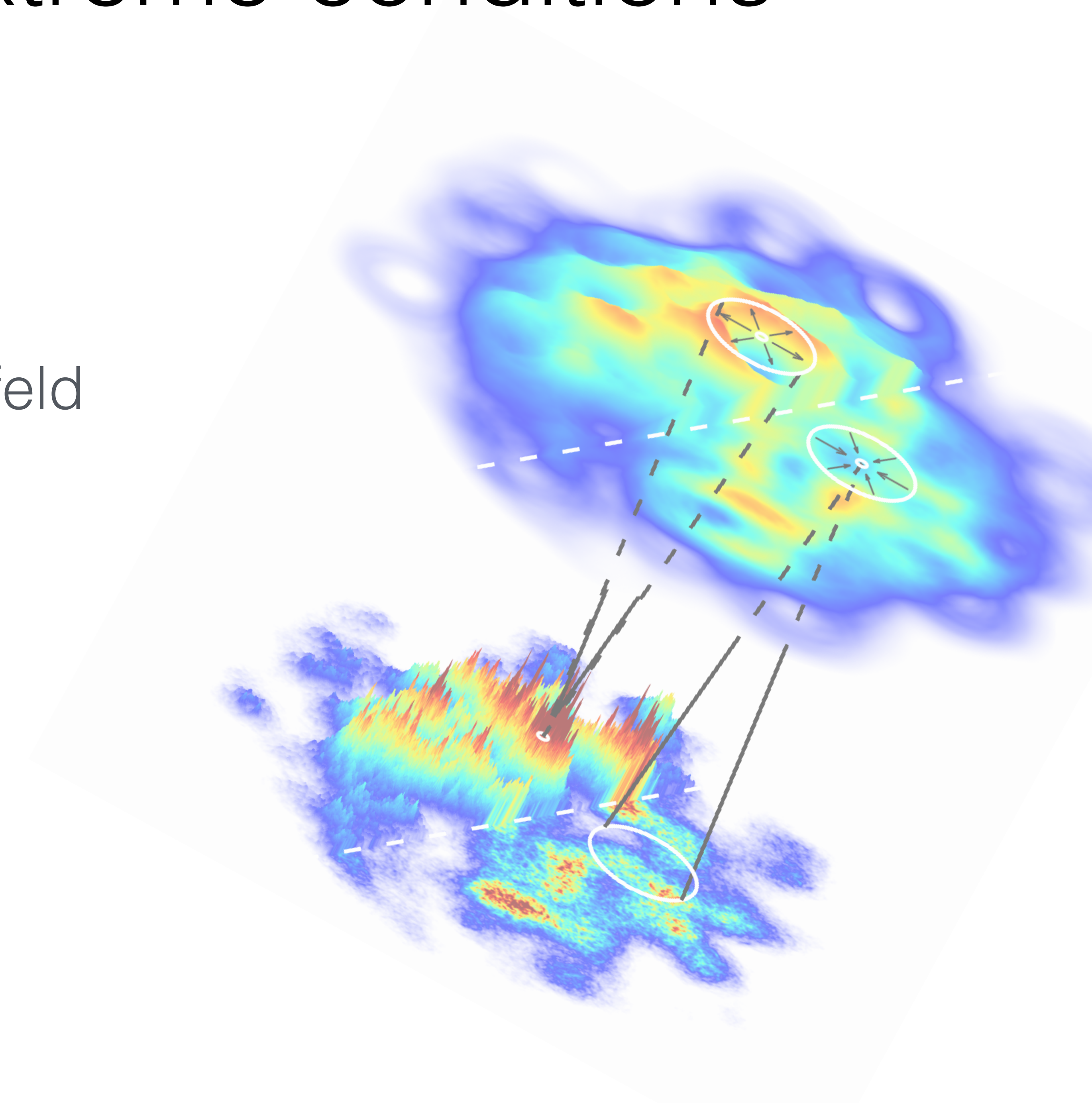
QCD matter under extreme conditions



Sören Schlichting | Universität Bielefeld

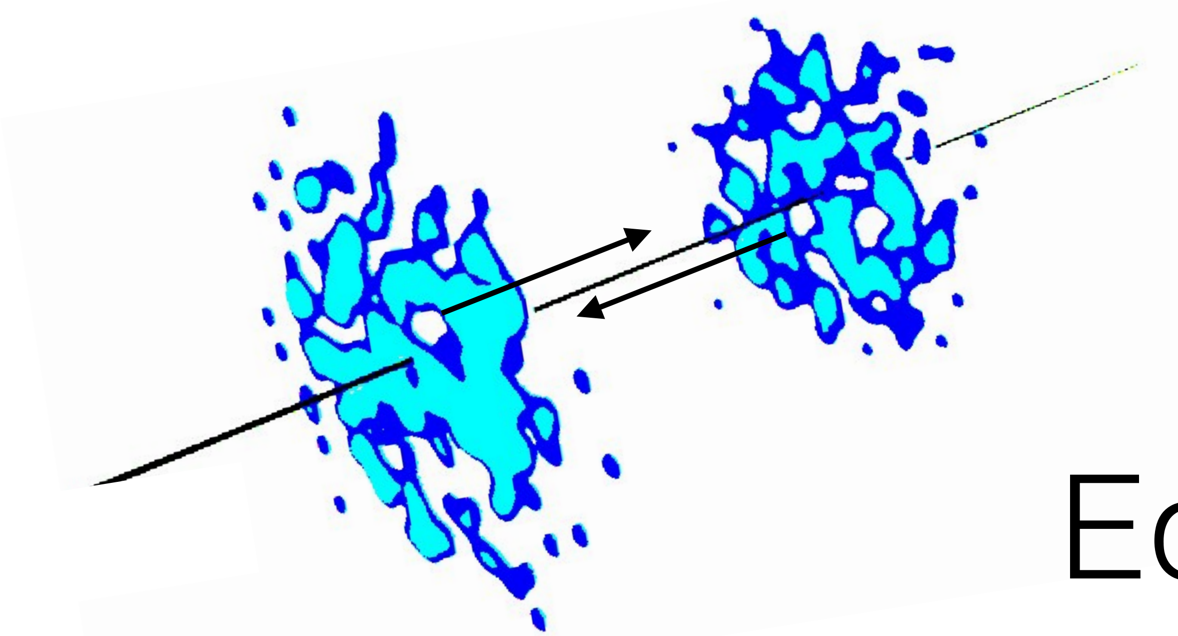
KHuK Meeting
Bad Honnef
Dec 2023

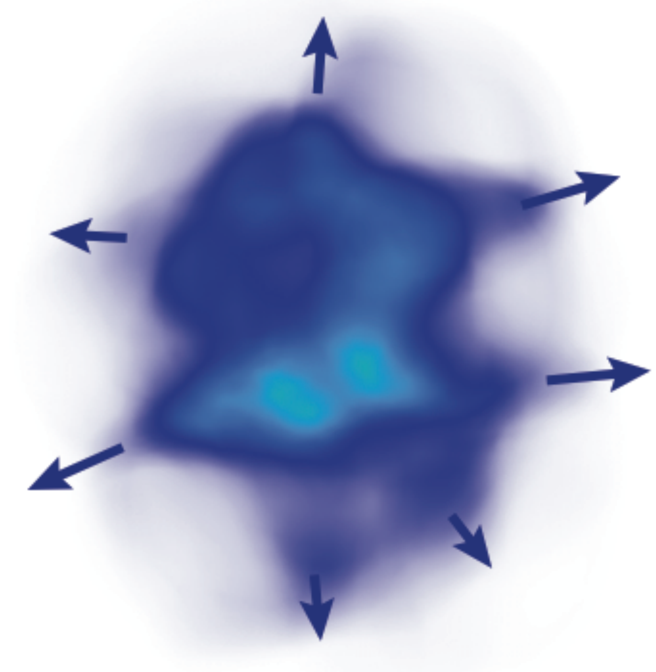
CRC-TR 211
Strong-interaction matter under extreme conditions

