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BROOKHAVEN NATIONAL LABORATORY

Equilibration in weak coupling approaches

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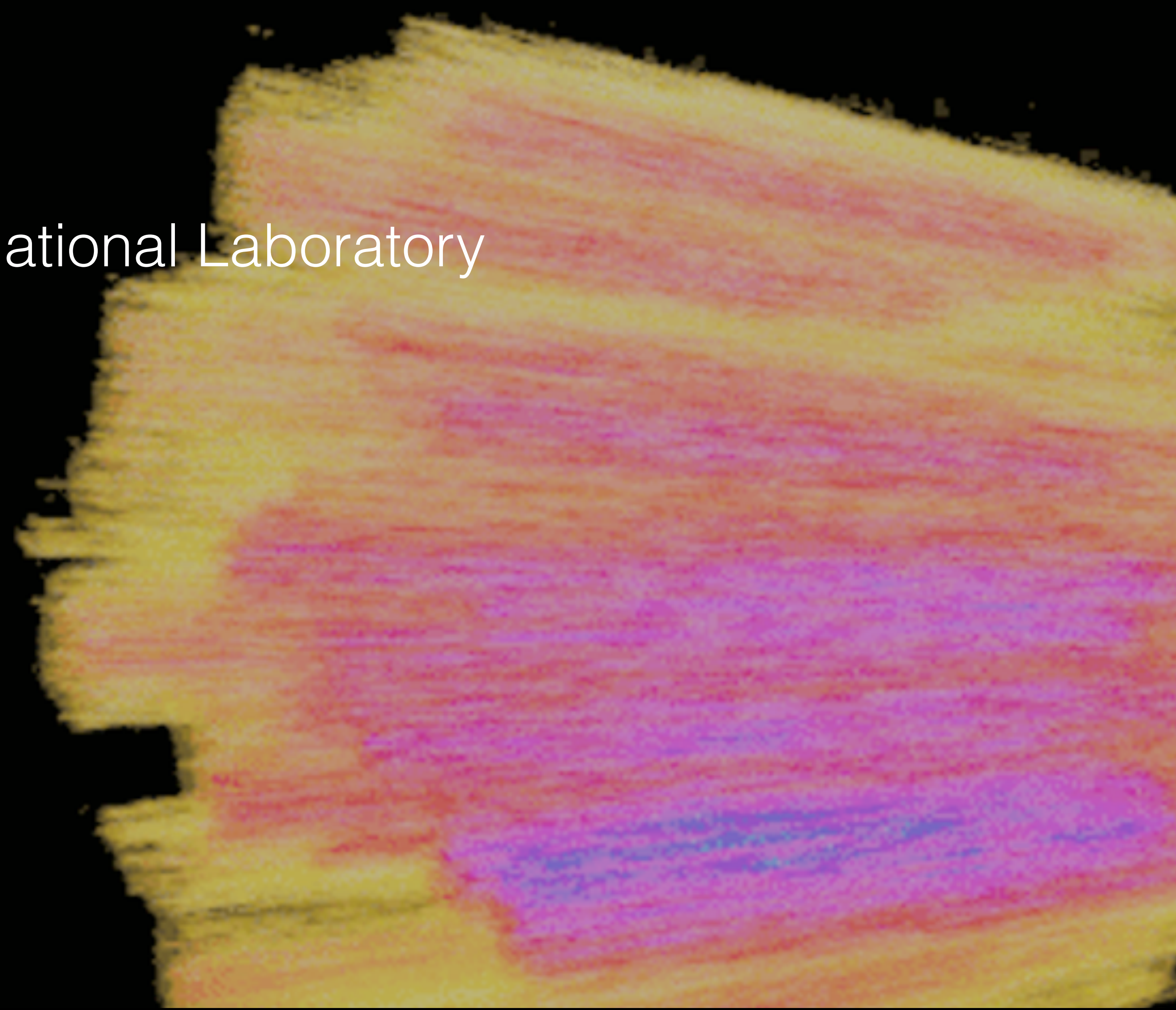


May 24 2016
Initial Stages 2016
Lisbon, Portugal

Objectives

1 Hydrodynamics extremely successful for description of soft physics observables in A+A collisions

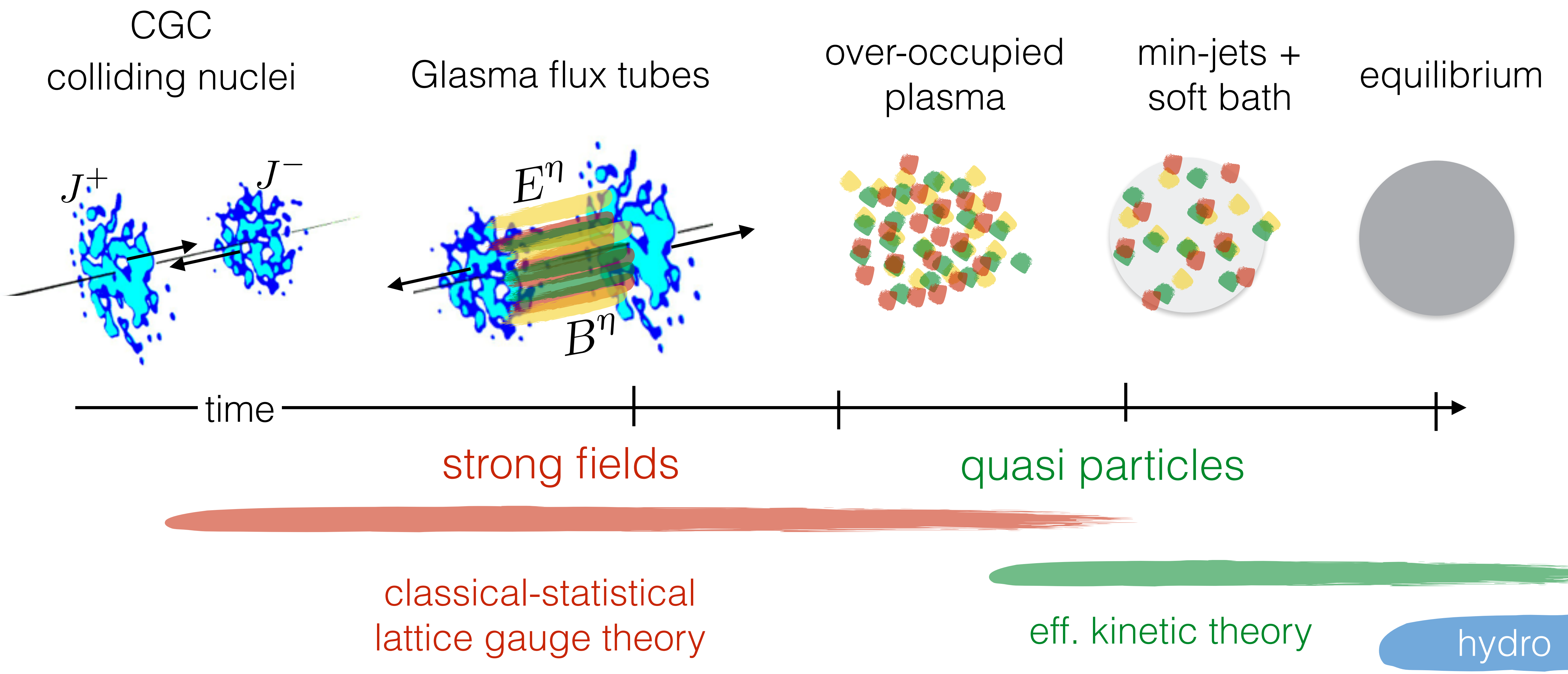
-> provide equilibration time
and initial conditions for hydro

2 Develop a microscopic understanding of how QGP is created from the high-energy collision of heavy nuclei

Energy density of initial state corresponds to temperature scale on the order~4 T_c (LHC)

-> weak-coupling methods can work

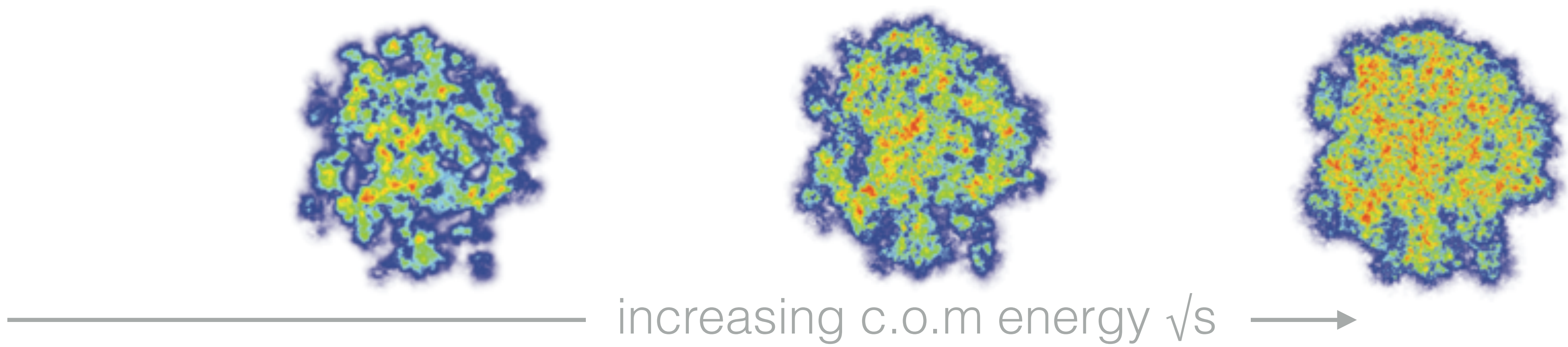
General picture at weak-coupling



Consistent theoretical description requires combination of different weak-coupling methods

Before the collision

Nuclei described in terms of distribution of color charges carried by the quarks & gluons inside



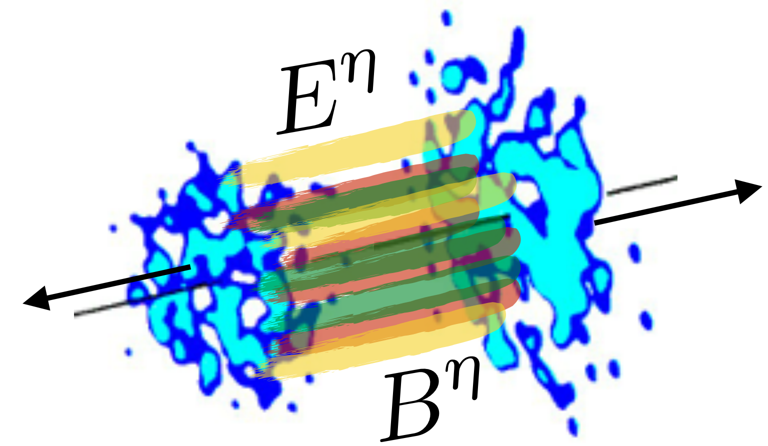
Color glass condensate: (McLerran, Venugopalan D49 (1994) 2233-2241)

Saturation of the gluon density occurs when phase-space density becomes non-perturbatively large

High-energy nuclei feature a non-perturbatively large number of gluons $\sim 1/\alpha_s$, with a typical momentum $Q_S(\sqrt{s})$

Early times ($0 < Q_s\tau < 1$)

Strong boost invariant classical fields E^η, B^η created immediately after the collision

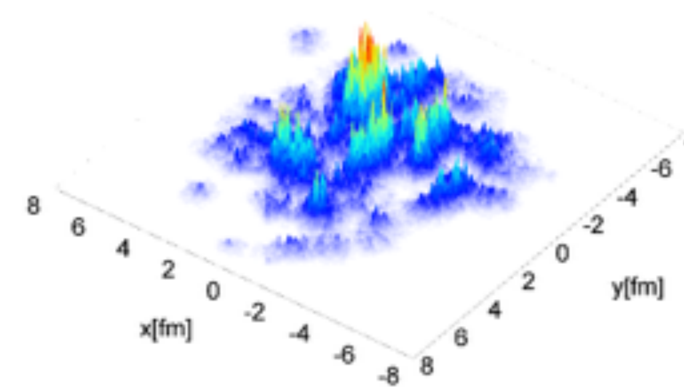


Decoherence of classical fields occurs on a time scale $1/Q_s$

- leading order (α_s) dynamics

  well studied analytically and numerically in classical-lattice gauge theory
  (c.f. talk by R. Fries)

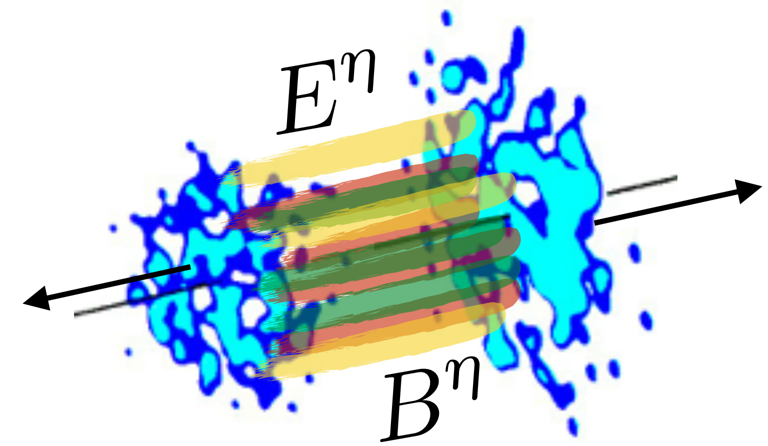
  classical fields remain boost invariant



IP-Glasma

Early times ($0 < Q_S\tau < 1$)

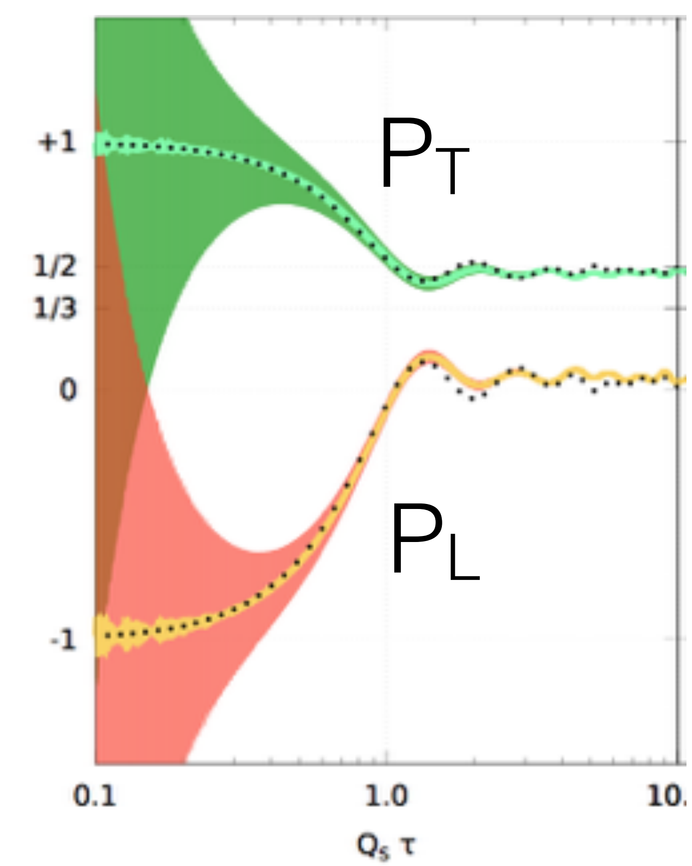
Strong boost invariant classical fields E^η, B^η created immediately after the collision



