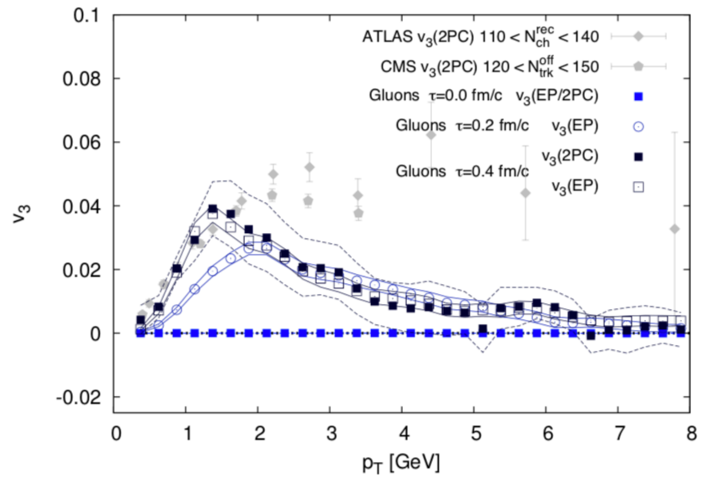
Dumitru,Gelis,McLerran,RV, 0804.3858
Kovchegov,Wertepny,1212.1195
Altinoluk et al.,1503.07126,1509.03223

Previously, odd coefficients v_{2n+1} believed to be zero in this approach; however parametrically the right order contribution (relative to v_{2n}) in first nontrivial correction in proton color charge density

McLerran,Skokov, 1611.09870
Kovner,Lublinsky,Skokov, 1612.07790
Kovchegov,Skokov, 1802.08166

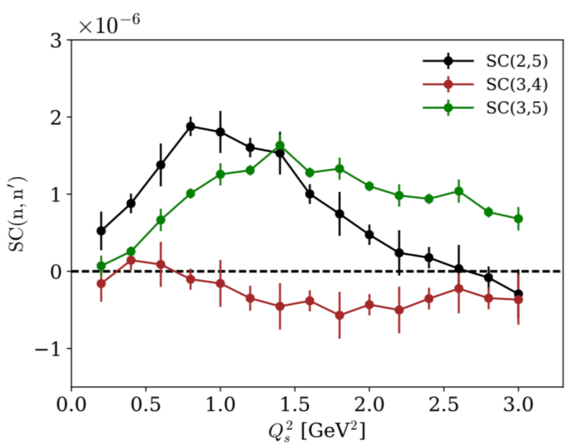
Can the initial state alone describe v_n data in small systems?



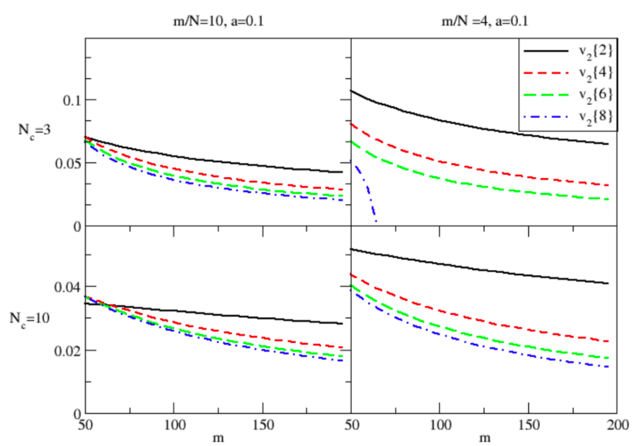


Schenke,Schlichting,RV,1502.01331

Yang-Mills simulations (IP-Glasma model) for $v_{2,3}$ in LHC p+A collisions reasonable agreement with low pT data



