Non-equilibrium QCD in Heavy-Ion Collisions

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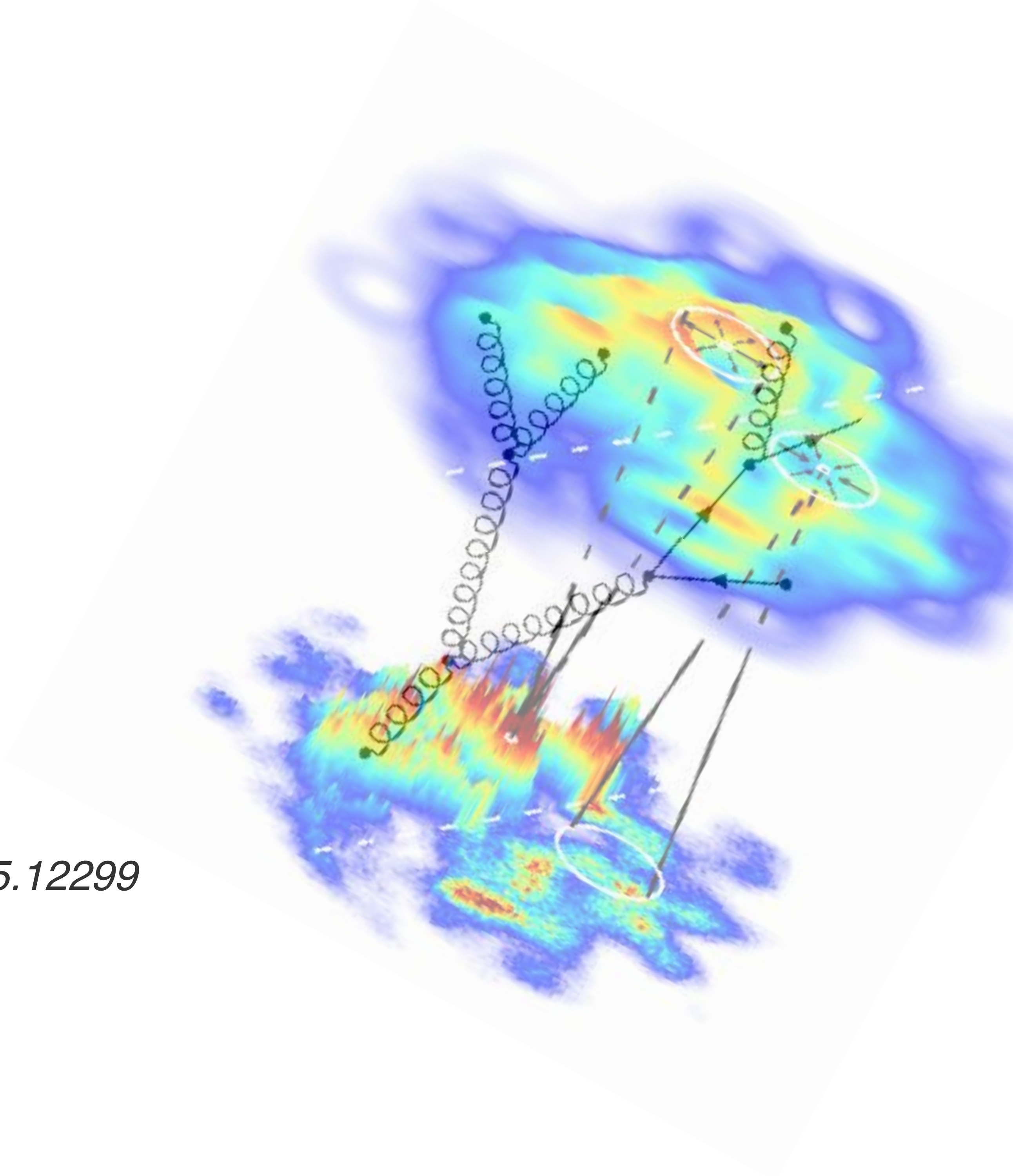

Reviews:
SS, Teaney, Ann.Rev.Nucl.Part.Sci. 69 (2019) 447-476
Berges, Heller, Mazeliauskas, Venugopalan arXiv:*2005.12299*

Theoretical Physics Colloquium @ ASU

Phoenix, AZ, Sept 2020

CRC-TR 211
Strong-interaction matter under extreme conditions

UNIVERSITÄT BIELEFELD

Overview

1. Introduction & Motivation

2. Basics of weak coupling thermalization in QCD plasmas

3. Early time dynamics & entropy production in high-energy Heavy-Ion Collisions

3. Conclusions & Outlook

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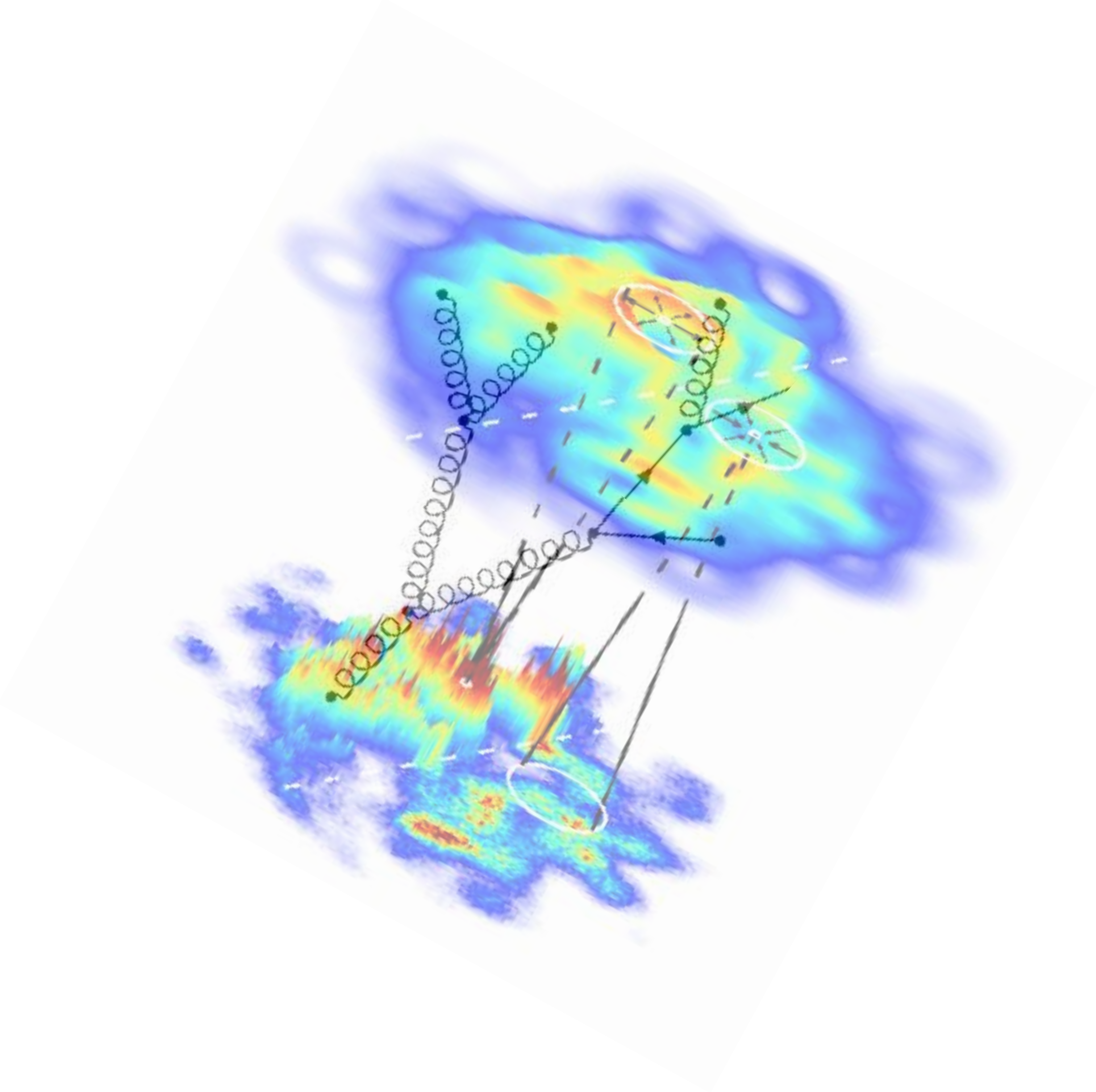


Introduction & Motivation

High energy Heavy-Ion Collisions

Science goal is to explore the structure and dynamics of the fundamental constituents of matter

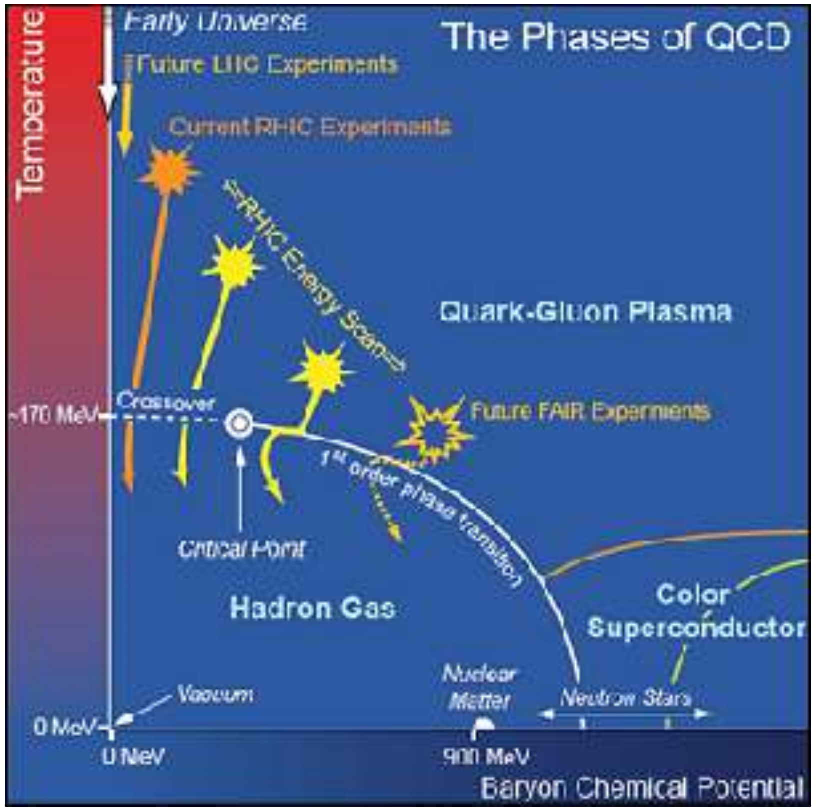
-> described by theory of strong interactions of quarks & gluons (QCD)

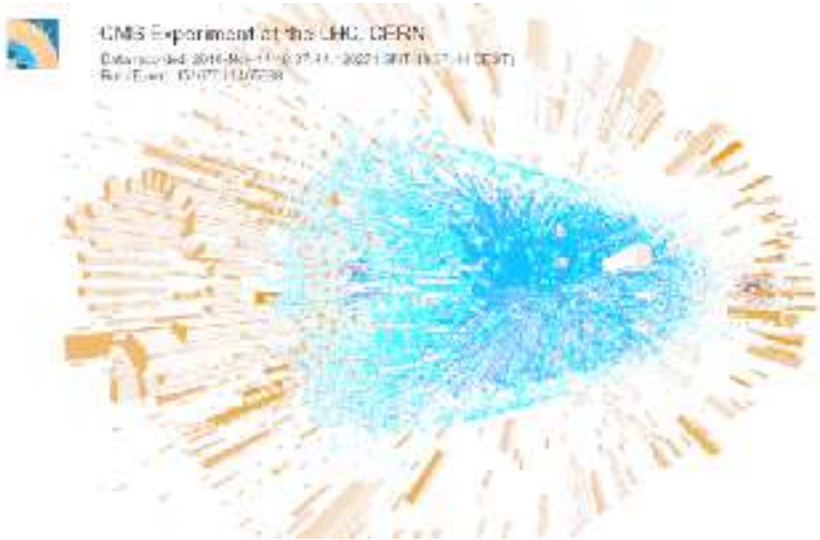
However under normal conditions, quarks & gluons confined in color neutral bounds states (p,n,π,K,…)

-> need extreme conditions (high resolution, high temperature) to “see” fundamental constituents

Explored in high-energy Heavy-Ion collisions experiments at RHIC (BNL) and LHC (CERN) as well as GSI/FAIR and NICA (Dubna)

Extraction of QCD properties from heavy-ion experiments requires profound understanding of the space-time dynamics of the collision

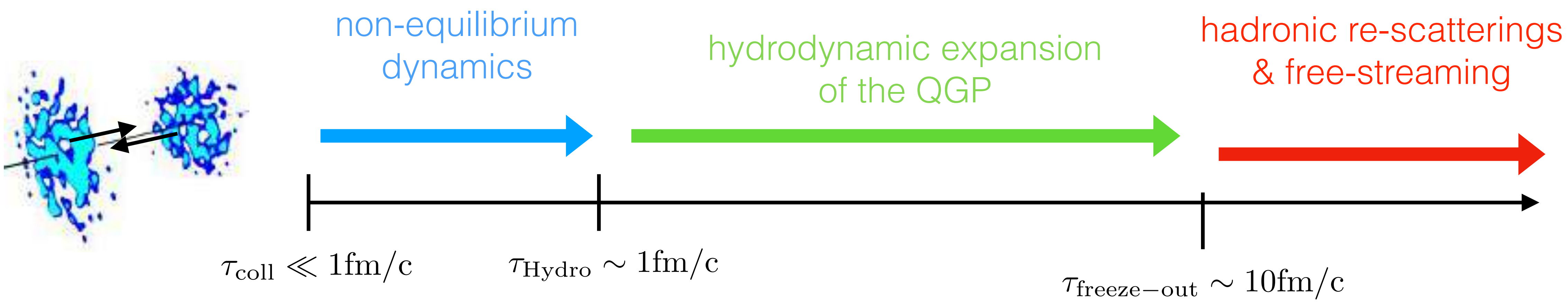




Dynamics of HICs

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 macroscopic description of the space-time dynamics of the QGP



non-equilibrium dynamics

hydrodynamic expansion of the QGP

hadronic re-scatterings & free-streaming

$\tau_{\mathrm{coll}} \ll 1\mathrm{fm/c}$

$\tau_{\mathrm{Hydro}} \sim 1\mathrm{fm/c}$

$\tau_{\mathrm{freeze-out}} \sim 10\mathrm{fm/c}$

Space-time dynamics of HICs dominated by near-equilibrium hydrodynamic expansion

Extremely successful phenomenology based on hydrodynamic models with parametrized initial state ~ 1 fm/c

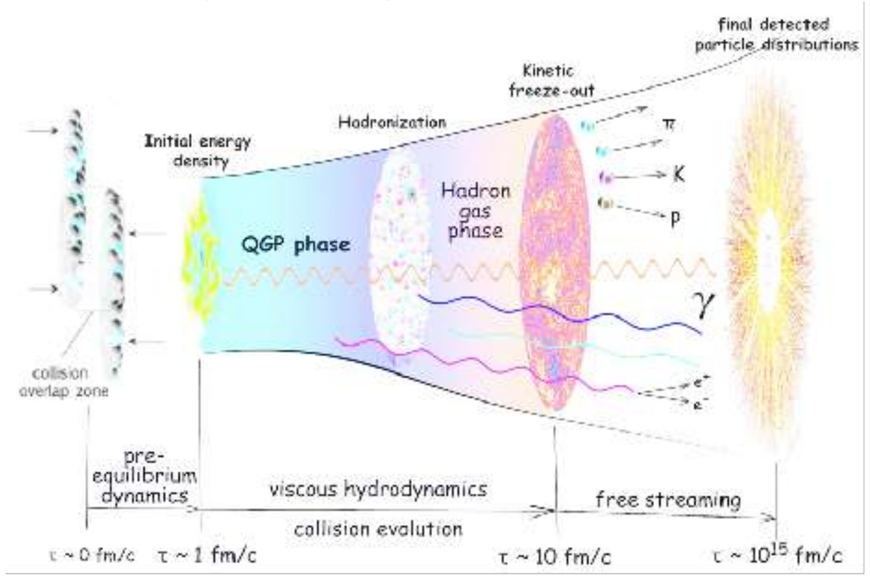
Small effects of pre-equilibrium dynamics on typical observables (v_n,$\langle p_T \rangle$,…)

Theoretical description of pre-equilibrium dynamics highly desirable

Equilibration of QCD plasmas

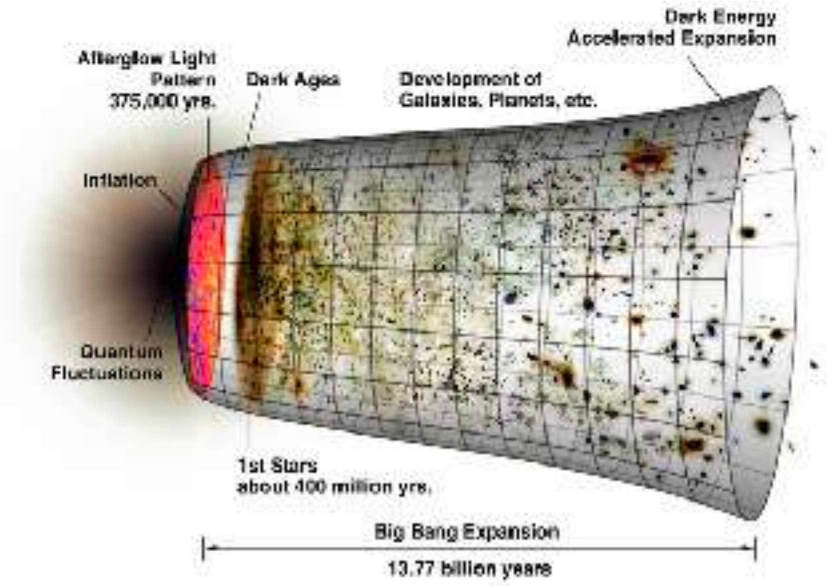
High-Energy Heavy-Ion Collisions:

How does macroscopic description as viscous fluid (macrosccopic variables e,u^{μ}) emerge from non-equilibrium dynamics of “primordial” far-from equilibrium plasma created in the collision?