Decoherence of classical fields occurs on a time scale $1/Q_s$

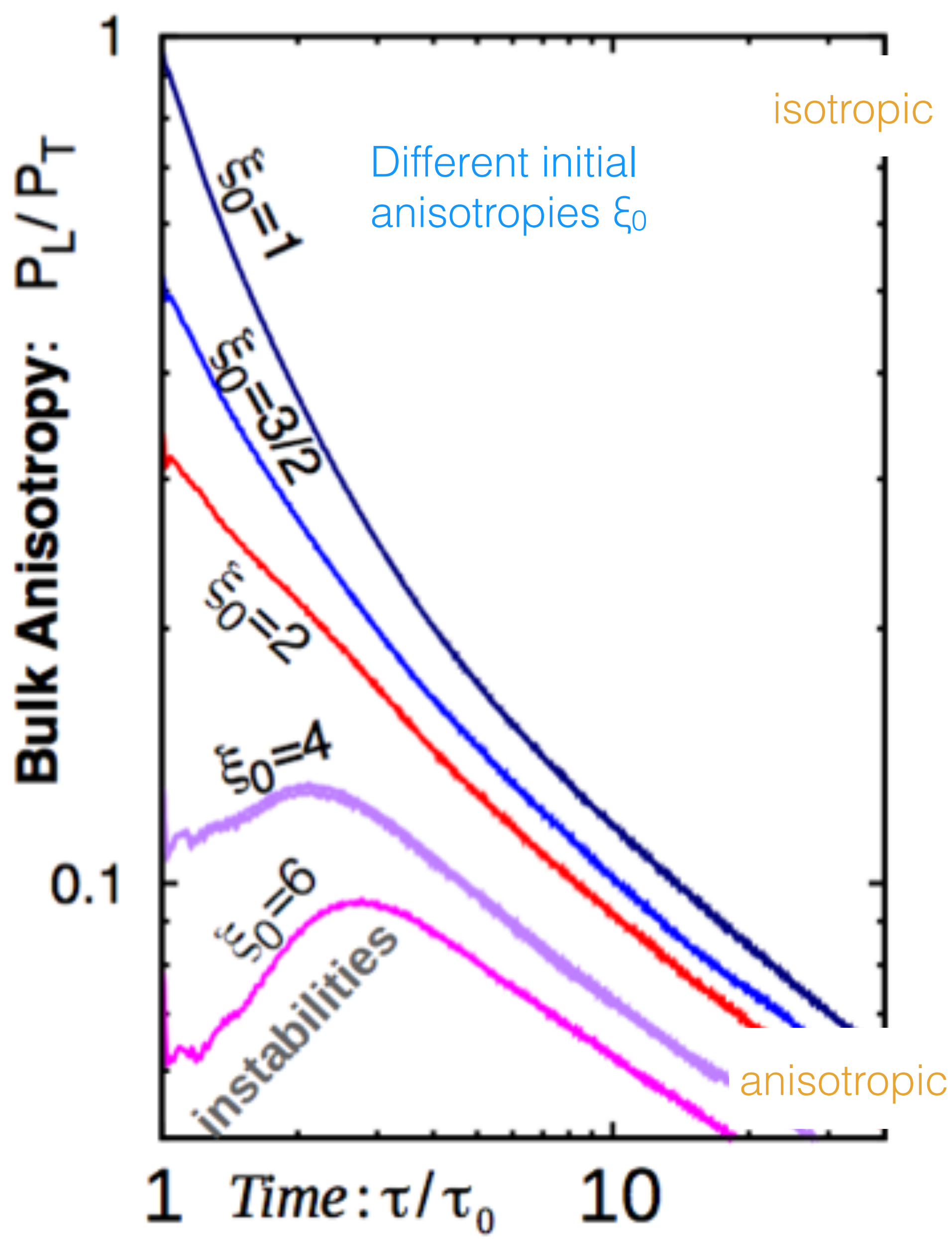
- next-to-leading order (α_s) corrections break boost invariance

  -> plasma instabilities lead to an increase of longitudinal pressure



(Epelbaum,Gelis PRL 111 (2013) 232301,
Berges, Schenke, SS , Venugopalan NPA 931 (2014) 348-353)

Classical regime ($1<Q_S\tau<\alpha_S^{-3/2}$)



Classical field interactions are not sufficiently strong to restore isotropy beyond $1/Q_S$

-> anisotropy of the plasma increases again

No sign of plasma instabilities playing a significant role at later times $Q_S\tau > 1$

(Berges, Boguslavski, SS, Venugopalan PRD 89 (2014) 074011; 89 (2014) 114007)

Classical regime ($1<Q_s\tau<\alpha_s^{-3/2}$)

Classical field evolution ($\tau>1/Q_s$) of hard modes can be accurately described in terms of weakly interacting quasi particles

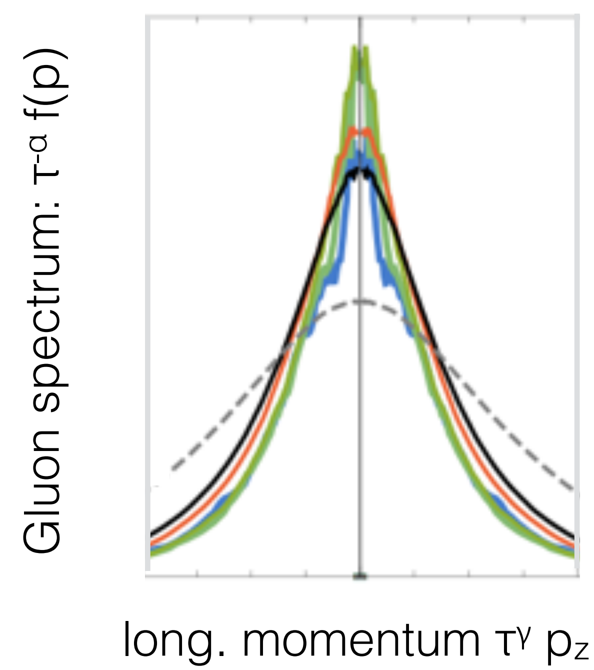
-> classical particle/field duality

Effective kinetic description

(Arnold, Morre, Yaffe JHEP 0301 (2003) 030)

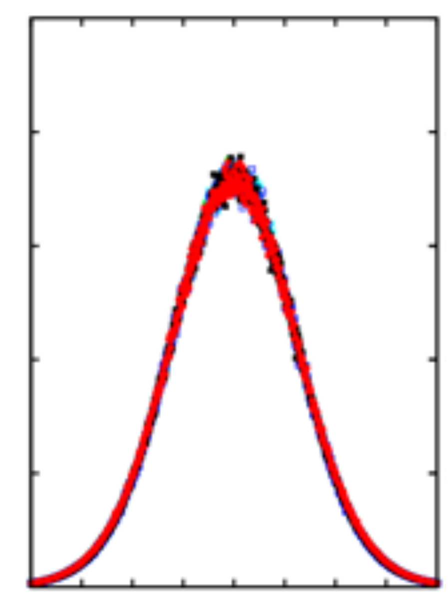
$$\frac{df}{dt} = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f]$$

Kinetic theory



Kurkela, Zhu
PRL 115 (2015) 182301

Classical Yang-Mills



Berges, Boguslavski, SS, Venugopalan
PRD 89 (2014) 074011

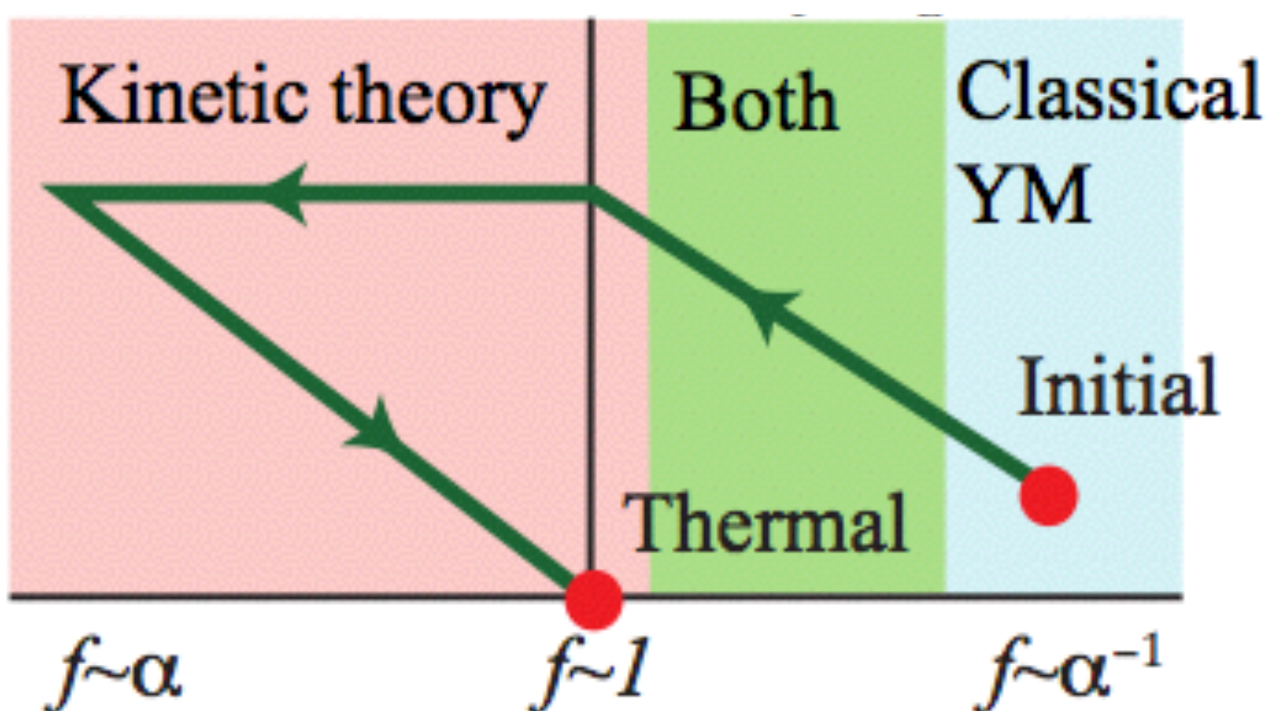
-> Effective kinetic description (AMY) can be used to study dynamics of hard modes from $\tau > 1/Q_s$ all the way to equilibration

Bottom-up scenario

Equilibration process beyond $\tau \sim 1/Q_s$ occurs as a three step process
(Baier et al. PLB 502 (2001) 51-58)

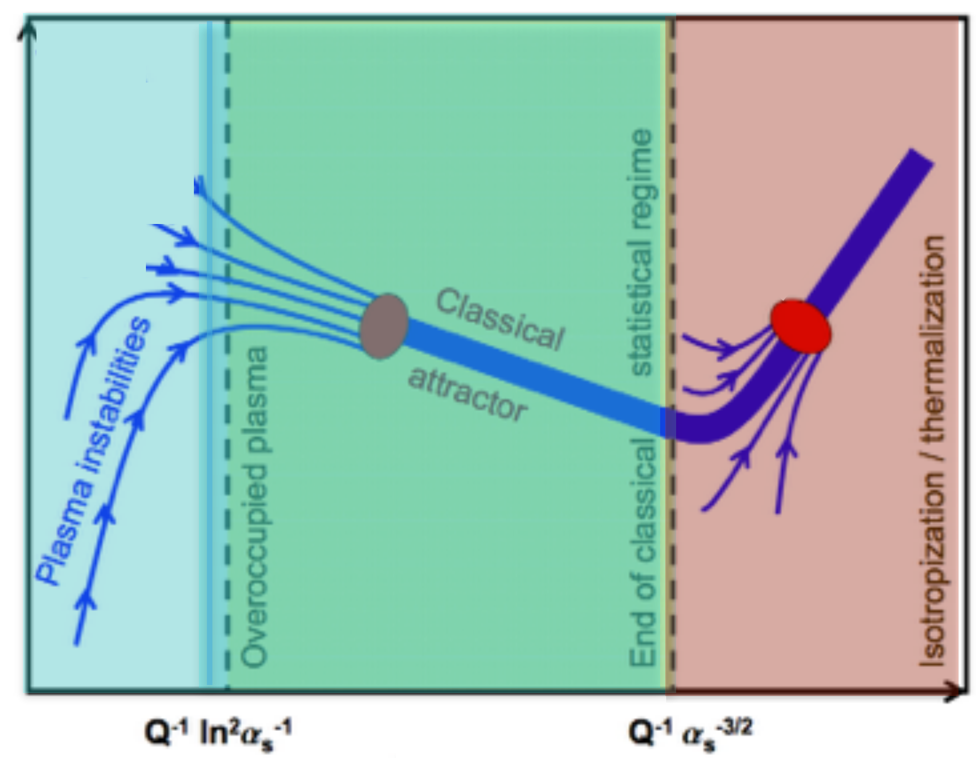
Kurkela arXiv:1601.03283

Anisotropy: P_L / P_T



Occupancy: f

Berges, Boguslavski, SS, Venugopalan
PRD 89 (2014) 074011



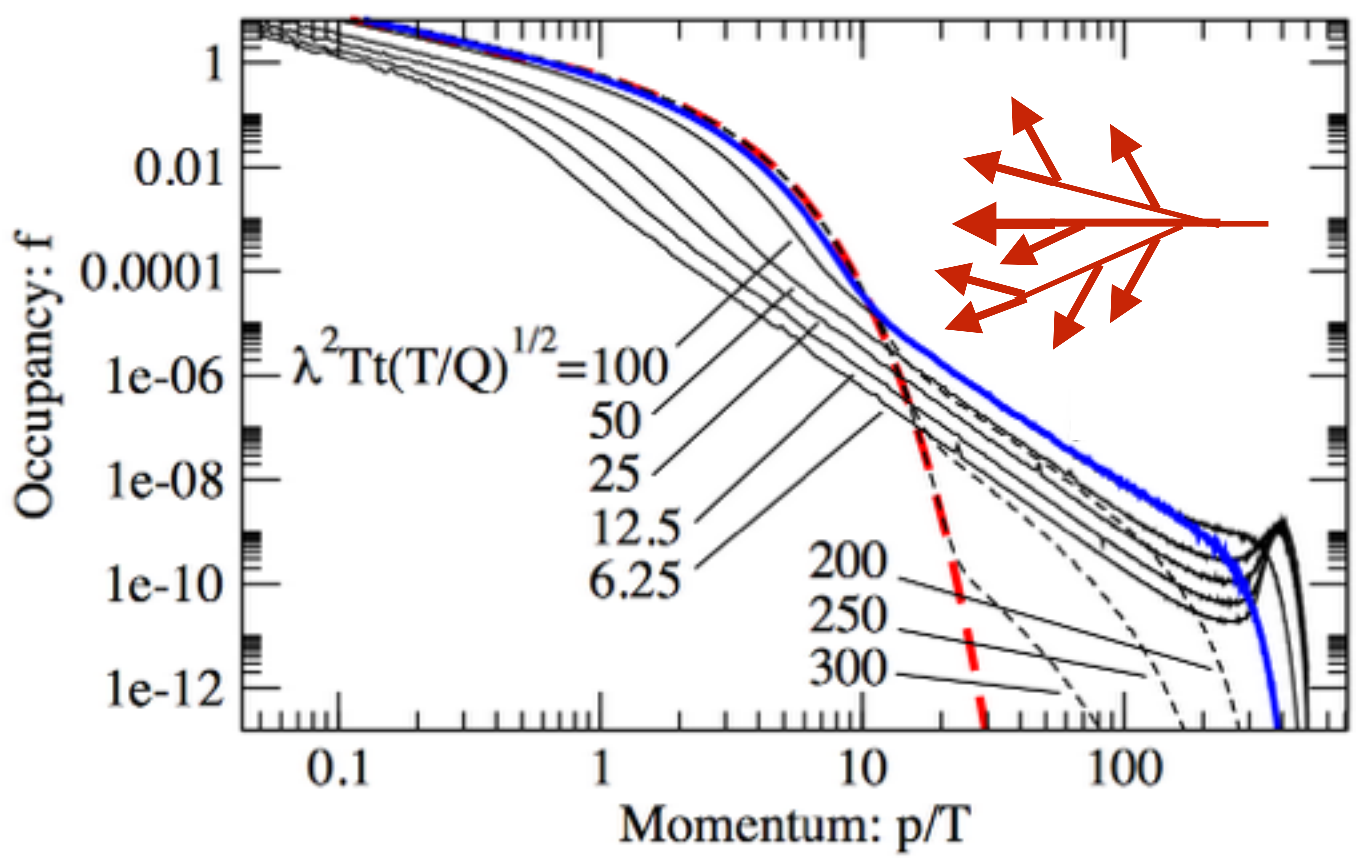
Evolution time: τ

Need to switch from classical Yang-Mills to kinetic description
to describe approach to equilibrium

Quantum regime ($Q_s\tau > \alpha_s^{-3/2}$)

Inelastic processes dominate and lead to a radiative break-up

-> mini-jets loose all their energy to soft thermal bath



Kurkela, Lu PRL 113 (2014) 182301

equilibration <-> (mini-) jet quenching

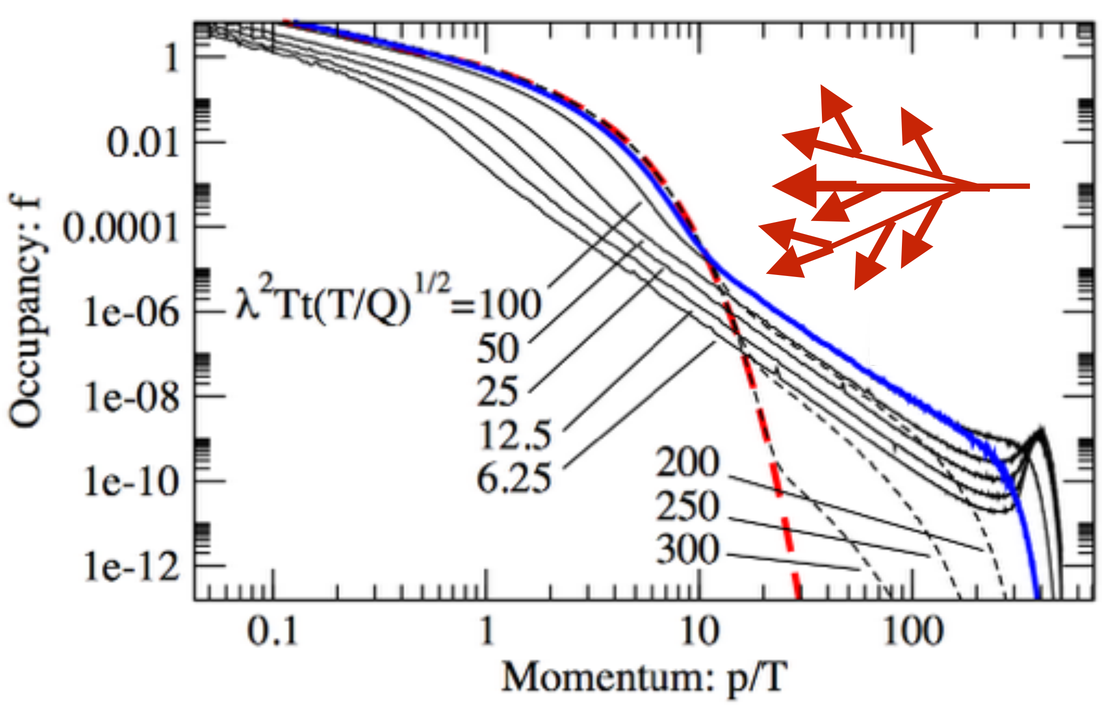
Quantum regime ($Q_s\tau > \alpha_s^{-3/2}$)