FSP ALICE
Erforschung von Universum und Materie

UNIVERSITÄT BIELEFELD

1



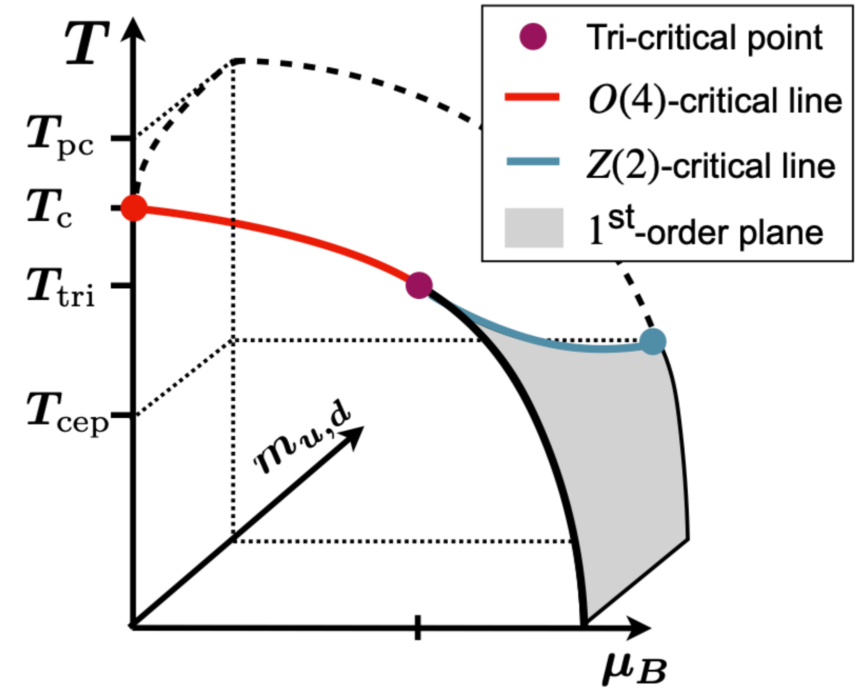


Equilibrium properties
of QCD matter

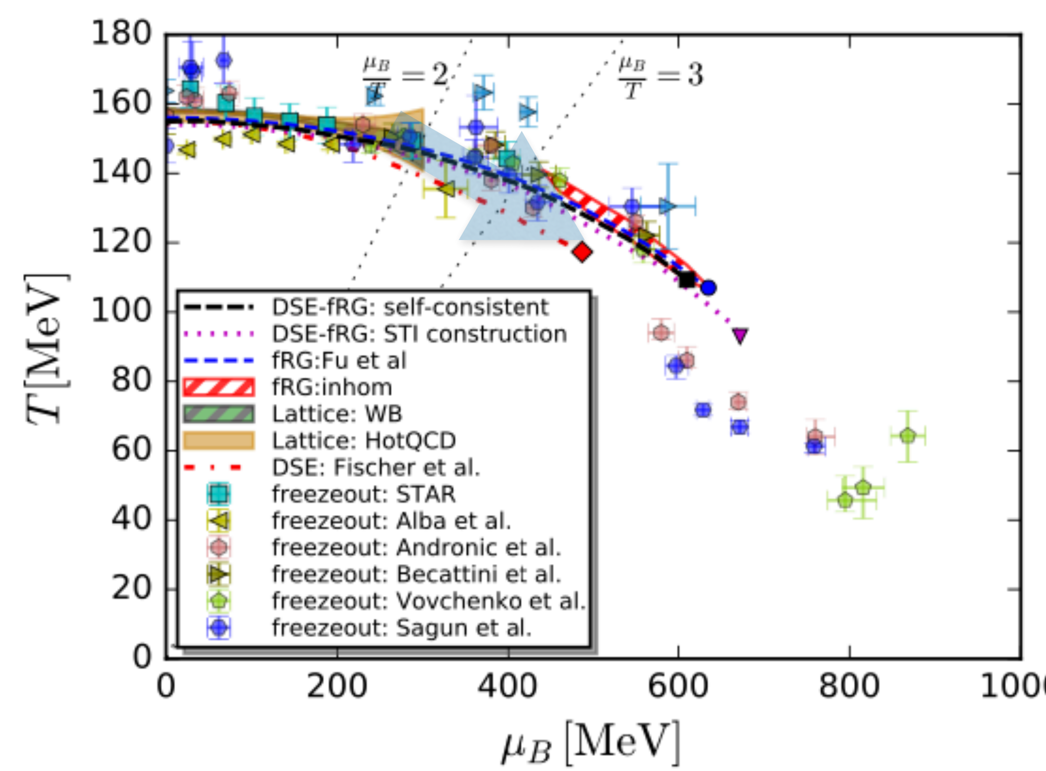
QCD Thermodynamics

Based on first principle QCD calculations on the lattice (μ_B=0) or functional methods

- Phasediagram
- Equation of state
- transport properties
  (with sizeable uncertainties from analytic continuation)



Aarts et al. Prog.Part.Nucl.Phys. 133 (2023) 104070



Chiral transition in 2+1flavor QCD

Expect second order O(4) transition in the limit $m_{u/d}$->0

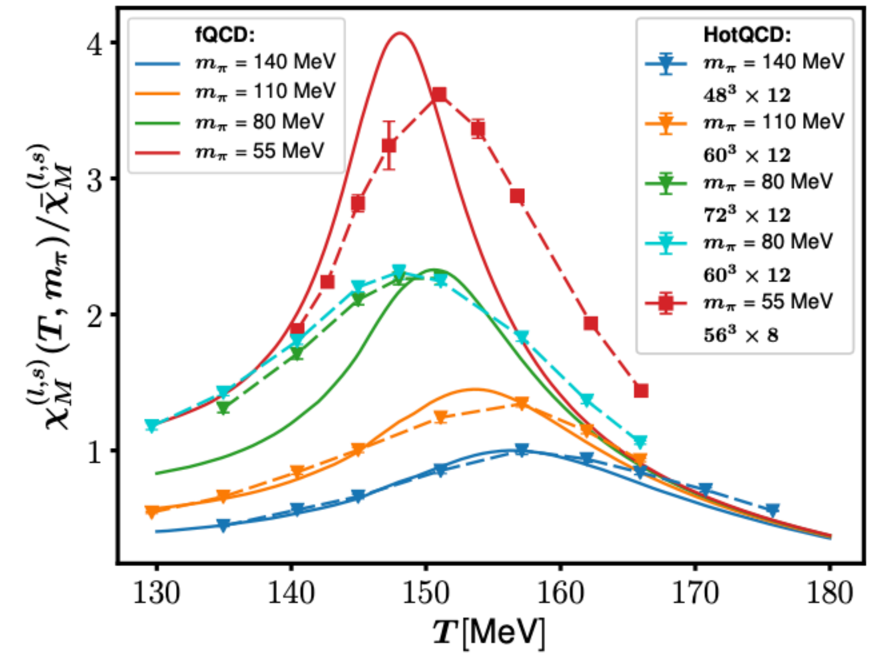
Evidence of O(4) scaling reported in lattice QCD & FRG calculations for lighter than physical m_π

Kaczmarek et al. arXiv:2003.07920 [hep-lat]

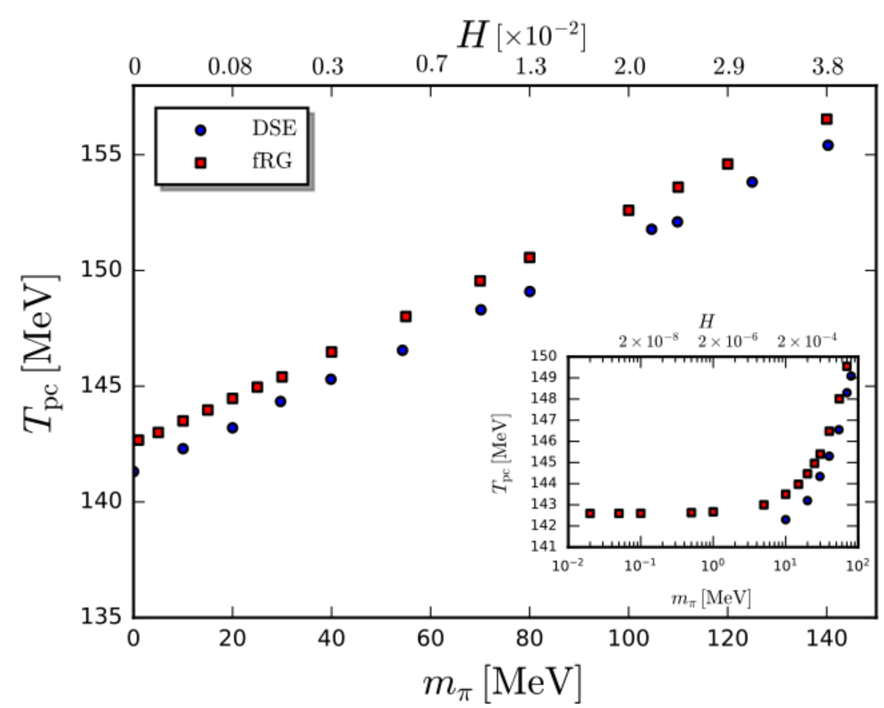
T_C ~130-140 MeV < T_{PC} ~ 155 MeV

New FRG calculations suggest that actual scaling region may be as small as m_π~2–5MeV

Braun et el. arXiv:2310.19853 [hep-ph]