Dusling,Mace,RV, 1706.06260

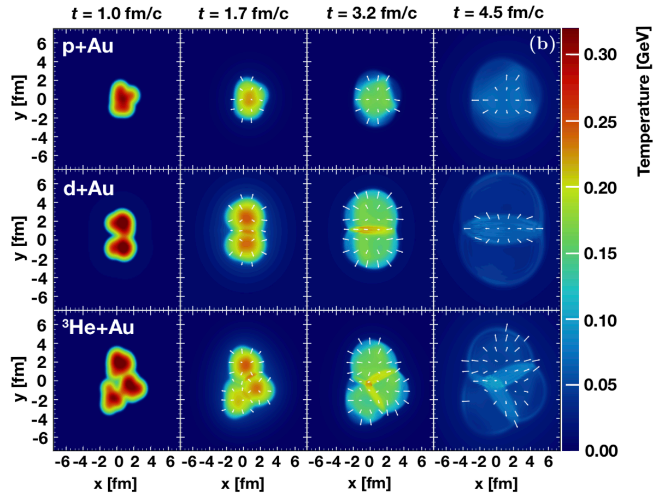


Blok,Wiedemann, 1812.04113

Systematics of v_n {k}, with k=2,4,6,..
are also reproduced in simple initial state models

No quantitative comparisons

Can the initial state alone describe v_n data in small systems?

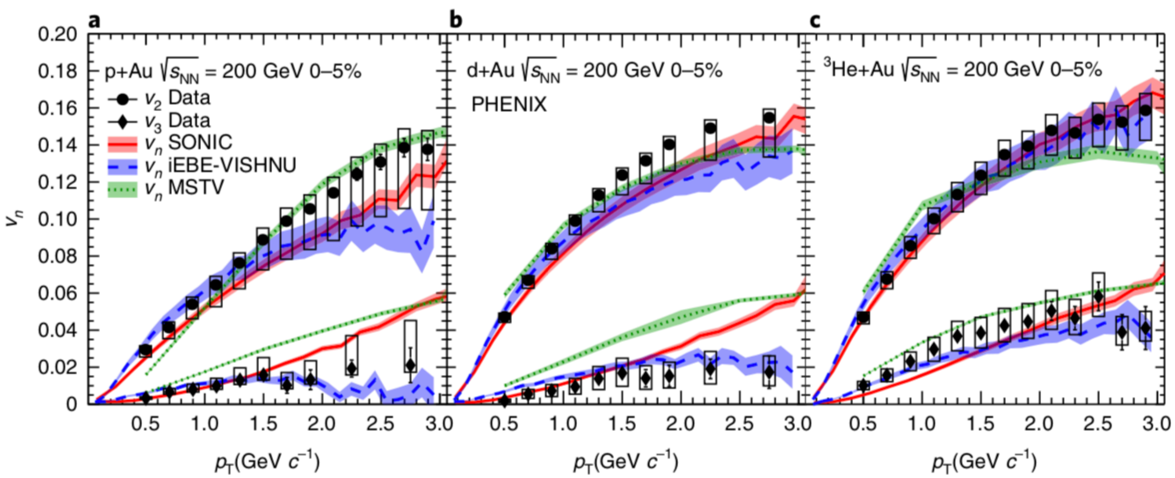


Small system scan at RHIC

Expectations from MC Glauber+hydro models are that one sees an increasing hierarchy of $v_{2,3}$ From p+Au, to d+Au, to ^{3}He+Au

PHENIX, Nature Phys. 15 (2019)