Inelastic processes dominate and lead to a radiative break-up

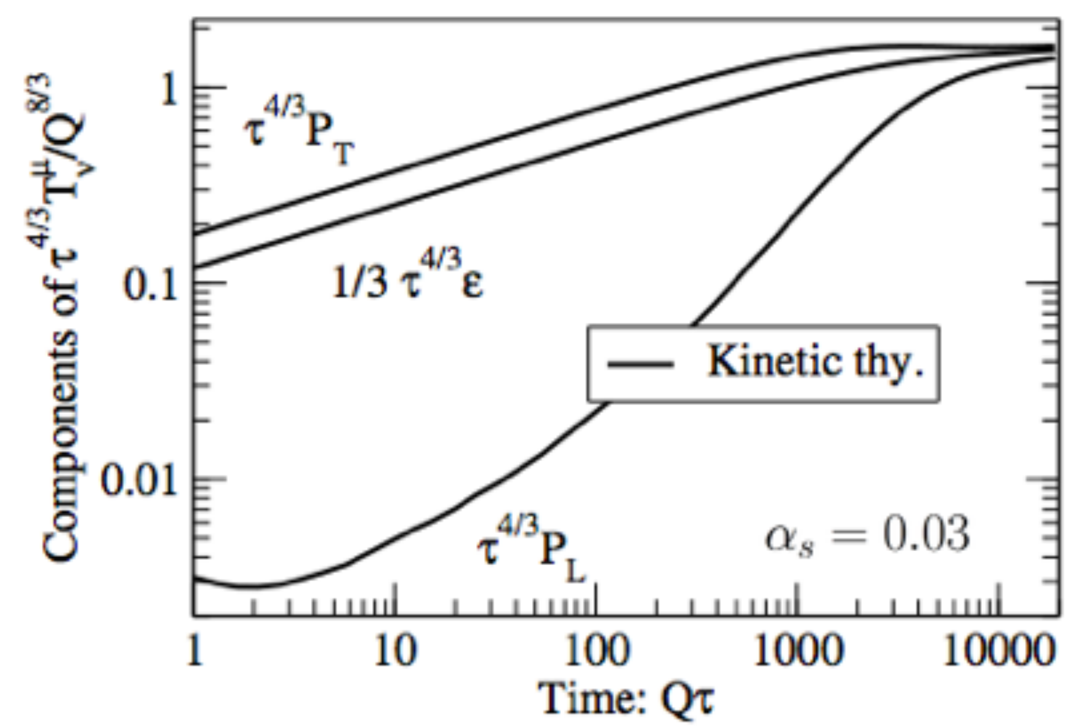
-> mini-jets loose all their energy to soft thermal bath

Soft bath heating up due to energy deposited by mini-jets

-> longitudinal pressure rises and system isotropizes



Kurkela, Lu PRL 113 (2014) 182301



Kurkela, Zhu PRL 115 (2015) 182301

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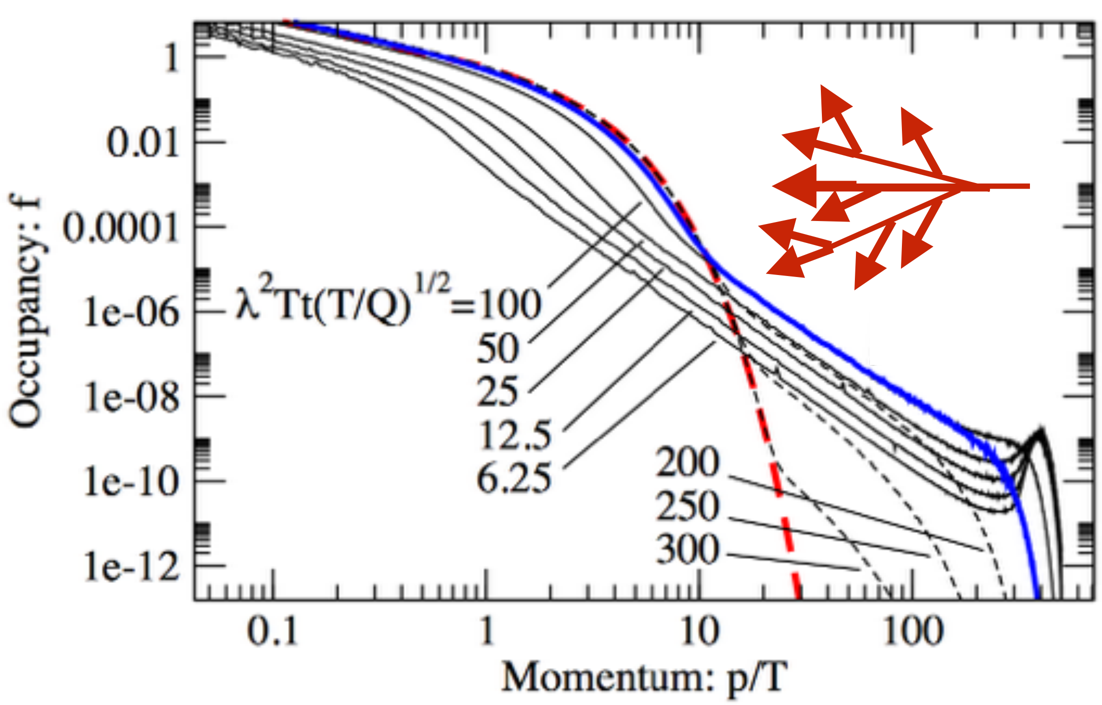

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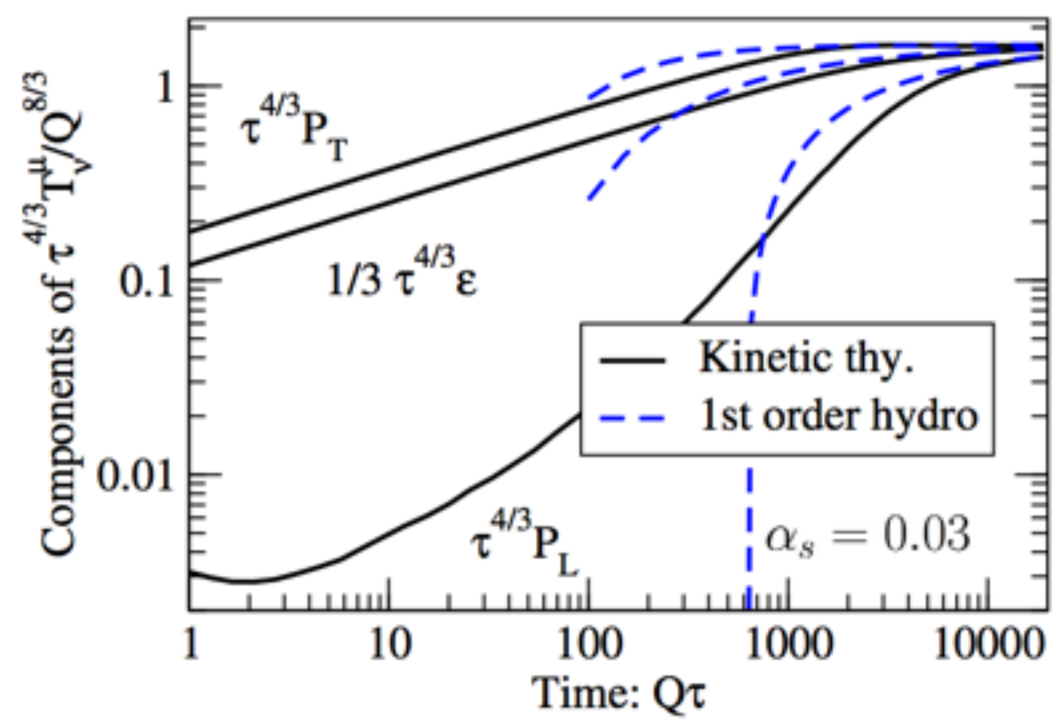

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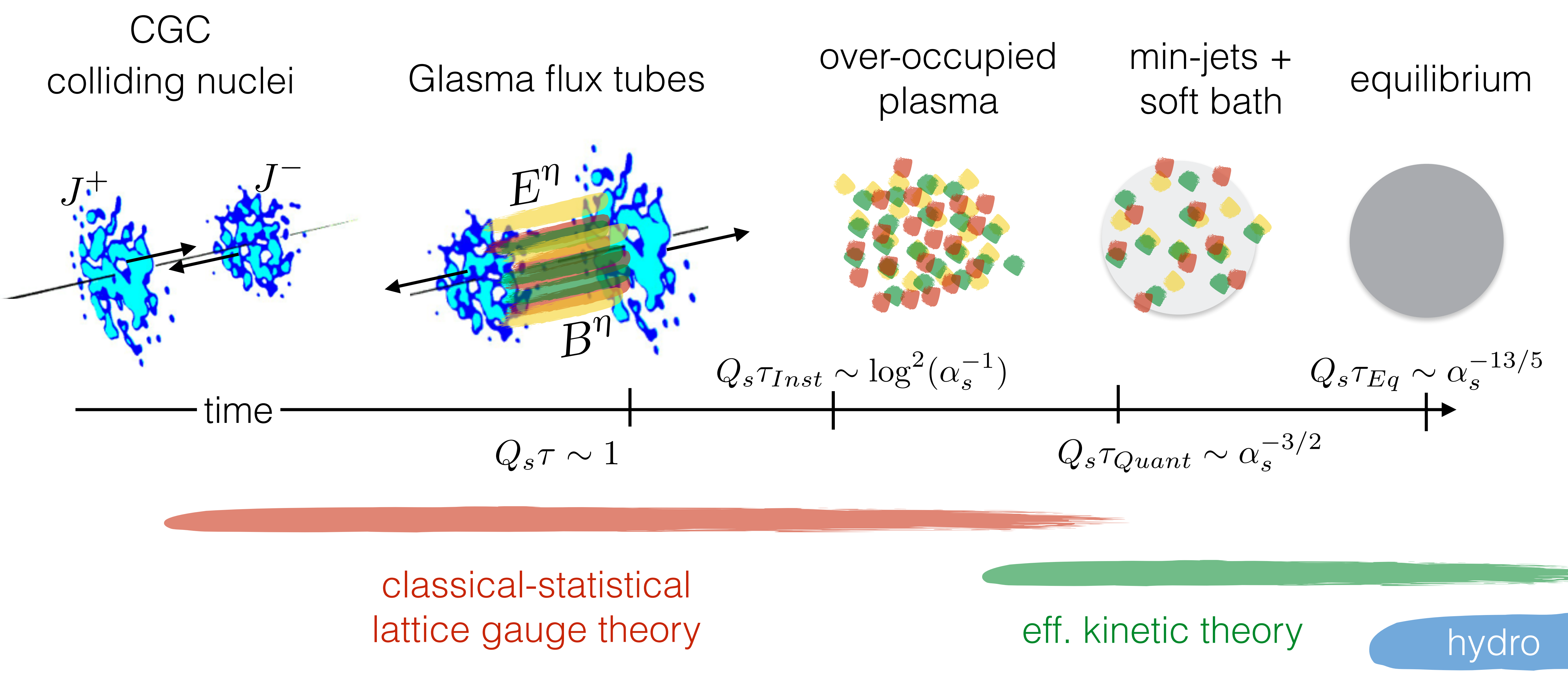
-> smooth matching to hydro-dynamics (no free parameters)

Equilibration process

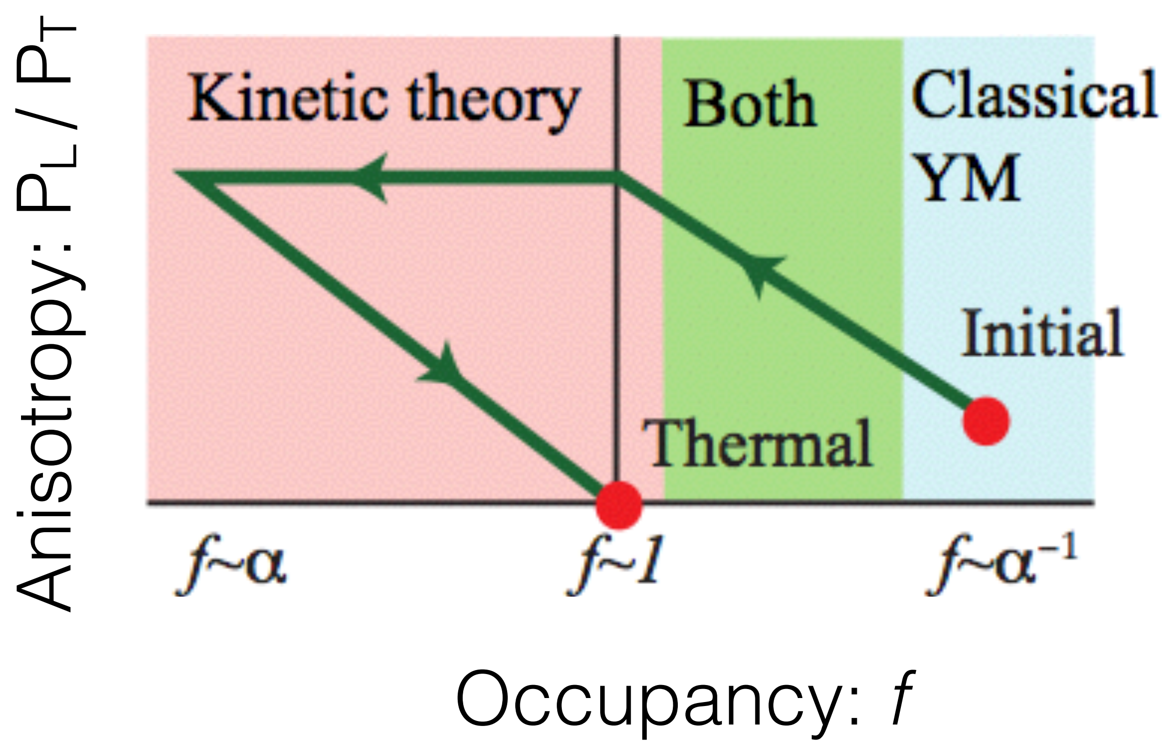
Clear understanding of the dynamics in the weak-coupling limit

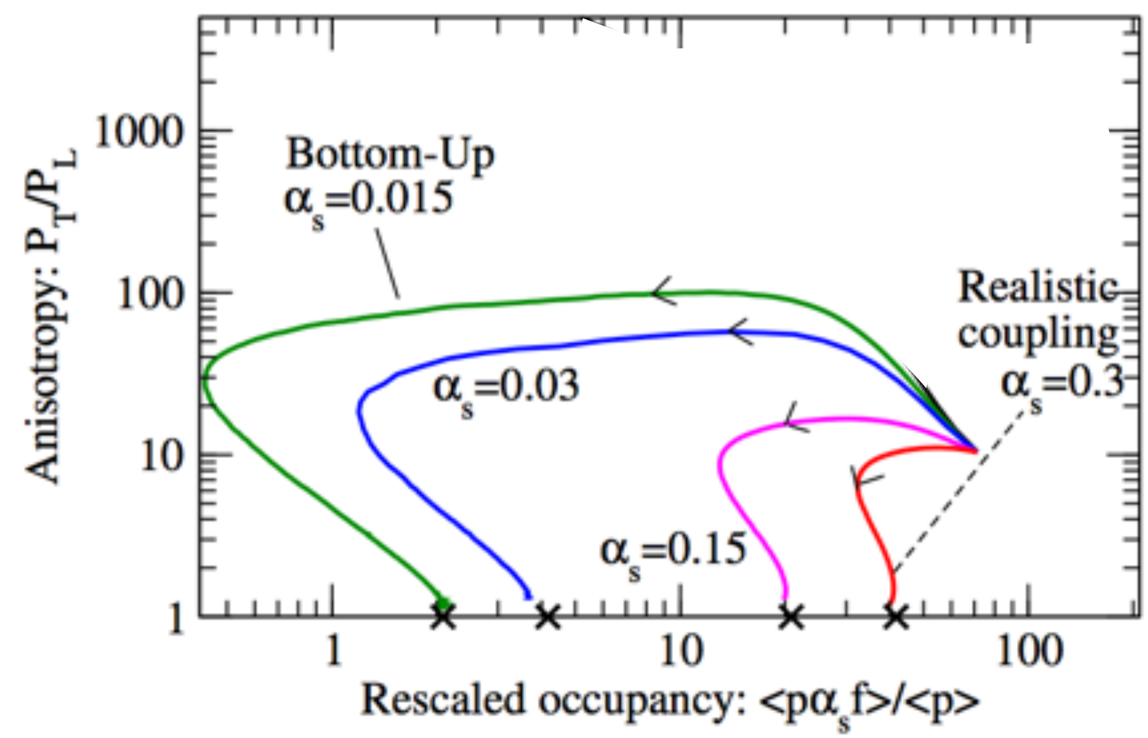


Developed the tools to compute equilibration process from combination of weak-coupling methods