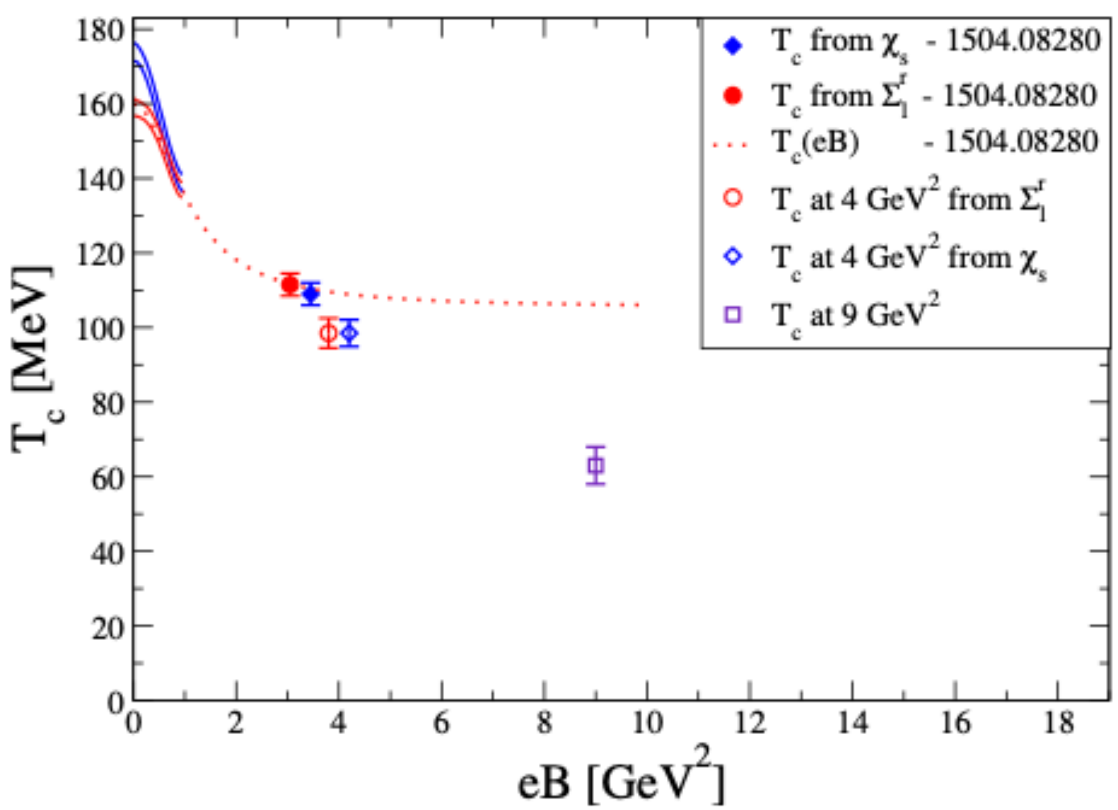


Braun et al PRD 102 (2020) 5, 056010

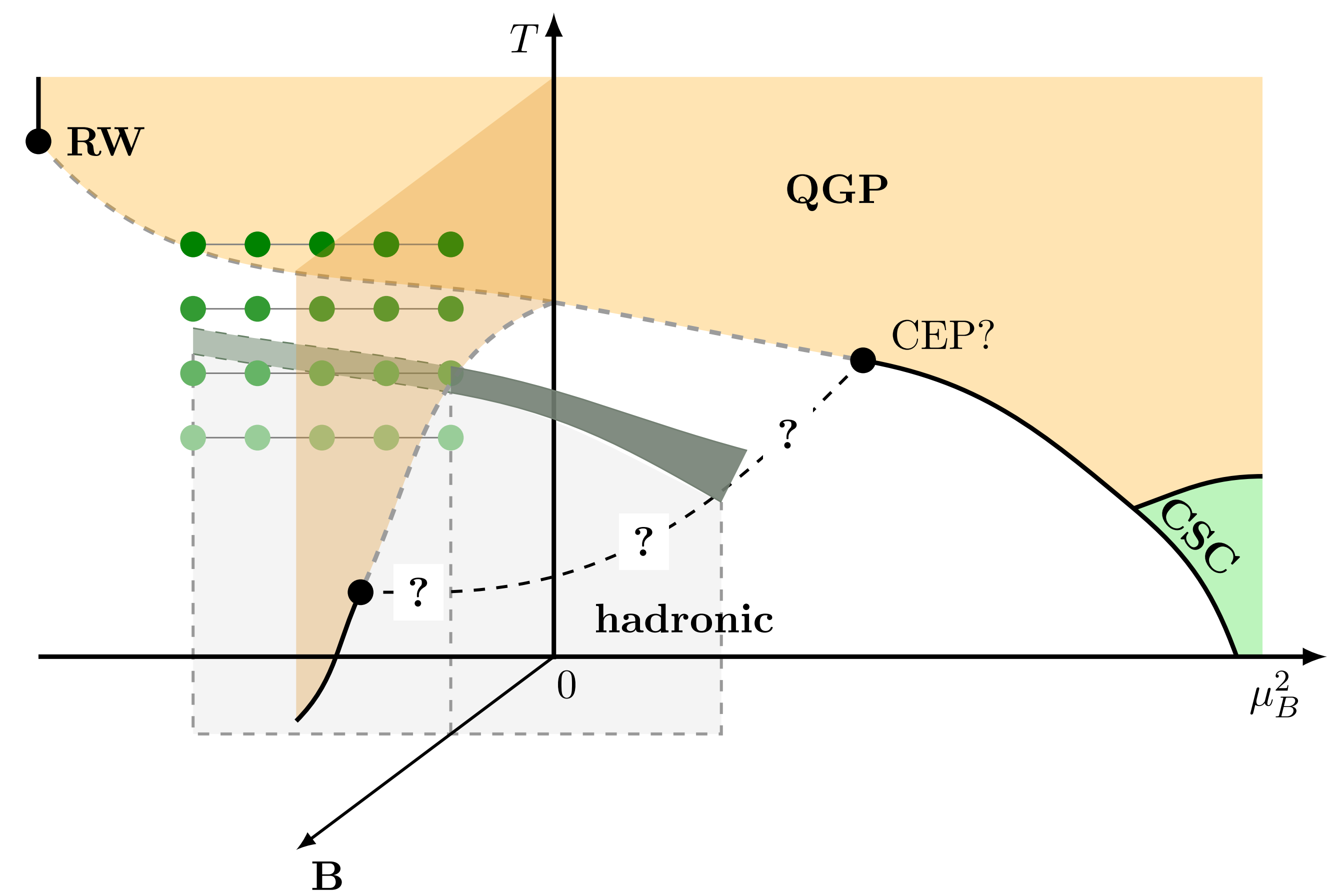


Braun et el. arXiv:2310.19853 [hep-ph]

Critical point at non-zero B



D'Elia et al. PoS LATTICE2022 (2023) 184



4 GeV^2 < eB_C < 9 GeV^2

63 MeV< T_C < 98 MeV

could be connected to critical point at finite μ_B

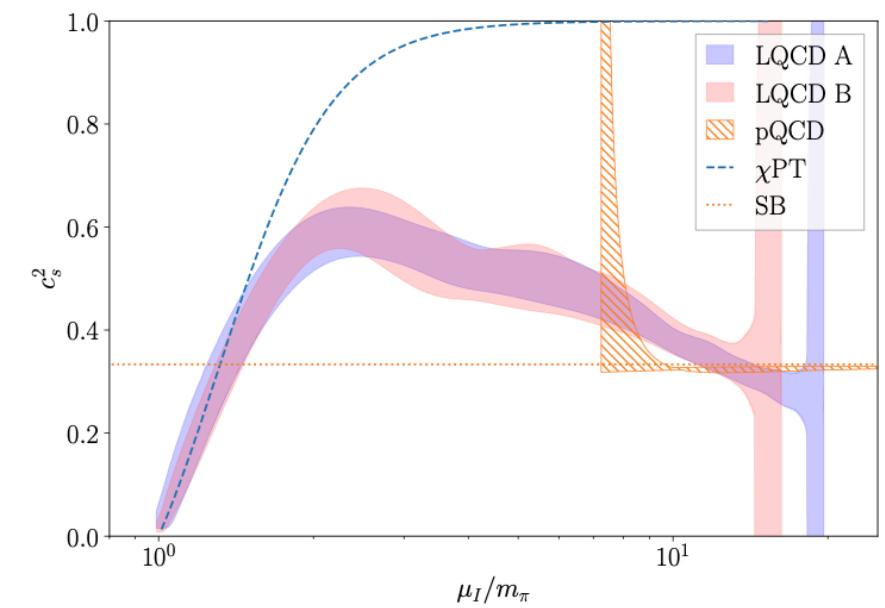
work in progress (Bielefeld, Wuppertal) to determine phase diagram in T,μ_B plane

Equation Of State

Equation of state at finite Isospin density calculable from lattice QCD at T=0 and T≠0

Brandt et al *JHEP* 07 (2023) 055

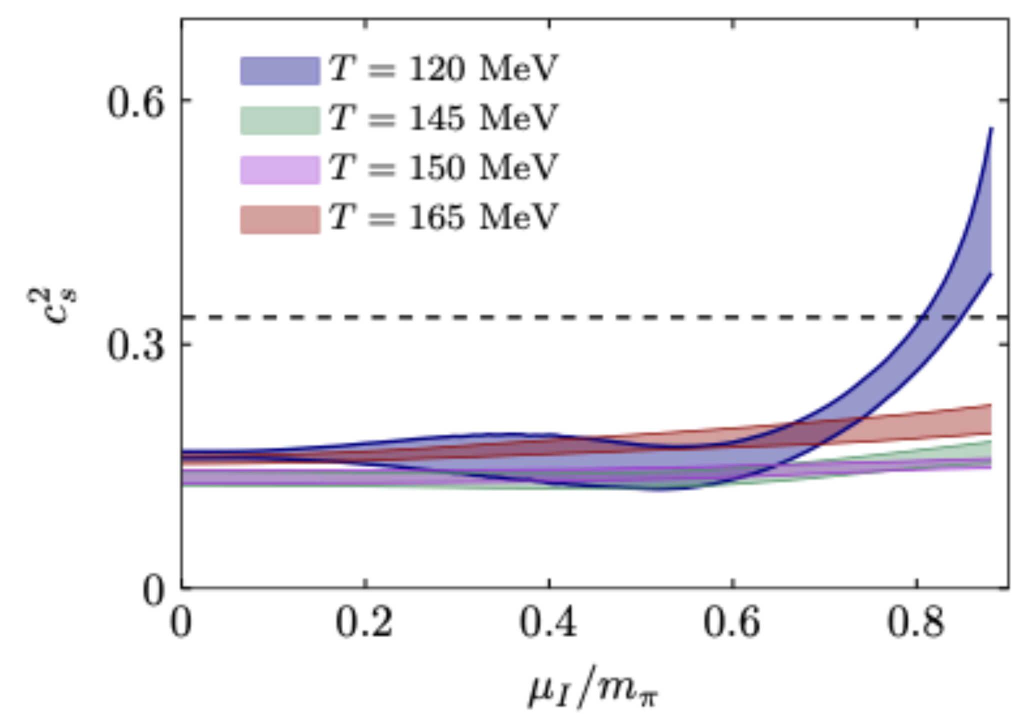
Abbot et al. arXiv:2307.15014 [hep-lat]



Speed of sound exceeds $c_S^2=1/3$ at moderately large densities

Pressure at finite Isospin provides upper bound for pressure at finite Baryon density

Moore, Gorda arxIv:2309.15149 [nucl-th]

