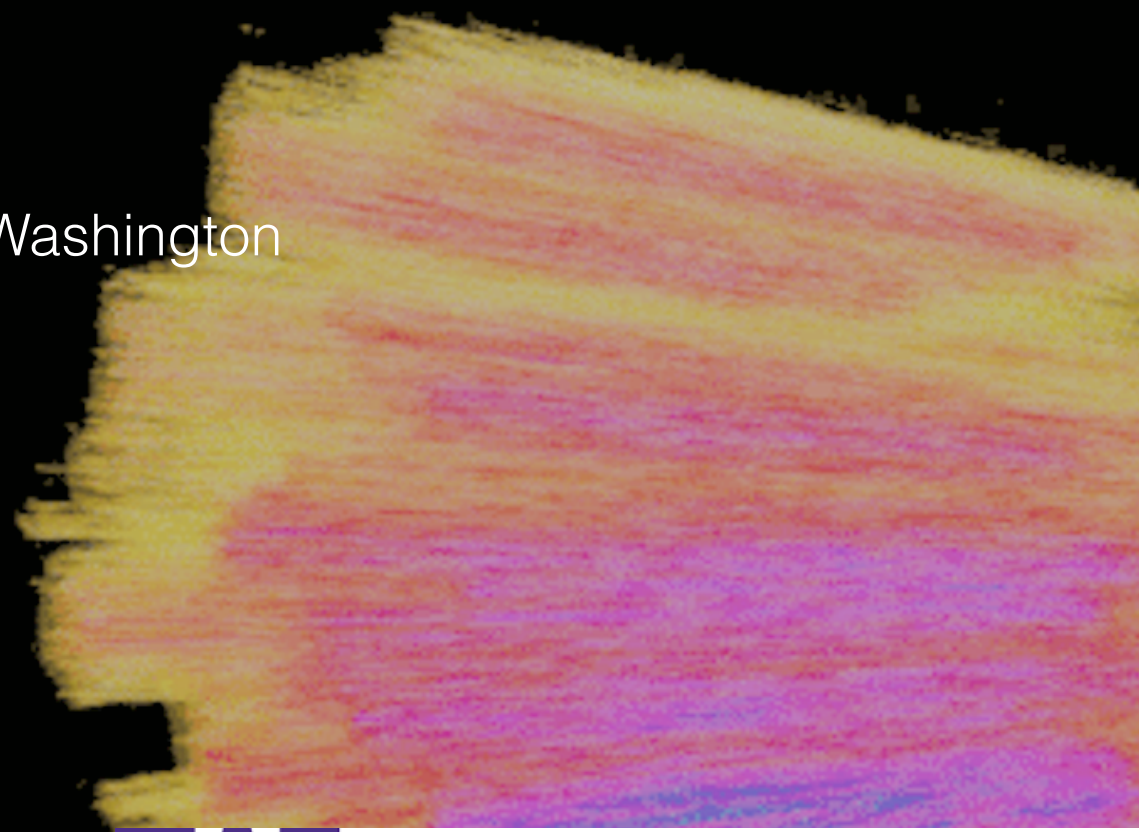
U.S. DEPARTMENT OF ENERGY | Office of Science

Recent developments in Heavy-Ion Theory

Sören Schlichting | University of Washington



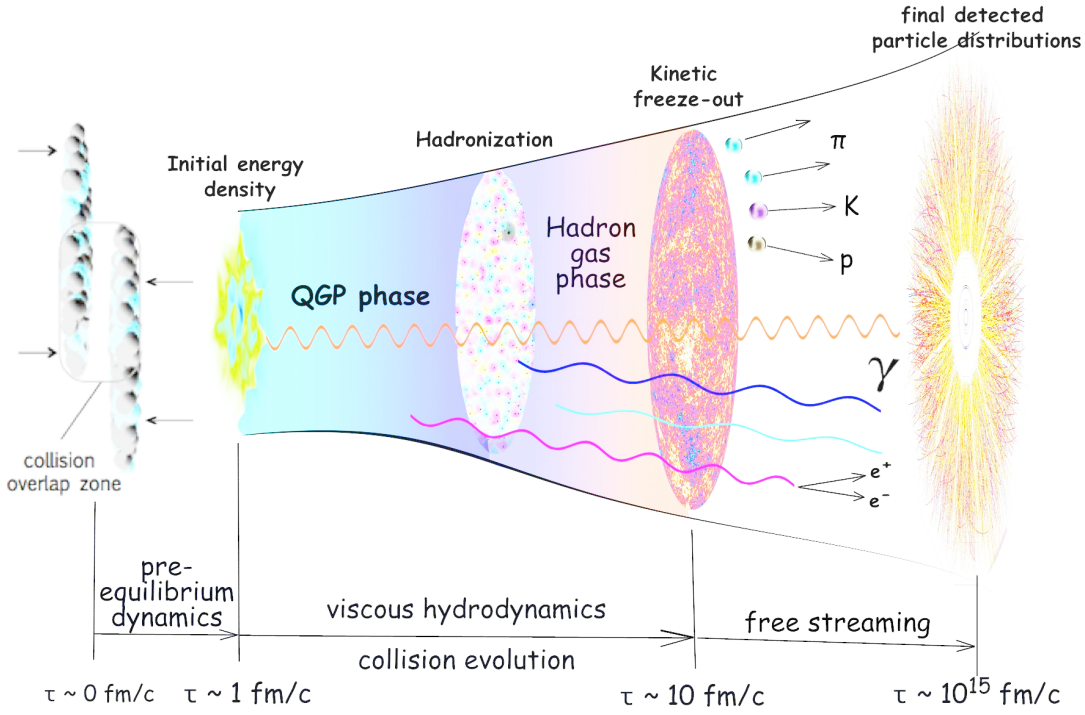
Feb 01 2017
APS GHP Meeting
Washington DC