C. Shen (PhD Thesis)

Early Universe:

How is Standard Model Matter produced and equilibrated between end of Inflation and BBN?



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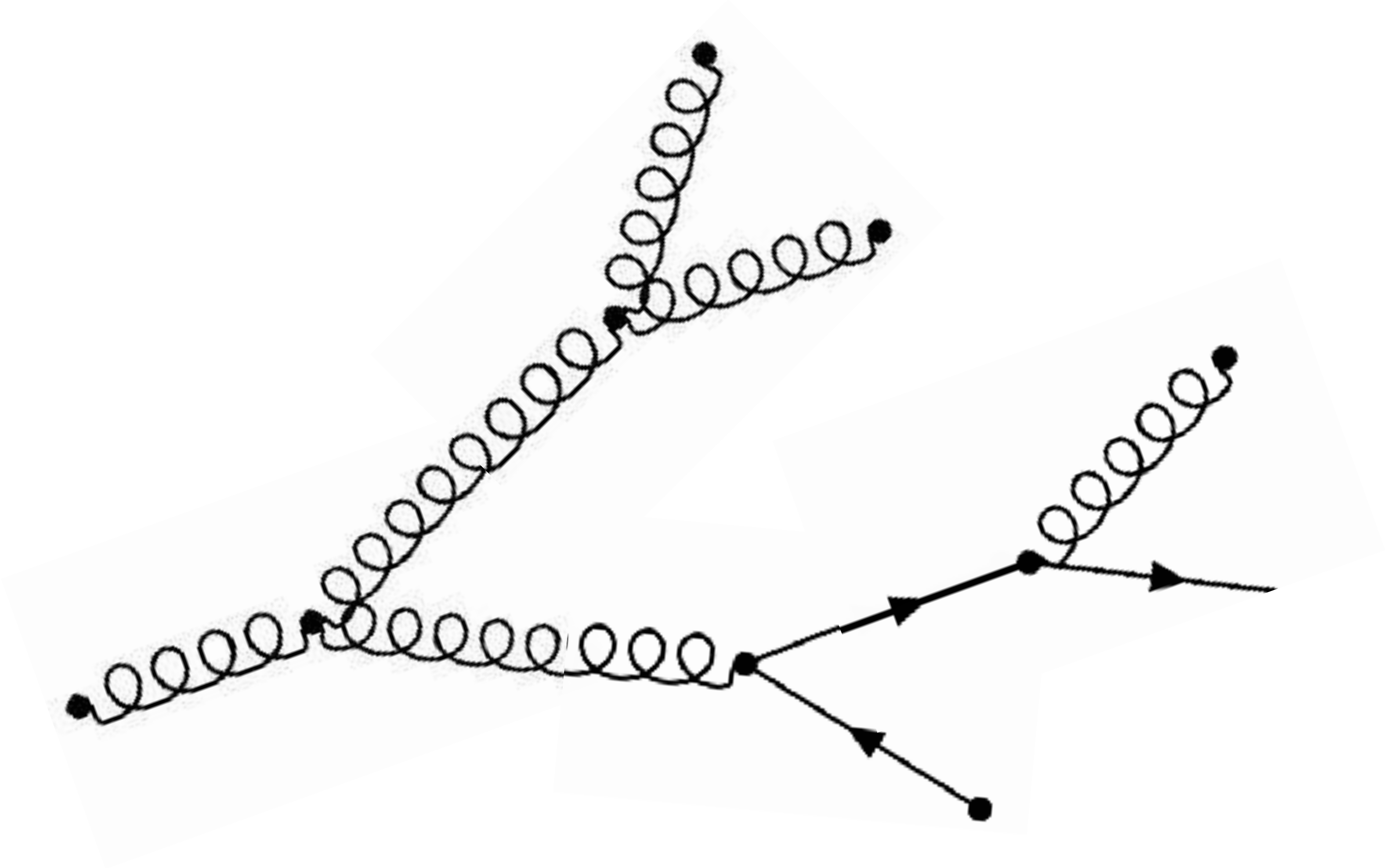


Basics of weak coupling thermalization in QCD plasmas

Non-equilibrium QCD

Generally there is no exact way to study non-equilibrium dynamics in an interacting quantum field theory

In high-energy QCD first principles studies are feasible in two limits

Weak coupling limit of QCD

Description in terms of the fundamental degrees and freedom (quarks & gluons) based on kinetic theory/classical-statistical simulations

Strong coupling limit ($g^2 N_c >> 1$) of related theories

Description based on holographic methods for strongly coupled gauge theories (N=4 SYM)

Will use weak-coupling description based on (LO) QCD kinetic theory ($\alpha_s << 1$) to describe dynamics of non-equilibrium QCD plasmas

-> Extrapolate findings to realistic coupling strength ($\alpha_s \sim 0.3$) when addressing HICs

Non-equilibrium QCD

Effective kinetic theory of QCD at LO*

Arnold,Moore,Yaffe JHEP 0301 (2003) 030

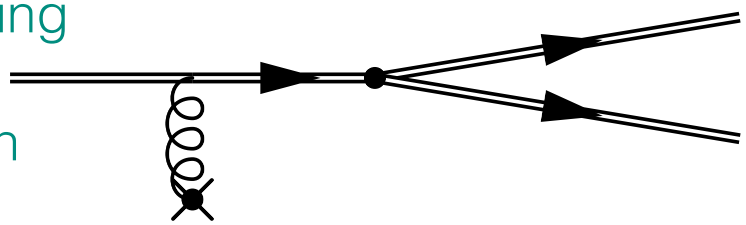
$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{2\leftrightarrow 2}[f] + C_{1\leftrightarrow 2}[f]$$

Characteristic features:

- ultra-relativistic massless quasi-particles (g,u,ubar,d,dbar,s,sbar)
- elastic (2<->2) & in-elastic (1<->2) proccesses at the same order

elast. 2<->2 scattering
screened by Debye mass

collinear 1<->2 Bremsstrahlung
incl. LPM efffect
via eff. vertex re-summation



Solve numerically as integro-differential equation, with in-medium matrix elements for 2<->2 and 1<->2 processes self-consistently determined

*Note that expansion is in g rather than $\alpha_s = g^2/4\pi$

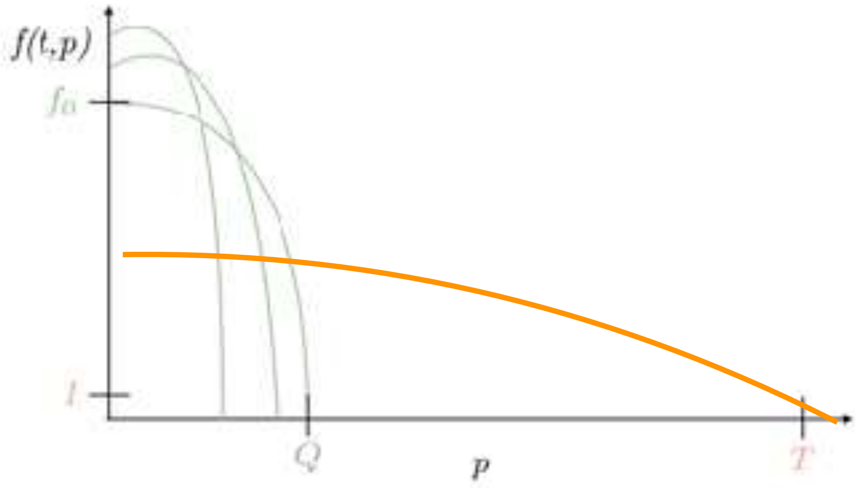
Basics of weak-coupling thermalization

Before addressing the complex problem of thermalization in HICs it is interesting to start with thermalization of homogenous & isotropic QCD plasmas

Kurkela, Moore *JHEP* 12 (2011) 044

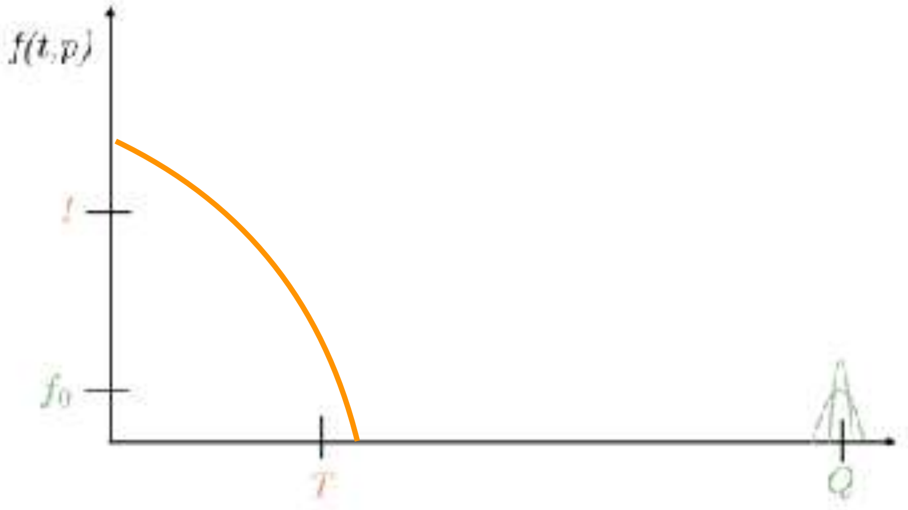
If we focus on initial states from from-equilibrium can distinguish two qualitiatively different cases

Over-occupied QCD plasma



Energy carried by large number of low energy dof's <p> << T (e.g. due to instabilities)

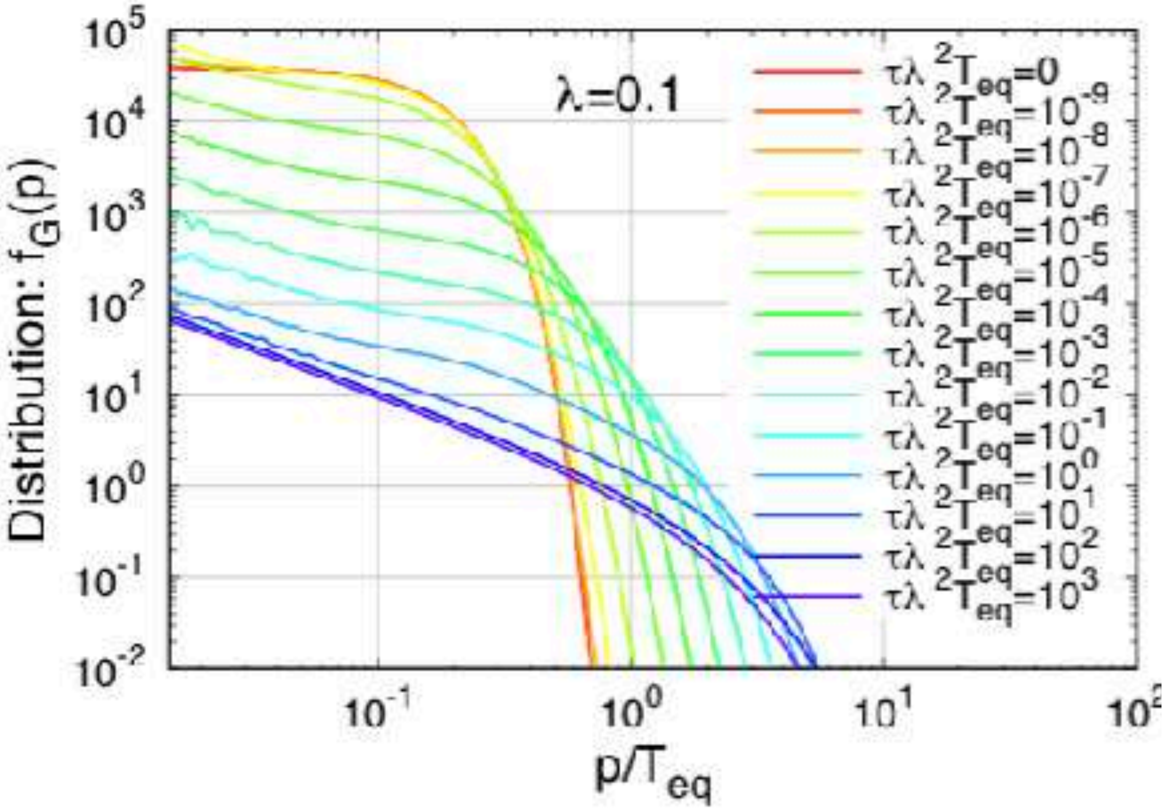
Under-occupied QCD plasma

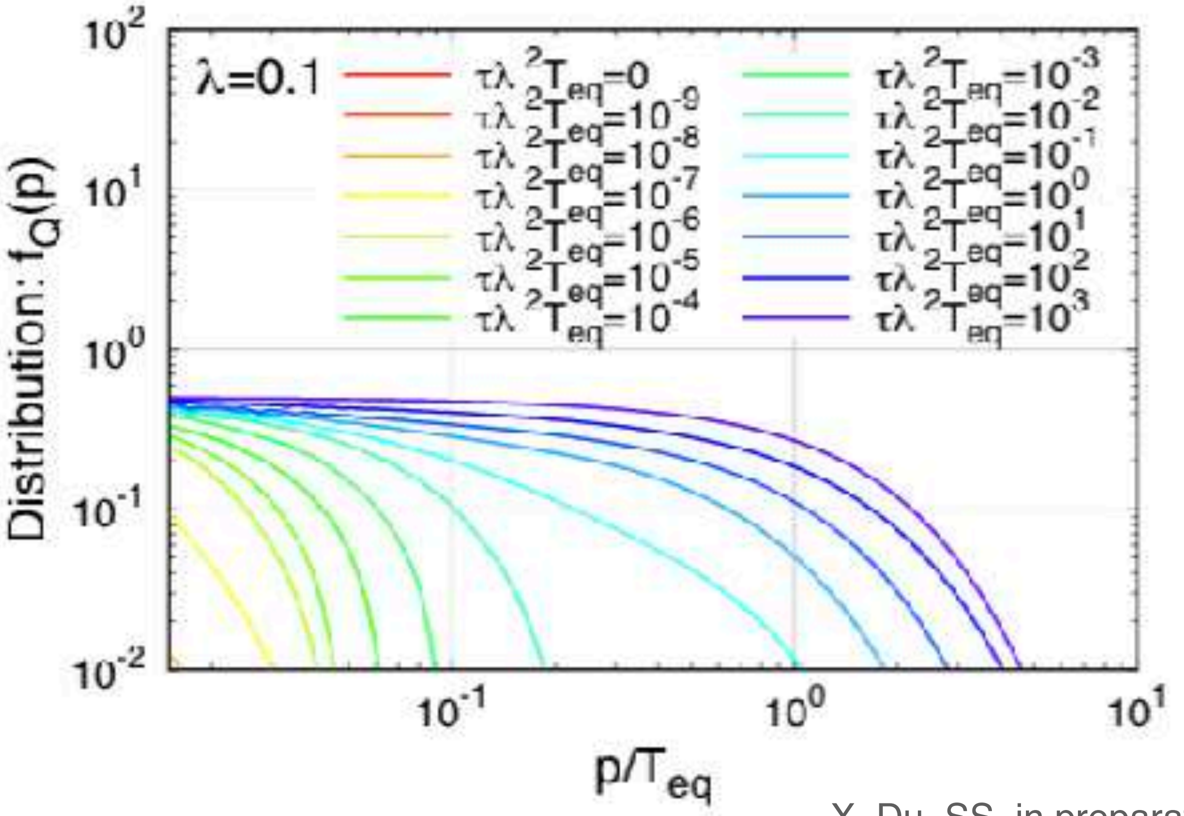


Energy carried by small number of high energy dof's <p> >> T (e.g. high-energy jets)