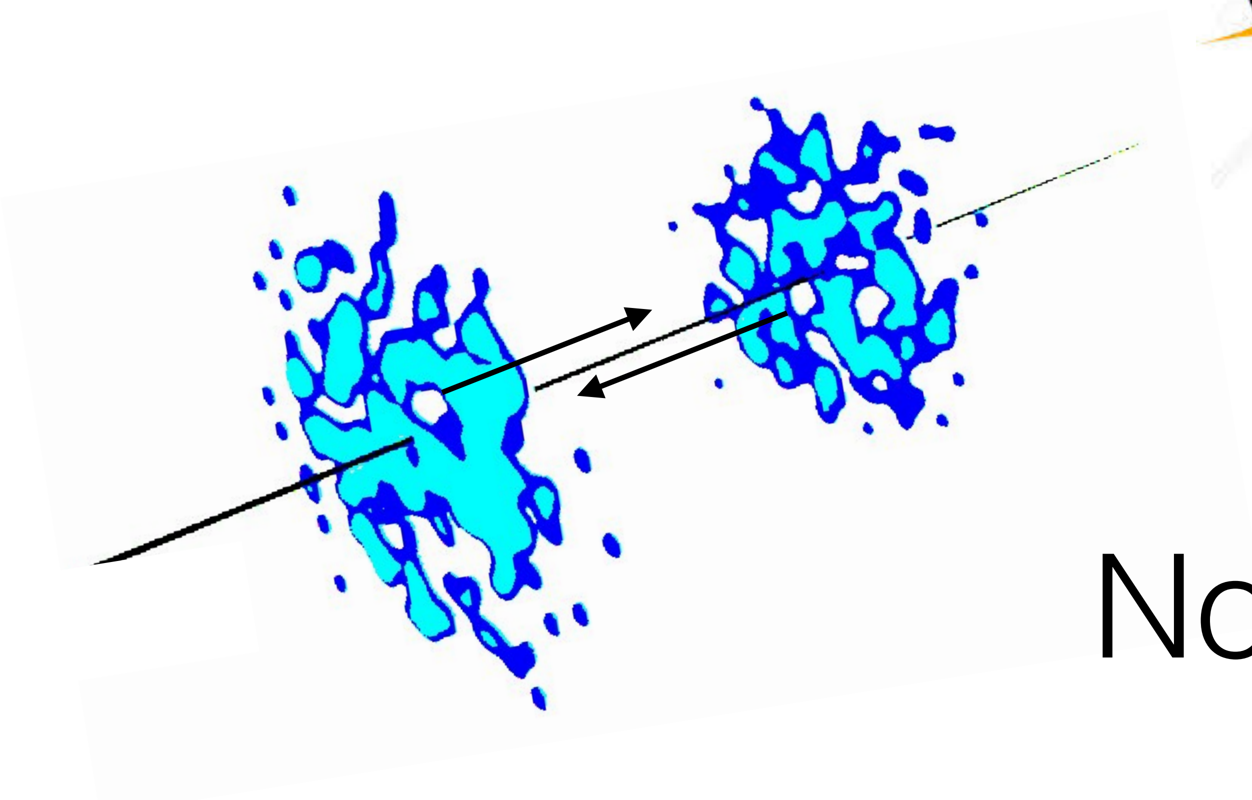


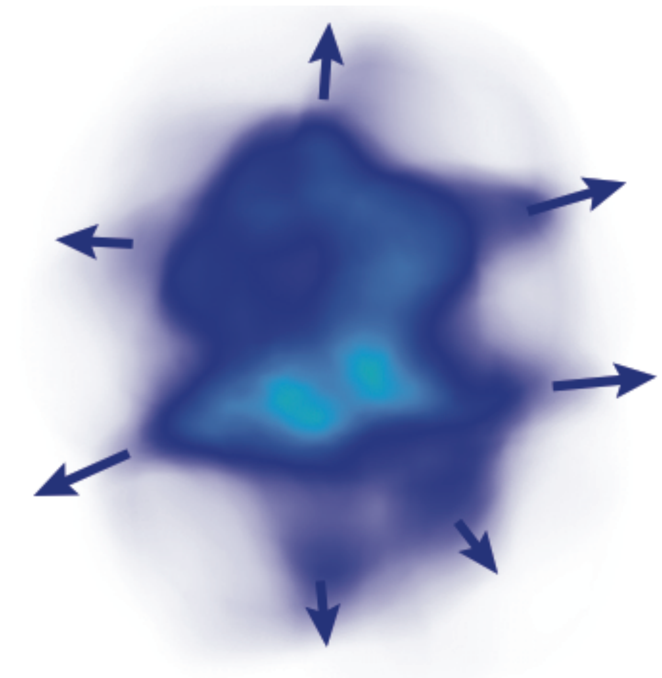
Brandt et al *JHEP* 07 (2023) 055

Indirect implications for NS & Heavy-Ion physics

Fujimoto,Reddy arXiv:2310.09427 [nucl-th]

2



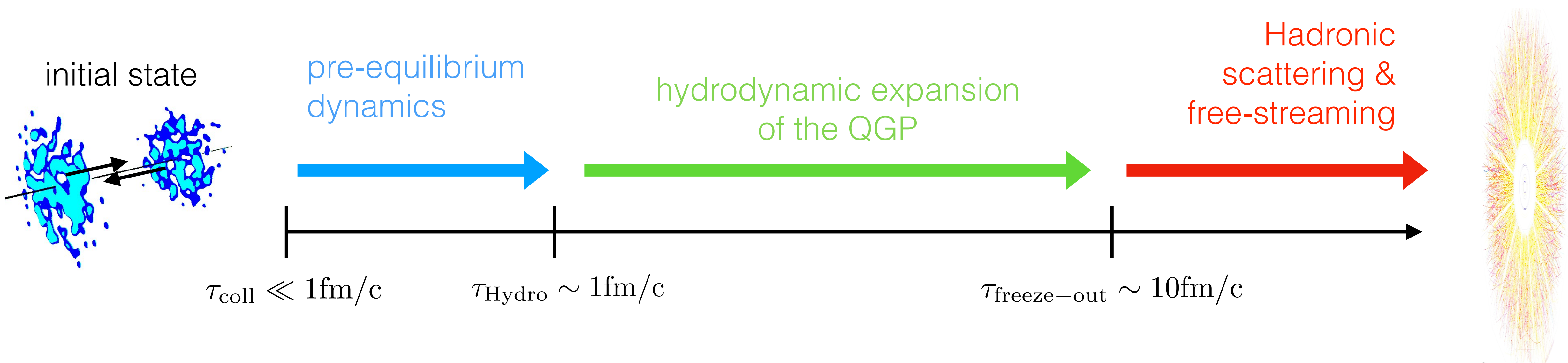


Non-equilibrium QCD matter in HICs

Heavy-Ion Collisions

Dynamical description of Heavy-Ion collisions from underlying theory of QCD remains an outstanding challenge

Standard model of nucleus-nucleus (A+A) collisions based on effective descriptions of QCD exploiting clear separation of time scales in the reaction dynamics



Cold QCD Matter

Non-Equilibrium QCD Matter

(Near-)Equilibrium QCD Matter

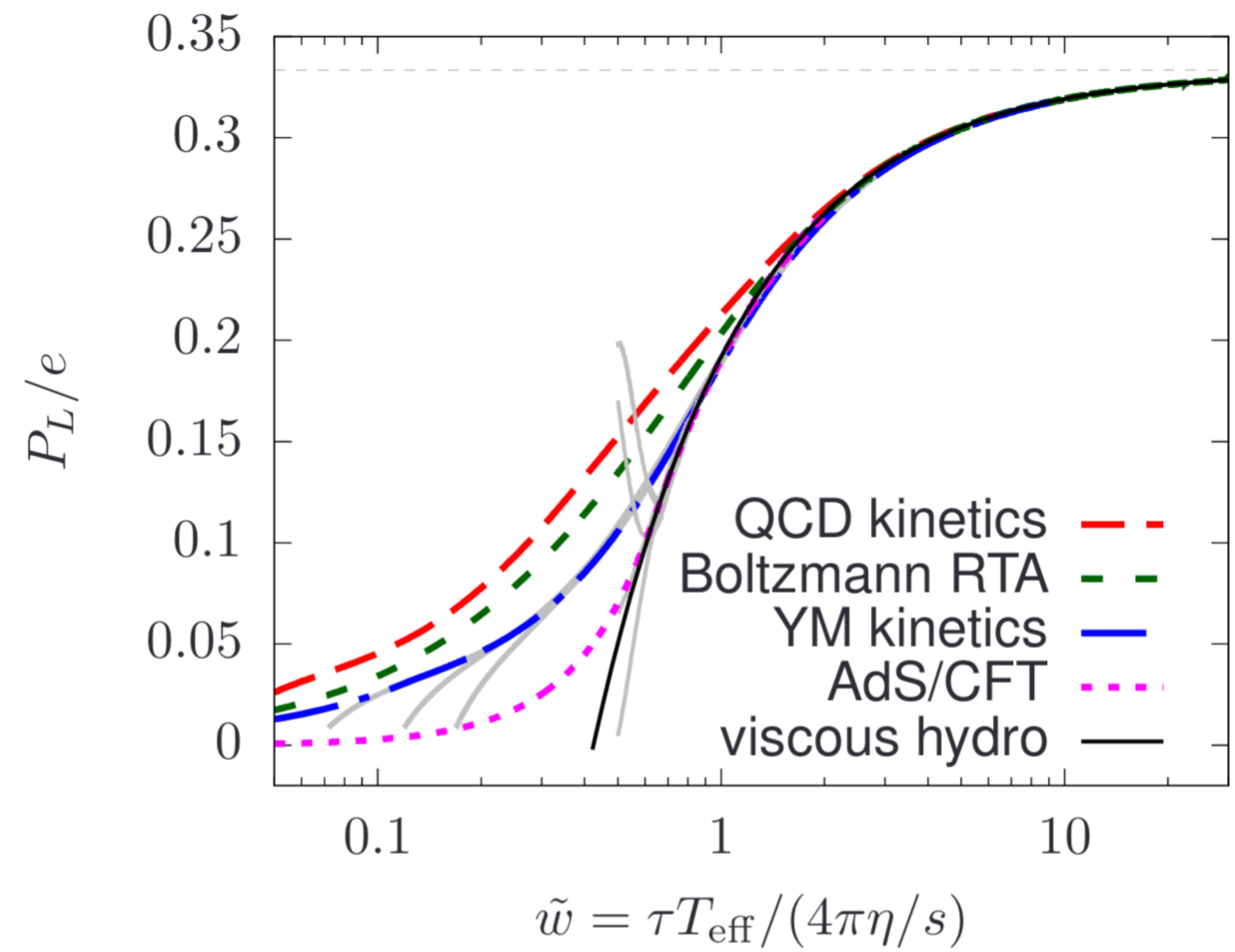
Hadrons

Significant progress in understanding formation of near-eq. QGP

Hydrodynamics in Heavy-Ion Collisions

System initially highly anisotropic due to rapid long. expansion; near-equilibrium hydrodynamic description requires some level of isotropy

Different microscopic calculations in QCD/YM/RTA Kinetic theory & AdS/CFT show similar results for pressure isotropization



Effective hydrodynamic description applicable on time scales

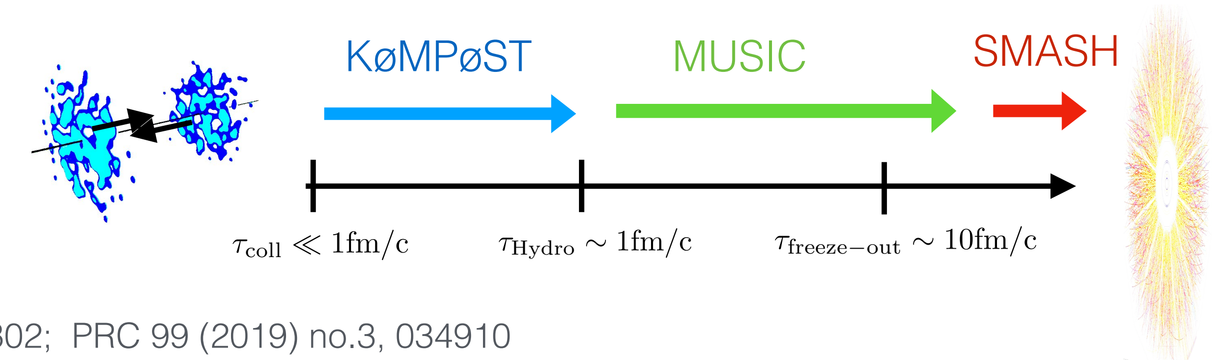
$$\tau_{\mathrm{hydro}} \approx \frac{4\pi\eta/s}{T_{\mathrm{eff}}(\tau)} \qquad \tau_{\mathrm{hydro}} \approx 1.1\,\mathrm{fm} \left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}} \left(\frac{\langle\tau s\rangle}{4.1\,\mathrm{GeV}^2}\right)^{-1/2}$$

when QGP is still quite far from equilibrium

YM: Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910 QCD: Kurkela, Mazeliauskas PRL 122 (2019) 142301; RTA: Strickland JHEP 12 (2018) 128; Kamata, Martinez, Plaschke, Ochsenfeld, SS PRD 102 (2020) 5, 056003
AdS/CFT: Romatschke PRL 120 (2018) no.1, 012301 Hydro vs. RTA: Strickland, Noronha, Denicol, PRD 97 (2018) 3, 036020