Beyond weak coupling

Extrapolate leading order weak coupling description to physical values α_s=0.3





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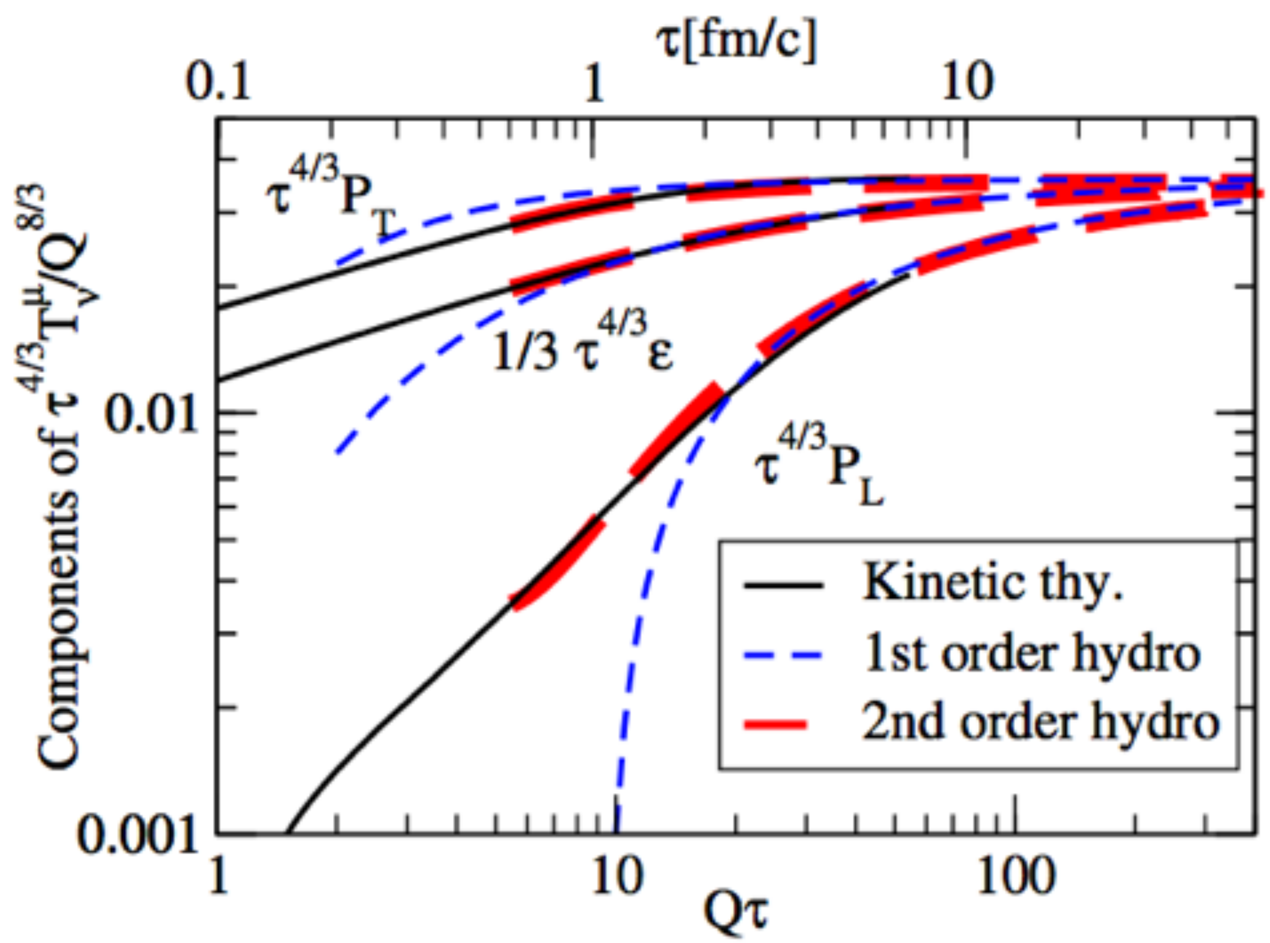
Even though distinctions become less clear
basic mechanism remains the same

Onset of hydrodynamics



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Smooth matching to second order viscous hydrodynamics on a time scale ~1 fm/c

(c.f. talk by Yan Zhu)

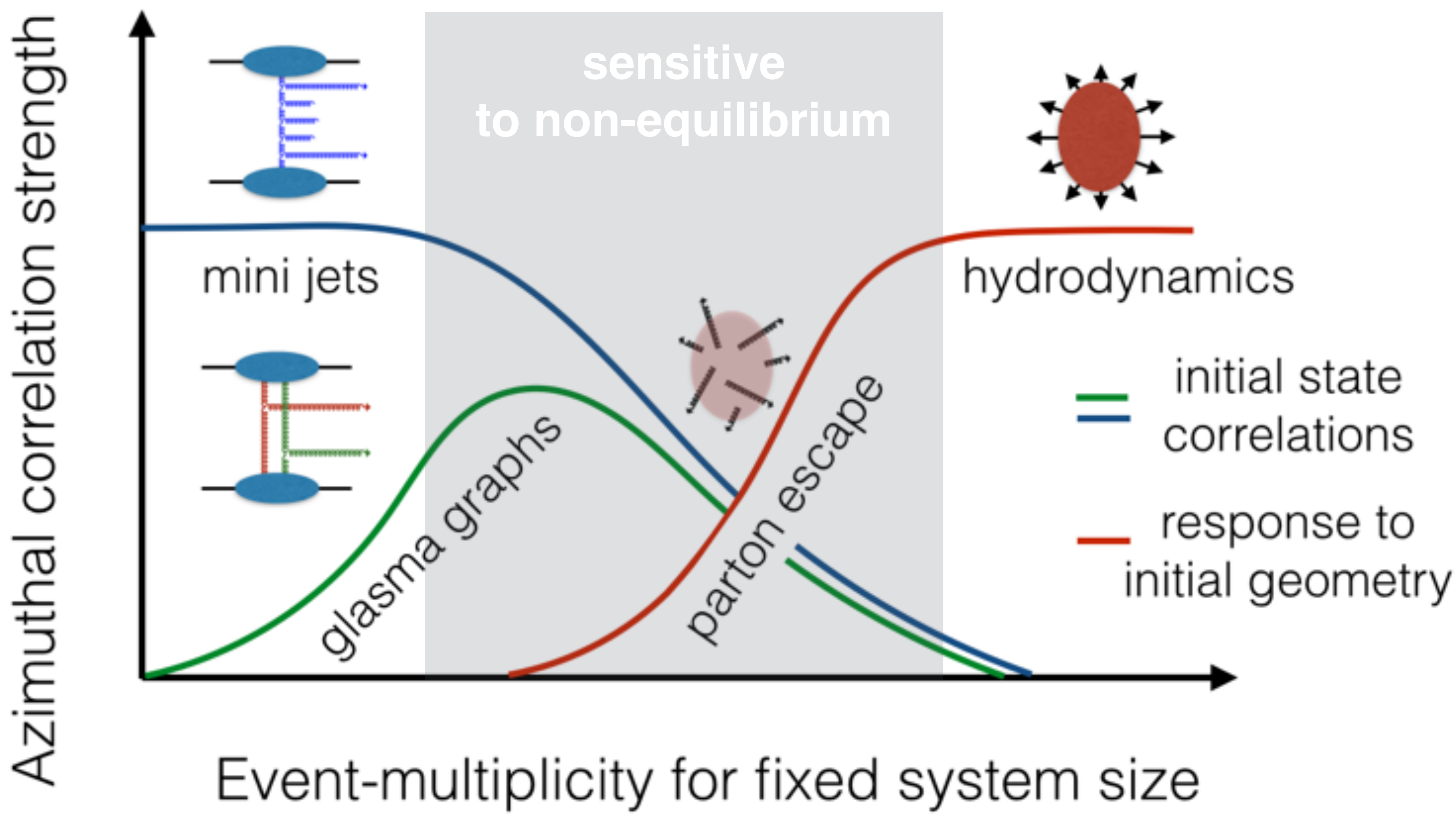
Pressure evolution matches for $P_L/P_T \sim 1/5$

-> Equilibration takes much longer than ~1 fm/c for expanding system

Initial conditions for hydro from weak-coupled equilibrium dynamics

(c.f. talk by Aleksas Mazeliauskas)

Exploring pre-equilibrium dynamics in small systems?



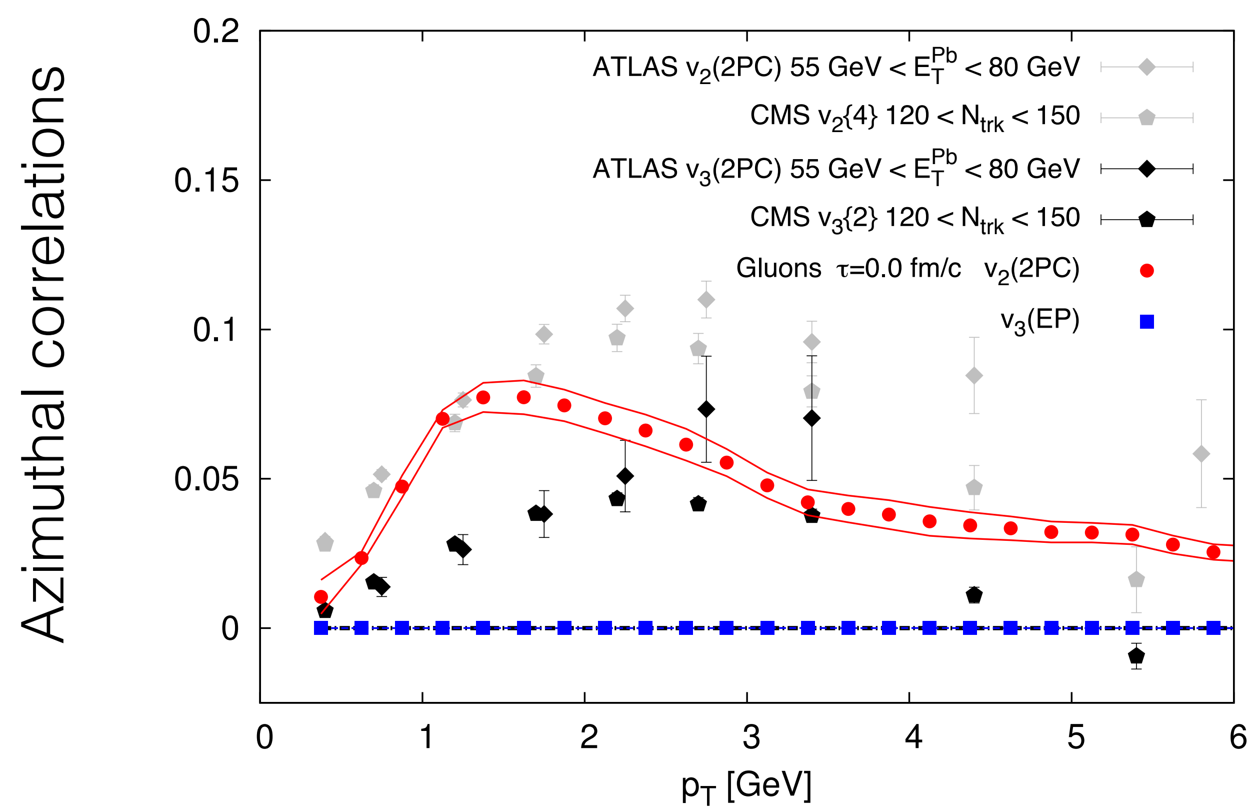
-> Small systems provide a unique laboratory to probe early time dynamics.

(SS arXiv:1601.01177)

Early time dynamics in p+A

Initial state immediately after the collision ($\tau=0^+$)

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

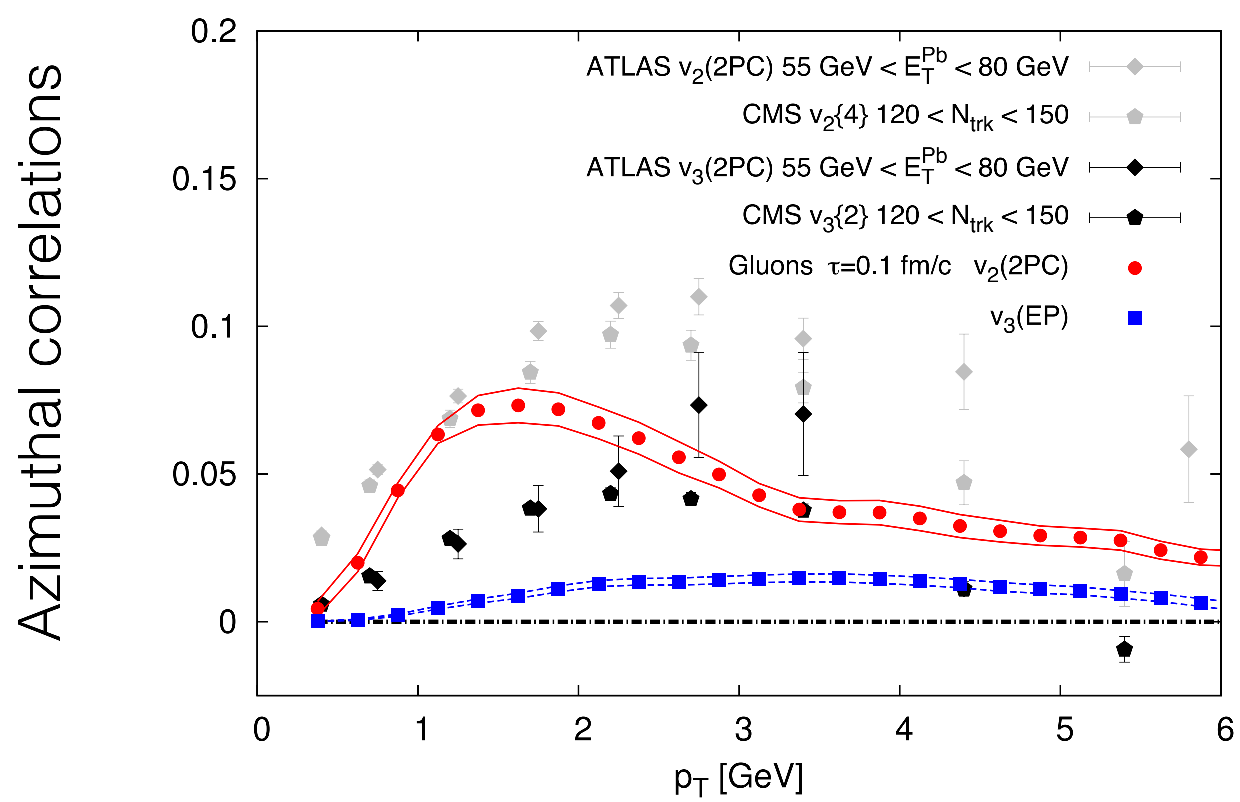


-> Significant momentum space correlations v_2 at $\tau=0$ due to production mechanism.