Glauber+ hydro models reproduce the observed hierarchy in v_2 and v_3



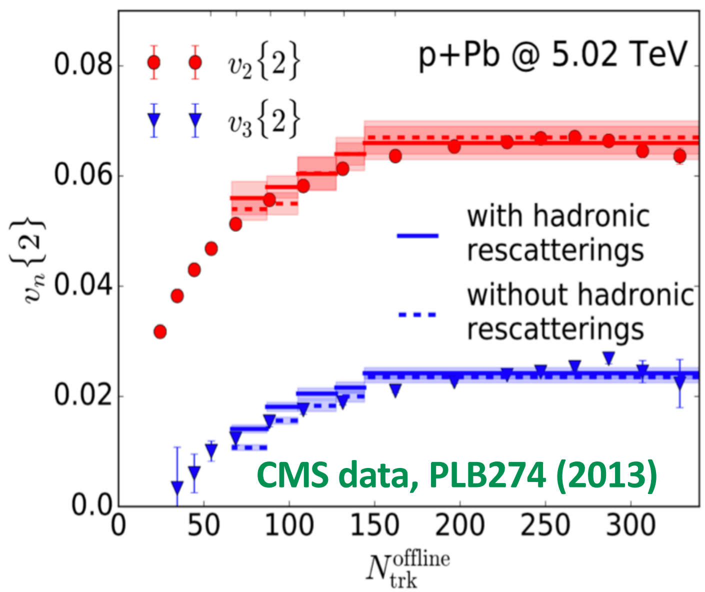
The CGC (dilute-dense MSTV) model also observed the hierarchy

MSTV: Mace,Skokov,Tribedy,RV, PRL (2018)

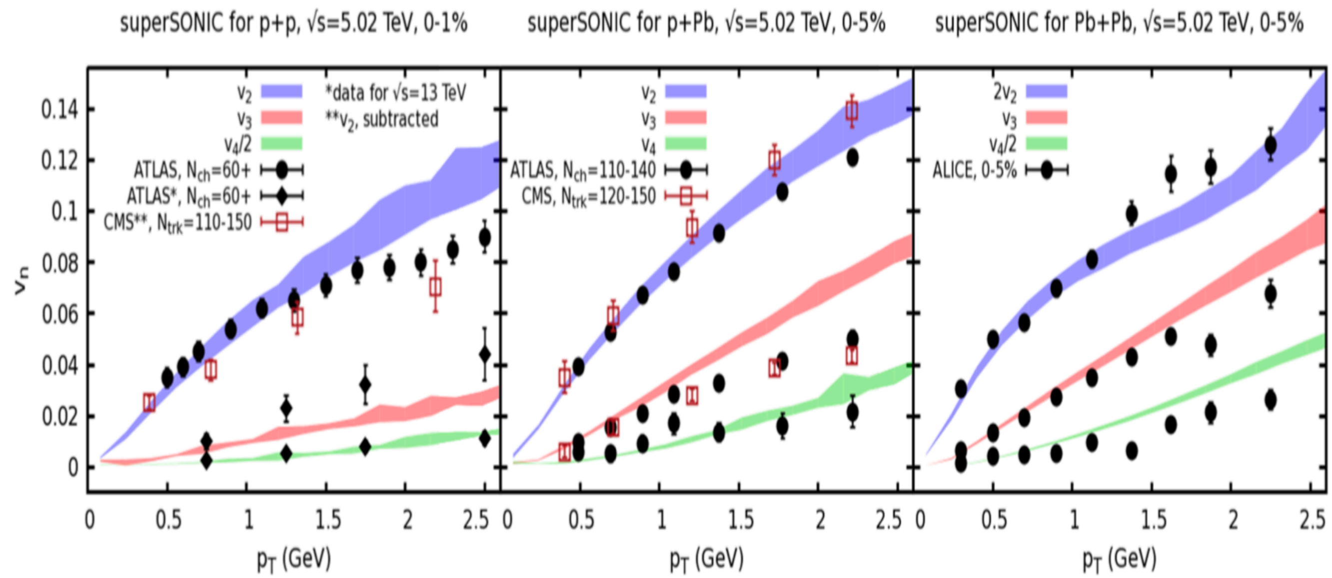
However this was due to a unit conversion ($\hbar c$) error in the MSTV code – the hierarchy only exists at momenta < 0.5 GeV – MSTV does not reproduce the data

MSTV: Erratum submitted to PRL

Glauber+Hydro models also describe features of LHC data



Shen et al., PRC95 (2017); also, Bozek, Broniowski PRC88 (2013)



Weller,Romatschke,1701.07145

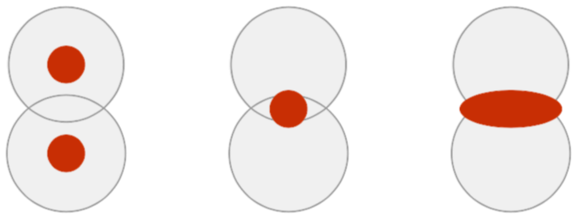
So is the ridge due to hydro, just as in the larger systems?