Over-occupied QCD plasmas

Enhanced scattering rates at early times lead to effective memory loss even before system thermalizes





X. Du, SS, in preparation

Self-similar evolution of gluon distribution $f_G(t,p)$ associated with energy transport to UV

$$f_g(t,p) = t^{\alpha} f_g^S(t^{\beta} p)$$

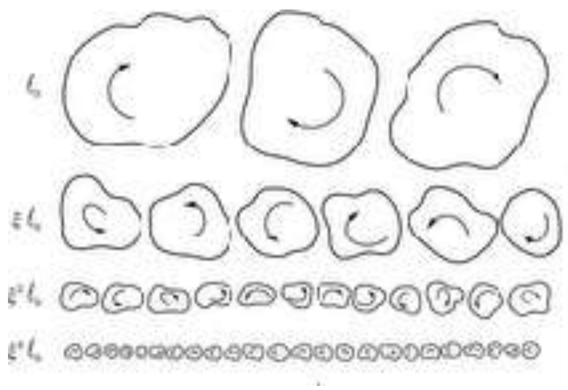
SS Phys.Rev.D 86 (2012); Abrao York, Kurkela, Lu, Moore *Phys.Rev.D* 89 (2014) 7
Berges, Boguslavski, SS, Venugopalan *Phys.Rev.D* 89 (2014) 11;
Berges, Mazeliauskas Phys.Rev.Lett. 122 (2019)

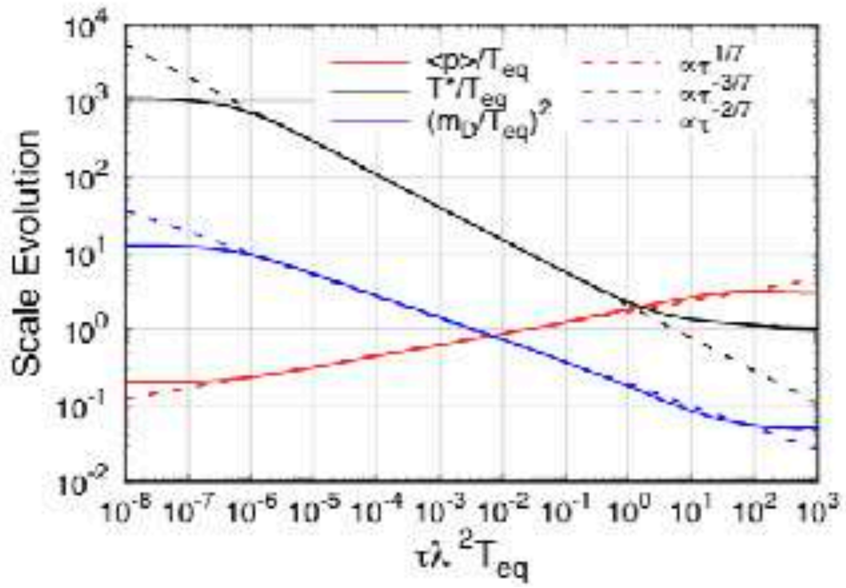
Quarks are sub-dominant and simply follow gluon distribution

$$f_q(t,p) = \quad f_q^S(t^{\beta} p)$$

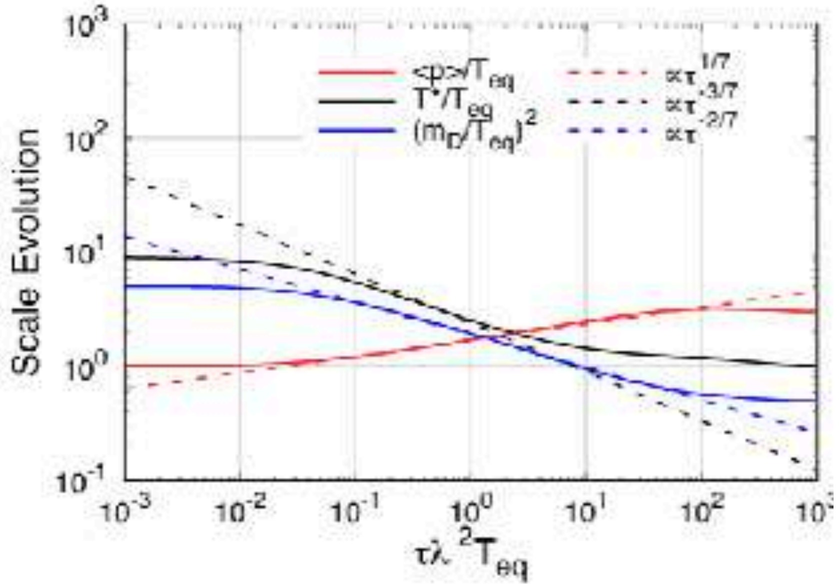
Over-occupied QCD plasmas

Self-similar scaling behavior associated with energy transport towards UV is anologous to direct energy cascade in decaying turbulence

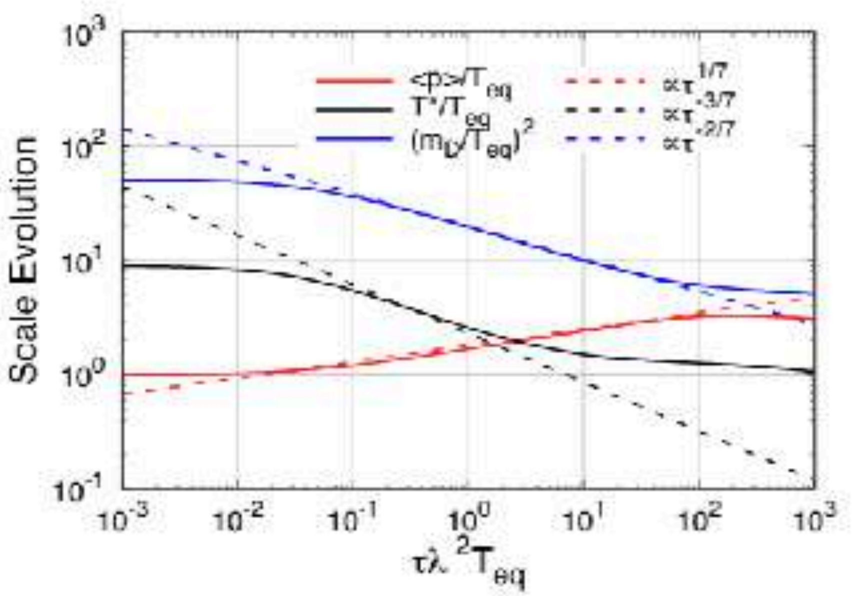




$\lambda = 0.1$



$\lambda = 1$



$\lambda = 10$

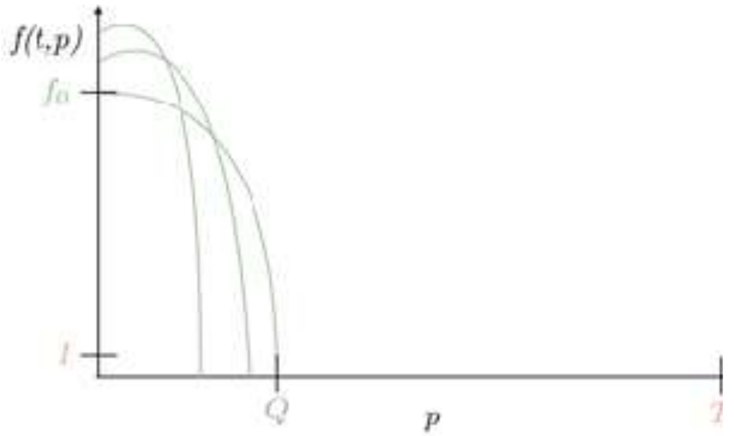
Same scaling behavior persist even for moderately large values of the coupling constant until energy transfer to the UV is complete and the system thermalizes

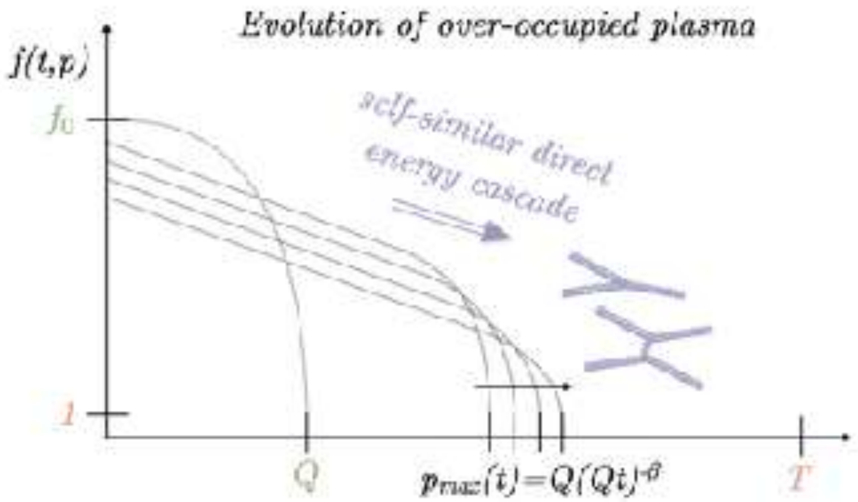
X. Du, SS, in preparation

$\alpha = -4/7 \quad \beta = -1/7$

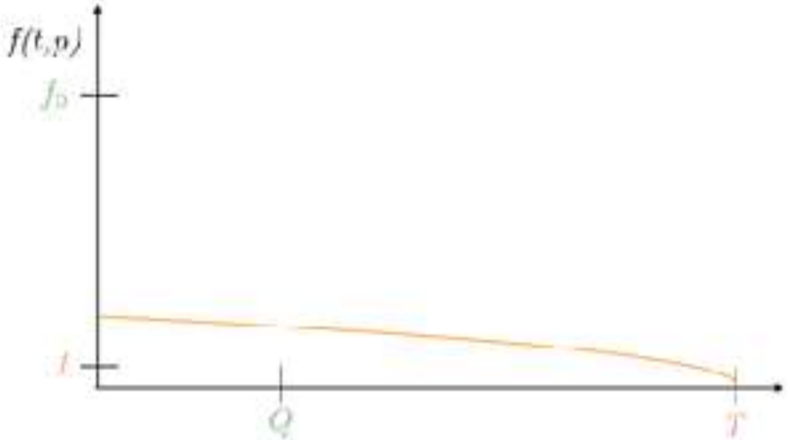
Over-occupied QCD plasmas

Initial state
far from-equilibrium
Q<< T





Thermal equilibrium



Thermalization time

Kurkela, Lu Phys.Rev.Lett. 113 (2014) 18
SS, Teaney Ann.Rev.Nucl.Part.Sci. 69 (2019)

$$t_{\text{thermal}} \sim \alpha_s^{-2} f_0^{-1/4} Q^{-1} \sim \alpha_s^{-2} T^{-1}$$

Non-perturbative classical-statistical simulations give same picture but are unable to describe approach to equilibrium

Berges, Boguslavski, SS, Venugopalan *Phys.Rev.D* 89 (2014) 11;
Mace, SS, Venugopalan *Phys.Rev.D* 93 (2016) 7; Berges, Mace SS Phys.Rev.Lett. 118 (2017) 19

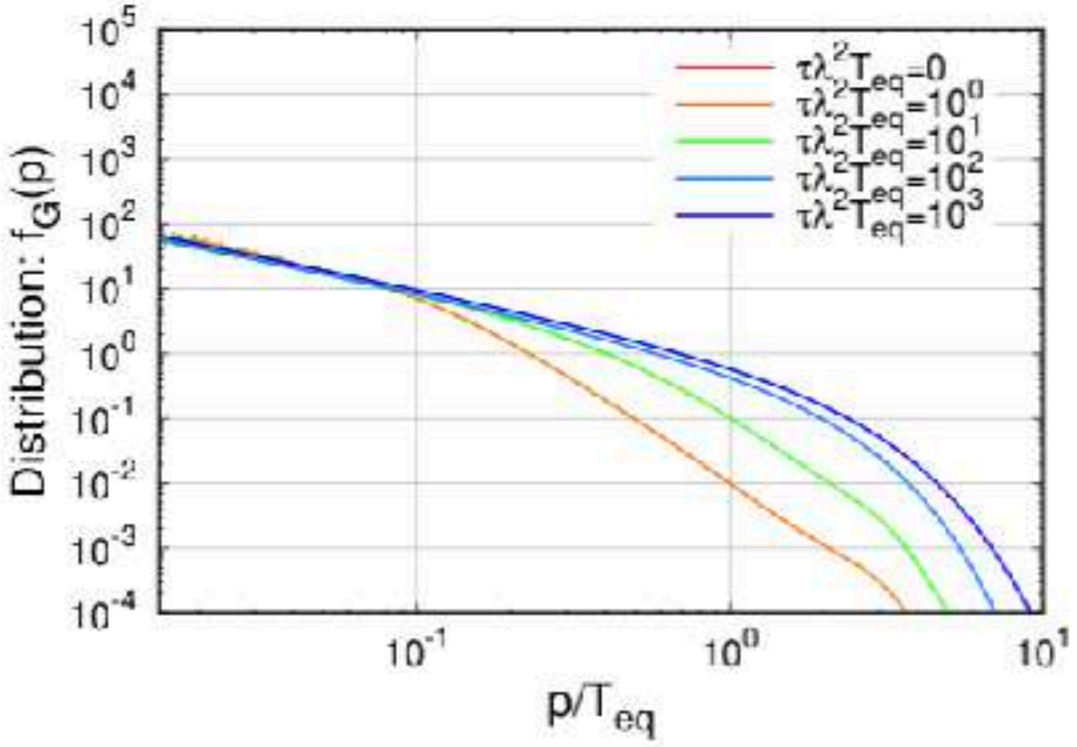
Same kind of thermalization pattern emerges in a variety of far-from-equilibrium systems incl. relativistic and non-relativistic Bose gases