-> No odd harmonics for gluons without final-state interactions. Initial spectrum symmetric under $\mathbf{k}_T$<->-$\mathbf{k}_T$

Early time dynamics in p+A

Classical Yang-Mills evolution after the collision
— includes re-scattering of produced gluons



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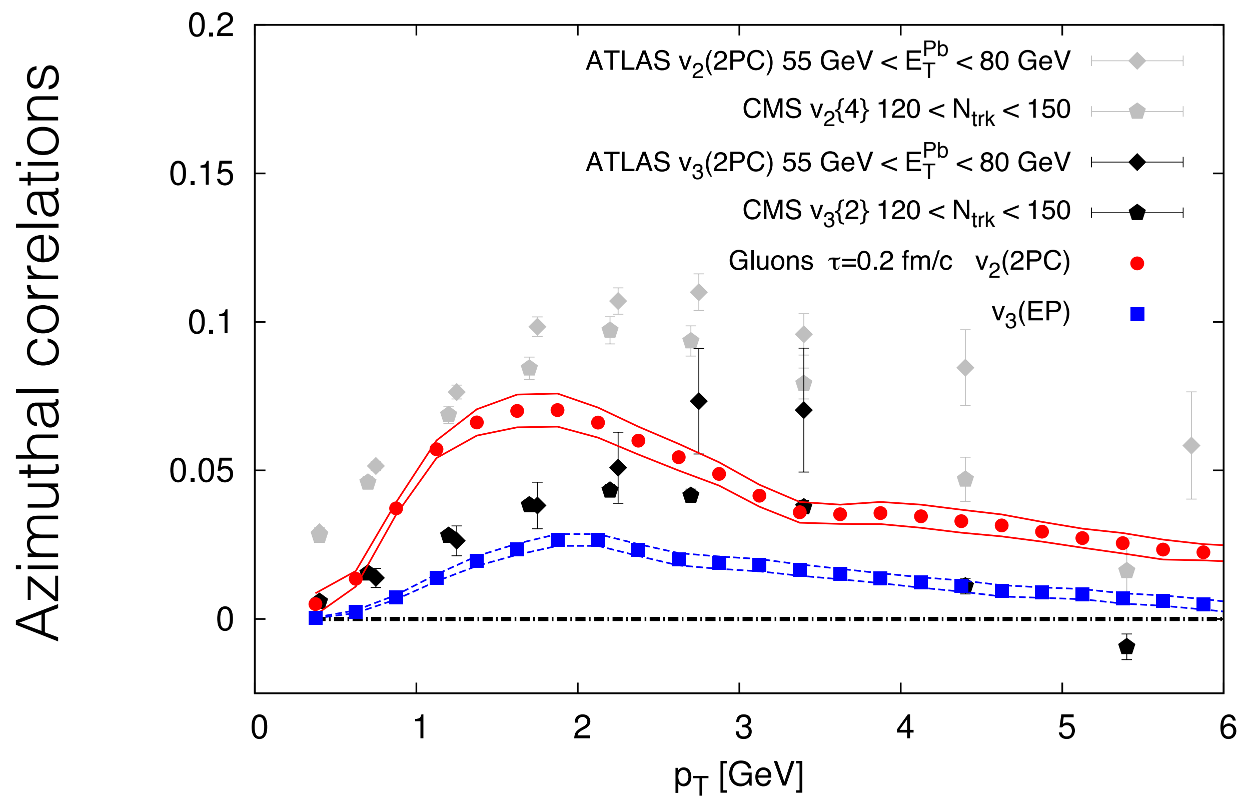

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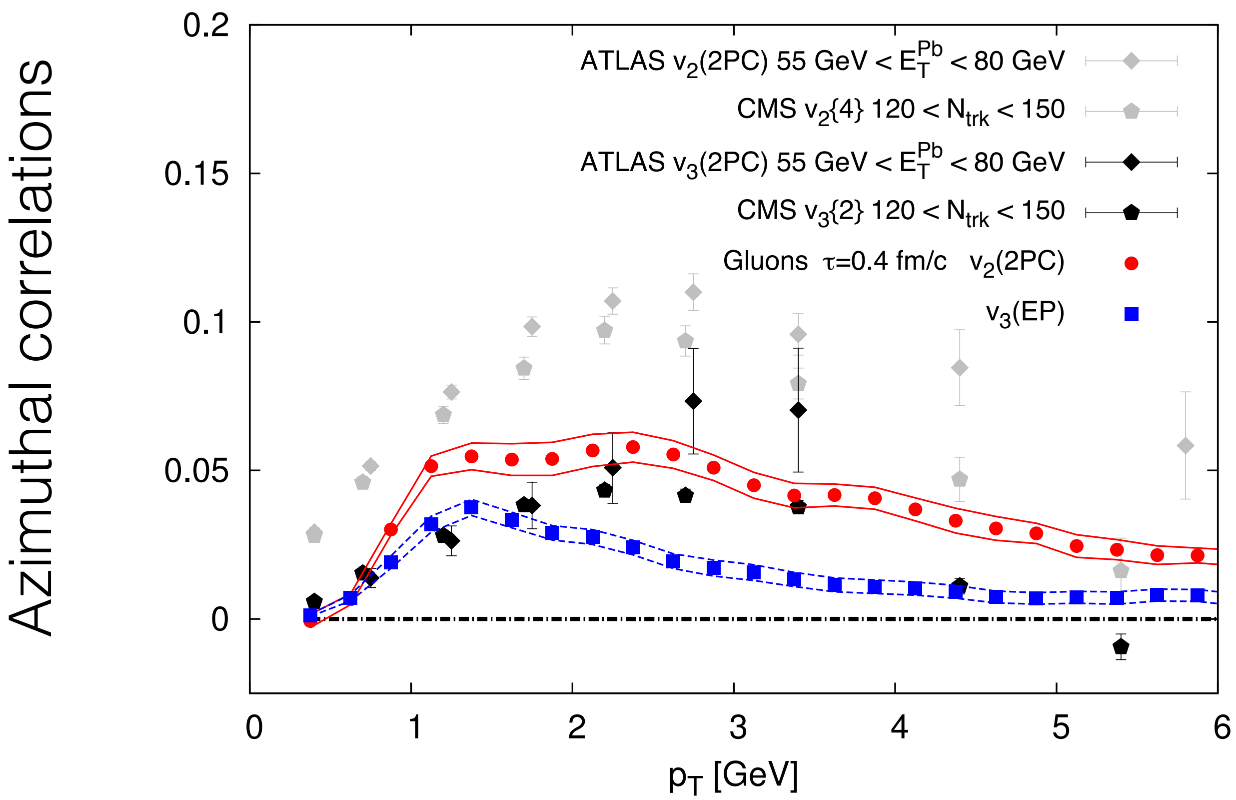


-> Clear modifications of correlations due to pre-equilibrium dynamics on a time scale ~0.4 fm/c

Quantitative understanding requires theoretical description which consistently takes into account initial state and final state effects.

Conclusions & Outlook

Development of leading order weak-coupling approach to equilibrium

-> first results look promising in terms of phenomenology

Ultimate goal: Qualitative insights -> Quantitative framework

-> Screening in anisotropic plasmas

-> Quarks & chemical evolution

-> 3D structure of Glasma fields

Several applications beyond bulk phenomenology

-> small systems

-> electromagnetic & hard probes

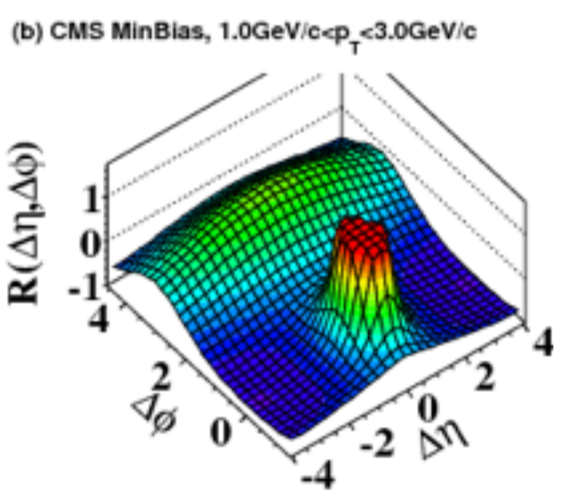
-> sphaleron transitions & chiral magnetic effect

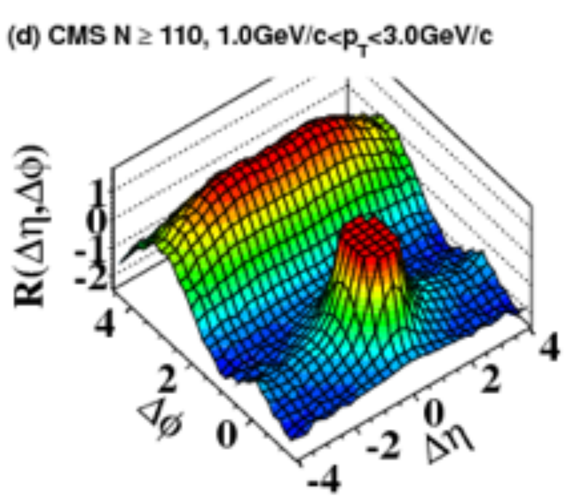
(Mace,SS,Venugopalan PRD93 (2016) 074036 ; Mueller,SS,Sharma in preparation)