UNIVERSITY of WASHINGTON

Big picture & Big questions

Space-time evolution of HIC

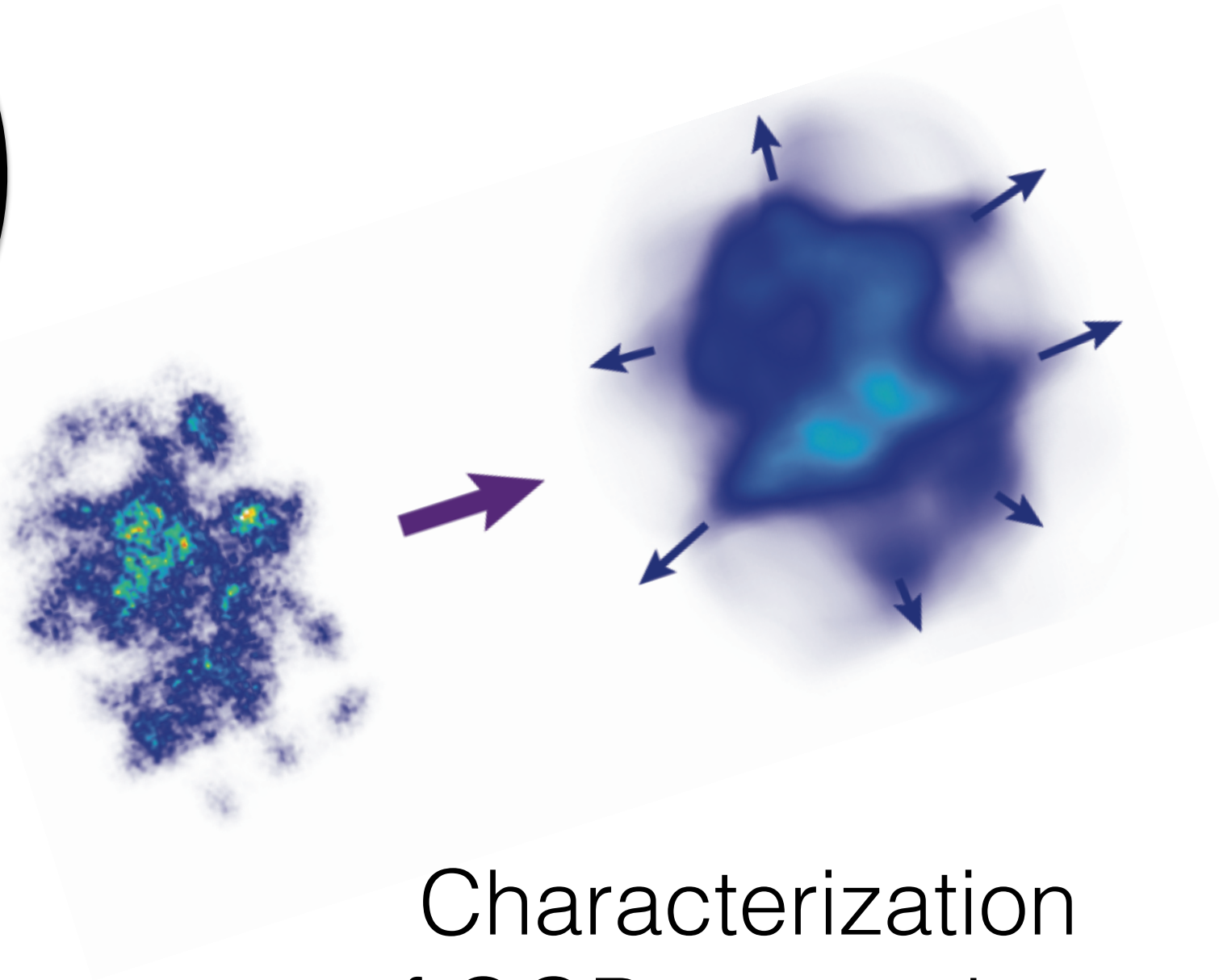
Collision of heavy-nuclei at high-energies creates a hot plasma of quarks and gluons which cools by hydrodynamic expansion, undergoes re-hadronization and hadronic re-scattering until evolution freezes out



C. Shen (PhD Thesis)

- Characterization & understanding of QGP properties
  - Bulk properties, Hard/heavy probes, Electro-magnetic radiation
- Description of the dynamical formation of QGP
  - Early-time dynamics & equilibration process, Conditions for QGP formations

1



Characterization
of QGP properties

Characterization of QGP

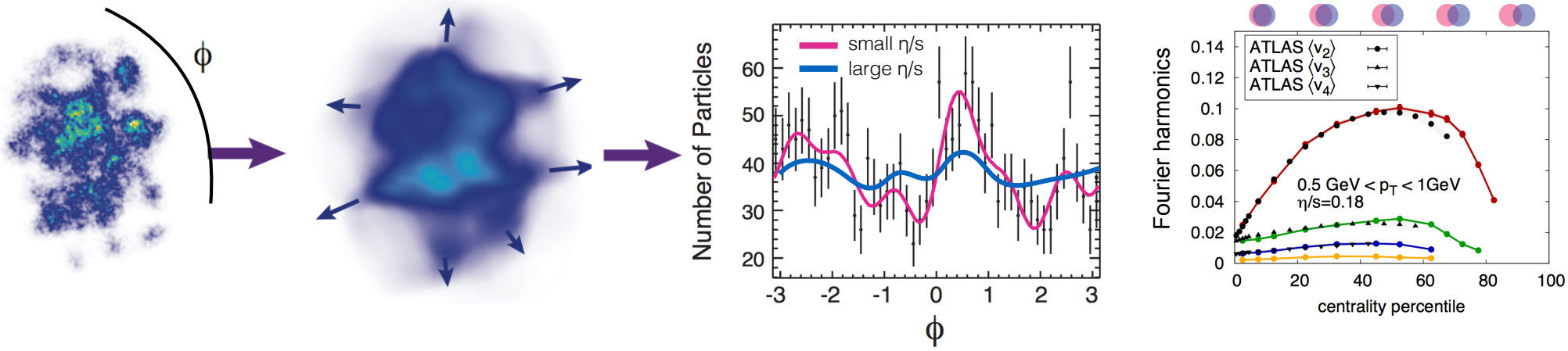
Bulk properties: Space-time evolution of QGP phase described by relativistic viscous hydrodynamics

Initial state
τ=0.2 -1 fm /c

Hydrodynamic expansion

Azimuthal anisotropy

Statistical analysis

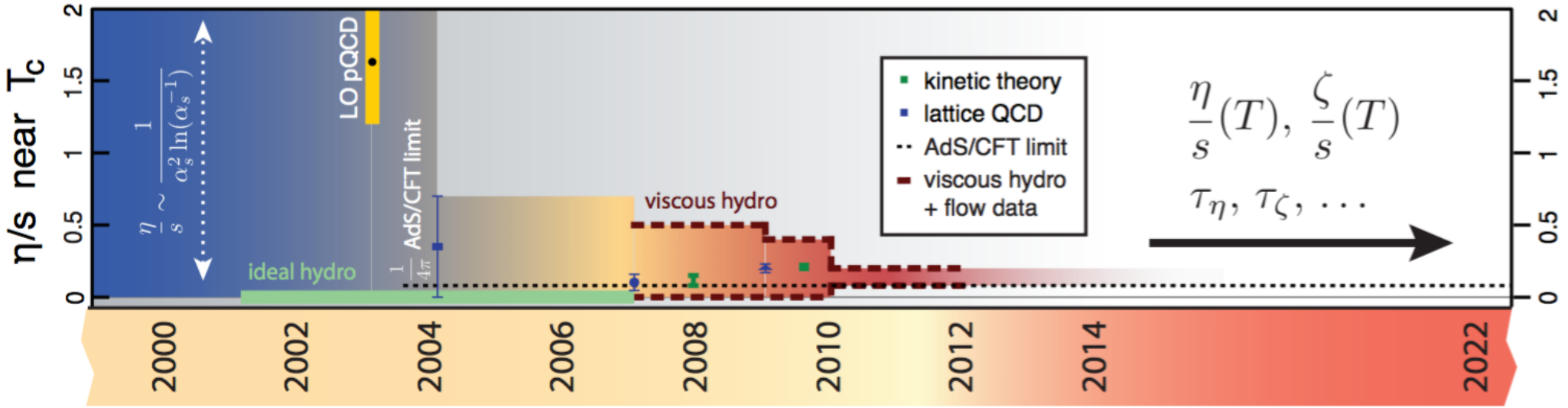


B.Schenke, R.Venugopalan, PRL 113 (2014) 102301

Extraction of transport properties η/s, ζ/s, …
by comparison to experimental measurement

Characterization of QGP

Broad theoretical efforts and experimental advances lead to increasingly precise determination of η/s



Hot and Dense QCD White Paper (2012)