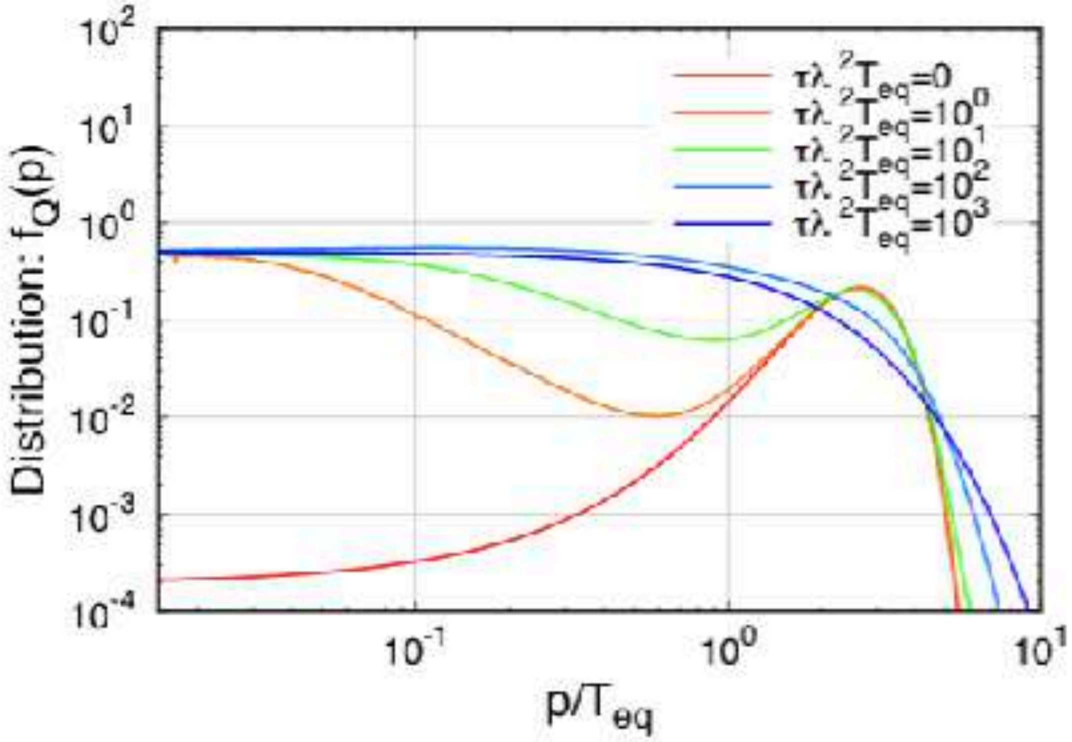
Micha, Tkachev *Phys.Rev.D* 70 (2004) 043538; Berges, Boguslavski, SS Venugoplan *Phys.Rev.Lett.* 114 (2015) 6, 061601;
Berges, Heller, Mazeliauskas, Venugopalan arXiv:2005.12299

Under-occupied QCD plasmas

Even for relatively small scale separation evolution shows characteristic features of “bottom-up” thermalization

Baier et al. Phys.Lett.B 502 (2001)





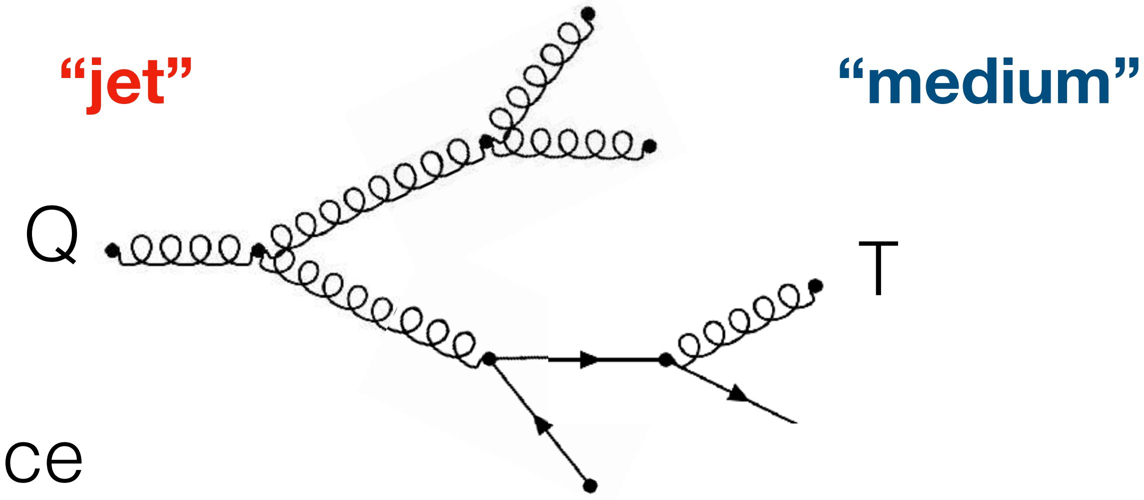
Hard particles emit soft quark/gluon radiation

X. Du, SS, in preparation

Soft quarks/gluons thermalize and form a thermal bath with low temperature

Inverse energy cascade deposits energy of hard particles into soft-thermal bath

Under-occupied QCD plasmas



Inverse energy cascade associated with scale invariant energy flux from hard sector ~Q to soft sector ~T

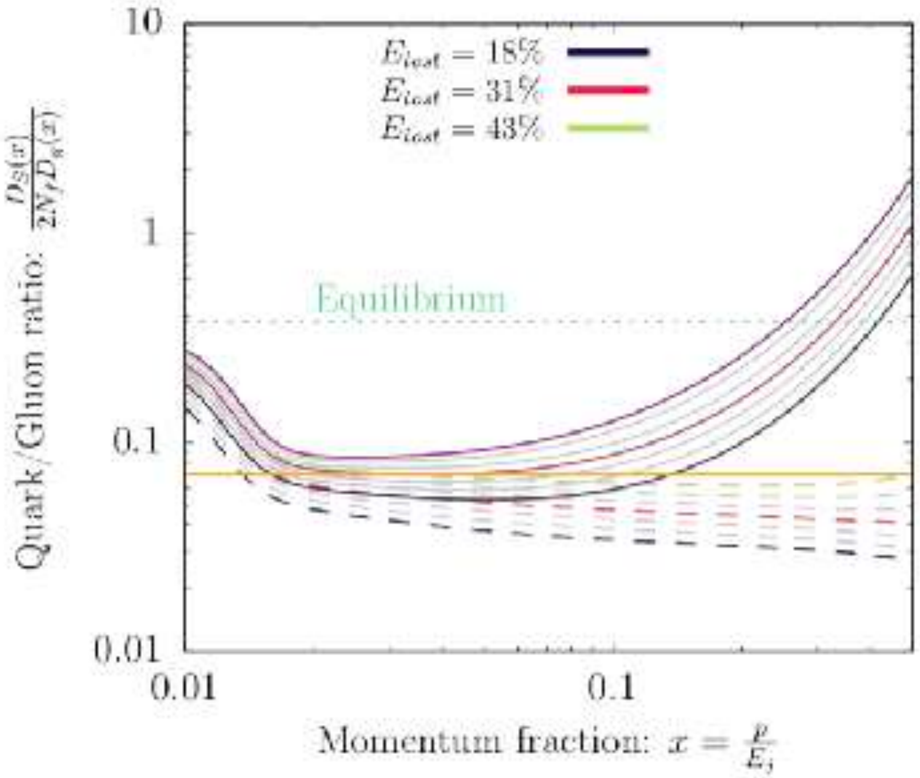
Standard features of weak wave turbulence observed for sufficiently large scale separatio (e.g. high-energy Jet in thermal medium)

Kolmogorov spectrum $f_{g/q}(T<<p<<Q) \sim p^{-7/2}$

Baier et al. Phys.Lett.B 502 (2001),; Blaizot, Iancu, Mehtar-Tani *Phys.Rev.Lett.* 111 (2013) 052001; Mehtar-Tani, SS *JHEP* 09 (2018) 144

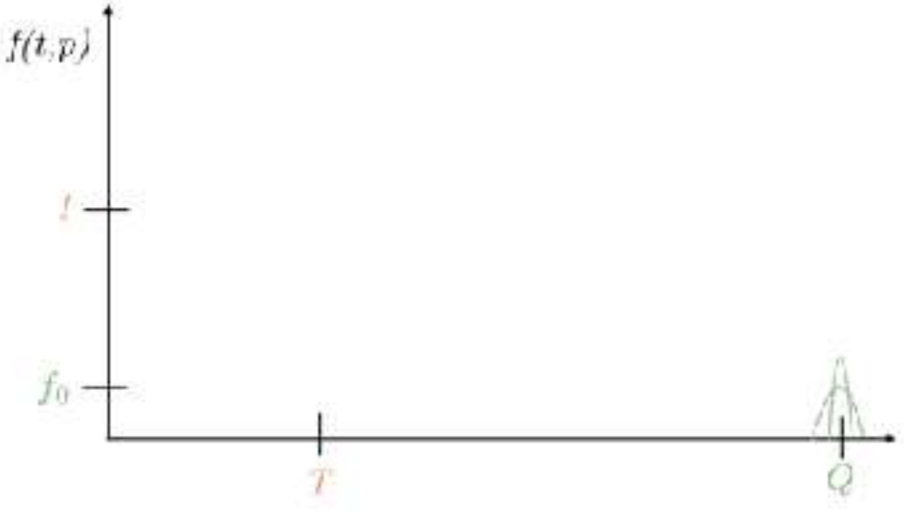
Chemistry $f_Q(T<<p<<Q) / f_g(T<<p<<Q)$ determined by balance of g->qqbar and q->qg processes

Mehtar-Tani, SS *JHEP* 09 (2018) 144   I. Soudi, SS, arXiv:2008.04928

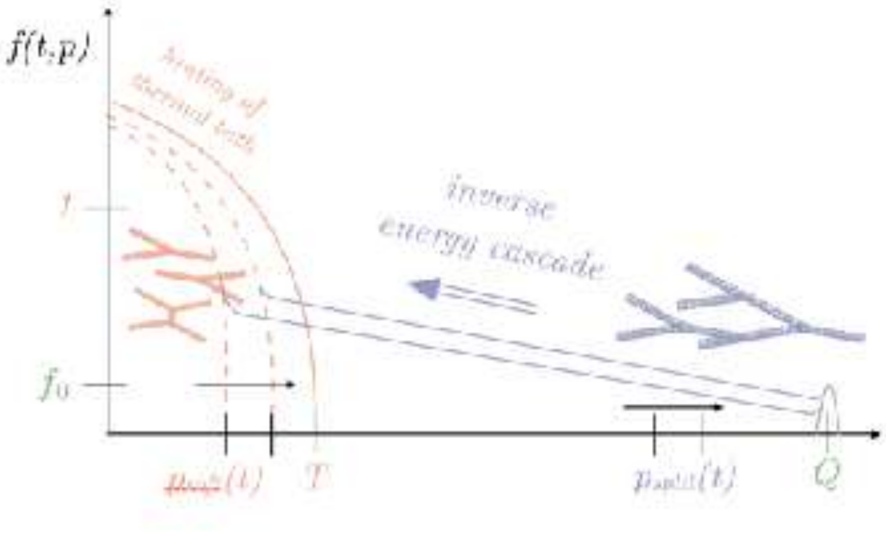


I. Soudi, SS, arXiv:2008.04928

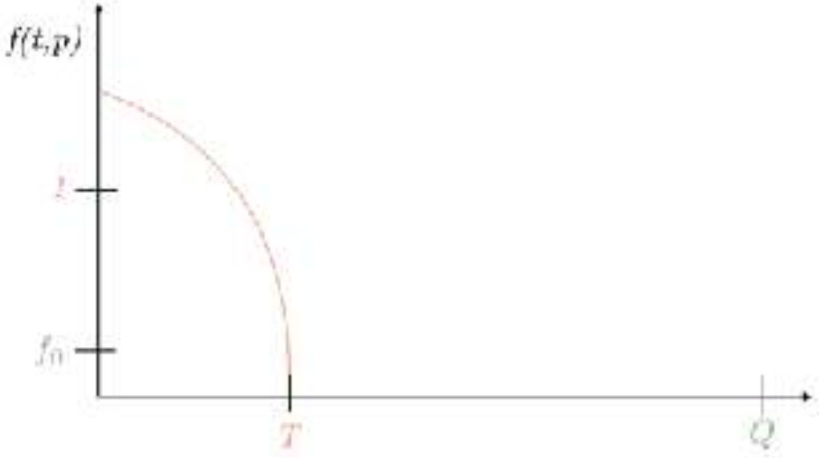
Under-occupied QCD plasmas



Initial state
far from-equilibrium
Q>> T



radiative break-up
via inverse energy cascade



Thermal equilibrium

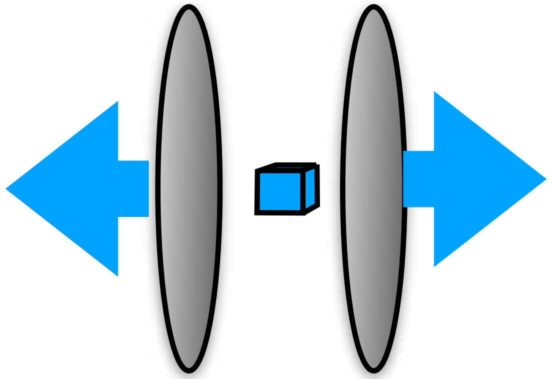
Thermalization time

Kurkela, Lu Phys.Rev.Lett. 113 (2014) 18
SS, Teaney Ann.Rev.Nucl.Part.Sci. 69 (2019)

$$t_{\rm thermal} \sim \alpha_s^{-2} f_0^{-3/8} Q^{-1} \sim \alpha_s^{-2} T^{-1} \sqrt{\frac{Q}{T}}$$

“Bottom-up” thermalization is delayed due to reduced splitting rates of high-momentum particles $\Gamma_{\rm inel}(Q) \sim (T/Q)^{1/2}\, \Gamma_{\rm eq}$

Expanding systems created in HICs



Non-equilibrium QCD plasma created immediately after the collision of heavy nuclei is subject to a rapid longitudinal expansion

Since particles with large p_{long} escape quickly central region, the central QGP will be highly anistotropic with $p_T >> p_{long}$ and becomes increasingly dilute

Generally interested in evolution over short time scales τ~1fm/c << R_A where transverse expansion of QGP (~1/R) can be neglected

Describe non-eq. QGP locally as approximately homogenous in transverse plane and invariant under long. boosts

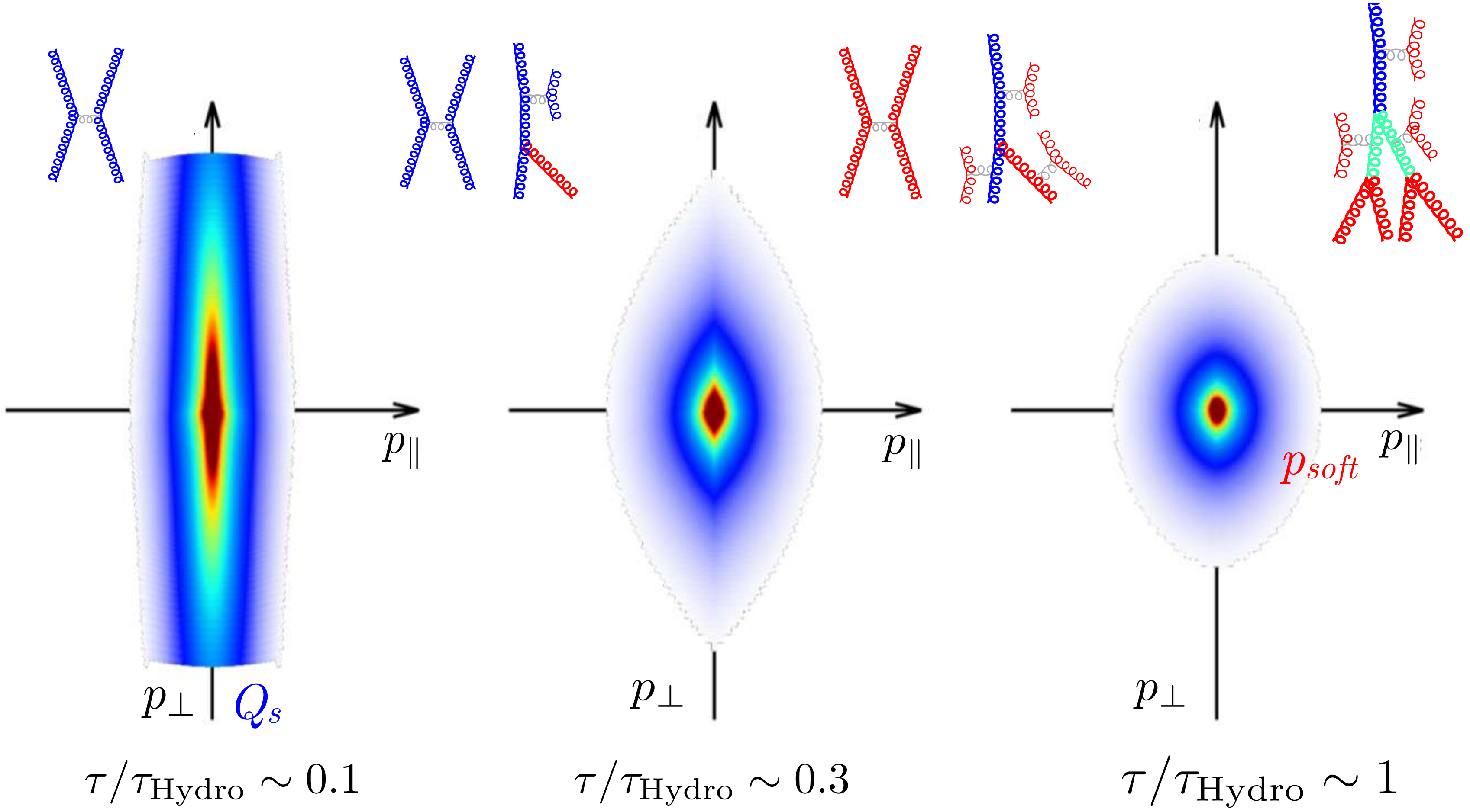
Energy momentum tensor assumes average form