Backup

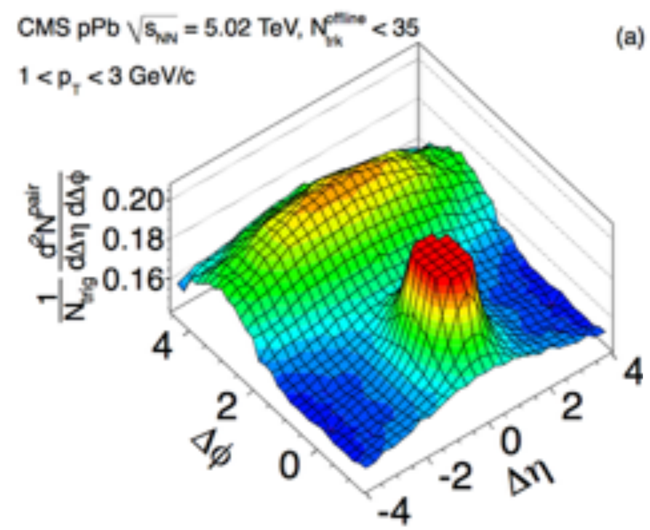
The ridge in p+p,p+Pb & Pb+Pb

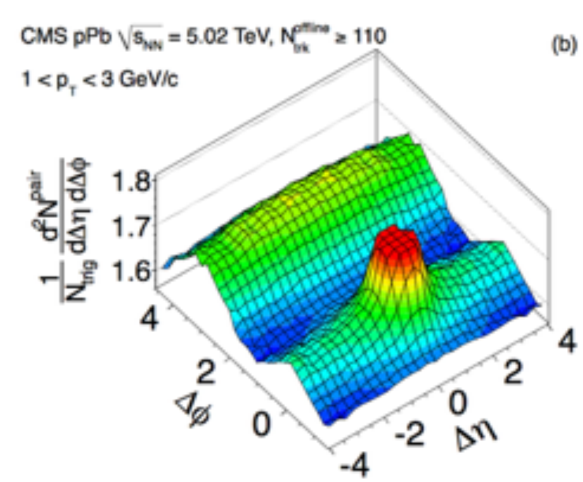
p+p @ 7 TeV



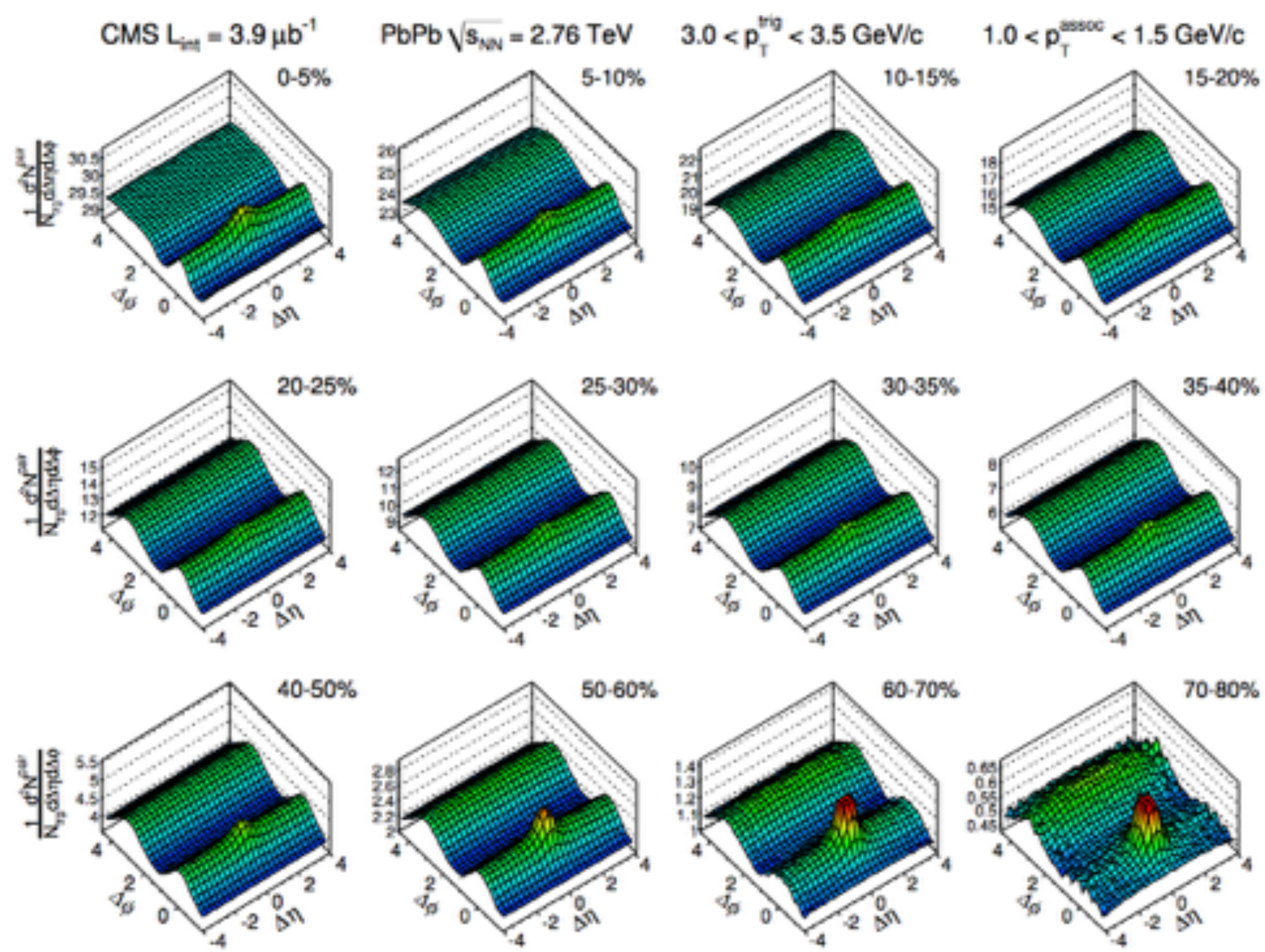


p+Pb @ 5.02 TeV



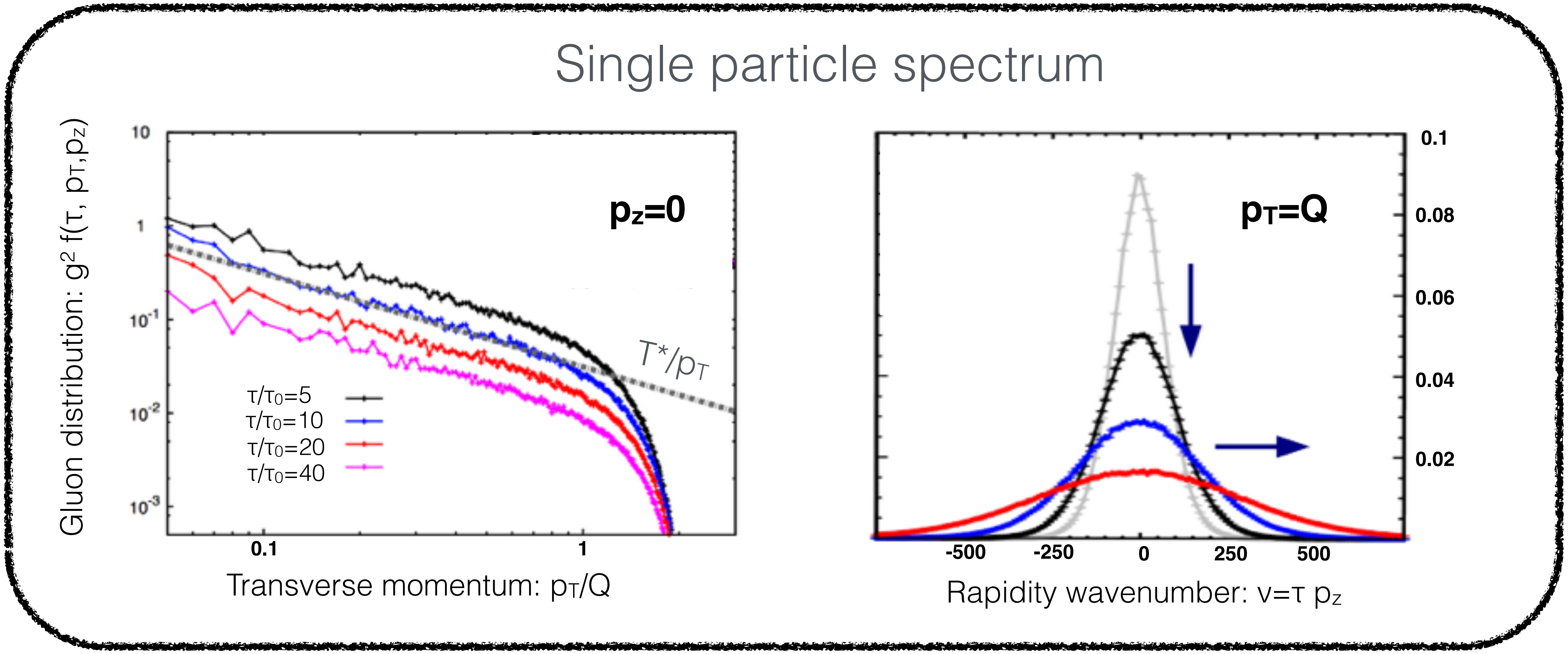


Pb+Pb @ 2.76 TeV



Gluon spectra

Evolution in classical regime

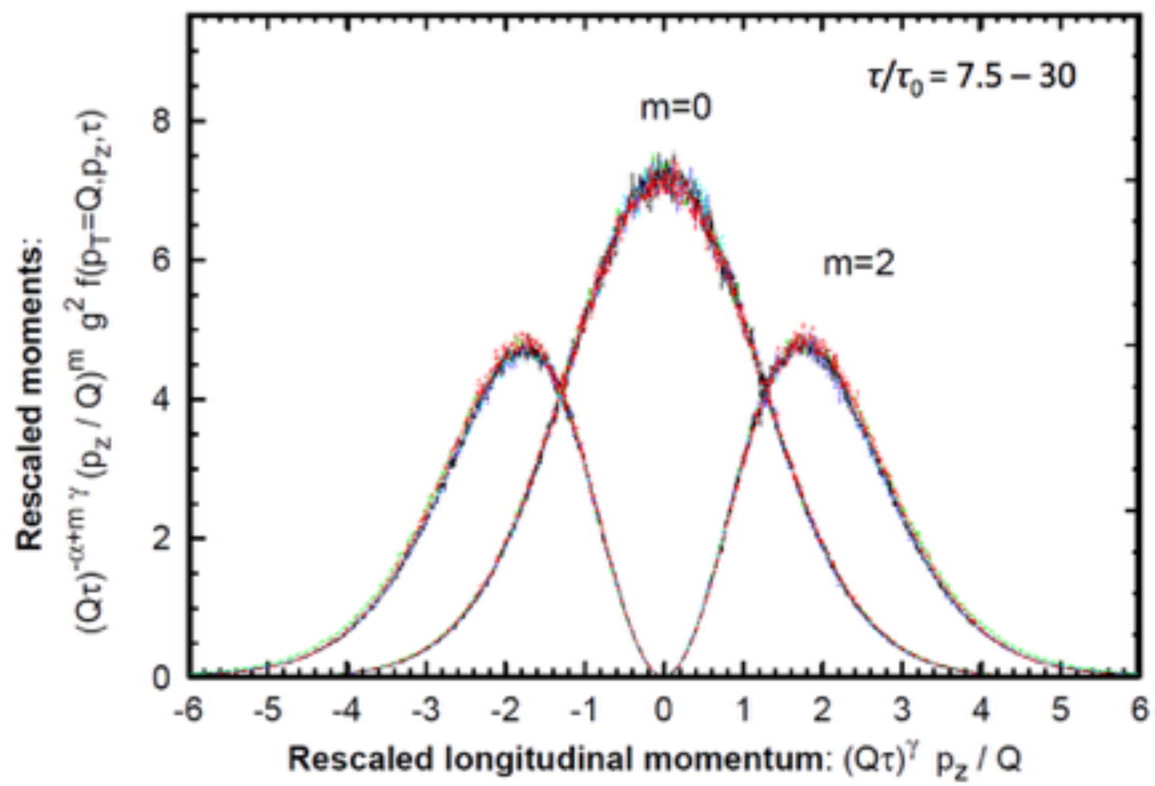


Transverse spectrum shows thermal-like $1/p_T$ behavior up to Q_s.

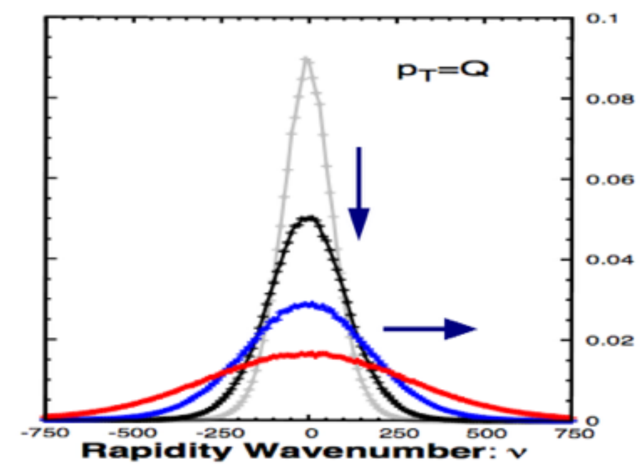
Dynamics in the scaling regime consists of *longitudinal momentum broadening* — not strong enough to completely compensate for red-shift due to longitudinal expansion

(Berges,Boguslavski,SS,Venugopalan PRD 89 (2014) 074011; 89 (2014) 114007)

Self-similarity



rescaling



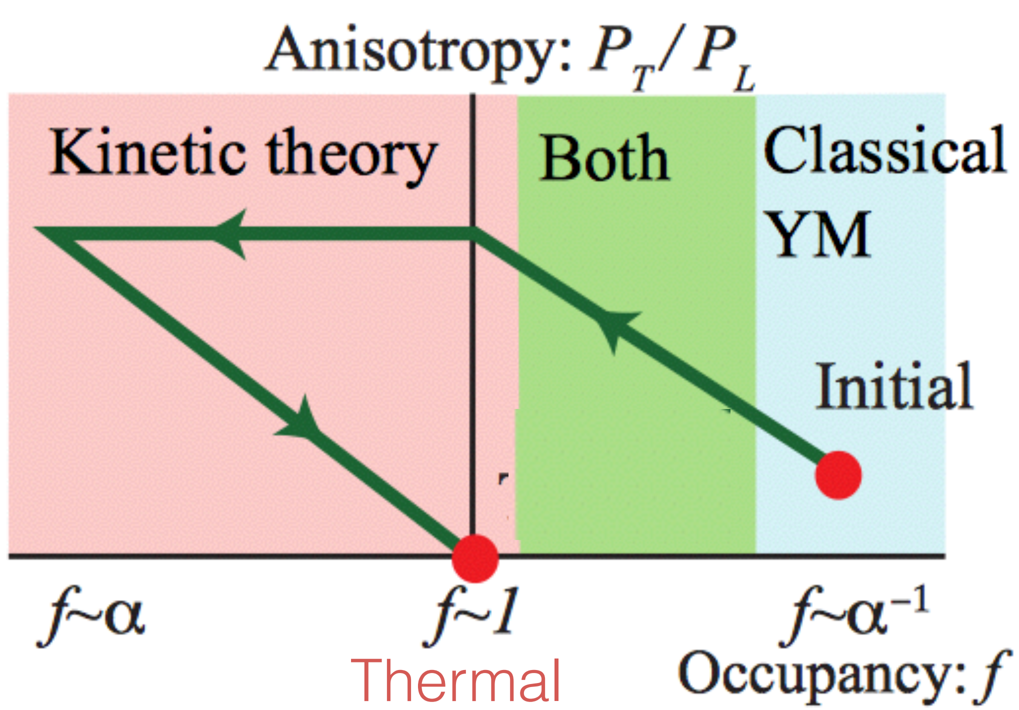
Dynamics can be entirely described in terms of universal scaling exponents *α=-2/3, β=0, γ=1/3* and scaling function *f_S* extracted from simulations

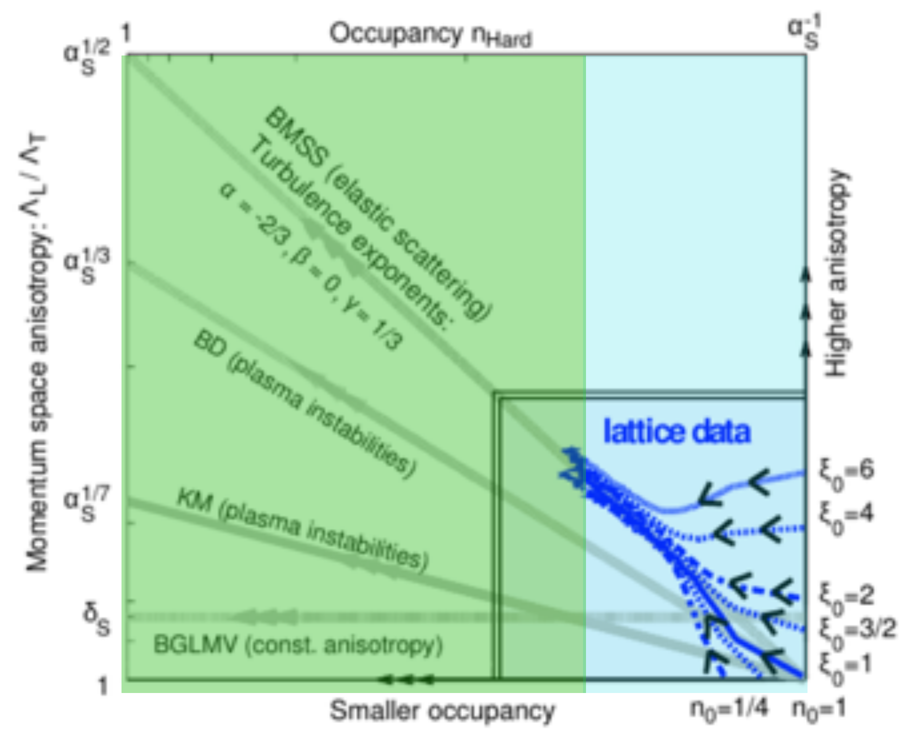
$$f(p_T, p_z, \tau) = (Q\tau)^{\alpha} f_S\Big((Q\tau)^{\beta} p_T, (Q\tau)^{\gamma} p_z\Big)$$

(Berges,Boguslavski,SS,Venugopalan PRD 89 (2014) 074011; 89 (2014) 114007)

Quantum regime

Equilibration process

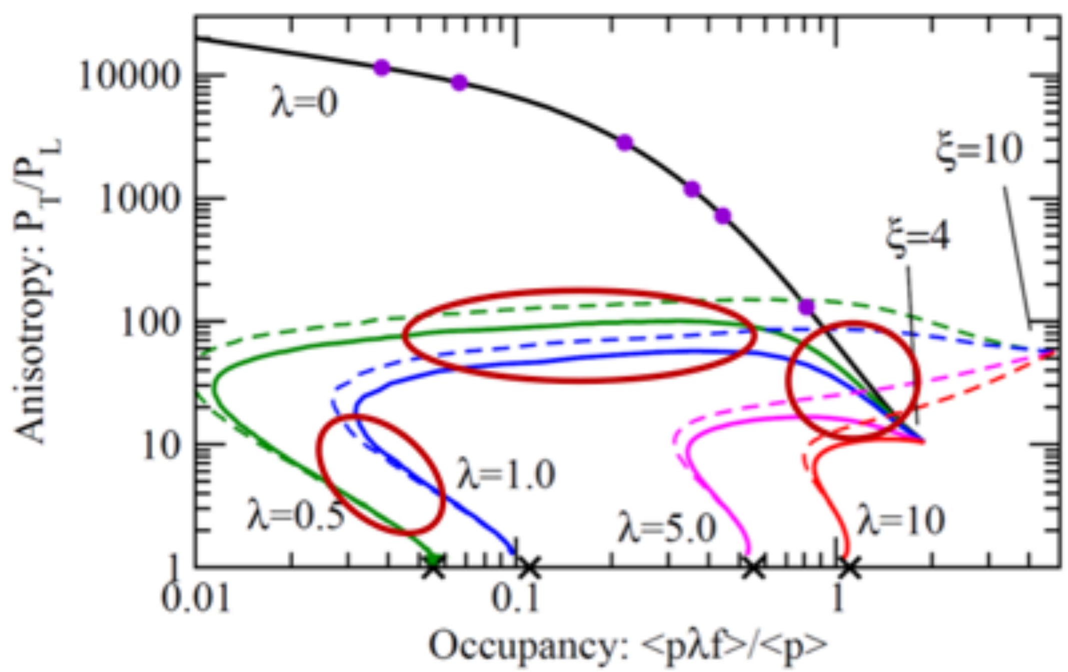




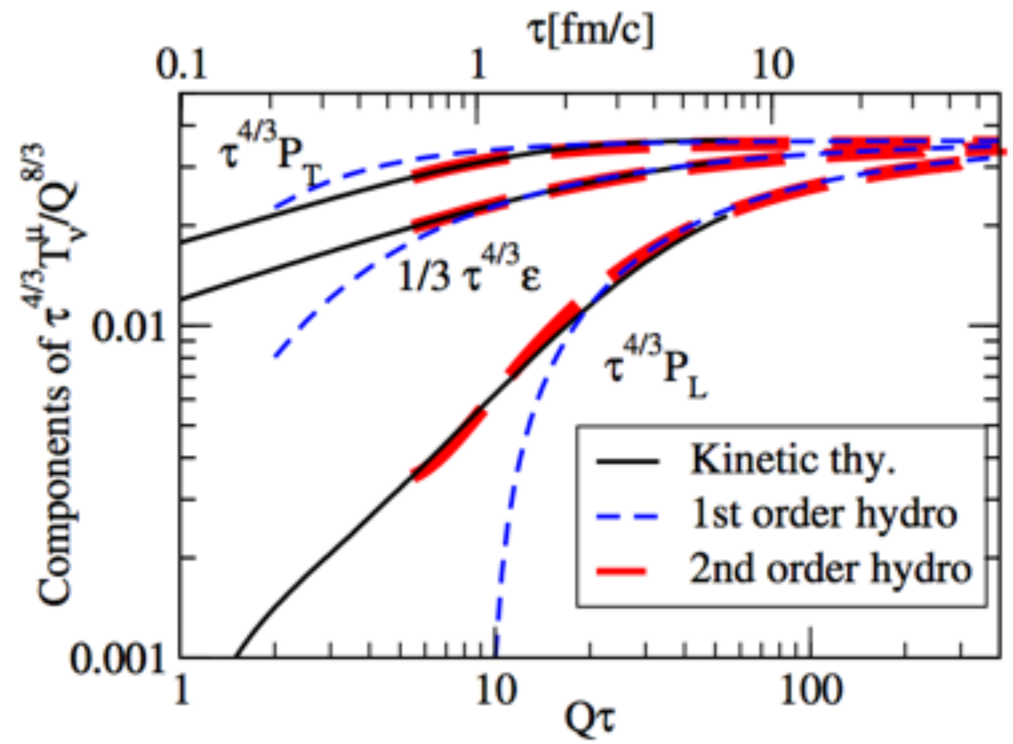
Quantum regime

- Numerical study of effective kinetic description (AMY 2<->2 + eff. coll. 1<->2)

Kurkela & Zhu PRL 115 (2015) 18, 182301



Clear observation of the three distinct stages of “bottom up” scenario



Hydrodynamic behavior on time scales ~1 fm/c when extrapolating weak coupling description to α_s =0.3

-> Viscous hydrodynamics applicable already for large pressure anisotropies

Expanding scalars & Universality

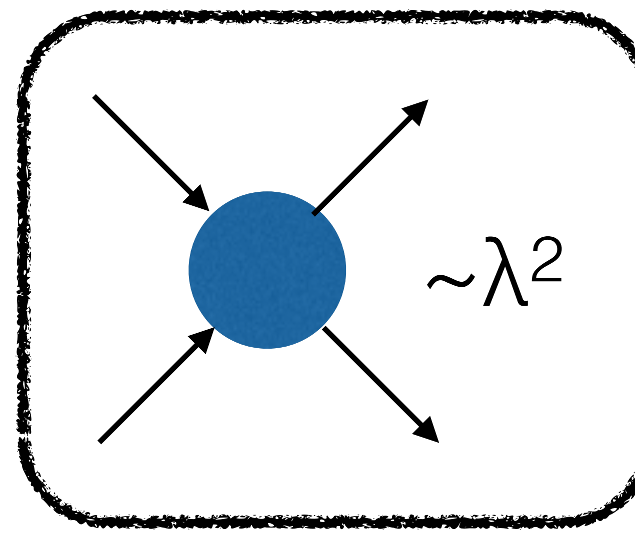
Expanding scalar field theory

Consider massless N-component scalar field theory with quartic self-interaction

$$\boxed{S[\varphi] = \int d^4x \sqrt{-g(x)} \left(\frac{1}{2}(\partial_\mu \varphi_a) g^{\mu\nu} (\partial_\nu \varphi_a) - \frac{\lambda}{24N} (\varphi^2)^2 \right)}$$

in a longitudinally expanding setup.