Event-by-event pre-eq dynamics

Effective macroscopic description of pre-eq dynamics in HICs on event-by-event basis available in KøMPøST

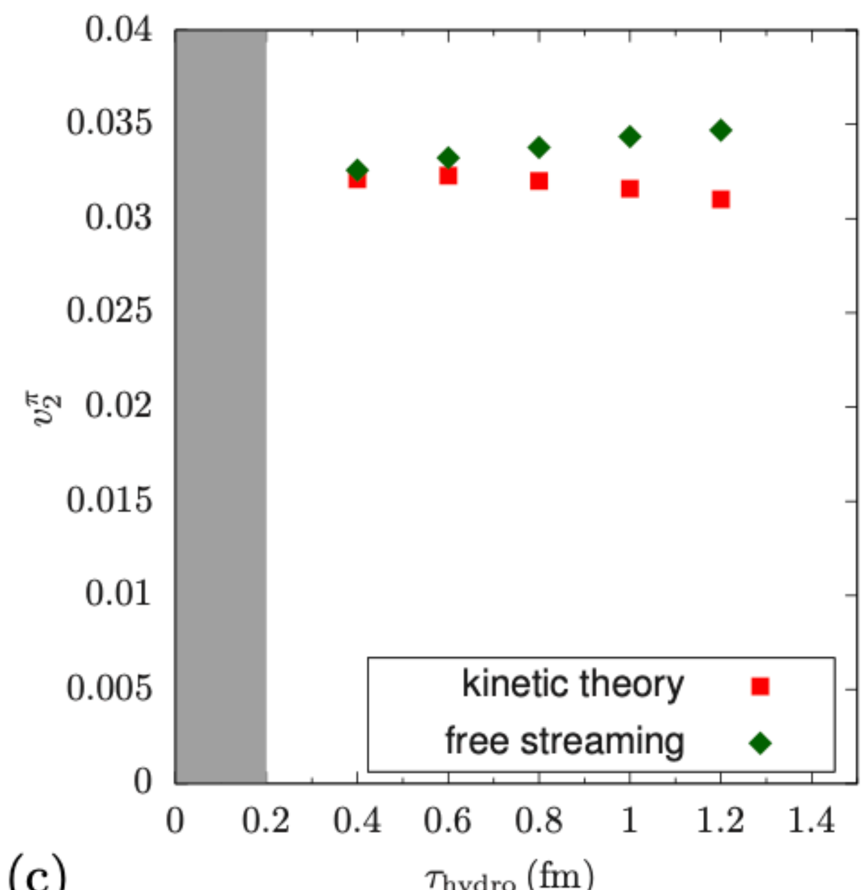


KøMPøST: Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910

No significant effect of pre-equilibrium phase on typical heavy-ion bulk observables

Controlled extraction of QGP transport properties without large uncertainties from early times

Difficult to gain experimental access to early time non-equilibrium dynamics in heavy-ion collisions



(c)

Electromagnetic probes (γ)

Electromagnetic probes (γ, l^+l^-) produced throughout space-time evolution of HICs escape collision unscathed as they do not interact strongly with the QGP

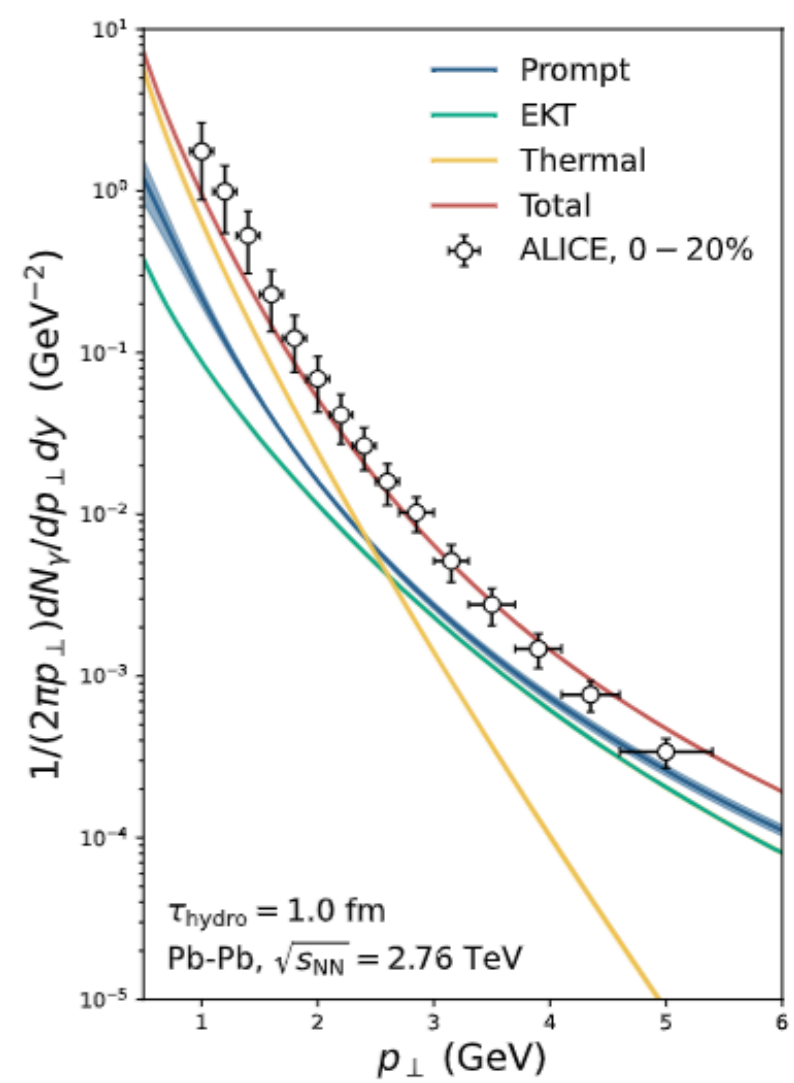
New calculation of LO pre-eq photon production in QCD Kinetic Theory

Garcia-Montero et al. 2308.09747 [hep-ph]

Universal scaling of photon p_T spectrum in terms of shear viscosity η/s and entropy density $dS/d\eta \sim (T\tau^{1/3})^3$

$$\frac{dN}{d^2x_T d^2p_T dy} = (\eta/s)^2\, \tilde{C}_\gamma^{ideal}\, \mathcal{N}_\gamma\left(\tilde{w}, \sqrt{\eta/s}\, p_T / \left(T\tau^{1/3}\right)_\infty^{3/2}\right)$$