$T^{\mu\nu} = \mathrm{diag}(e, p_T, p_T, p_L)$ with $p_L << p_T$ at early times

Microscopic evolution

Evolution of homogenous boost invariant system in QCD kinetic theory

Kurkela, Zhu PRL 115 (2015) 182301; Keegan,Kurkela,Mazeliauskas,Teaney JHEP 1608 (2016) 171;
Kurkela, Mazeliauskas, Paquet, SS, Teaney PRL 122 (2019) no.12, 122302; PRC 99 (2019) no.3, 034910



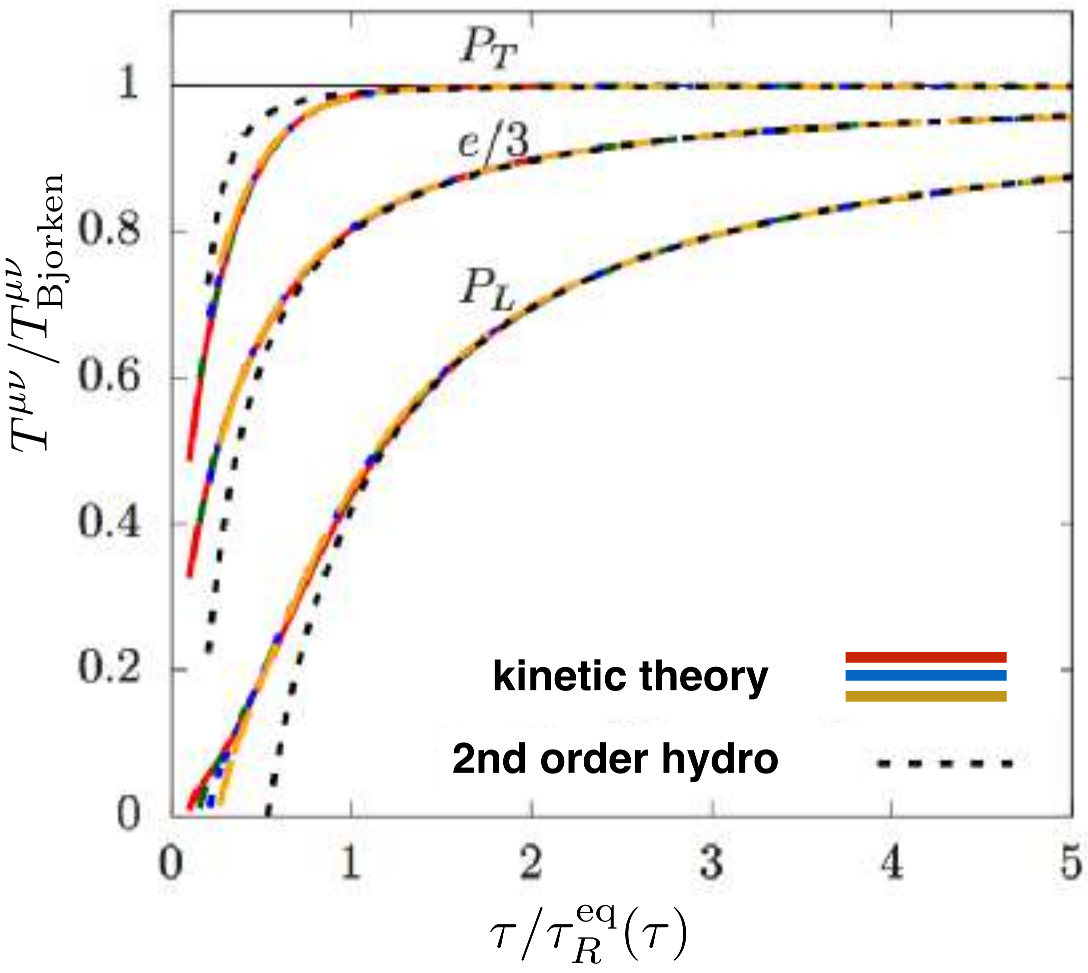
Eventually equilibration of expanding QCD plasma proceeds
a la ``bottom-up” via radiative break-up

Hydrodynamic behavior

Hydrodynamics describes the macroscopic evolution of energy-momentum tensor $T^{\mu\nu}$ based on an expansion around local thermal equilibrium

$$Kn \sim \lambda_{micro}/L_{macro} \qquad Re^{-1} \sim \delta T^{\mu\nu}_{dissipative}/T^{\mu\nu}_{eq}$$

Since the system is highly anisotropic at early times ($P_L << P_T$), key question is to understand evolution of $T^{\mu\nu}$ towards local equilibrium ($P_L = P_T$)



Equilibration process controlled by a single equilibrium relaxation rate

$$\tau_R^{\rm eq}(\tau) = \frac{4\pi\eta/s}{T_{\rm eff}(\tau)}$$

Simulations at different coupling (λ=5-20) strength indicate small sensitivity to α_s when compared in units of τ_R^{eq}

Kurkela, Zhu PRL 115 (2015) 182301
Kurkela, Mazeliauskas, Paquet, SS, Teaney 1805.01604; 1805.00961

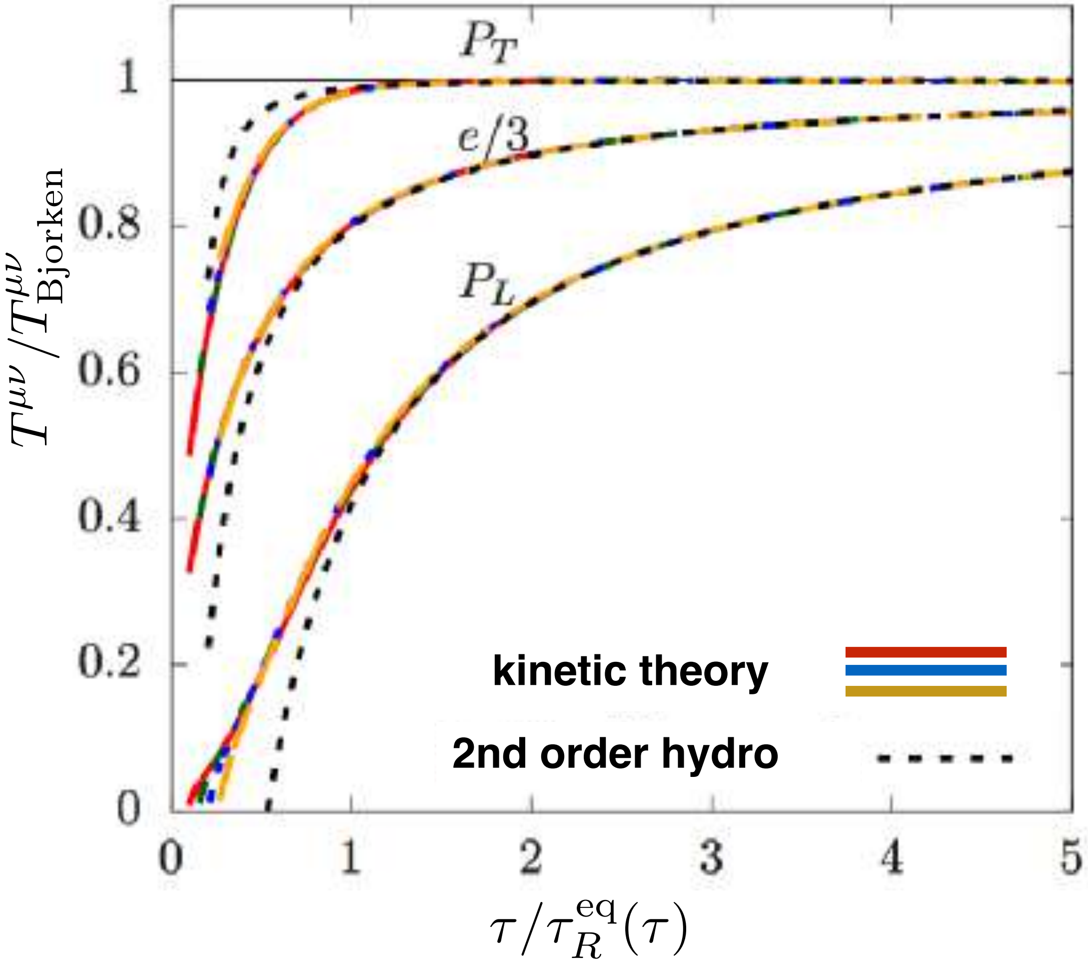
Hydrodynamic behavior

Effective description in viscous hydrodynamics becomes applicable on time scales

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

in line with earlier phenomenological estimates

Kurkela, Zhu PRL 115 (2015) 182301
Kurkela, Mazeliauskas, Paquet, SS, Teaney 1805.01604; 1805.00961



Viscous hydrodynamics becomes applicable when

$$Kn \sim \tau_R^{eq}(\tau)/\tau \sim 1$$

$$Re^{-1} \sim 1 - T^{\mu\nu}/T^{\mu\nu}_{\text{Bjorken}} \sim 1$$

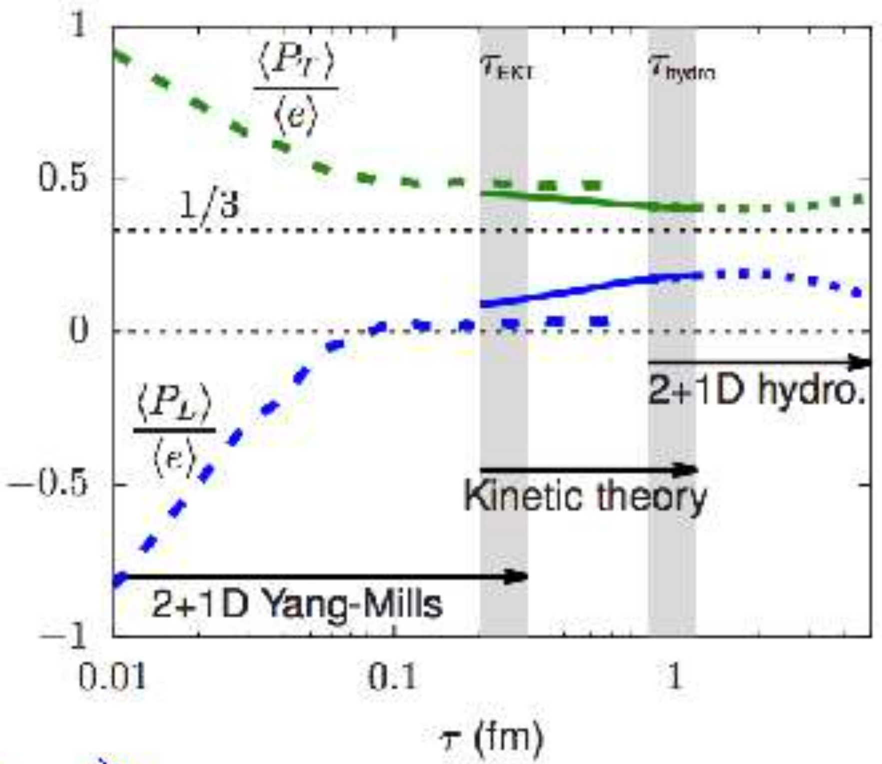
Surprising effectiveness of viscous fluid dynamics also found e.g. at strong coupling

Heller,Janik,Witaszczyk PRL 108 (2012) 201602
Romatschke PRL 120 (2018) no.1, 012301
…

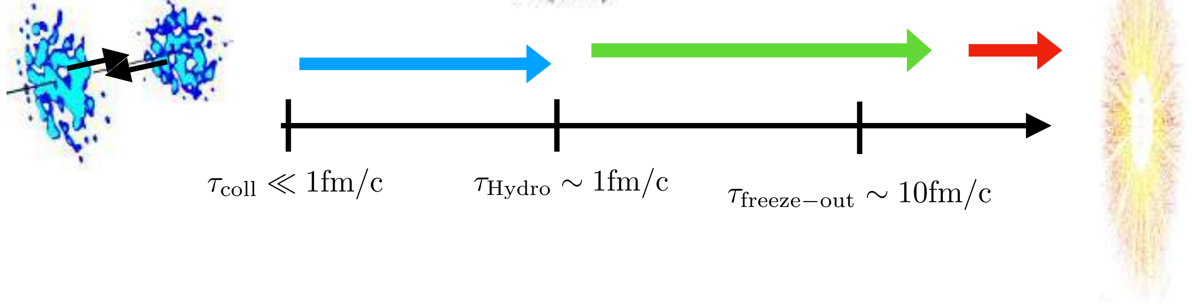
Dynamics of HICs

Based on progress in understanding early time dynamics & equilibration can now describe HIC from beginning to end by matching different effective descriptions of QCD

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



Effects of including pre-equilibrium dynamics on experimental observables generally small



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

Difficult to gain experimental access to early time non-equilibrium dynamics in A+A collisions