Even though perturbatively there is no preference for small angle scattering, one at least expects elastic processes to dominate



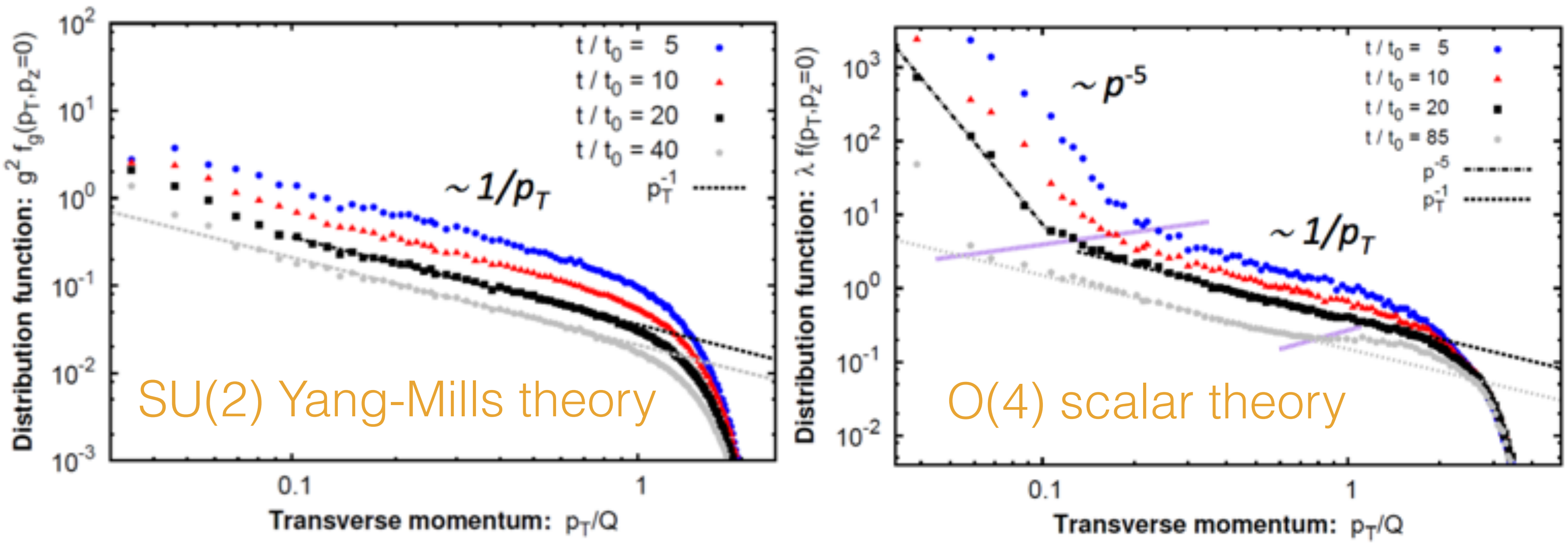
-> Energy conservation
& Particle number conservation

(Berges,Boguslavski,SS,Venugopalan PRL114 (2015) 061601)

Comparison of simulations

Comparison of longitudinally expanding Yang-Mills and scalar field theory in the classical regime of high occupancy

Evolution of the single particle spectrum



Scalar theory shows three distinct scaling regimes at soft ($\sim p^{-5}$), intermediate ($\sim 1/p_T$) and hard momenta ($\sim$const)

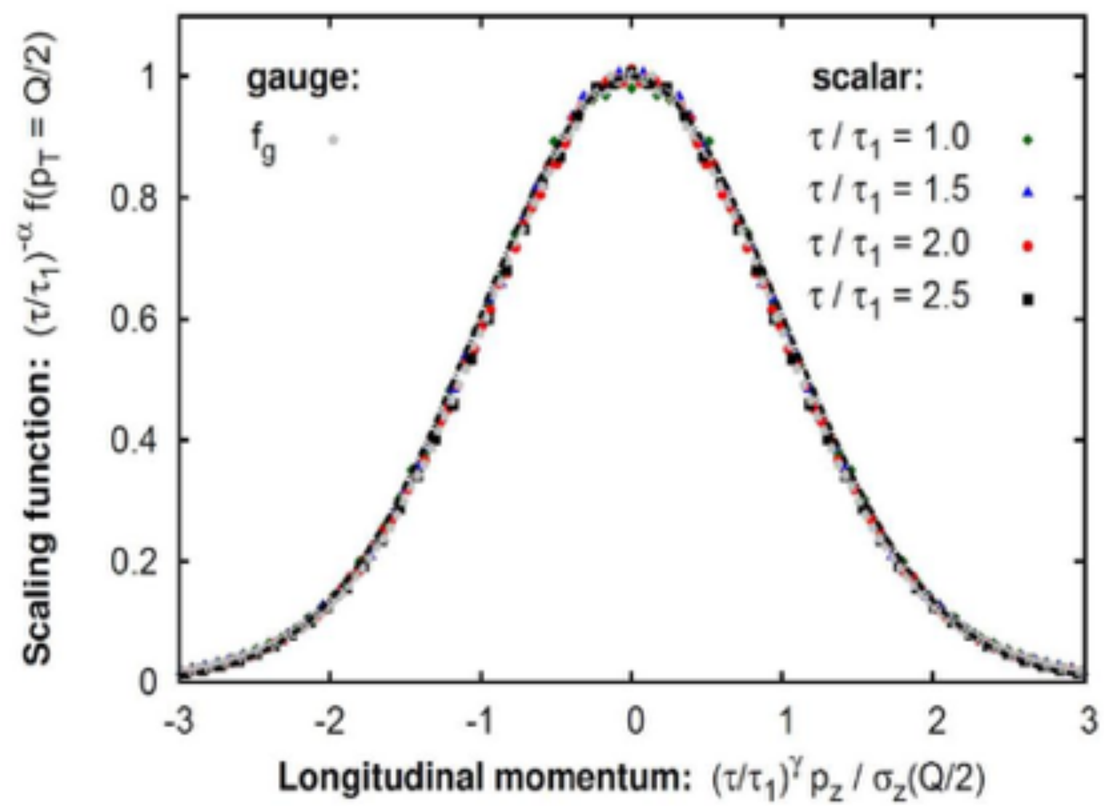
->Common $\sim 1/p_T$ scaling regime

(Berges,Boguslavski,SS,Venugopalan PRL114 (2015) 061601)

Universality far from equilibrium

Scaling exponents and scaling functions agree in the inertial range of momenta, where both theories show $1/p_T$ behavior

Normalized fixed-point distribution

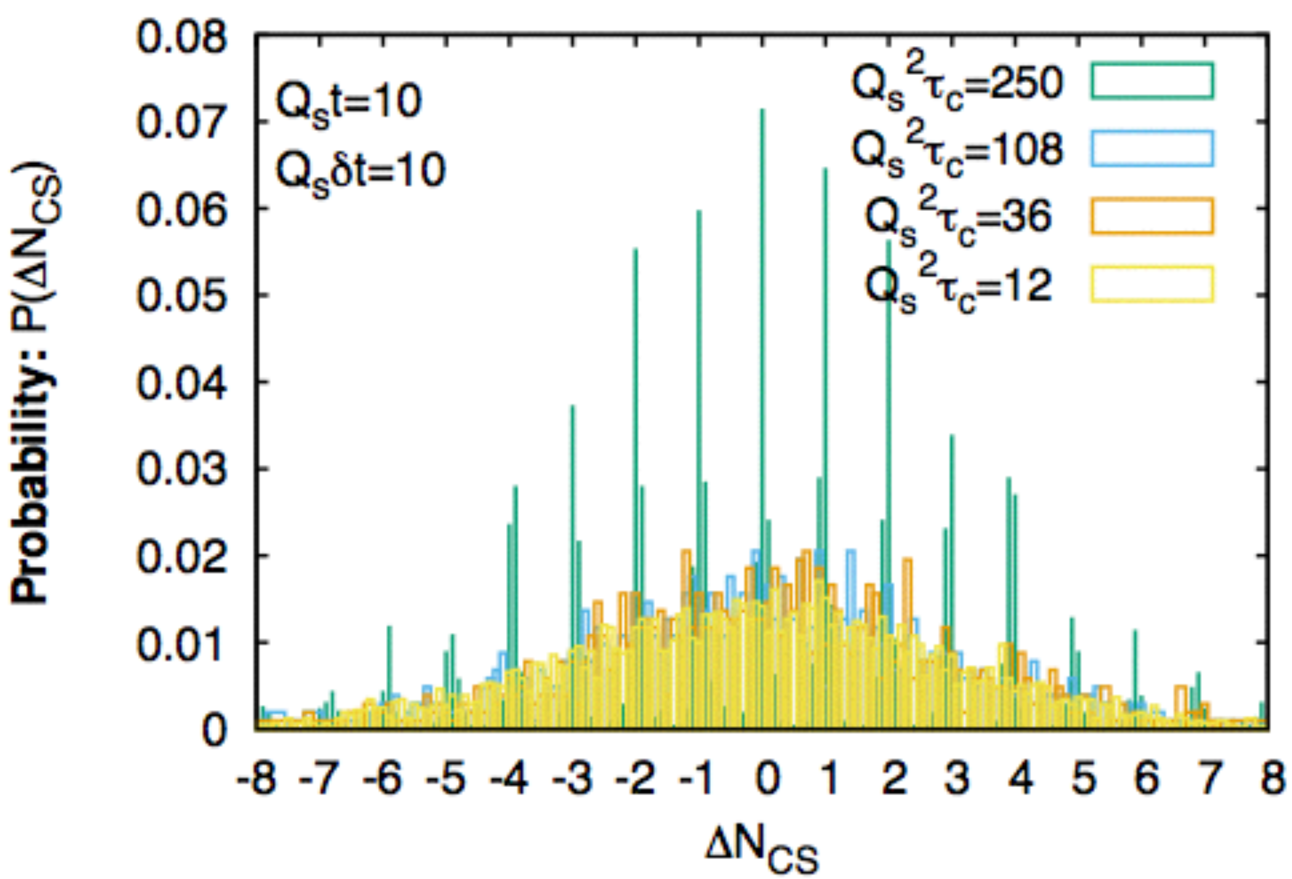


(Berges,Boguslavski,SS,Venugopalan PRL114 (2015) 061601)

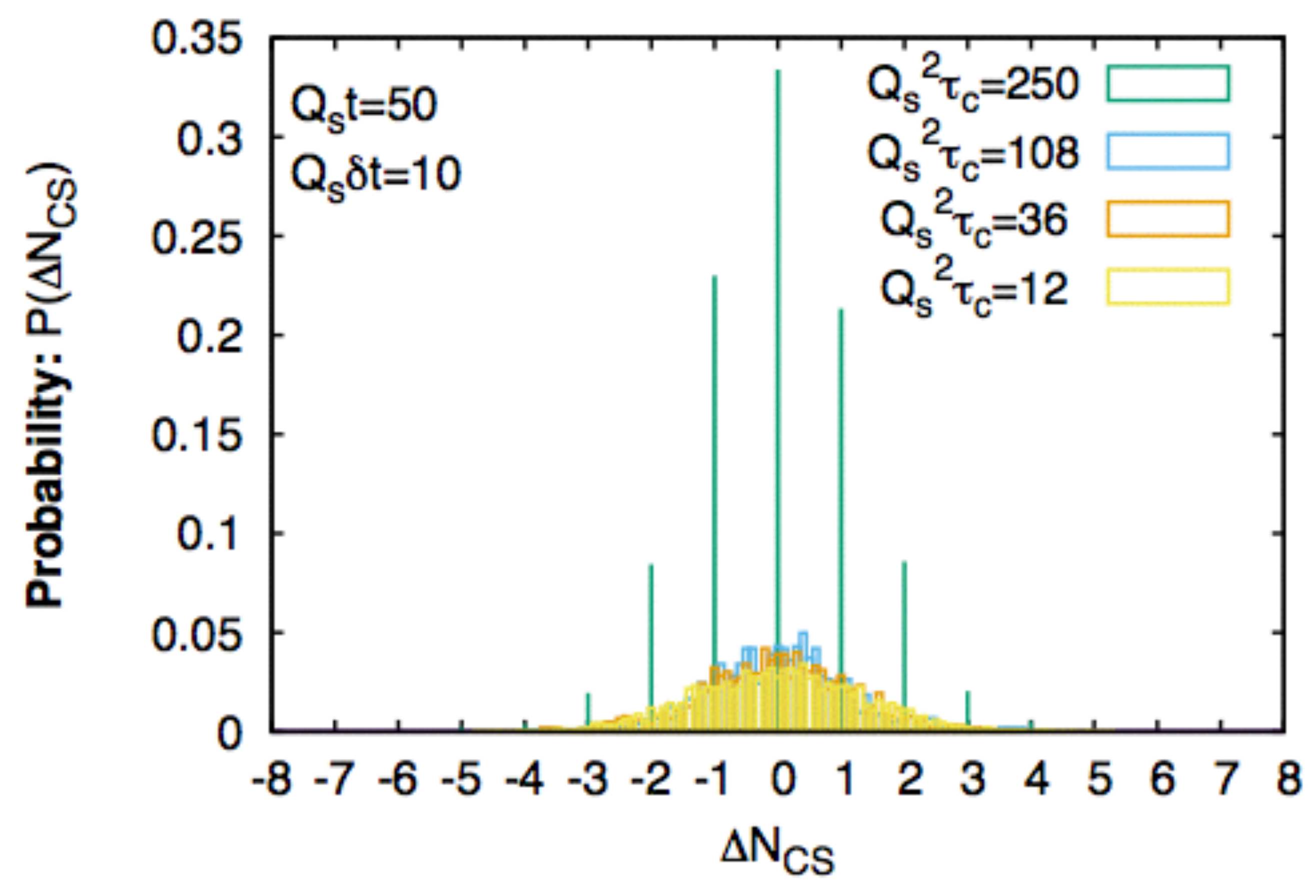
Sphalerons & CME

Chern-Simons number Histograms

Generated early (10<Qt<20)



Generated later (50<Qt<60)



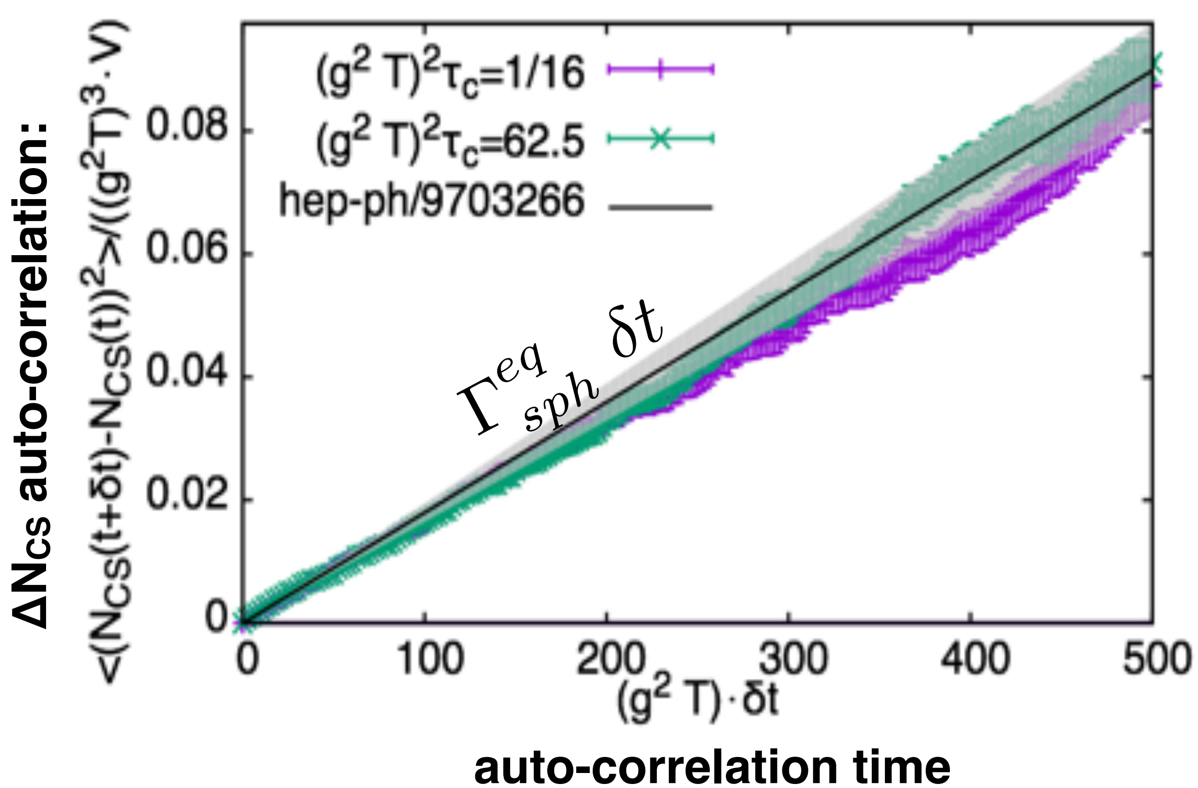
-> Early times dominate generation of axial charge imbalance