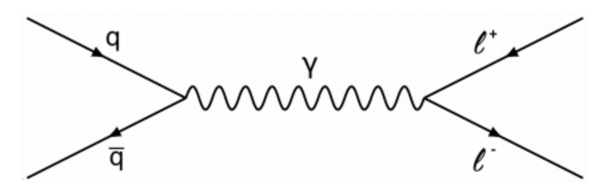
allows for event-by-event studies

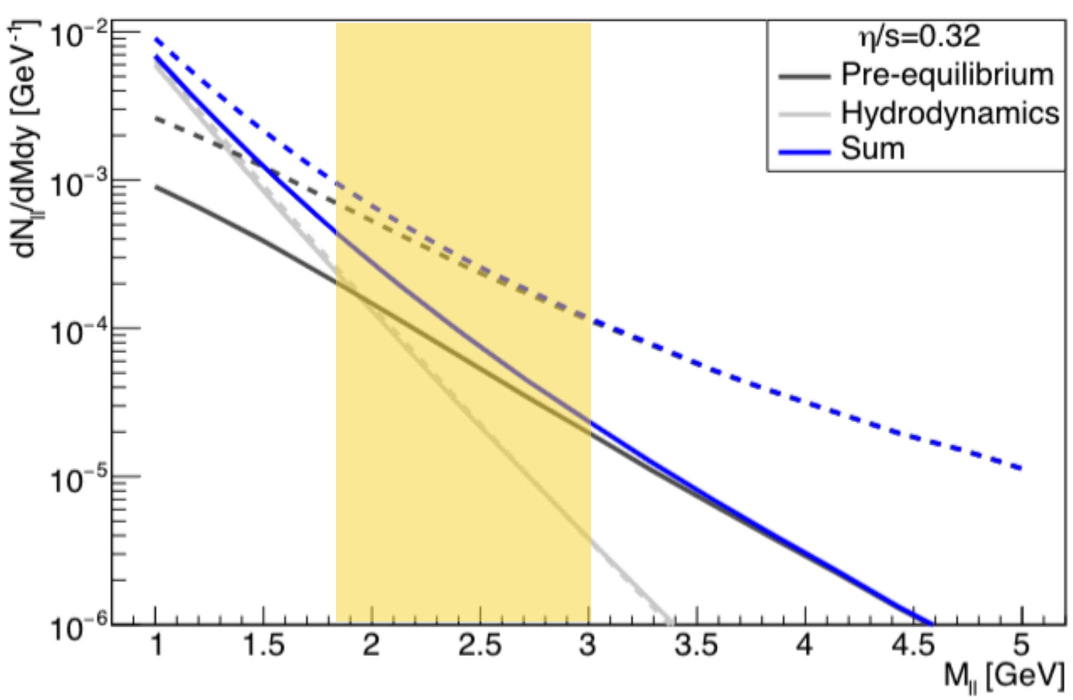


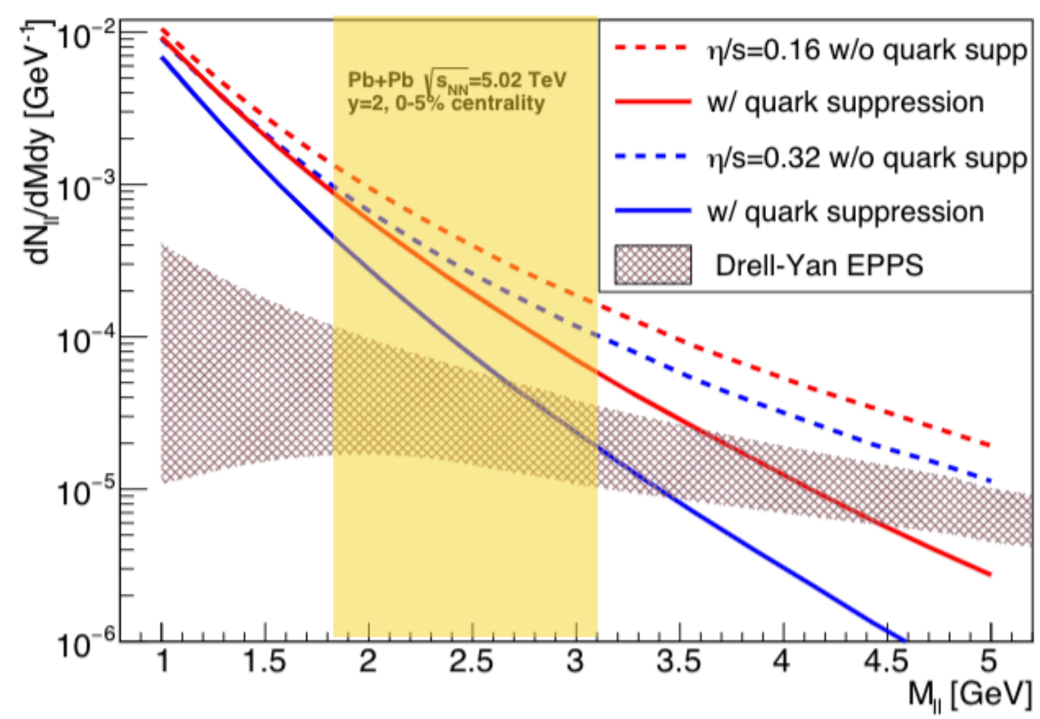
Sizeable pre-eq contribution at p_T>2GeV but not exceeding thermal+prompt contributions

Electromagnetic probes (l^+l^-)

Di-lepton ($e^+e^-/\mu^+\mu^-$) pairs with invariant mass M~GeVs pre-dominantly produced during the initial state as late stage production is suppressed by exp(-M/T)







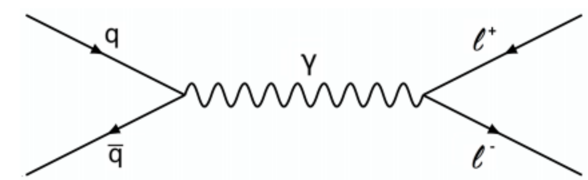
New window into pre-equilibrium dynamics for 1.5 GeV<M<3GeV

possibly accessible with LHC-Run 3 but certainly with next generation of heavy-ion detectors (ALICE3,LHCb,…)?

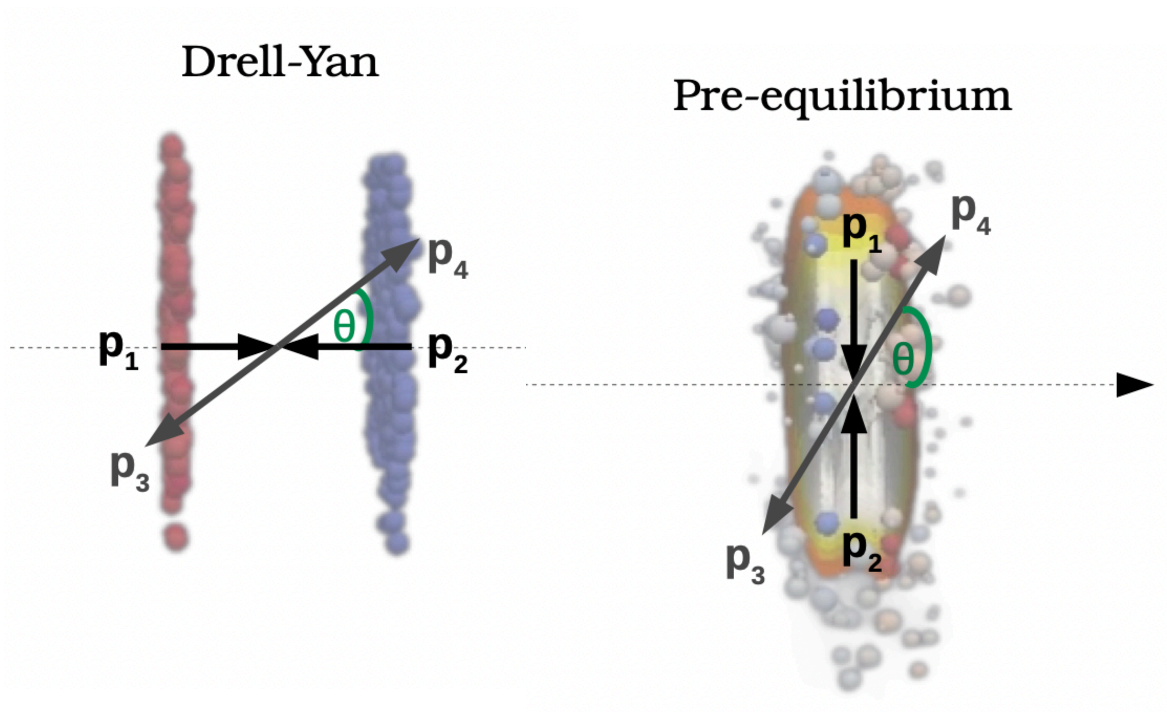
Coquet,Du,Ollitrault,SS,Winn; *PLB* 821 (2021) 136626; *NPA* 1030 (2023) 122579

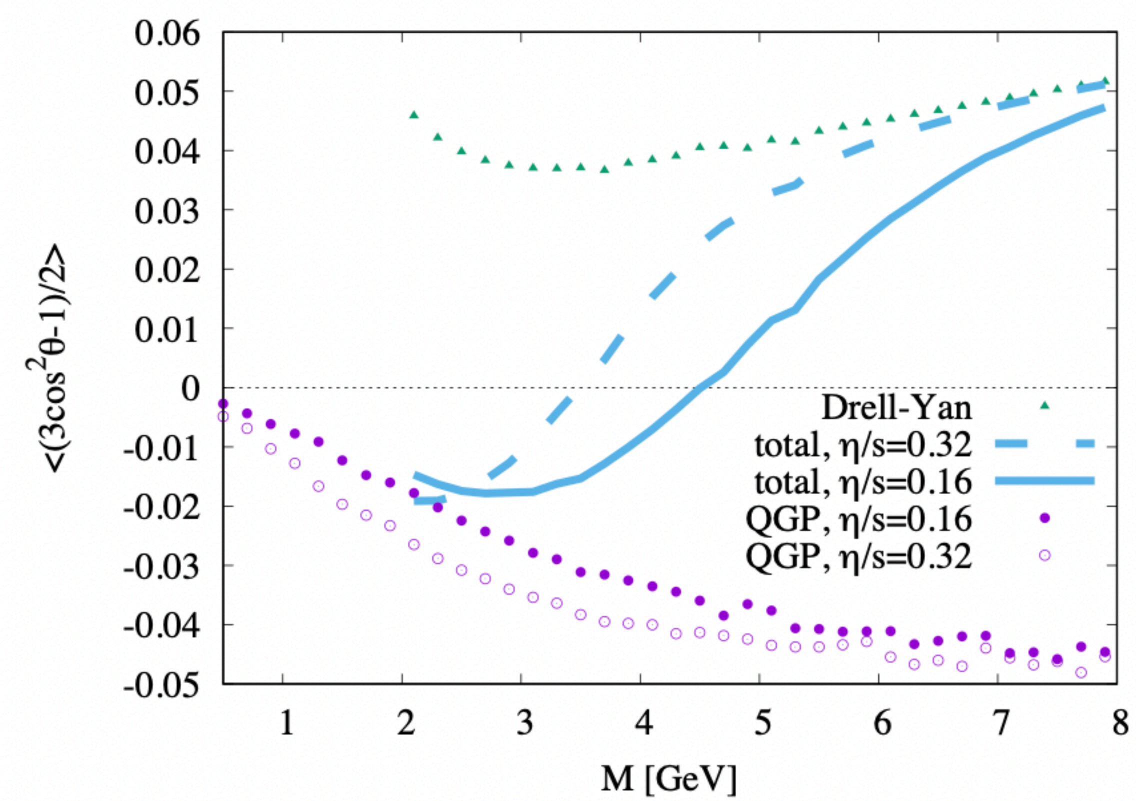
Electromagnetic probes (l^+l^-)

Direct probe of QGP pressure anisotropy during the pre-equilibrium phase via polarization in Collins-Soper frame



Exploit preference for orientation of l^+l^- pair to be correlated with $q\bar{q}$ pair