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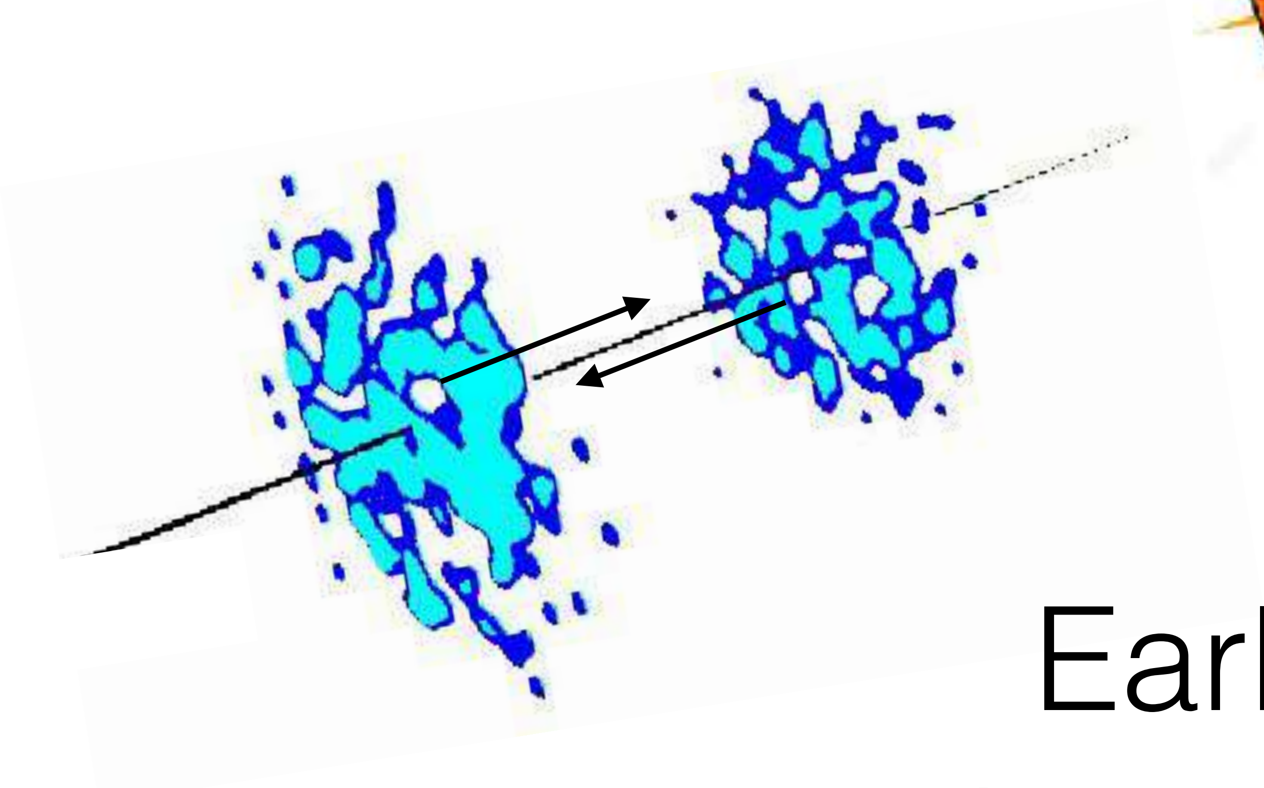
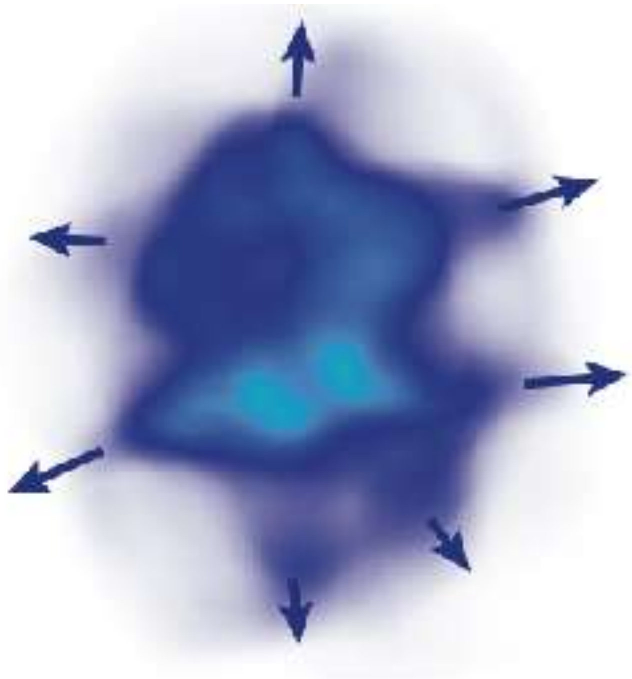
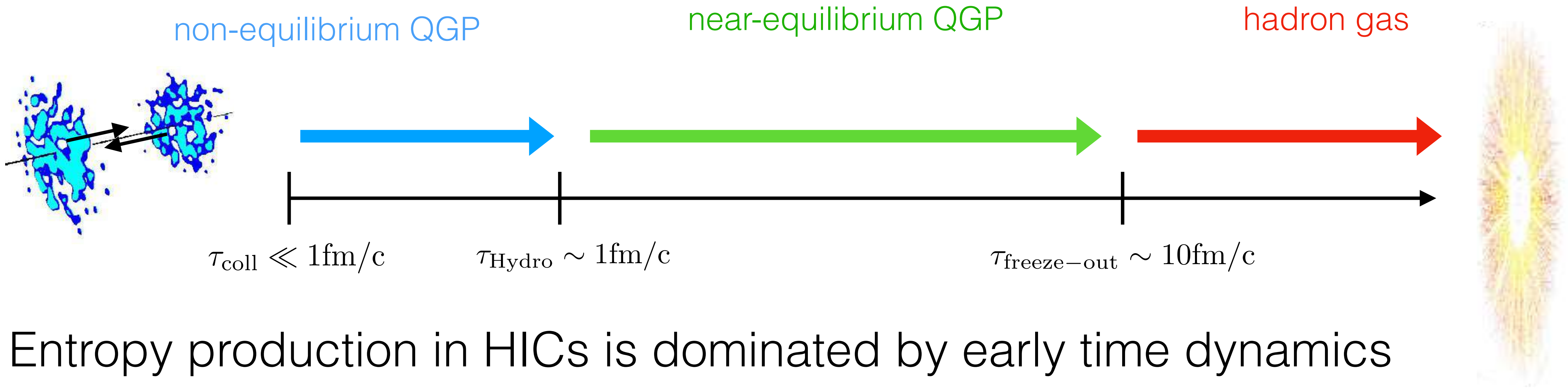




Early time dynamics & entropy production in HIC

Sensitivity to Initial state

Entropy production occurs only when system is significantly out-of-equilibrium



Entropy production in HICs is dominated by early time dynamics and directly accessible by measurement of $dN_{ch}/d\eta$

Schematically:

$$\left\langle \frac{dE_\perp}{d\eta}\right\rangle_{\tau_{\rm coll}} \xrightarrow[\text{initial entropy production}]{} \left\langle \frac{dS}{d\eta}\right\rangle_{\tau_{\rm Hydro}} \xrightarrow{\text{(nearly) isentropic expansion}} \left\langle\frac{dS}{d\eta}\right\rangle_{\tau_{\rm freeze-out}} \approx \left\langle\frac{dS}{d\eta}\right\rangle_{\tau_{\rm Hydro}} \xrightarrow[\text{freeze-out}]{} \left\langle\frac{dN_{\rm ch}}{d\eta}\right\rangle \approx \left\langle\frac{S}{N_{\rm ch}}\right\rangle\left\langle\frac{dS}{d\eta}\right\rangle_{\tau_{\rm freeze-out}}$$

Based on insights from non-equilibrium studies, can now make relation between $dE/d\eta$ and $dN_{ch}/d\eta$ explicit

Early time dynamics & entropy production

Non-equilibrium initial state better characterized in terms of energy density (e), better to use entropy density (s) only once system is close to equilibrium

Energy momentum tensor assumes average form $T^{\mu\nu} = \mathrm{diag}(e, p_T, p_T, p_L)$

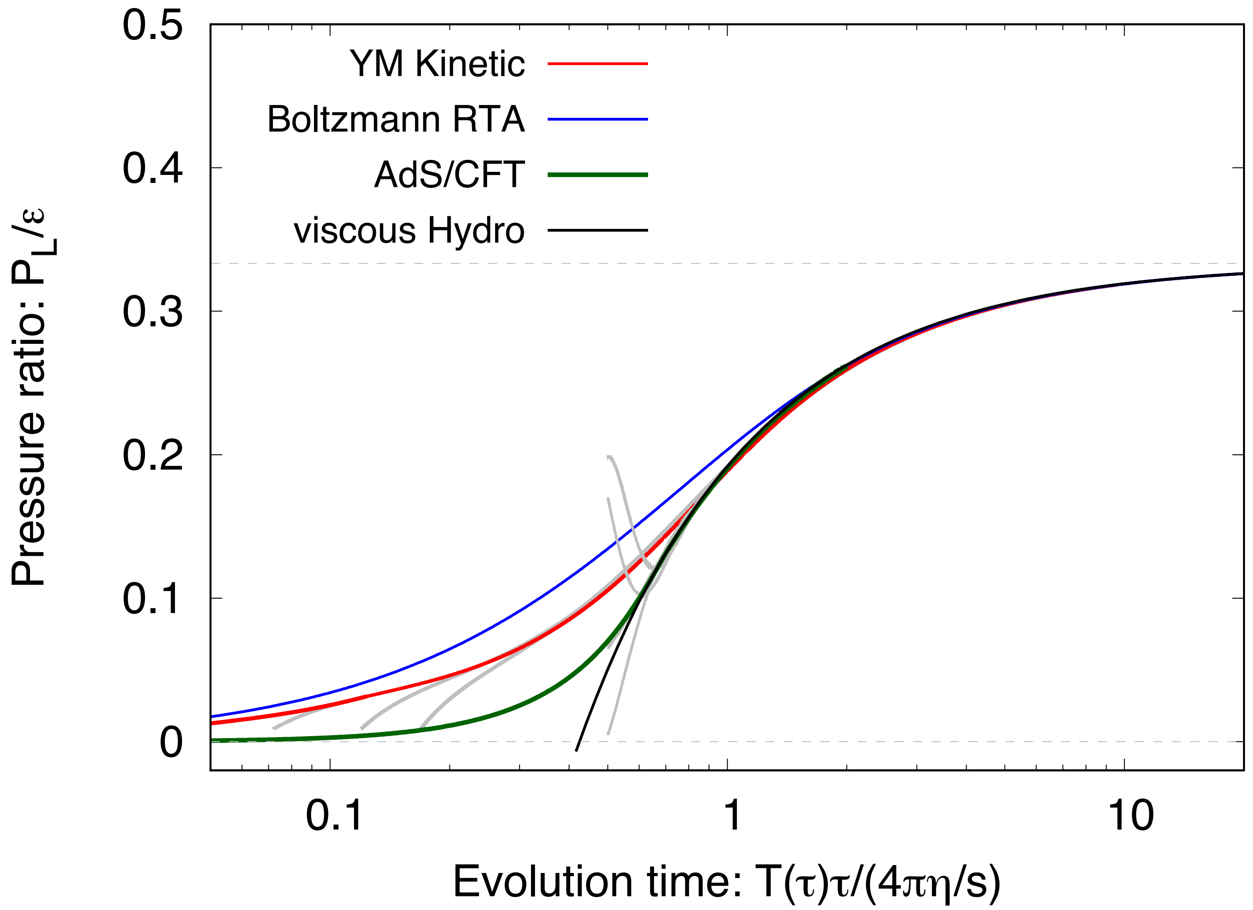
Evolution of energy density is governed by conservation equation

$$\partial_\tau \epsilon = -\frac{\epsilon}{\tau} - \frac{P_L}{\tau}$$

need equation of state/constitutive relation $P_L(e,\tau)$ to obtain evolution

Generally no constitutive equations out-of-equilibrium and P_L/e depends on microscopics

Hydrodynamic attractors



Non-equilibrium evolution towards hydrodynamics described by "hydrodynamic attractor"

Heller, Spalinski PRL 115 (2015) no.7, 072501

Effective constitutive relations for far-from-equilibrium systems

$$\frac{P_L}{\epsilon} = f(\epsilon, \tau) = f\left(\tilde{w} = \frac{T(\tau)\tau}{4\pi\eta/s}\right)$$

Despite clear microscopic differences the macroscopic features of the evolution are remarkably similar when compared in meaningful fashion

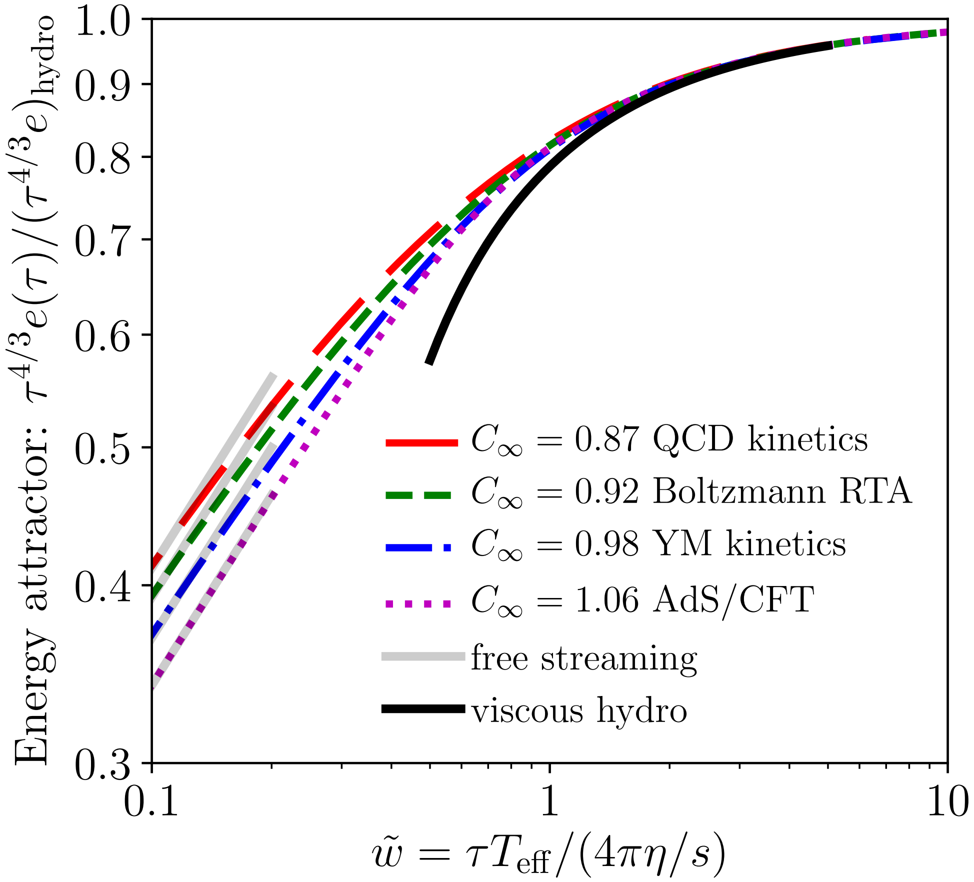
Universality at early times (free-streaming)
& late times (visc. hydrodynamics)

Romatschke *Phys.Rev.Lett.* 120 (2018) 1, 012301; Giacalone, Mazeliauskas, SS PRL 123 (2019) 26, 262301
Kurkela, Schee, Wiedemann, Wu *Phys.Rev.Lett.* 124 (2020) 10, 102301

Entropy production in HICs

Effective constitutive equation allows to obtain evolution of energy density from

$$e(\tilde{w}_\tau) = e(\tilde{w}_0)\exp\left(-\int_{\tilde{w}_0}^{\tilde{w}_\tau}\frac{d\tilde{w}}{\tilde{w}}\frac{1+P_L(\tilde{w})/e(\tilde{w})}{\frac{3}{4}-\frac{1}{4}P_L(\tilde{w})/e(\tilde{w})}\right)$$



Once QGP is close to equilibrium can use thermodynamic relations s=(e+p)/T and EOS once QGP to calculate entropy

$$(s\tau)_{\text{hydro}} = \frac{4}{3}C_\infty^{3/4}\left(4\pi\frac{\eta}{s}\right)^{1/3}\left(\frac{\pi^2}{30}\nu_{\text{eff}}\right)^{1/3}(e\tau)_0^{2/3}$$

Since overall entropy is approx. conserved during hydro expansion charged particle multiplicity at freeze-out directly determined

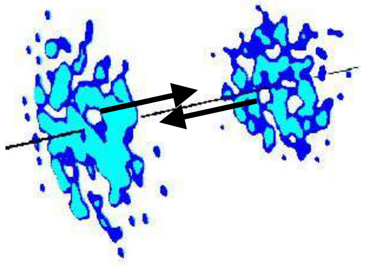
$$\frac{dN_{\text{ch}}}{d\eta} \approx A_\perp\,(s\tau)_{\text{hydro}}\frac{N_{\text{ch}}}{S}$$

Giacalone, Mazeliauskas, SS PRL 123 (2019) 26, 262301

Entropy production in HICs

Based on macroscopic considerations one can establish one-to-one correspondence between initial state energy density and charged particle multiplicity including all relevant pre-factors

$$\frac{dN_{\mathrm{ch}}}{d\eta} \approx \frac{4}{3}\left(\frac{N_{\mathrm{ch}}}{S}\right) A_{\perp} C_{\infty}^{3/4}\left(4\pi\frac{\eta}{s}\right)^{1/3}\left(\frac{\pi^2}{30}\nu_{\mathrm{eff}}\right)^{1/3}(\epsilon\tau)_0^{2/3}$$



Sensitivities/Uncertainties:

Equilibrium properties: $N_{ch}/S \sim 7.5$, $\nu_{eff} \sim 40$ approximately known