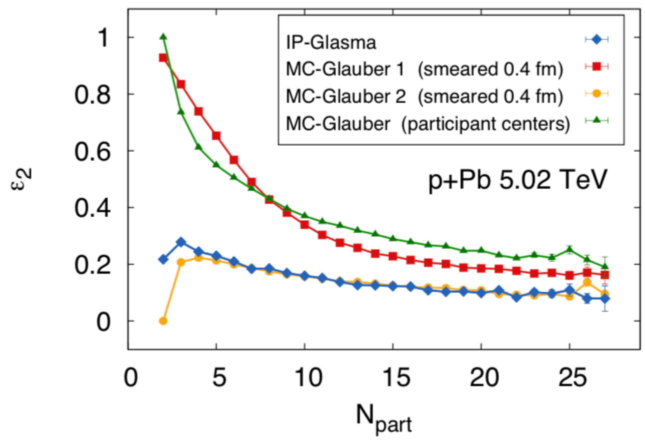
As noted previously, in context of “bottom-up” thermalization, this is feasible in principle

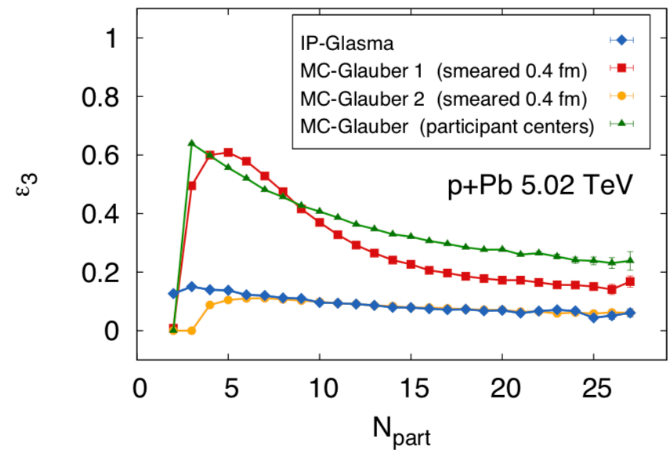
But…

Hydro extremely sensitive to initial conditions in small systems: what's driving what?

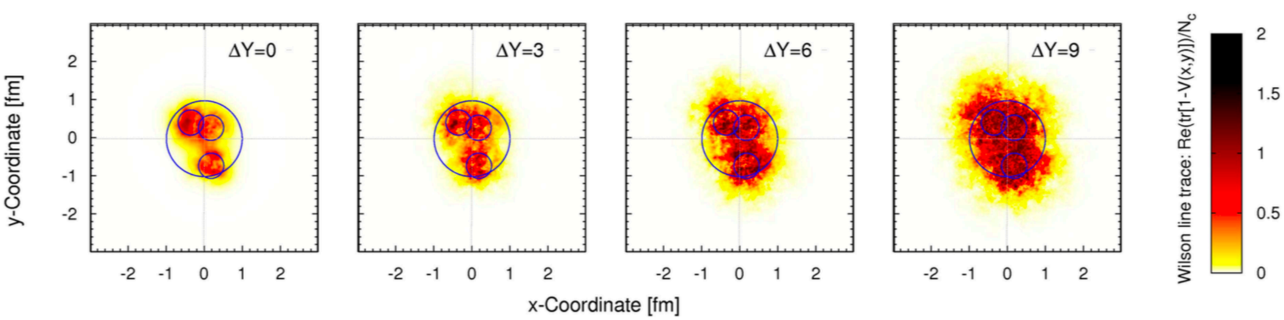
Bzdak,Schenke,Tribedy,RV, 1304.3403







Very little theory guidance
(no dynamical model of multi-particle production)