New standard of hydrodynamical modeling:

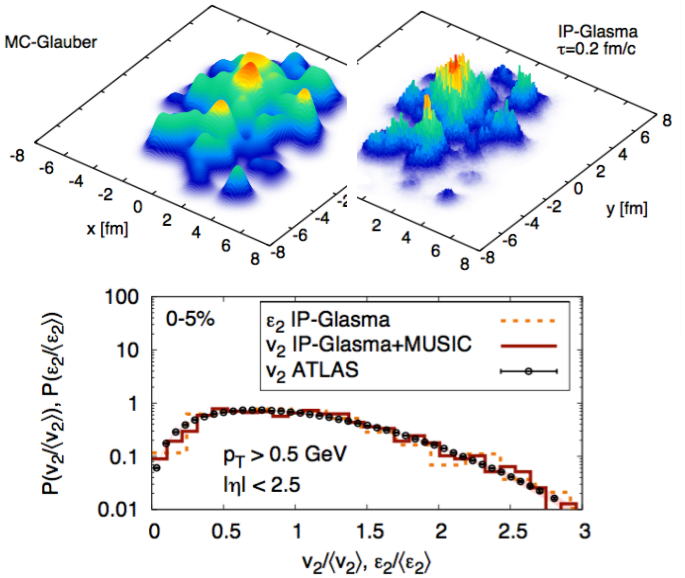
Event-by-event simulations, hadronic cascade, η/s(T) & ζ/s(T)

Characterization of QGP

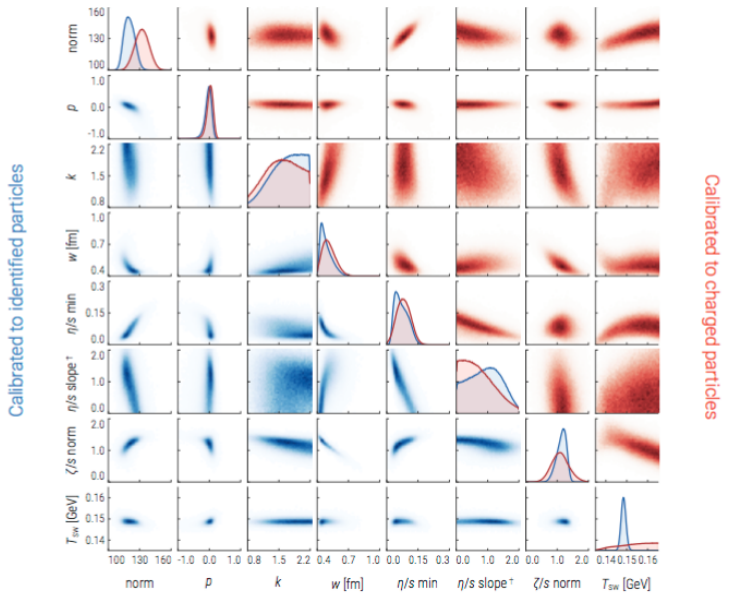
Challenge: Extraction of flow harmonics depends on initial state

… met by identification of observables which independently constrain the initial state

Schenke, Tribedy, Venugopalan, PRL 108 (2012) 252301



Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 110 (2013) no.1, 012302



Bayesian statistical analysis to simultaneously determine

Initial conditions & QGP properties

J. Bernhard, S. Moreland, S. Bass, J. Liu, U. Heinz, PRC 94, 024907 (2016)

S. Pratt, E. Sangaline, P. Sorenson, H. Wang, PRL 114 (2015) 202301

Characterization of QGP

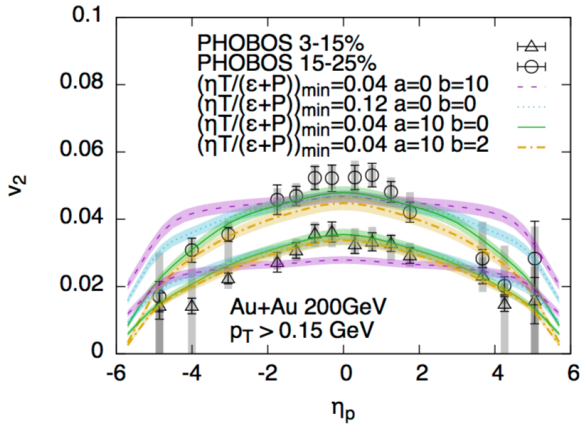
Several recent developments:

Effects of long. fluctuations and 3D evolution

New observables at top RHIC & LHC energies

preparation for RHIC BES II (2019-2020)

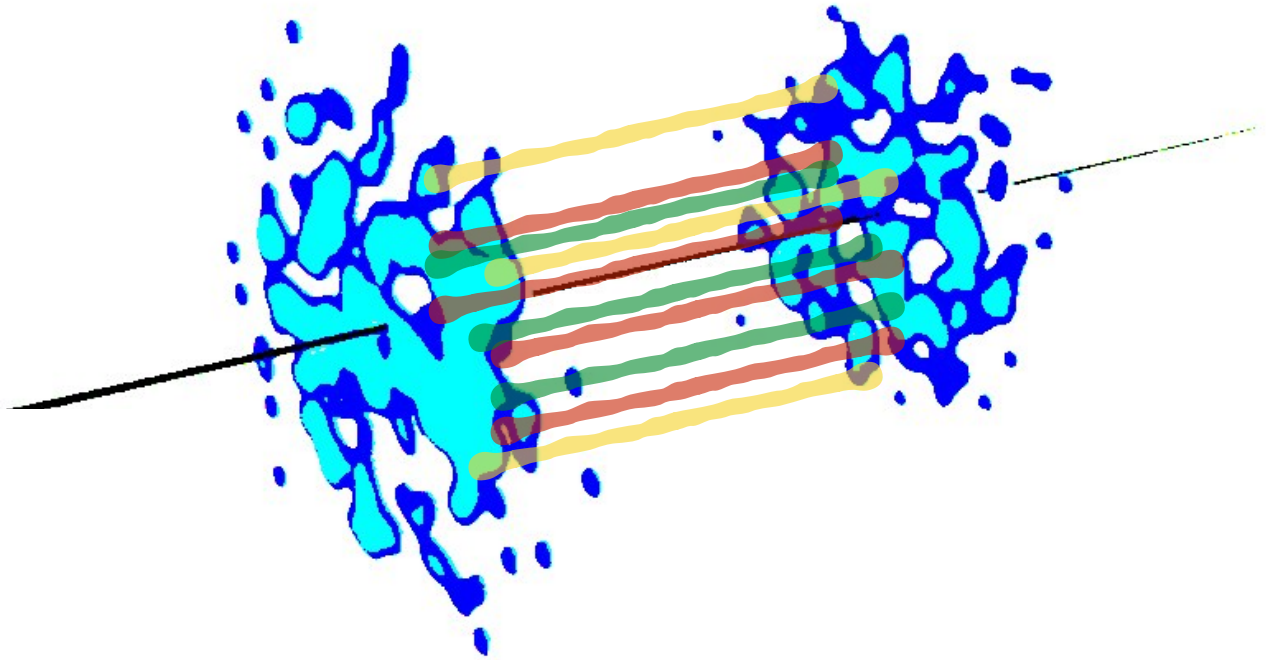
Denicol, Monnai, Schenke
PRL 116 (2016) no.21, 212301