Coquet,Du,Ollitrault,SS,Winn; arXiv:2309.00555

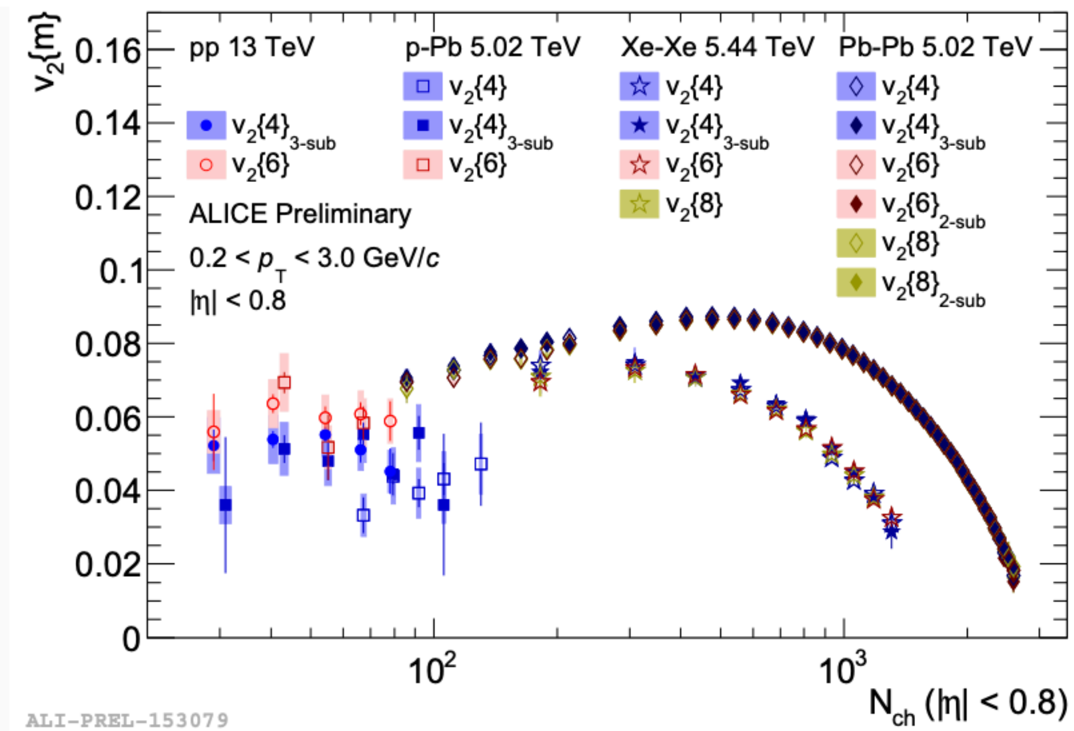
=> Need for collaboration between Theory/Experiment to realise successful measurements with next generation of LHC detectors

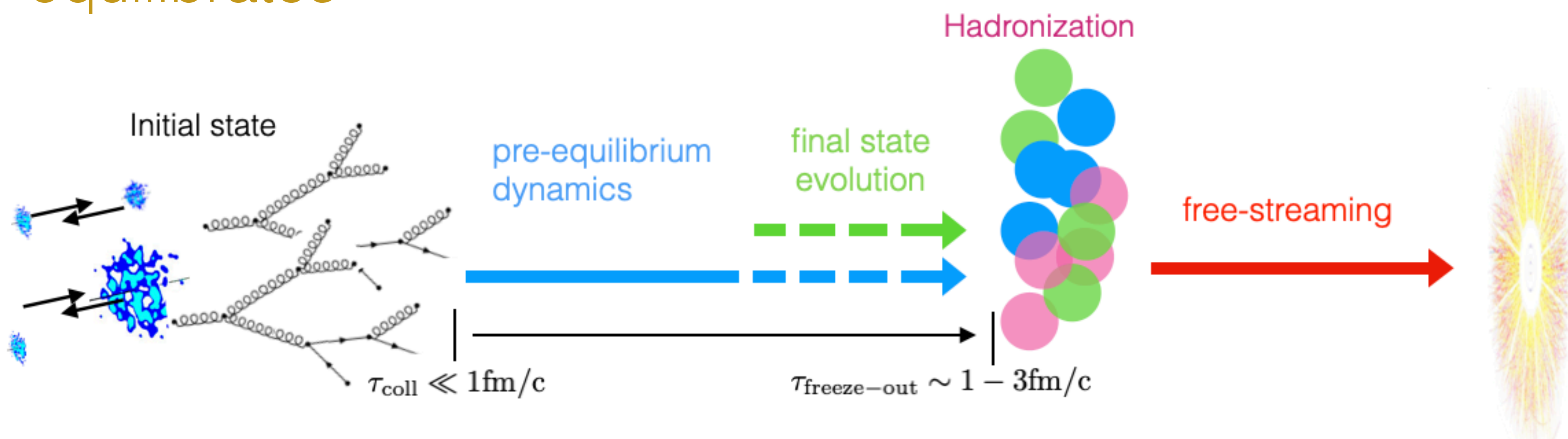
Small systems (p+p,p/d/He3+A)

Small system exhibit collective flow reminiscent of heavy-ion collisions

Sensitivity to non-eq. dynamics enhanced in small systems due to significantly shorter lifetime

System can fall apart before QGP equilibrates





What is range of applicability of standard model of HICs applicable?
Does it apply to p+p,p/d/He3+A and O+O collisions at RHIC/LHC?

Non-eq description of flow

Development of 2+1D QCD Kinetic Theory simulations in progress

meanwhile explored systematically within simplified description in conformal RTA

$$p^\mu \partial_\mu f = -\frac{p \cdot u}{\tau_R}(f - f_{\mathrm{eq}}),$$

Due to particular simplicity, all results only depends on initial geometry e(x_T) and one single opacity parameter

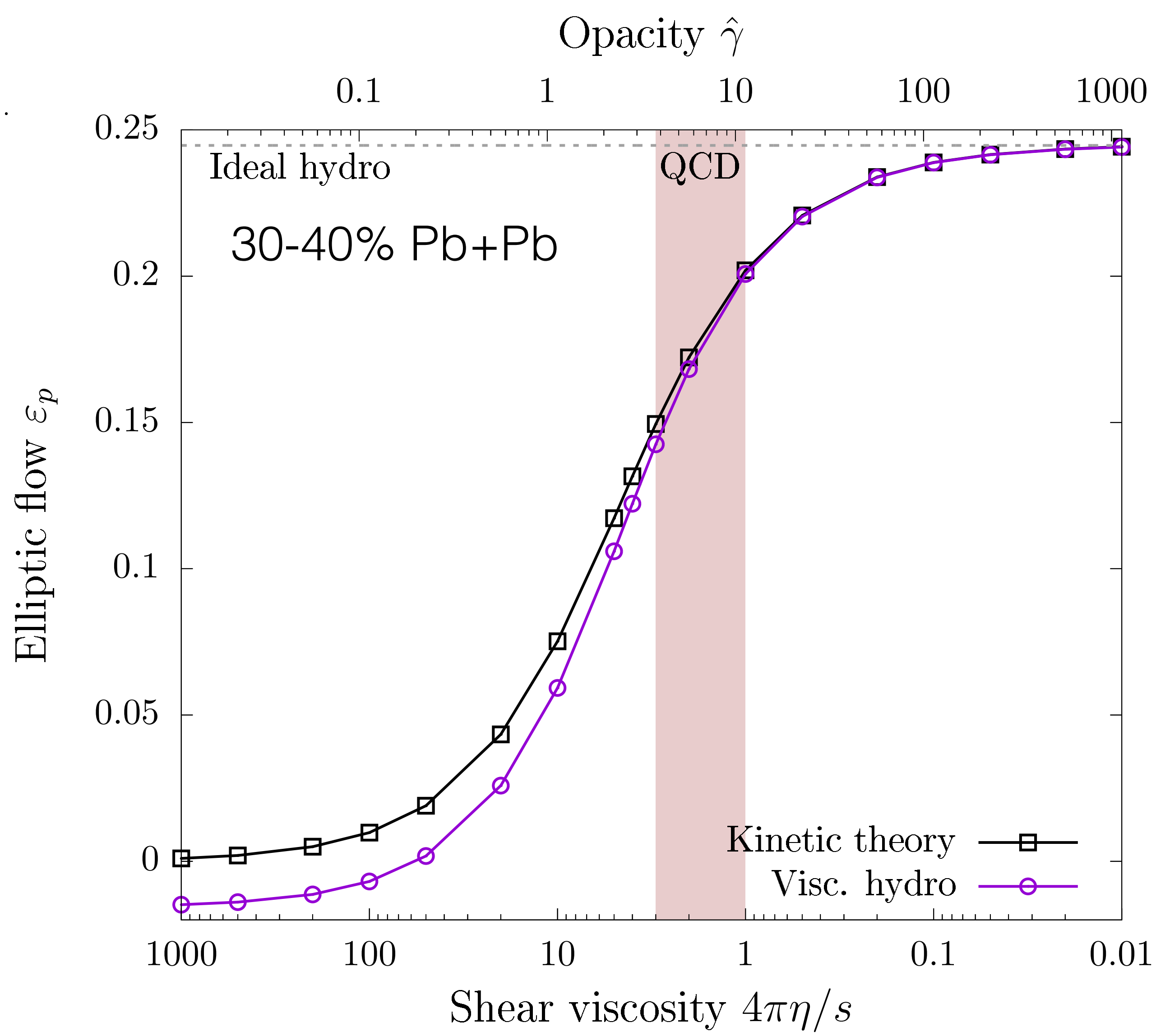
$$\hat{\gamma} = \frac{1}{5\eta/s}\left(\frac{R}{\pi a}\frac{\mathrm{d}E_\perp^0}{\mathrm{d}\eta}\right)^{1/4},$$

encodes dependence on system size, viscosity and collision energy

Ambrus,SS, Werthmann PRL 130 (2023) 15, 152301; PRD 107 (2023) 9, 094013; Kurkela, Taghavi, Wiedemann Wu PLB 811 (2020) 135901; Kurkela, Wiedemann, Wu EPJC 79 (2019) 11, 965; Kurkela, Wiedemann EPJC 79 (2019) 9, 759

Opacity dependence of Flow

Despite microscopic differences, smooth transition from non-interacting (η/s->∞) to strongly interacting limit (η/s->0)



Hydrodynamics accurately describes collective flow in semi-central Pb+Pb collisions at LHC if pre-equilibrium phase is described correctly