Schenke,Schlichting,1407.8458 , 1605.07158
For one particular implementation, Welsh, Singer,Heinz ,1605.09418
Hot-spot correlations, Albacete,Petersen,Soto-Ontoso, 1707.05592

JIMWLK evolution of model with three valence quarks- while inspired, has several ad hoc elements

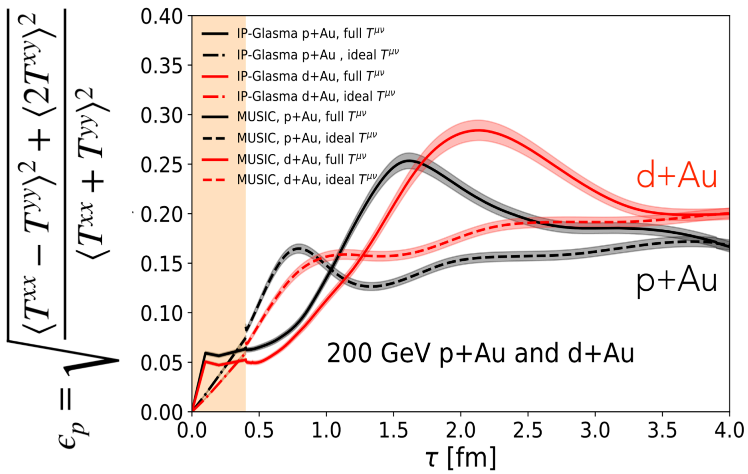
Spatial fluctuations in rare events poorly constrained by theory. Somewhat constrained by HERA incoherent $J/\psi's$
Mantysaari, Schenke, 1607.01711

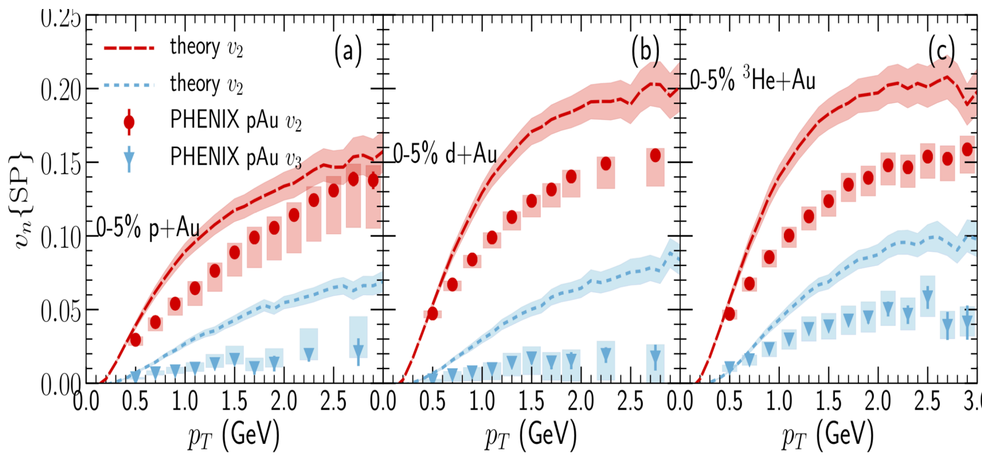
Possibly an opportunity for small systems

Hydro extremely sensitive to initial conditions in small systems: what's driving what?

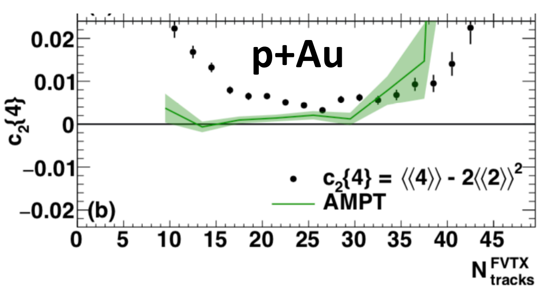
IP-Glasma+hydro (MUSIC)+transport (URQMD)