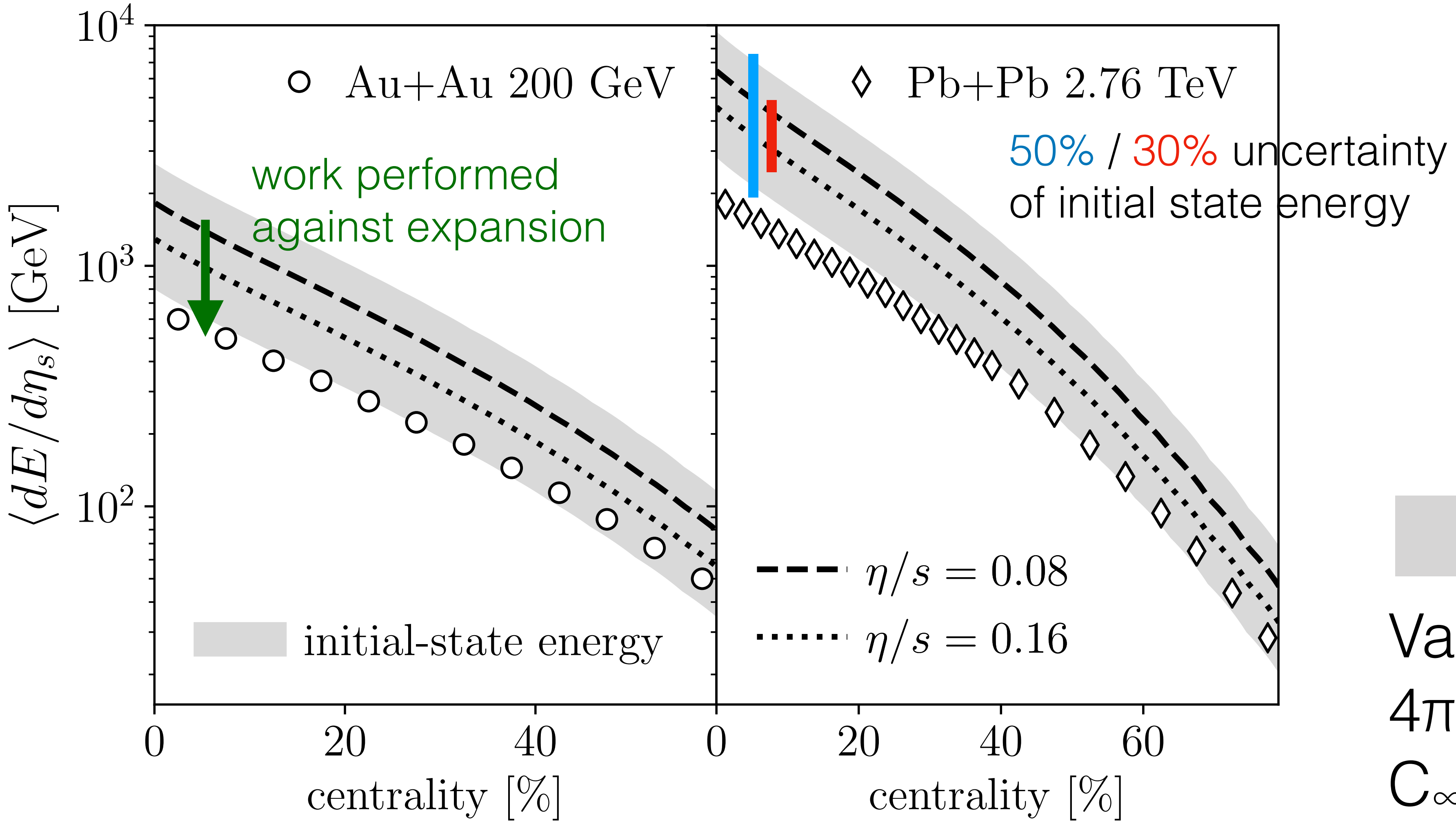
Non-equilibrium/transport properties:
$C_\infty \sim 0.95 \pm 0.15$ surprisingly well constraint
$4\pi\ \eta/s \sim (1\text{-}3)$ not well constraint in relevant temperature range ($T \sim 4T_c$)

Initial state energy density:
$(\epsilon\tau)_0$ significant uncertainties from small-x TMDs
and perturbative corrections

Giacalone, Mazeliauskas, SS PRL 123 (2019) 26, 262301

Initial state in HICs

Extraction of initial state energy dE/dη from final measured multiplicity



work performed against expansion

50% / 30% uncertainty of initial state energy

▨

Variations of 4π η/s=(1-3) & C∞~0.95±0.15

Sensitivity to η/s and (eτ)₀ can be exploited to obtain combined constraints on initial state & transport properties

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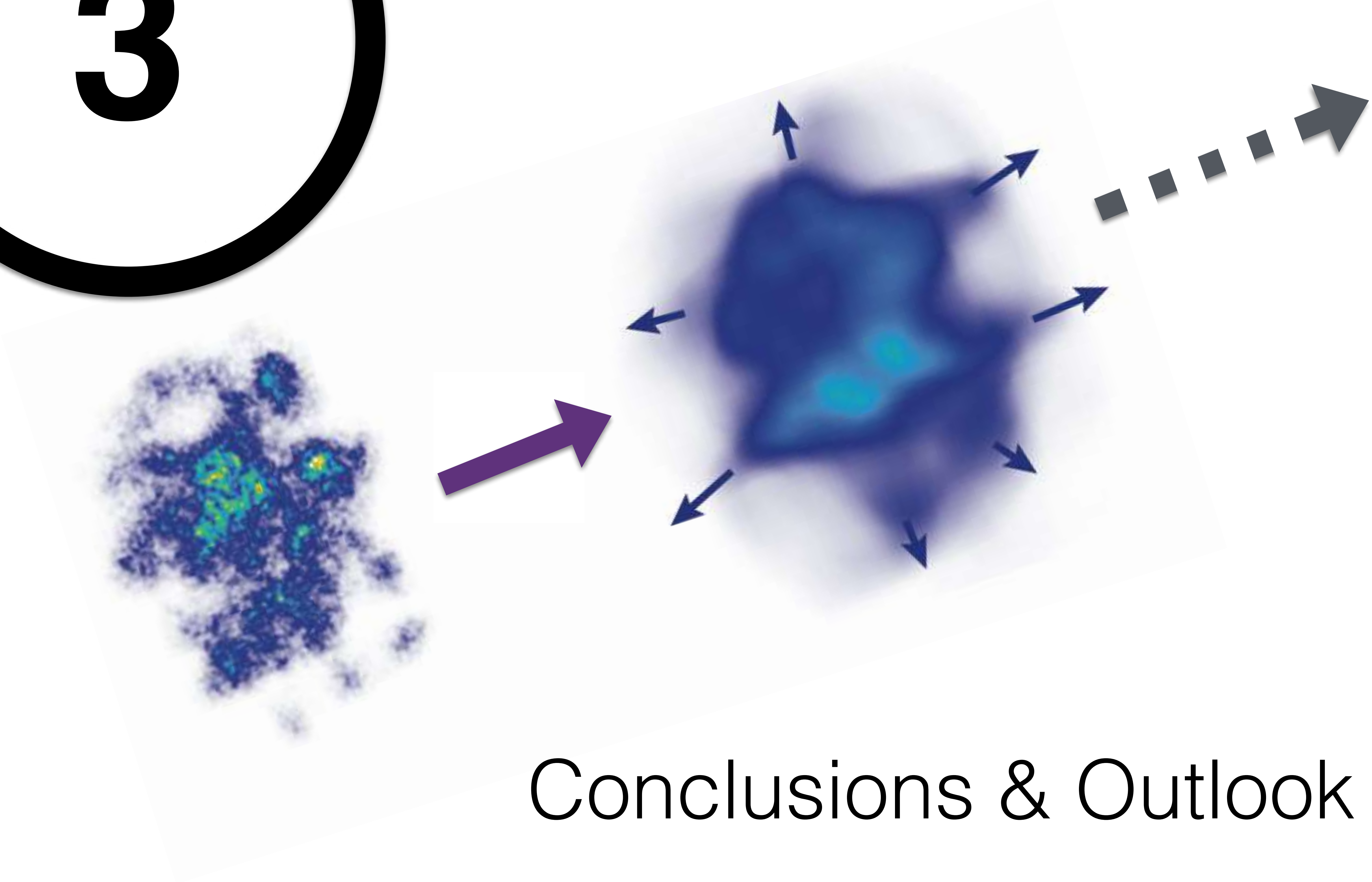


Conclusions & Outlook

Significant progress in understanding non-equilibrium QCD dynamics wrt onset of hydrodynamic behavior & equilibration of QGP

— Established thermalization of patterns of QCD(-like) plasmas
— Viscous hydrodynamics != local thermal equilibrium

-> Implications for non-equilibrium plasmas in early universe?

Studies have reached a level where they can connect properties of initial state with experimental measurements and useful phenomenological results can be obtained

KoMPoST: Eff. macroscopic description of non-Eq QCD in heavy-ion collisions including transverse dynamics

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

Establishing link between initial state and finale state important to connect Heavy-Ion Physics to Physics at EIC & Hadron Colliders

Small-x gluon (G)TMDs determine initial state energy density in A+A as well as (forward) di-jet production in p+p/A or e+p/A

So far investigations have mostly focused on bulk equilibration in A+A collisions

Electro-magnetic & hard probes, small systems (p+p/A), non-equilibrium effects in jet-medium interactions provide promising avenues to further explore non-equilibrium QCD in heavy-ion collisions

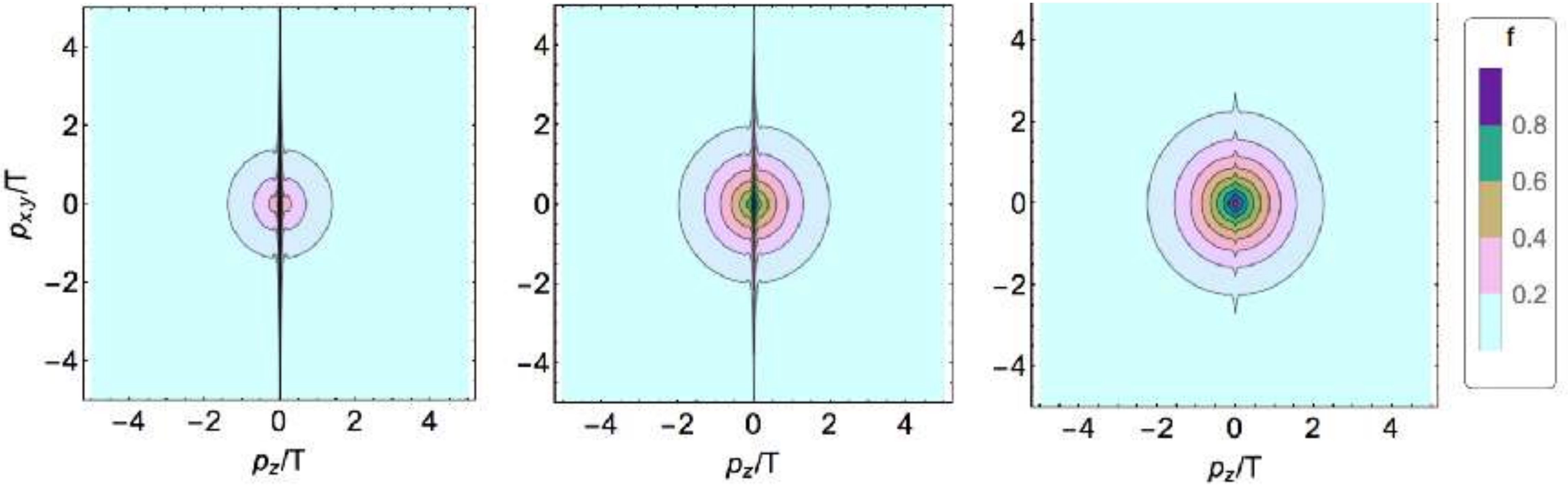
Backup

Non-equilibrium towards hydrodynamics

Evolution of homogenous boost invariant system in Boltzmann RTA

M. Strickland JHEP 1812 (2018) 128

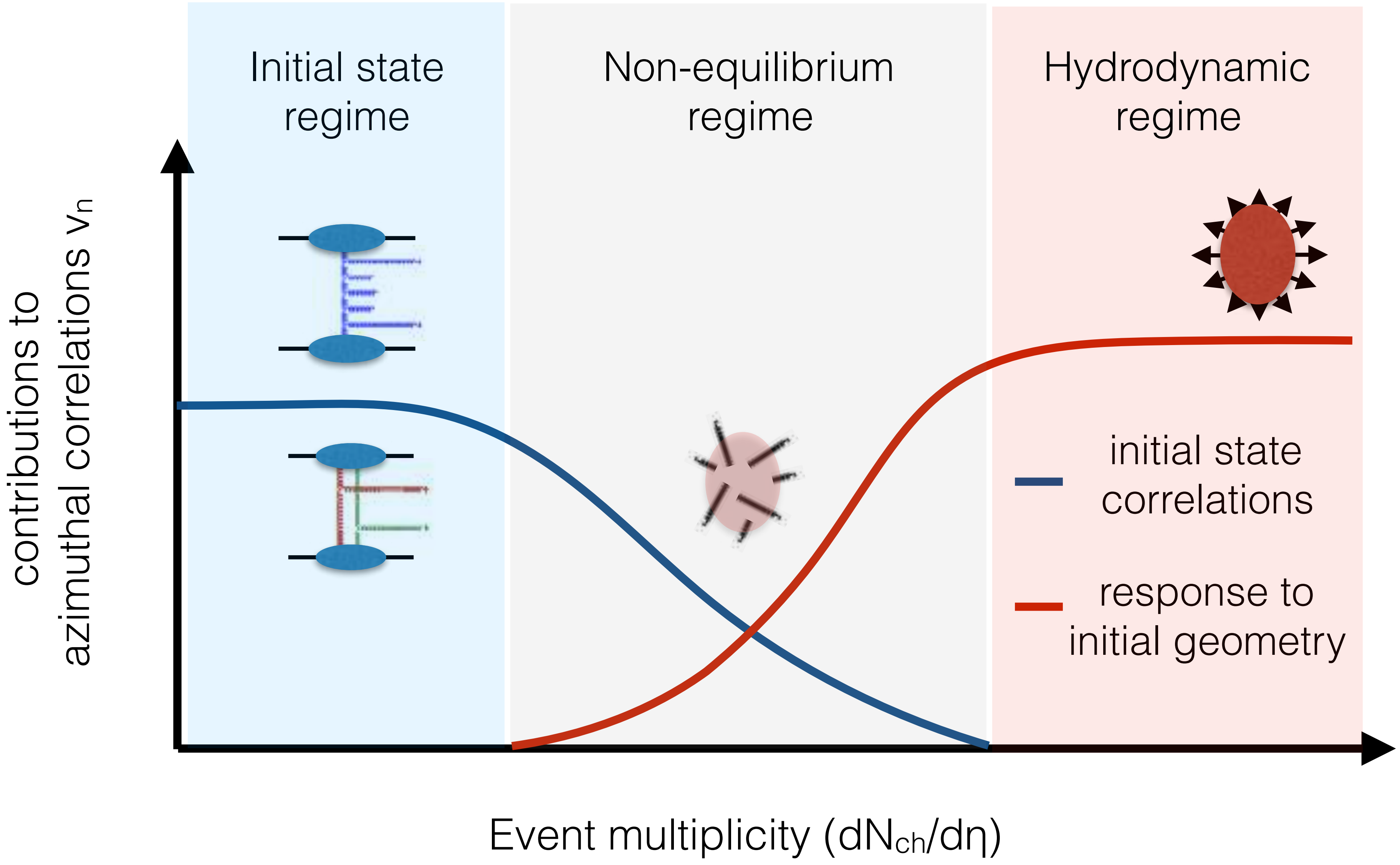
$$p^\mu \partial_\mu f(x,p) = -\frac{p^\mu u_\mu(x)}{\tau_R(x)} \Big[f(x,p) - f_{\rm eq}(x,p) \Big]$$



$\tau/\tau_{\rm Hydro} \sim 0.16$ $\tau/\tau_{\rm Hydro} \sim 0.4$ $\tau/\tau_{\rm Hydro} \sim 0.9$

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

Shorter life-time of the system (~R) increases sensitivity to initial state and non-equilibrium dynamics



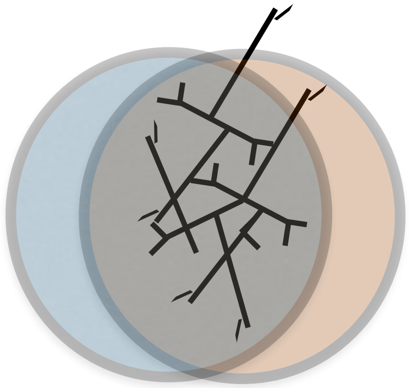
Some additional control parameters (p_T ,…) besides multiplicity $dN_{ch}/d\eta$

Hydrodynamic QGP in small systems?