Quantifying the sphaleron rate

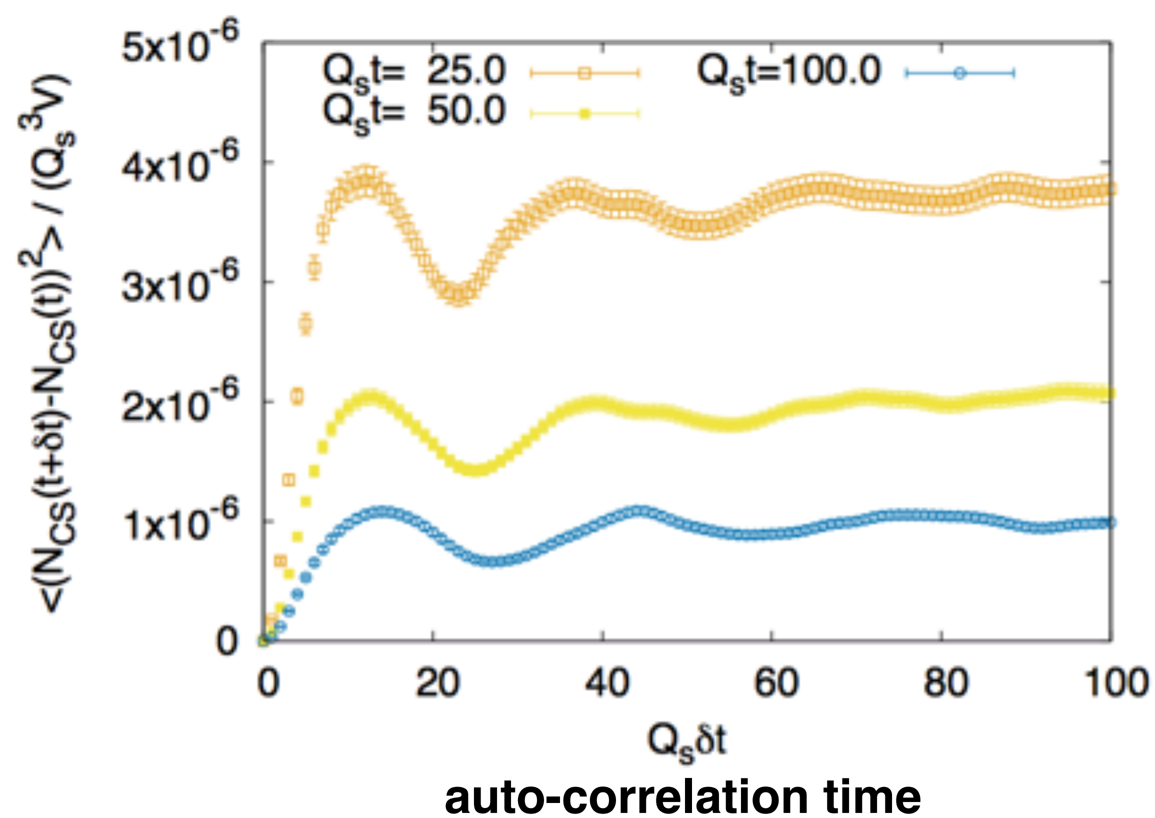
Extract auto-correlation function of the Chern-Simons number

$$\frac{1}{V}\left\langle \left(N_{CS}(t+\delta t) - N_{CS}(t)\right)^2 \right\rangle = \Gamma^{eq}_{sph}\,\delta t$$

Equilibrium:



Glasma:



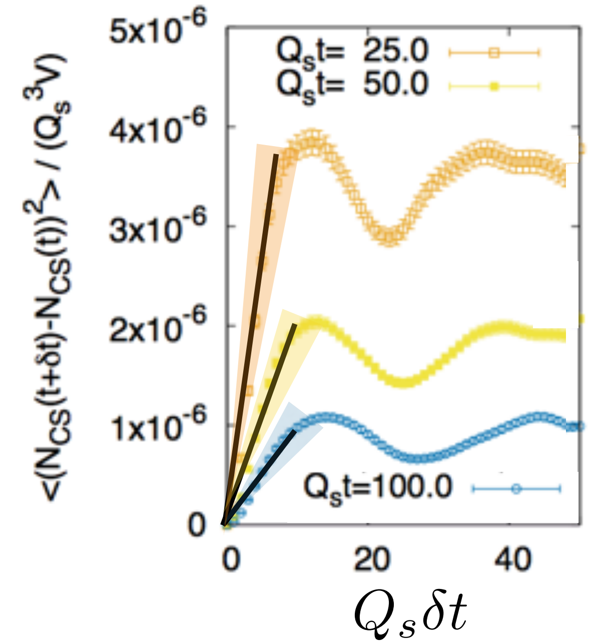
-> Simple probabilistic picture not applicable in the Glasma — clear non-Markovian emerge from the auto-correlation function

Mace, SS, Venugopalan [arXiv:1601.07342]

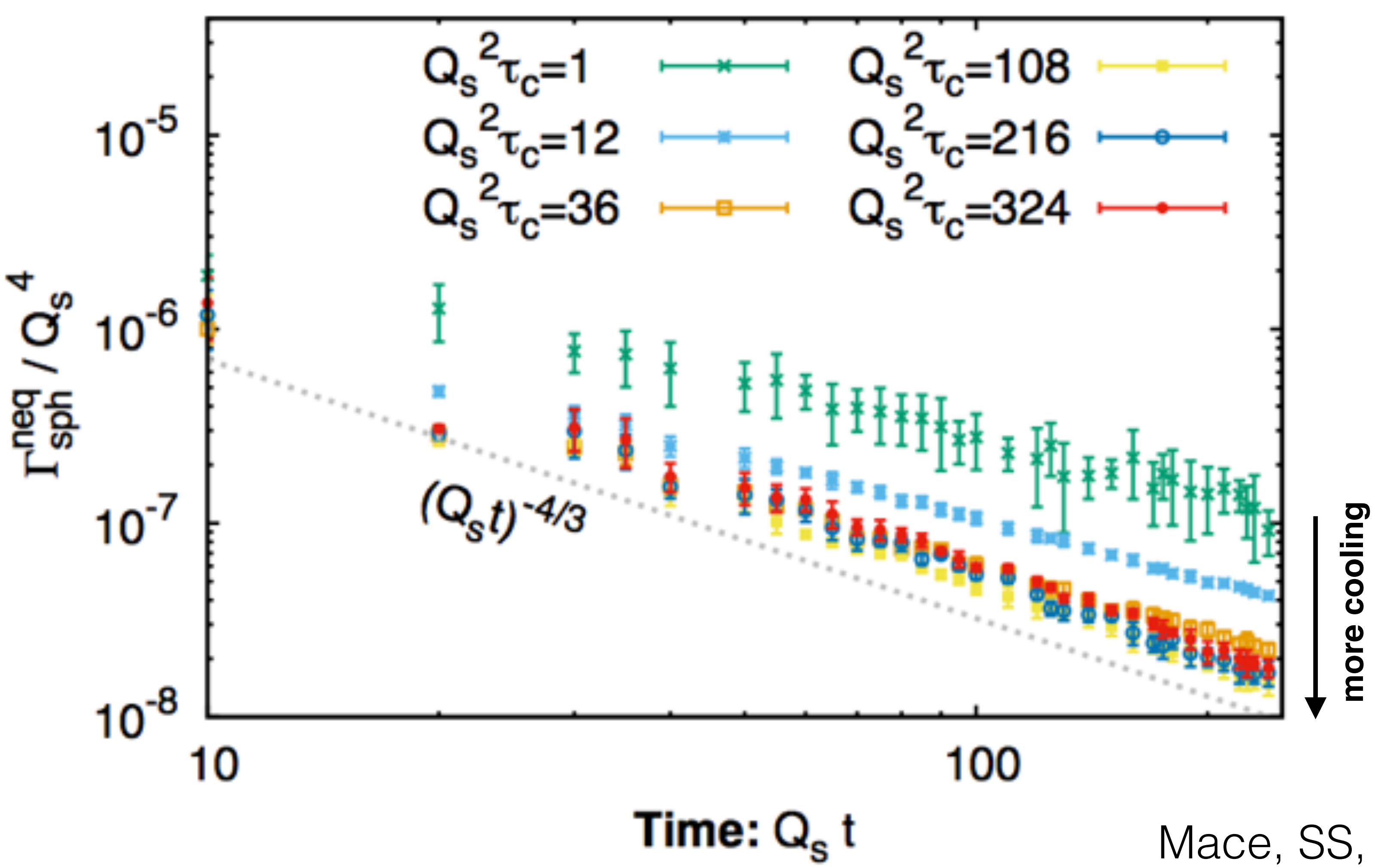
Quantifying the sphaleron rate

Define non-equilibrium sphaleron rate by the early rise of the auto-correlation function

$$\Gamma^{neq}_{sph}(t) = \left\langle \frac{(N_{CS}(t+\delta t) - N_{CS}(t))^2}{V\ \delta t} \right\rangle_{Q_s \delta t < 10}$$



Non-equilibrium sphaleron rate



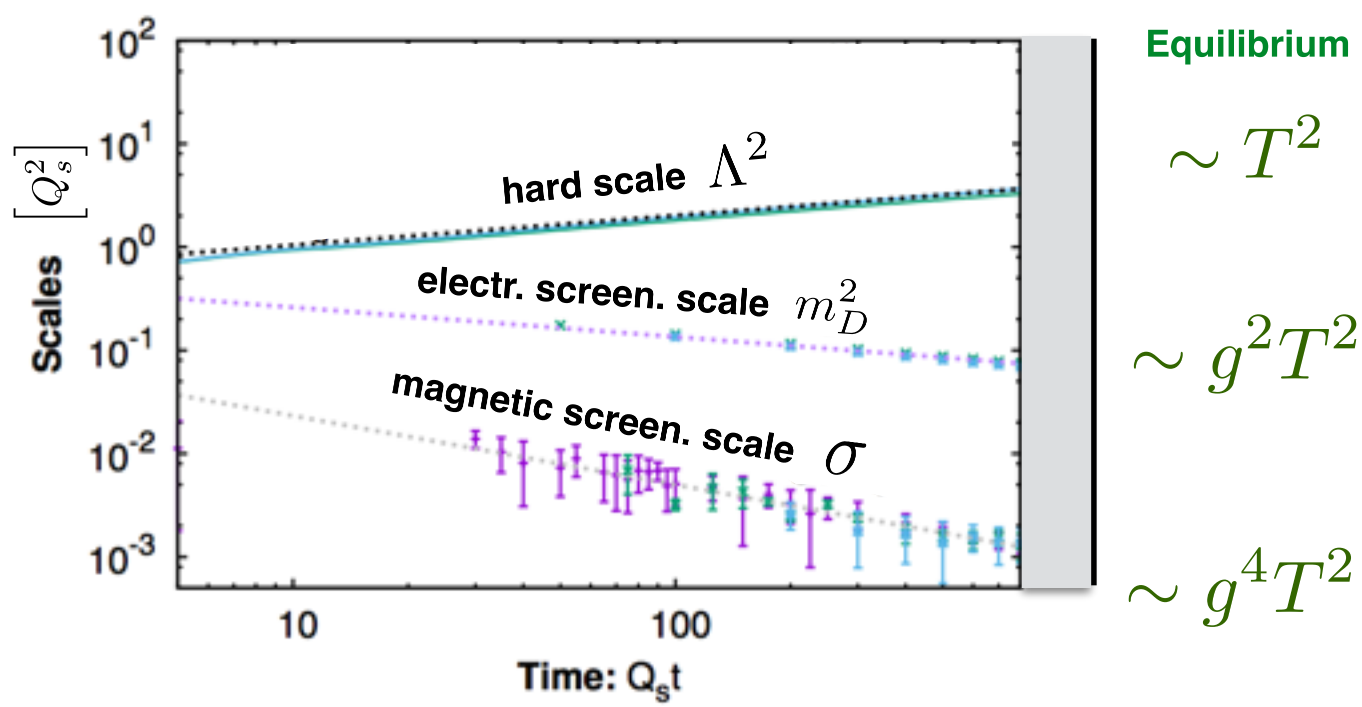
- Sizeable contribution from field strength fluctuations
- Strong time dependence observed — rate is largest at early times and decreases rapidly as a function of time

Mace, SS, Venugopalan [arXiv:1601.07342]

Do we understand the non-equilibrium sphaleron rate?

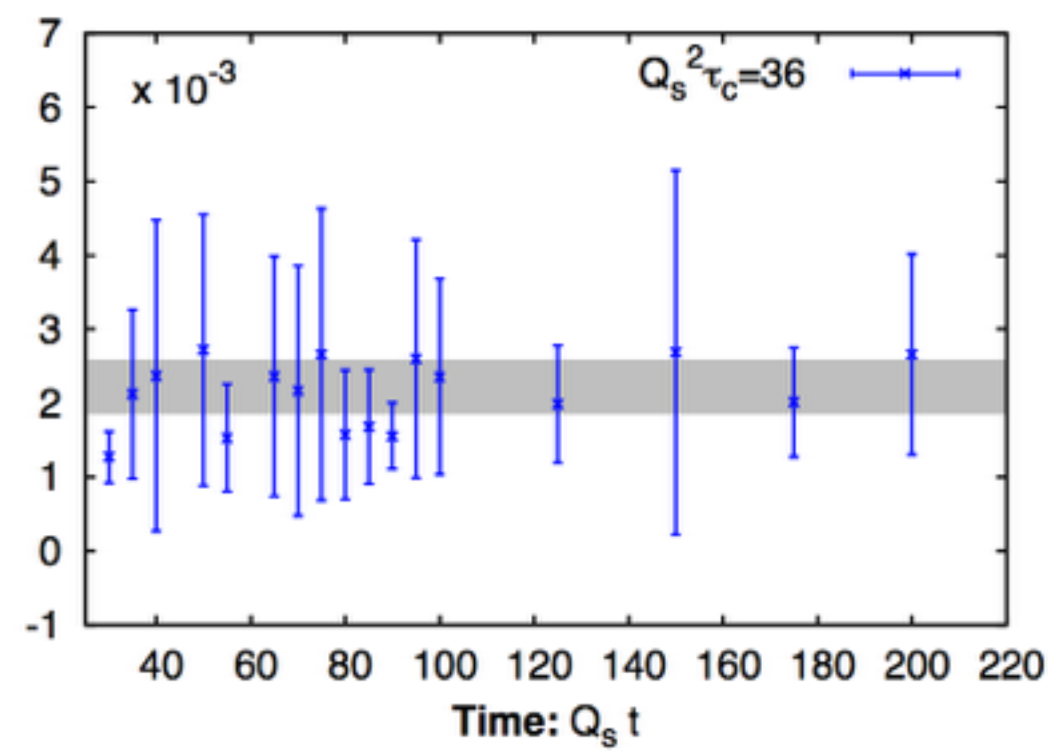
Since in equilibrium Γ_{sph} is controlled by modes on the oder of the magnetic screening scale $\sim \sqrt{\sigma}$, one should really compare Γ_{sph}/σ^2

Characteristic scales



-> Separation of scales emerges dynamically

Sphaleron rate Γ_{sph}/σ^2

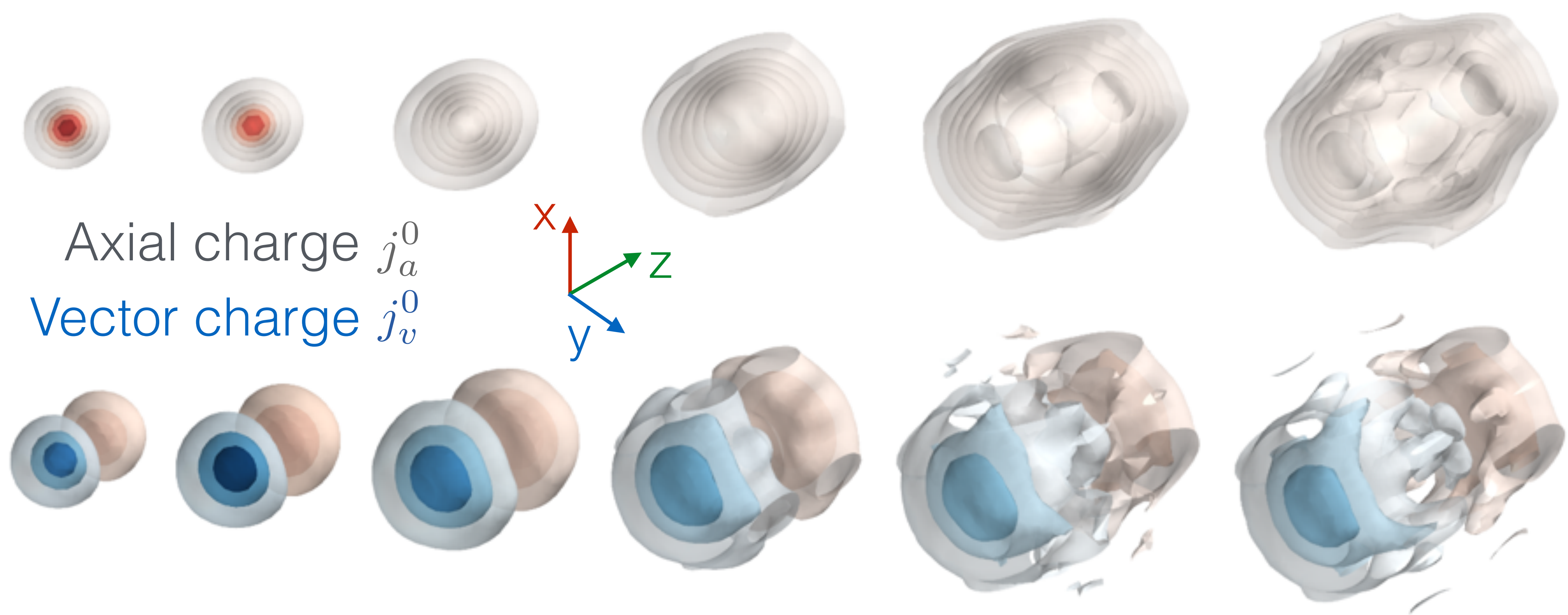


-> Non-equilibrium sphaleron rate dominated by modes on the order of the magnetic screening scale

Chiral Magnetic Effect

Evolution of axial/vector charges during and after sphaleron transition in the presence of magnetic field

-> Based on real-time lattice simulation with dynamical fermions



(Mueller,SS,Sharma in preparation)