Significant progress towards precise characterization of QGP bulk properties with systematic uncertainty quantification

Dynamical origin of QGP transport properties ($\eta/s|_{TC} << 1$) remains elusive

2



Early time dynamics &
equilibration process

Early time dynamics & equilibration

Goal: Dynamical description of early-time dynamics, equilibration process and onset of hydrodynamic behavior

-> Initial conditions for hydrodynamic evolution from microscopic dynamics

Significant progress in qualitative understanding from two limiting cases

- strong coupling limit in super-symmetric gauge theories

- weak-coupling limit of QCD

Even though real-world QCD is not super-symmetric and not necessarily weakly coupled at RHIC & LHC energy scales

constrain behavior from opposite limits

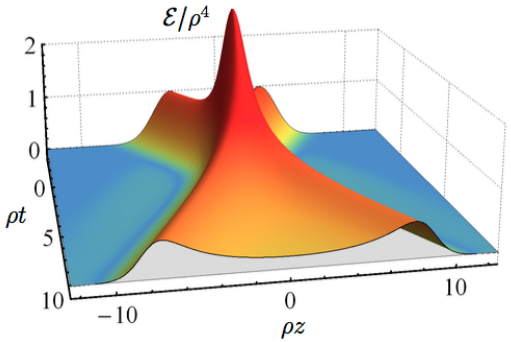
Early time dynamics & equilibration

Strong coupling picture (N=4 SYM):

Holographic description in terms of gravitational dual in AdS_5

-> collisions of gravitational shock waves

Review: Chesler, Yaffe, JHEP 1407 (2014) 086

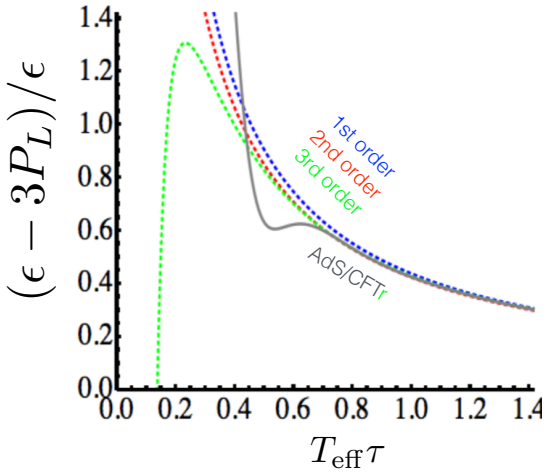


Casalderrey-Solana, Heller, Mateos, v.d. Schee
PRL 111 (2013) 181601

Even though local thermal equilibrium reached only on large time scales, viscous hydrodynamics applicable under extreme conditions (pressure aniso. ~ O(1))

->visc. hydro describes approach to local thermal equilibrium

Heller, Janik, Witaszczyk
PRL 108 (2012) 201602



-> Change of paradigm: equilibration vs. hydrodynamization

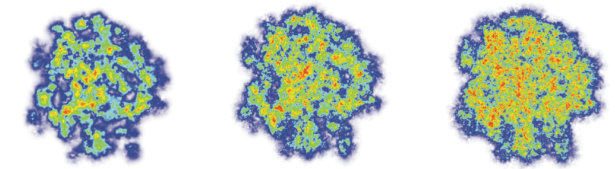
Early time dynamics & equilibration

Weak coupling picture:

Energy deposition in high-energy collisions dominated by small-x gluons

-> Color-Glass Condensate effective field theory

McLerran, Venugopalan PRD49 (1994) 2233-2241, Kovner, McLerran, Weigert D52 (1995) 6231-6237, …



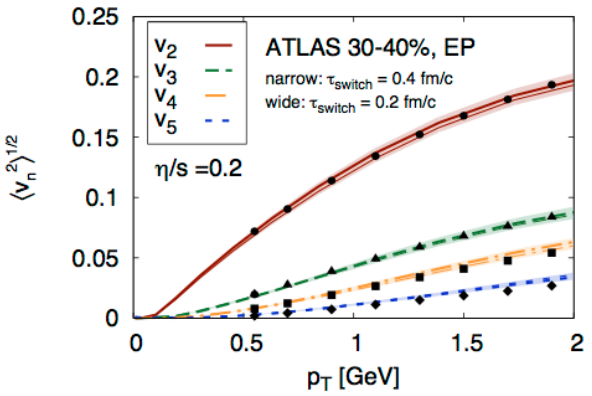
increasing c.o.m energy √s

Successful microscopic description of initial state based on input from DIS fits (IP-Glasma)

event-by-event eccentricities, multiplicity distributions, …

Schenke, Tribedy, Venugopalan, PRC 86 (2012) 034908, PRL 108 (2012) 252301, …

Gale, Jeon, Schenke, Tribedy, Venugopalan, PRL 110 (2013) no.1, 012302

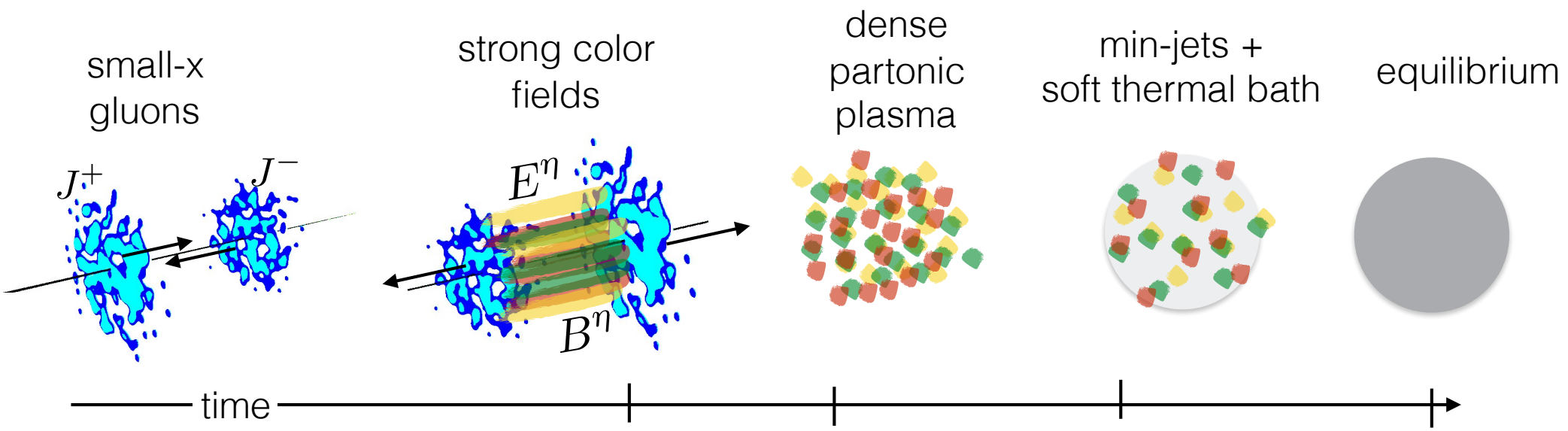


Gale, Jeon, Schenke, Tribedy, Venugopalan
PRL 110 (2013) no.1, 012302

Challenge for a long time has been to understand equilibration mechanism

Early time dynamics & equilibration

Weak coupling picture:



classical-statistical lattice gauge theory

eff. kinetic theory

hydro

Complete description of early-time dynamics by combination of weak-coupling methods