Non-equilibrium dynamics of QGP controlled by the ratio of hydrodynamization time (τ_{Hydro}) and system size (R)

τ_{Hydro} >> R: insufficient time to achieve equilibrated QGP

τ_{Hydro} << R: long lived hydrodynamic QGP phase



Based on estimates of the hydrodynamization time critical multiplicity can be estimated

$$\frac{\tau_{\text{Hydro}}}{R} \simeq \left(\frac{4\pi(\eta/s)}{2}\right)^{\frac{3}{2}} \left(\frac{dN_{\text{ch}}/d\eta}{63}\right)^{-\frac{1}{2}} \quad <=> \quad \left.\frac{dN_{\text{ch}}}{d\eta}\right|_{\text{crit}} = 63 \left(\frac{\eta/s}{2/4\pi}\right)^{3} \left(\frac{\tau_{\text{Hydro}}}{R}\right)^{-2}$$

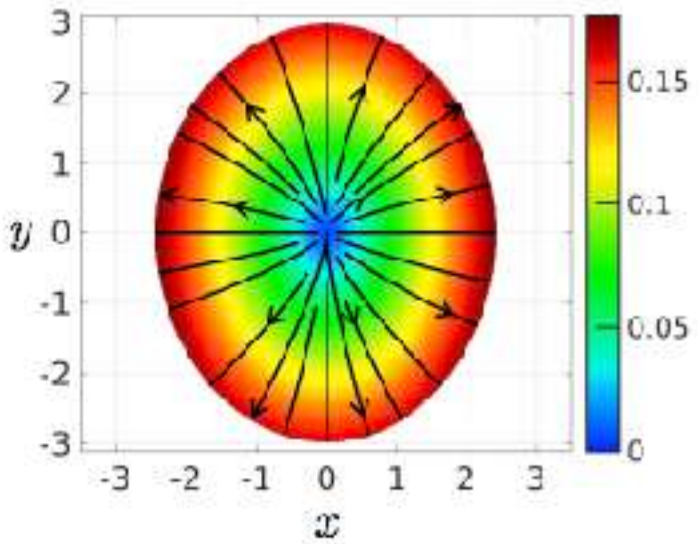
where $\left.\frac{dN_{ch}}{d\eta}\right|_{min.\ bias}^{p+p\ 7TeV} \sim 6$, $\left.\frac{dN_{ch}}{d\eta}\right|_{min.\ bias}^{p+Pb\ 5.02TeV} \sim 16$, $\left.\frac{dN_{ch}}{d\eta}\right|_{0-5\%}^{Pb+Pb\ 2.76TeV} \sim 1600$

Experimental results in small systems mostly fall into the regime $\tau_{\text{Hydro}}/R \sim 1$ dominated by non-equilibrium phase

Pre-flow ($T^{\tau i}$) & Viscous corrections (T^{ij})

Gradients in x_T induce off-diagonal components of $T^{\mu\nu}$

P. Chesler JHEP 1603 (2016) 146



Universal pre-flow: early expansion of matter insensitive to microscopic details

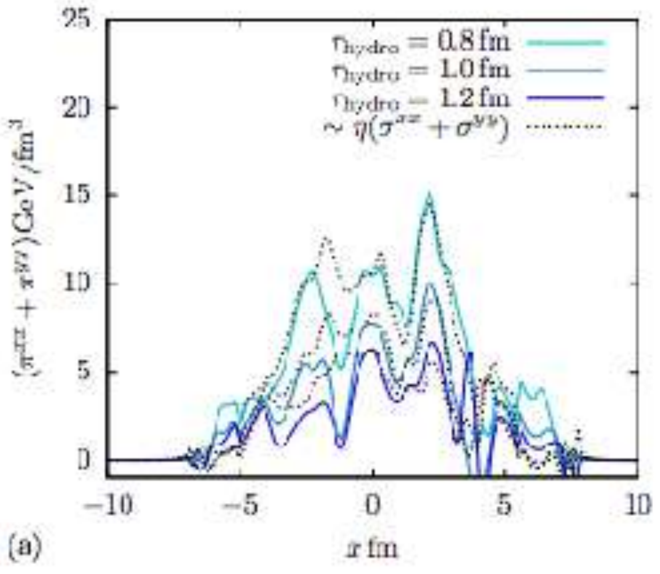
Pratt, Vredevoogd PRC79 (2009) 044915
Kurkela, Mazeliauskas, Paquet, SS, Teaney PRC 99 (2019) no.3, 034910

$$\frac{T^{\tau i}(\tau,\mathbf{x})}{T^{\tau\tau}(\tau,\mathbf{x})} \approx -\frac{(\tau-\tau_0)}{2}\frac{\partial^i T^{\tau\tau}(\tau_0,\mathbf{x})}{T^{\tau\tau}(\tau,\mathbf{x})}$$

not indicative of onset of hydrodynamic flow

Viscous corrections: long wavelength components satisfy hydrodynamic constitutive equations approximately at $\tau=\tau_{\text{Hydro}}$

$$\pi^{\mu\nu}(\tau_{\text{Hydro}},\mathbf{x}) \approx \pi^{\mu\nu}_{\text{NS}}$$



Pre-flow package KoMPoST provide unified description of pre-equilibrium evolution of $T^{\mu\nu}$ based on linear response to gradients

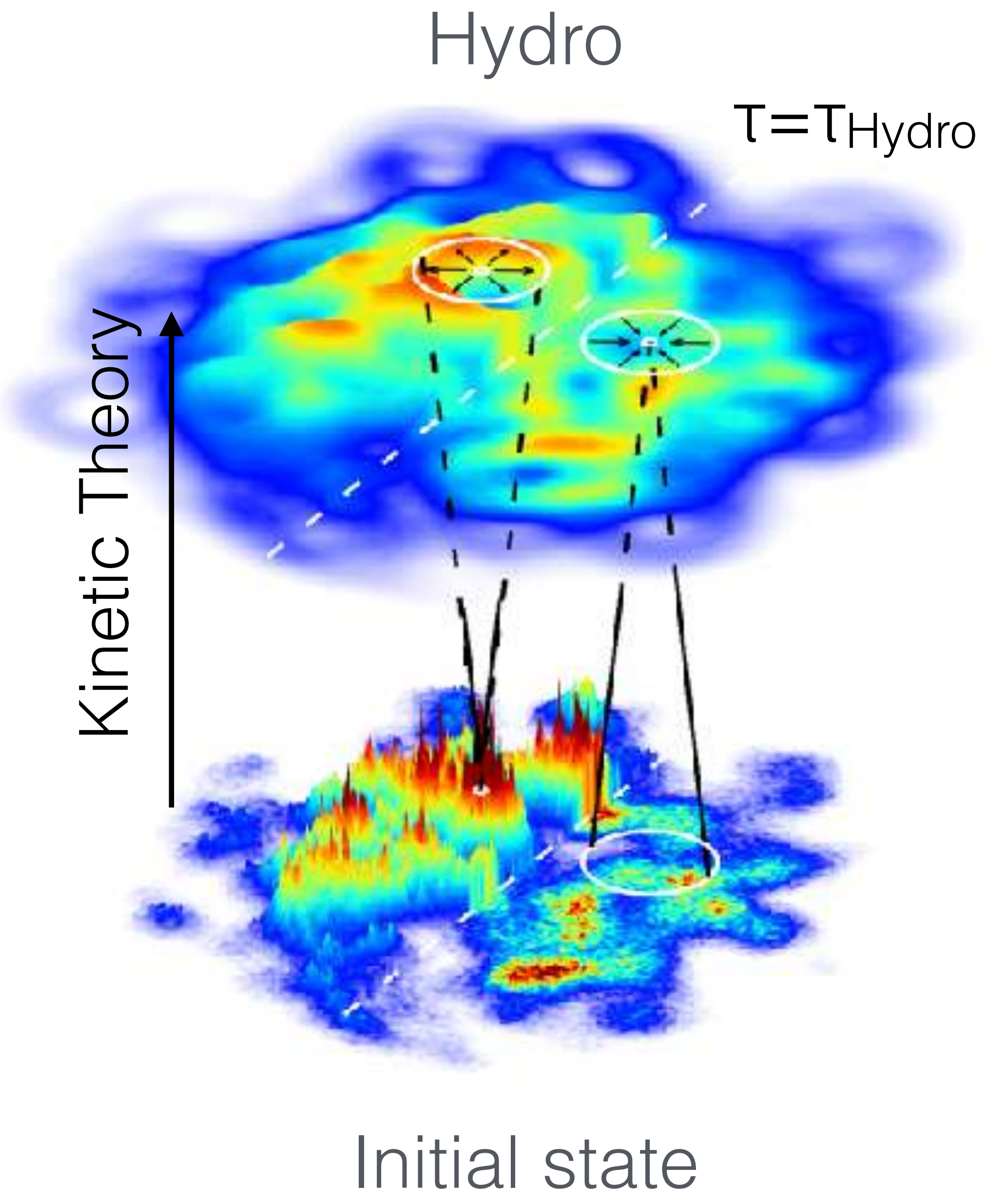
KoMPoST

Macroscopic description of pre-equilibrium dynamics

Exploit memory loss to use macroscopic degrees of freedom $T^{\mu\nu}$ for description of pre-equilibrium dynamics

Separation of scales between evolution time τ_{Hydro} and typical size scale of gradients R_A

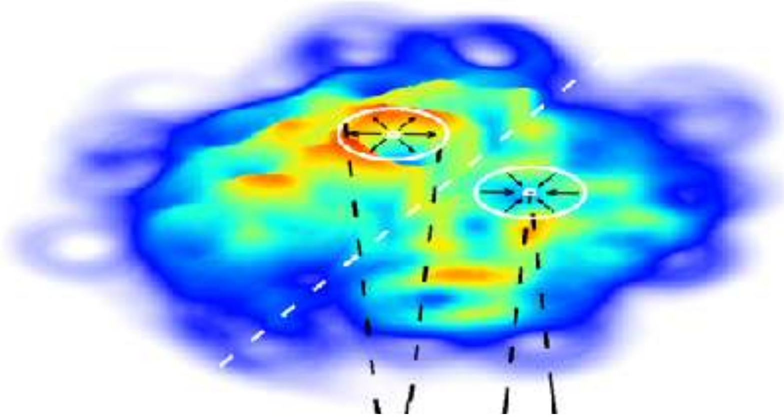
Decomposing $T^{\mu\nu}(x)$ into a local average $T^{\mu\nu}_{BG}(x)$ and fluctuations $\delta T^{\mu\nu}(x)$,are small on scales $c(\tau_{Hydro}-\tau_0)$, they can be treated in linear response theory



Keegan,Kurkela, Mazeliauskas, Teaney JHEP 1608 (2016) 171
Kurkela, Mazeliauskas, Paquet, SS, Teaney arXiv:1805.01604; arXiv:1805.00961

Non-equilibrium linear response

Energy-momentum tensor at τ_{Hydro} can be reconstructed directly from initial conditions

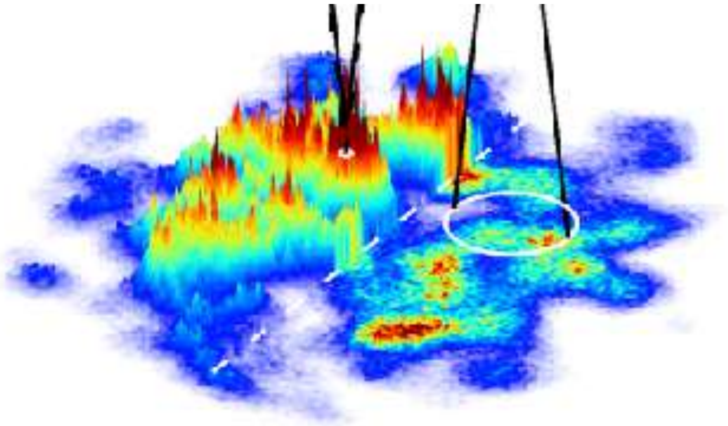


$$T^{\mu\nu}(\tau,x) = T^{\mu\nu}_{BG}(\tau) + \int_{\odot} G^{\mu\nu}_{\alpha\beta}(\tau,\tau_0,x,x_0)\delta T^{\alpha\beta}(\tau_0,x_0)$$

non-equilibrium evolution of (local) average background

non-equilibrium Greens function of energy-momentum tensor

Instead of event-by-event Monte-Carlo, effective kinetic theory simulations performed only once to compute evolution of background $T^{\mu\nu}_{BG}$ and Greens functions $G^{\mu\nu}_{\alpha\beta}$



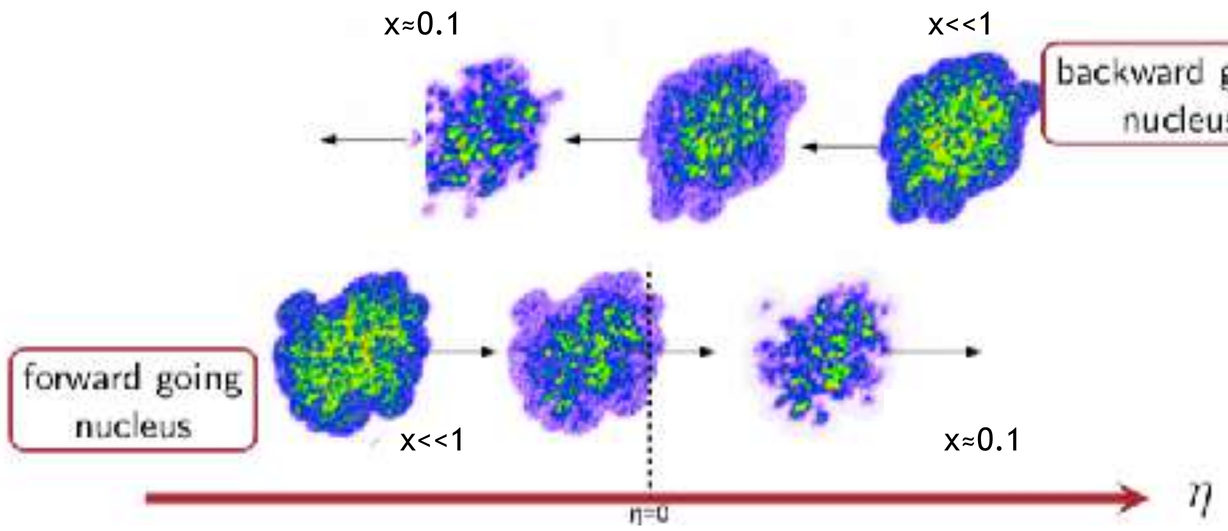
Kurkela, Mazeliauskas, Paquet, SS, Teaney arXiv:1805.01604; arXiv:1805.00961

Longitudinal dynamics (η)

Boost invariance (η~0) on average is reasonable assumption for symmetric high-energy collisions

Different models for long. fluctuations based on different degrees of freedom partons ,nucleons, strings, …

High-energy: Energy deposition at different η~y simultaneous probes gluon distribution at different x



SS Schenke PRC 94 (2016) no.4, 044907, McDonald, Jeon, NPA 982 (2019) 239-242, Ipp, Mueller PLB 771 (2017) 74-79

Space-time dynamics of baryon stopping at forward rapidities can also be addressed within small-x framework

McLerran, SS, Sen PRD99 (2019) no.7, 074009