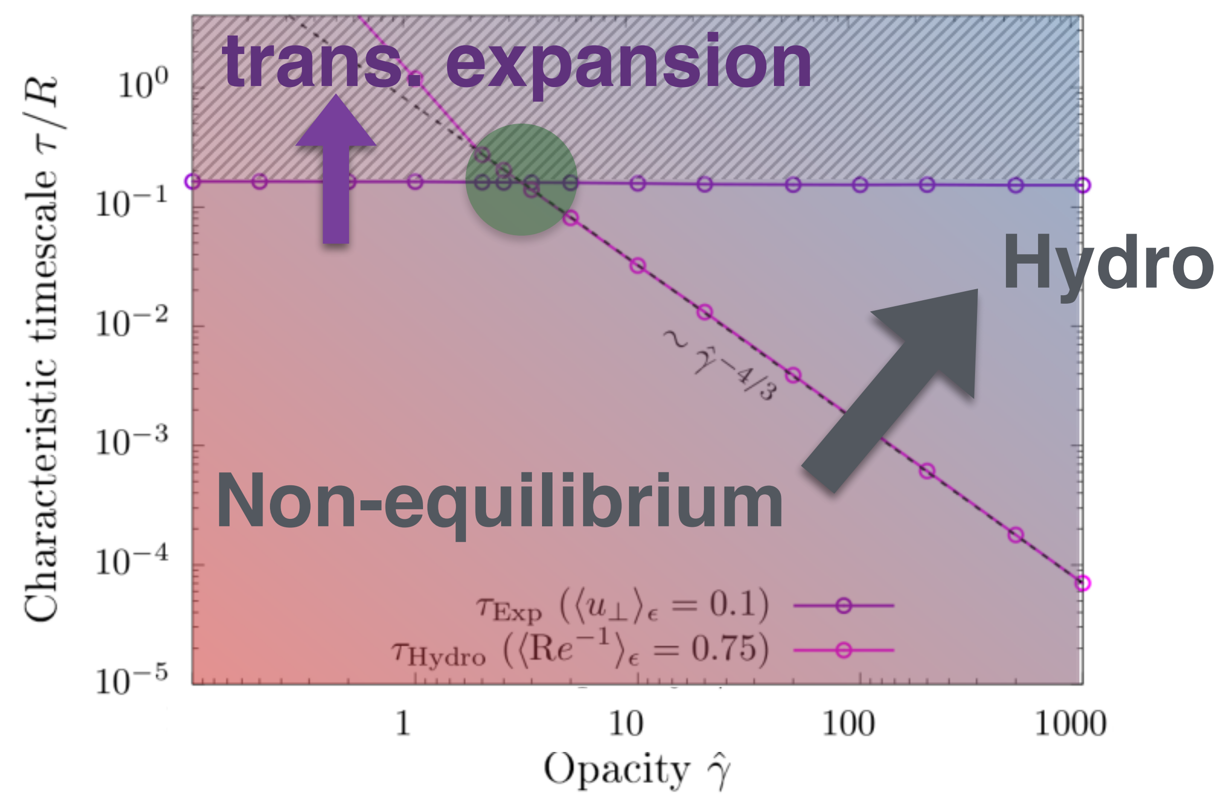
Strong sensitivity of elliptic flow to shear viscosity η/s in the relevant range

Ambrus,SS, Werthmann PRL 130 (2023) 15, 152301; PRD 107 (2023) 9

Hydrodynamics in small systems?

Development of transverse flow accurately described by hydrodynamics for opacities

$$\hat{\gamma} \gtrsim 3 - 4$$



Satisfied in central Pb+Pb collisions but questionable in p+p and p+Pb

- **pp:** $\hat{\gamma} \approx 0.88 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{0.4\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{5\,\mathrm{GeV}}\right)^{1/4}$
- **PbPb:** $\hat{\gamma} \approx 9.2 \left(\frac{\eta/s}{0.16}\right)^{-1} \left(\frac{R}{6\,\mathrm{fm}}\right)^{1/4} \left(\frac{\mathrm{d}E_\perp^{(0)}/\mathrm{d}\eta}{4000\,\mathrm{GeV}}\right)^{1/4}$

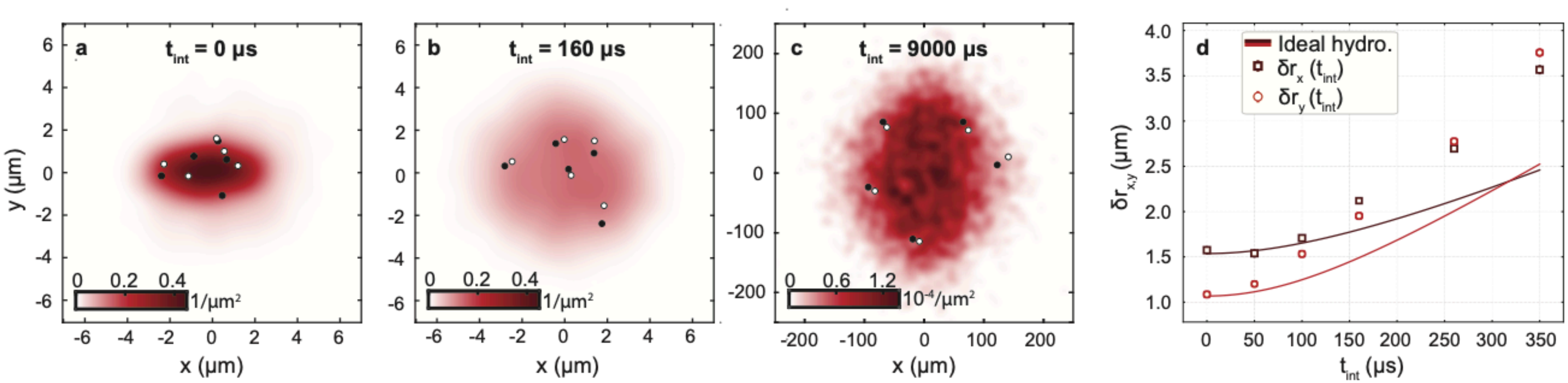
Estimate that exciting transition region γ~3 to be probed in O+O collisions at LHC

Ambrus,SS, Werthmann PRL 130 (2023) 15, 152301; PRD 107 (2023) 9

Hydrodynamics in small systems?

Explored also in Cold Atom experiments
with few trapped Ions

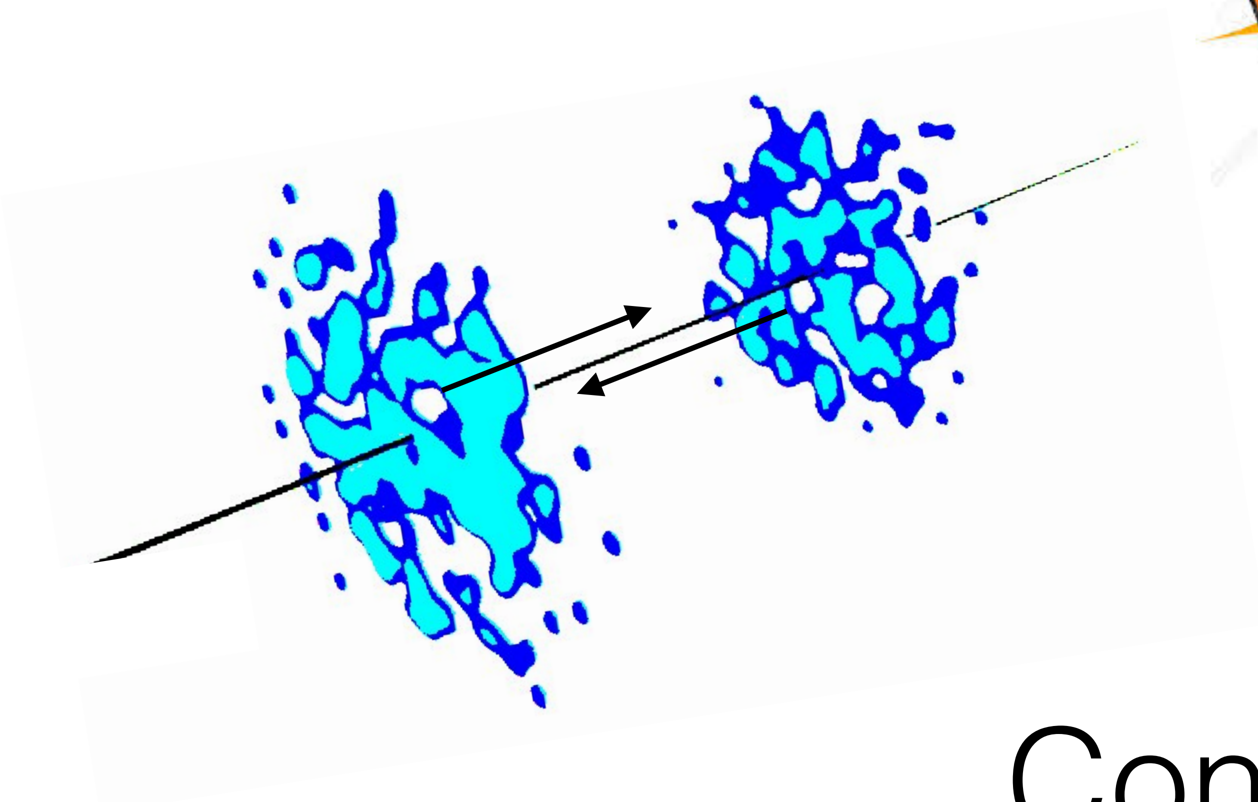
-> allows for time resolved measurements

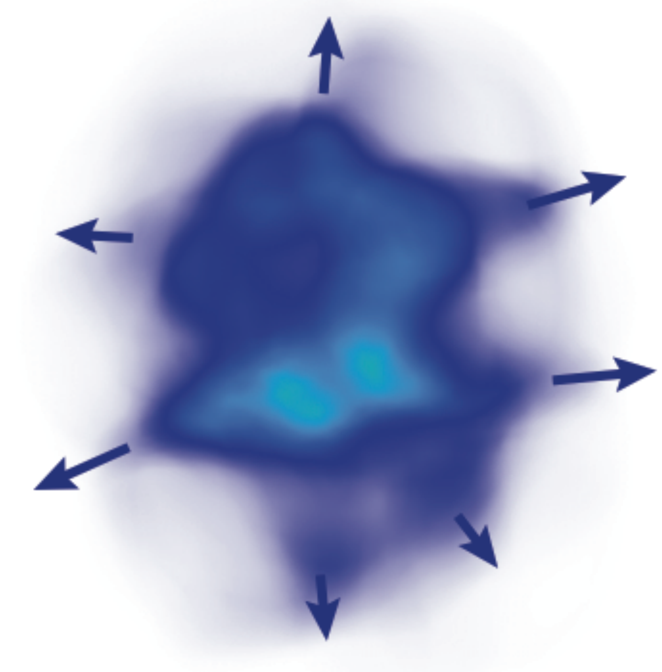


Brandstetter et al. arXiv:2308.09699

Claim "Emergence of Hydrodynamics" in system with very few constituents
BUT setup quite different from requirements for Heavy-Ion Collisions

4





Conclusions & Outlook

Conclusions & Outlook

Continuous progress in QCD Thermodynamics based on lattice and functional methods

- EoS, new ideas to tackle critical point

Exciting phenomenology of pre-equilibrium stage in HICs starting to emerge

- next generation of experiments may provide insights into non-equilibrium physics of QGP

Challenge to develop theoretically consistent description of QCD in small systems as macroscopic hydrodynamic description not applicable

- expect new insights from O+O collisions at RHIC & LHC