Early time dynamics & equilibration

Weak coupling picture:

In the (LO) weak-coupling limit equilibration proceeds as three step process:

Baier, Mueller, Schiff, Son PLB502 (2001) 51-58

Phase I: Evolution towards classical-attractor

quasi-particle description

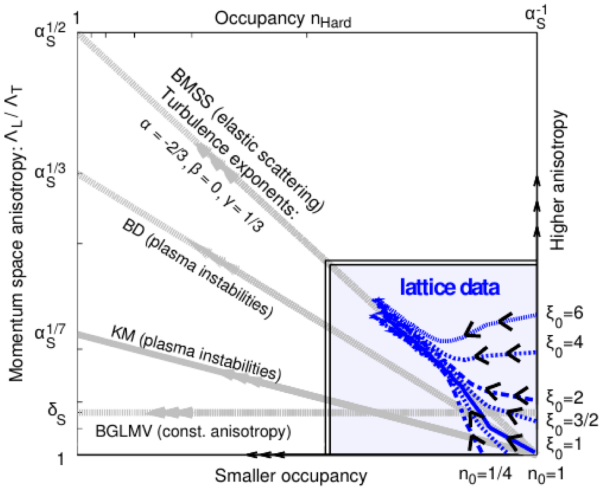
Phase II: Mini-jets undergo a radiative break-up cascade

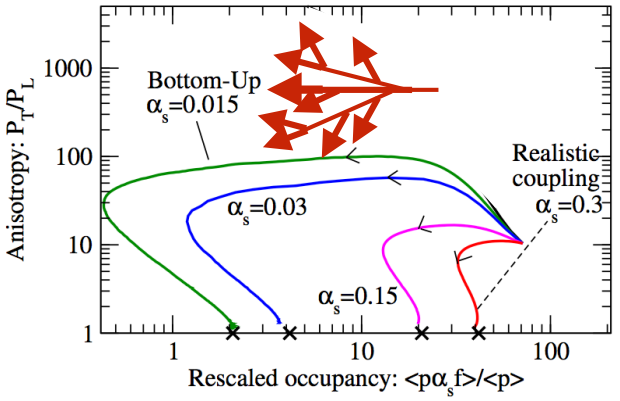
formation of soft thermal bath

Phase III: Quenching of mini-jets in soft thermal bath

isotropization of plasma

Berges,Boguslavski,SS, Venugopalan, PRD 89 (2014) no.7, 074011





Kurkela, Zhu PRL 115 (2015) 182301

Clear correspondence: Equilibration <-> Jet quenching

Early time dynamics & equilibration

Weak coupling picture:

Extrapolation to α_s=0.3 required to obtain phenomenologically relevant results at RHIC & LHC energies

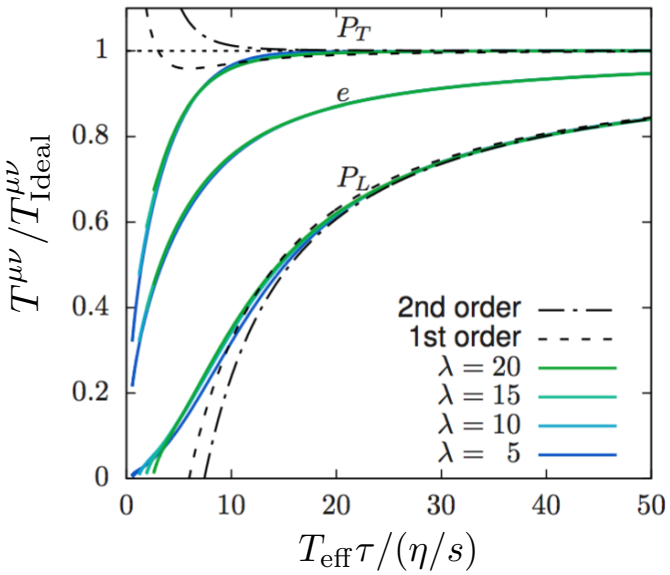
Viscous hydrodynamics applicable on time scales ~1 fm/c, when pressure anisotropies are O(1)

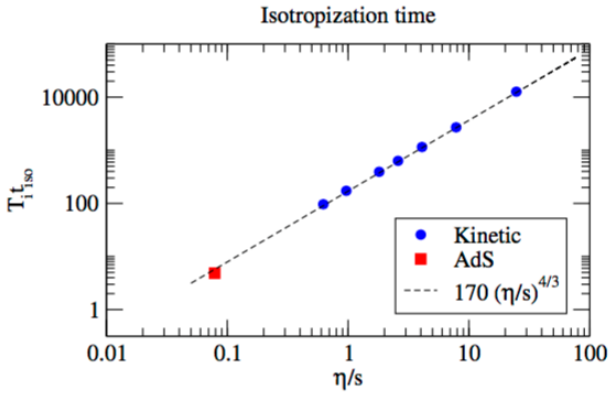
Kurkela, Zhu PRL 115 (2015) 182301

Smooth interpolation between weak coupling & strong coupling behavior

Keegan, Kurkela, Romatschke, v.d.Schee, JHEP 1604 (2016) 031

Kurkela, Mazeliauskas, Paquet, SS, Teaney (in progress)





Keegan, Kurkela, Romatschke, v.d.Schee JHEP 1604 (2016) 031

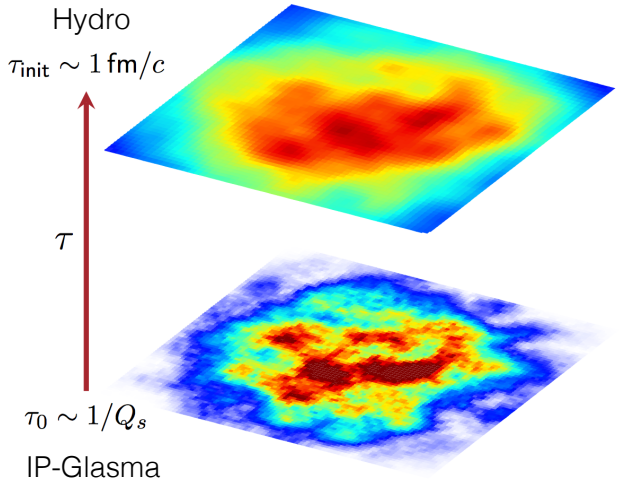
Early time dynamics & equilibration

Several recent developments:

Event-by-event (hydro) initial conditions from weakly coupled pre-equilibrium dynamics

Keegan, Kurkela, Mazeliauskas, Teaney JHEP 1608 (2016) 171
Kurkela, Mazeliauskas, Paquet, SS, Teaney (in progress)

talk by D. Teaney



Pre-equilibrium photon production

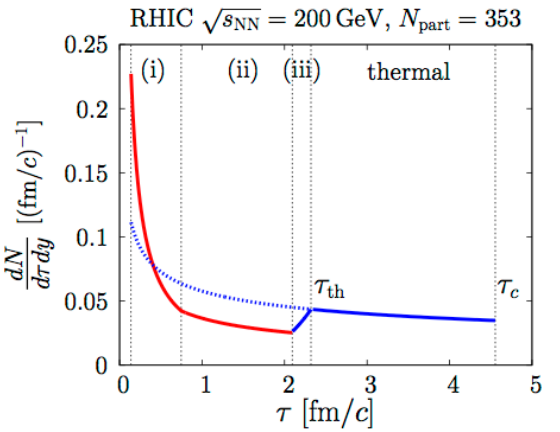
Berges, Reygers, Tanji, Venugopalan arXiv:1701.05604 [nucl-th]

talk by N. Tanji

Sphaleron transitions & anomalous transport

Mace, SS, Venugopalan, PRD 93 (2016) no.7, 074036
Mueller, SS, Sharma, PRL 117 (2016) no.14, 142301
Mace, Mueller, SS, Sharma, arXiv:1612.02477