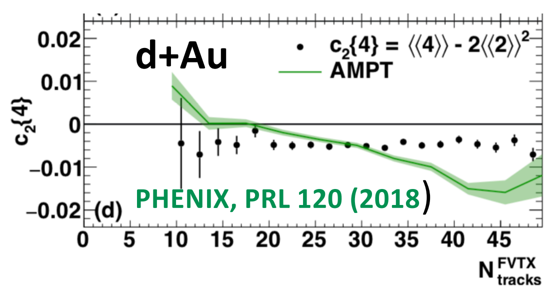
Shen,Schenke,Tribedy, in preparation





Significant differences between this IP-Glasma+hydro model (that fits A+A data) and Glauber+hydro models – differences in v_3 can be factors of 2-3. Some excess relative to data due to decorrelation of v_2 with rapidity (present in data but not in either model)





PHENIX, PRL 120 (2018)

No $v_2\{4\}$ in PHENIX data for p+Au collisions

$v_2\{4\} > 0$ in p+A in IP-Glasma+hydro
What is the result in Glauber+hydro?

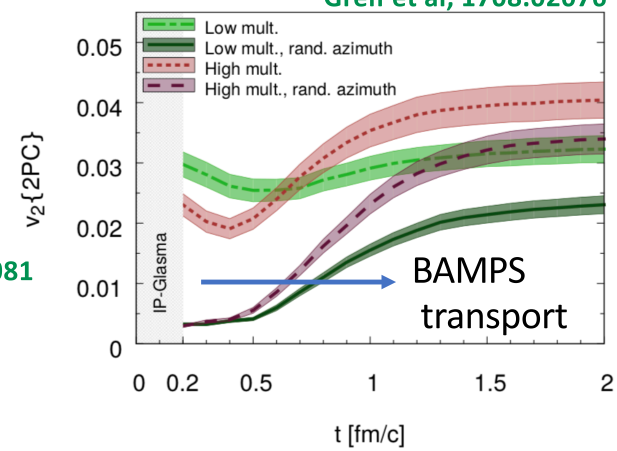
Open problems

Initial state approaches:

Glasma + kinetic theory: study relative contributions of CGC driven initial state correlations and geometry driven contributions to v_n
– even few scatterings can generate sizeable effects

Kurkela,Wiedemann,Wu, 1805.04081

Greif et al, 1708.02076



Example: IP-Glasma+BAMPS transport code of Greiner & Xu
Would be interesting to see similar studies by Kurkela et al.

Extension of CGC based approaches to better treat rare events:
What is the relative role of geometrical versus color charge fluctuations ? **talk by Giacalone**

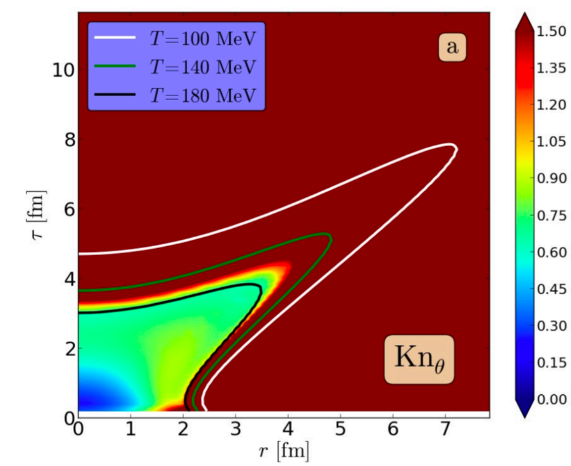
Hadronization and hadronic rescattering – **talk by Bierlich**

Hydro approaches:

Large viscous corrections for small systems
Expansion parameter – Knudsen # ~ 1 - at short times

Hydrodynamic fluctuations may be of order unity at the lowest $dN/d\eta$'s where large v_n's are seen – need to be quantified