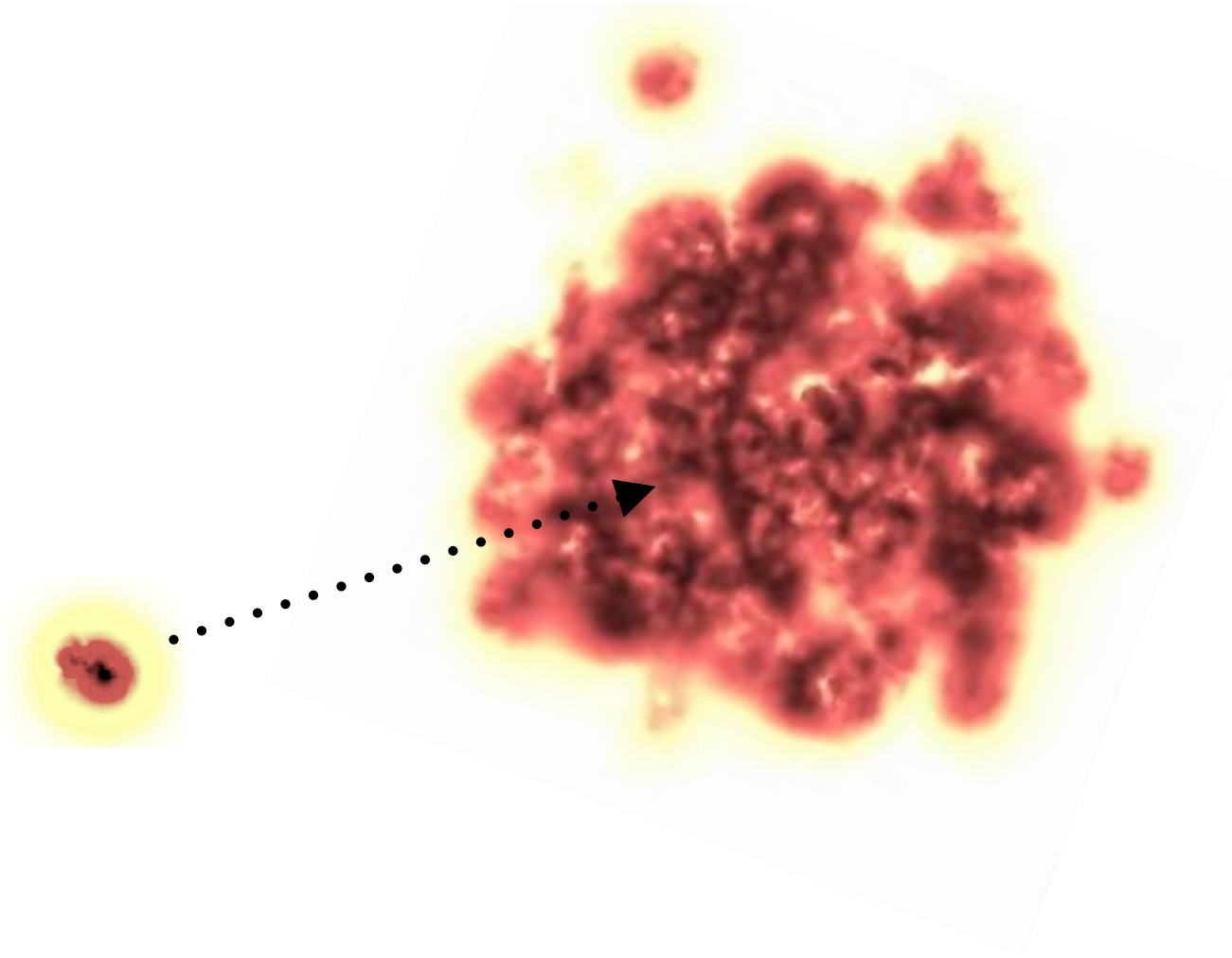
talk by N. Mueller



New qualitative insights into dynamics of QGP formation

Big challenge in the long run will be to go beyond leading order weak/strong coupling

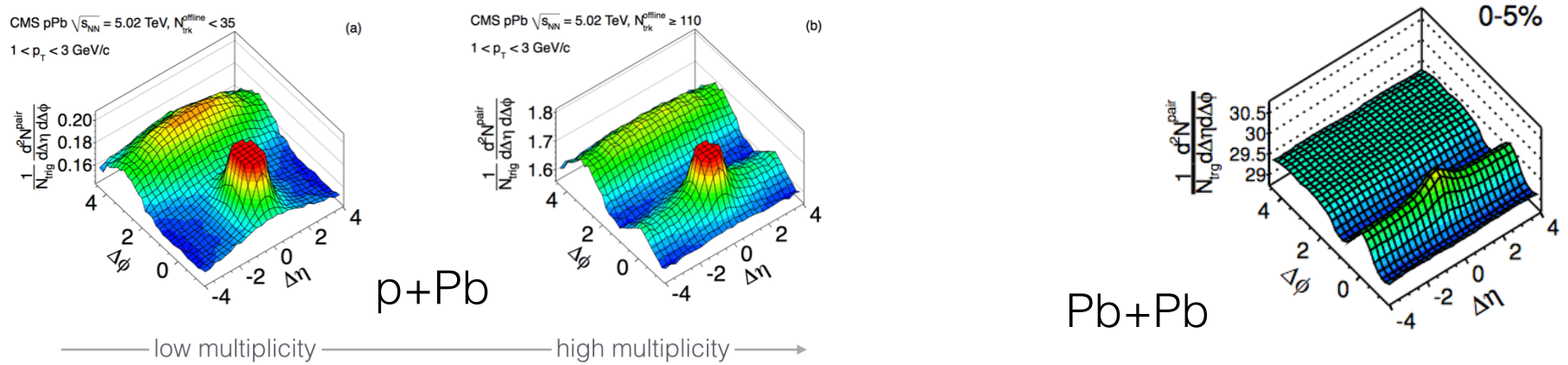
3



Small systems
(p+p,p/d/He3+A)

Small systems

Experimental discovery of pronounced long. range azimuthal correlations in (rare) high multiplicity p+p/A at LHC as well as p/d/He3+A collisions at RHIC



Even though important differences remain (e.g. jet-quenching), surprising similarities to heavy-ion collisions

Could be interpreted as signals for formation of “Small droplets of QGP” and hence provide new insights on conditions for QGP formation

Different theoretical explanations explored in terms of

Review: Dusling, Li, Schenke, Int.J.Mod.Phys. E25 (2016) no.01, 1630002

and/or initial state momentum correlations

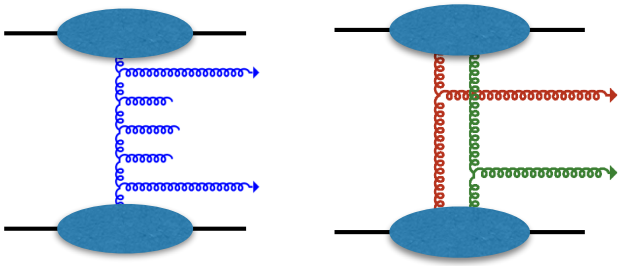
collective response to initial state geometry

Small systems

Initial state picture:

Observed correlations attributed
to initial state momentum correlations

Gelis,Lappi Venugopalan PRD 78 (2008) 054020, PRD 79 (2009) 094017
Dumitru, Gelis, McLerran,Venugopalan NPA8 10, 91 (2008)
Dumitru, Jalilian-Marian PRD 81 (2010) 094015

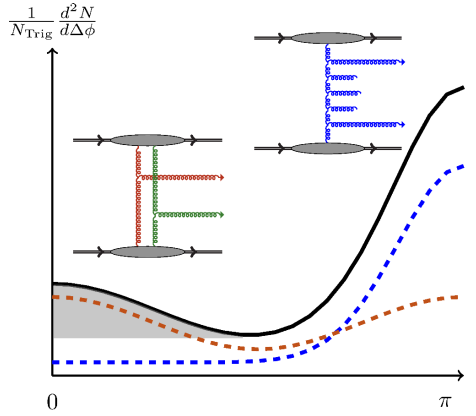


"Jet graph" **"Glasma graph"**

High-multiplicity events <-> rare configurations of proton wave-function featuring large number of small-x gluons

Dusling, Venugopalan PRD 87 (2013) 5, 051502, PRD 87 (2013) 5, 054014, PRD 87 (2013) 9, 094034

-> enhancement of Glasma graphs vs. Jet graph



Near-side long range correlation directly reflects multi-parton correlations inside projecile/target

Small systems

Initial state picture:

Successful phenomenology developed based on pert. small-x calculations

Dusling, Venugopalan PRD 87 (2013) 5, 051502, PRD 87 (2013) 5, 054014 …

Several new developments:

Event-by-event simulations

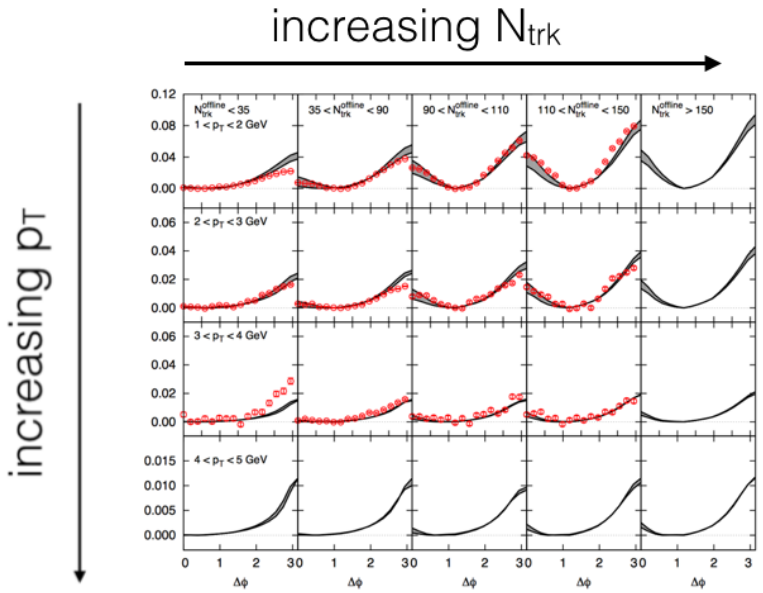
Schenke, SS, Venugopalan, PLB 747 (2015) 76-82

Schenke,SS,Tribedy, Venugopalan, PRL 117 (2016) no.16, 162301

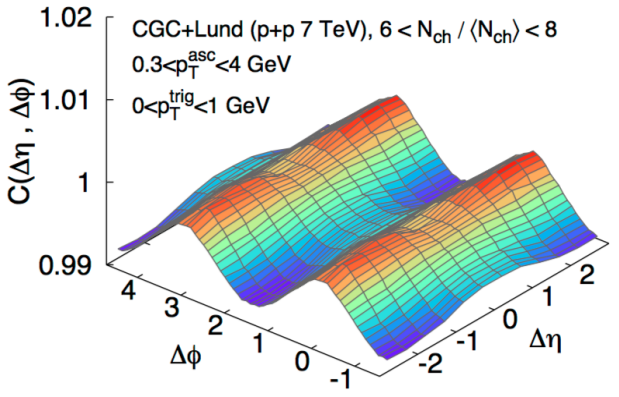
Multi-particle correlations

Dumitru, McLerran, Skokov PLB743 (2015) 134-137

Challenge so far has been to extend calculations to low p_T and high N_{trk}



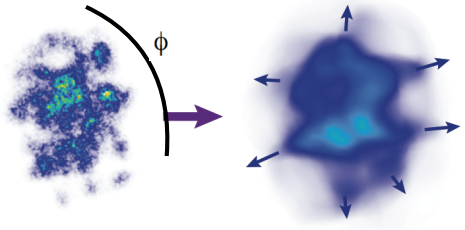
Dusling, Venugopalan, PRD 87 (2013) 9, 094034



Schenke,SS,Tribedy, Venugopalan, PRL 117 (2016) no.16, 162301

Small systems

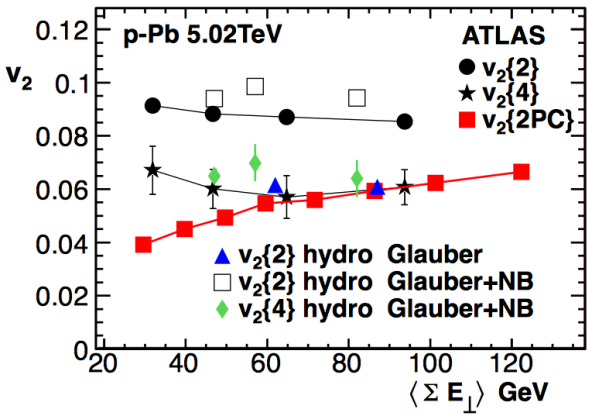
Hydrodynamic picture:



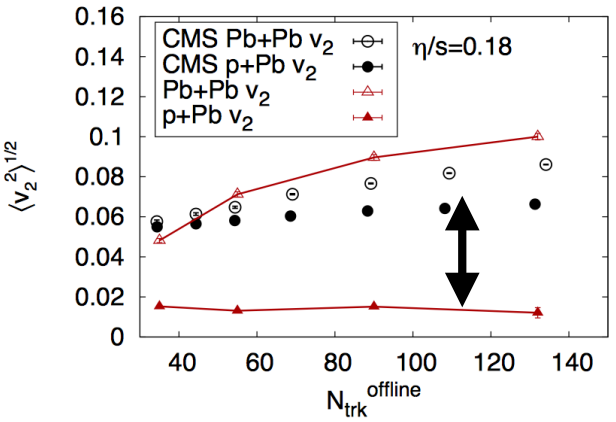
Observed correlations attributed to collective (hydrodynamic) response to initial state geometry

Quantitative description of experimentally observed correlation strength in high mult. p+p/A collisions possible provided non-trivial initial state geometry