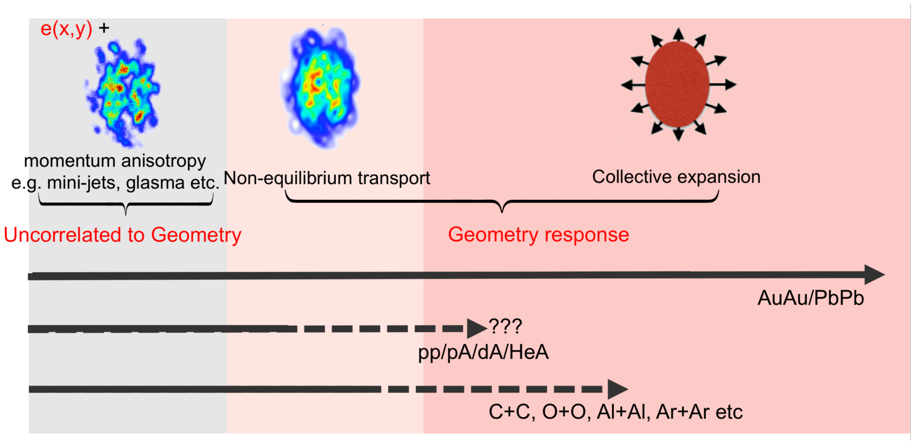
See for eg., Martinez,Schafer, 1812.05279

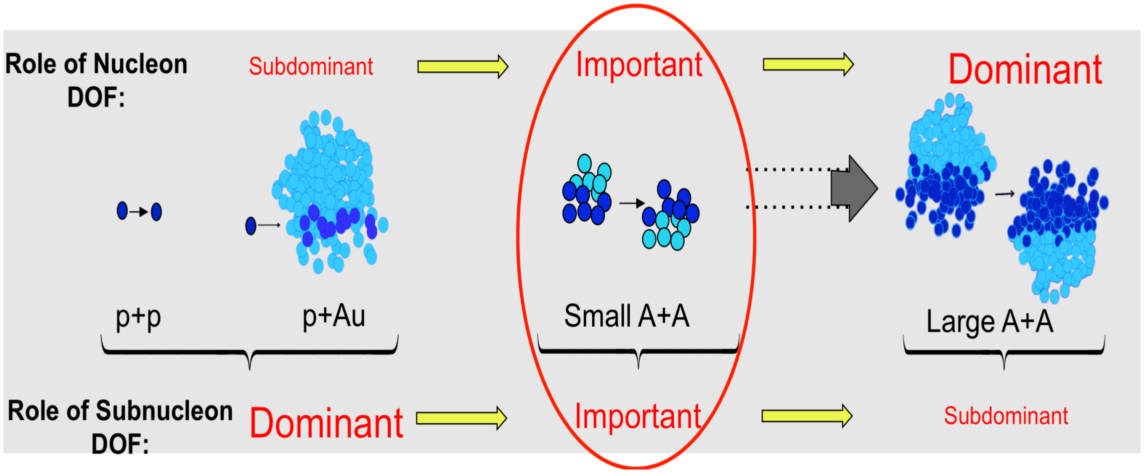


Niemi,Denicol,1404.7327

Opportunities

J. Jia, INT workshop, May 2019





Initial momentum anisotropy can survive and biases the final state geometry driven flow

Nie,Li,Jia,Ma, 1904.01422

Debate about role of nucleon vs subnucleon fluctuations

Role of jet quenching – no quenching seen in the small systems

"Shrinking the QGP" by doing symmetric and asymmetric light nuclear scans can help clarify all of these issues

Sievert,Hostler, arXiv:1901.01319

Quarkonium yields and correlations in light systems can also help distinguish between initial and final state scenarios. -- talk by **Elena Ferreiro**

Summary

Purely initial state scenarios are disfavored by RHIC light system scan
- results point to importance of final state effects

However, the initial shape and correlations greatly influence hydro results. Conversely, can data + hydro constrain the former ?

Since CGC+kinetic theory (bottom-up)+hydro are a robust explanation of A+A, need quantitative studies of just CGC+kinetic theory – how much rescattering is sufficient?

Match to PYTHIA and hadronic afterburner ?

Onia, Jets, photons add further discriminating power as do further scans of light symmetric/asymmetric nuclei at LHC and RHIC