Early results: large discrepancies between initial state models



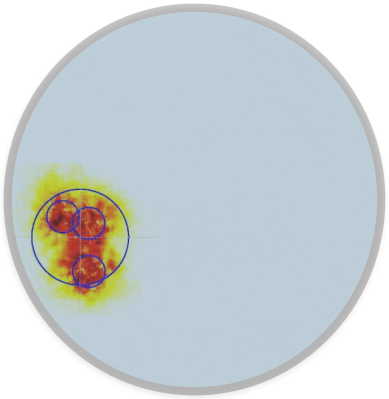
Bozek,Broniowski, PRC 88 (2013) 1, 014903



Schenke,Venugopalan, PRL 113 (2014) 102301

Small systems

Event geometry in p+p/A:



Event geometry in p+p/A collisions closely reflects b-dependence of gluon distribution in proton

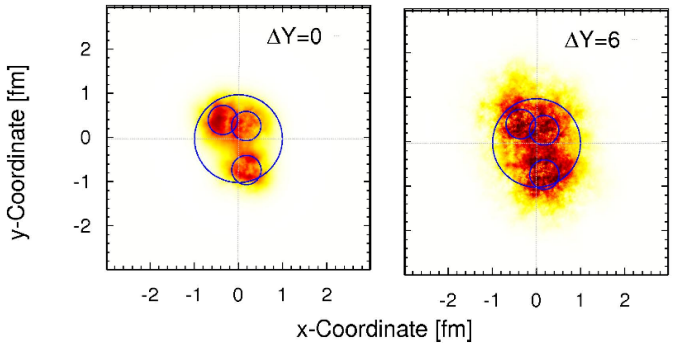
Schenke, Venugopalan PRL 113 (2014) 102301

-> event-by-event fluctuation of the proton necessary to generate sizable anisotropies

Single event different from inclusive averages probed in typical hadron structure functions (GPD's)

-> non-trivial shapes of unpolarized proton

-> shape fluctuations survive small-x evolution

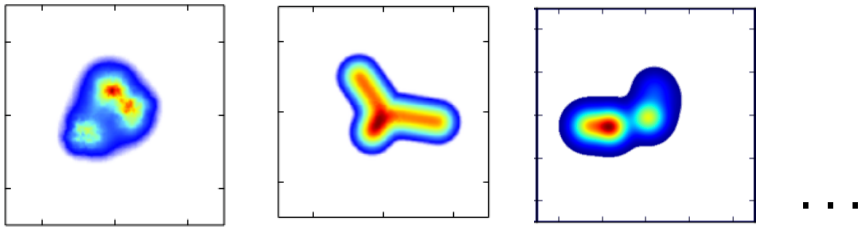


SS, Schenke PLB 739 (2014) 313-319

Small systems

Various models of fluctuating proton sub-structure emerging

Mäntysaari, Schenke PRD 94 (2016) no.3, 034042
Bozek, Broniowski, Rybczynski PRC 94 (2016) no.1, 014902
Habich, Miller, Romatschke, Xiang EPJ. C76 (2016) no.7, 408
Welsh, Singer, Heinz PRC 94 (2016) no.2, 024919
…



Need for independent constraints on proton fluctuations

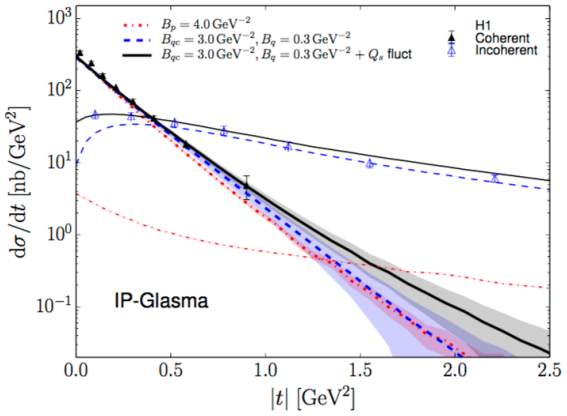
Coherent vs. in-coherent diffraction
(e+p->e+p'+J/Ψ)

talk by H. Mäntysaari

Mäntysaari, Schenke PRL 117 (2016) no.5, 052301 , PRD 94 (2016) no.3, 034042

Elastic p+p scattering

Albacete, Soto-Ontoso, arXiv:1605.09176



Mäntysaari, Schenke PRL 117 (2016) no.5, 052301

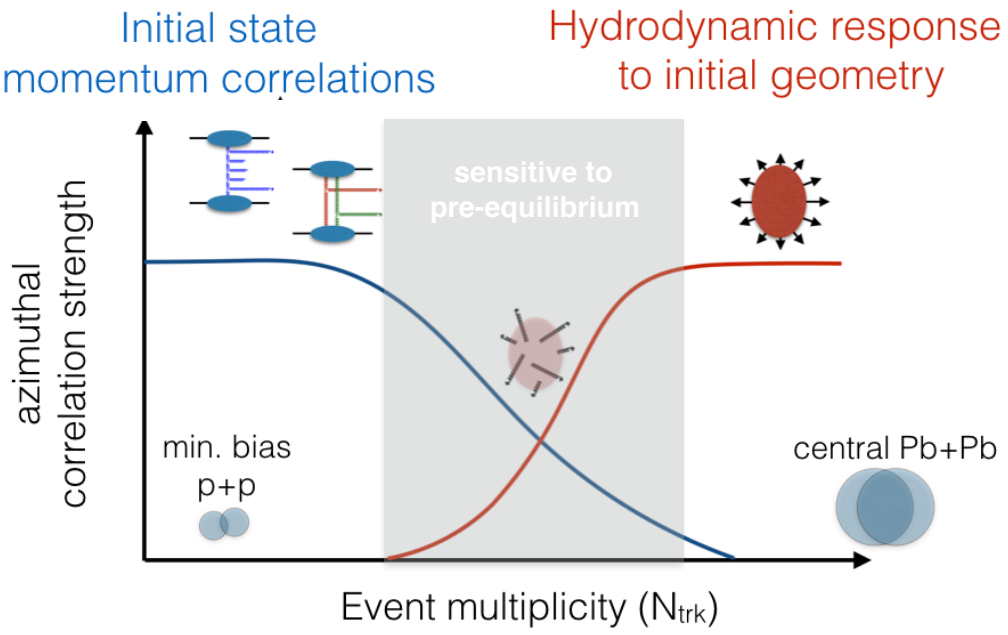
Need to identify aspects of proton structure relevant for high mult. p+p/A and connect with present/future knowledge of hadron structure (MPDs)

Small systems

So far calculations based on dominance of initial state or final state effects

Description across a wide range of multiplicities needs to account for both initial state & final state effects

-> closely related to understanding of pre-equilibrium dynamics



SS, Quark Matter 2015, NPA 956 (2016) 216-221

Challenge:

Identify observables which can unambiguously distinguish between different regimes

. . .

Several interesting developments I did not cover:

Jets & Jet-medium interaction

Heavy-flavors & Quarkonia

Critical fluctuations & signatures of QCD critical point

. . .

See Quark Matter '17 talks at: https://indico.cern.ch/event/433345

Conclusions & Outlook

Significant advances in theoretical description of space-time evolution of HIC leading towards a more and more precise characterization of QGP properties with systematic uncertainty quantification

Experimental result in small systems challenging theory to revisit some fundamental questions, regarding in particular the dynamics of QGP formation, and have started to open up new directions in relation to hadronic structure

New data coming out at QM 2017, exiting times for heavy-ion theory