Kinetic and Chemical Equilibration Of Quark Gluon Plasma at Zero and Finite Density

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Extreme Nonequilibrium QCD
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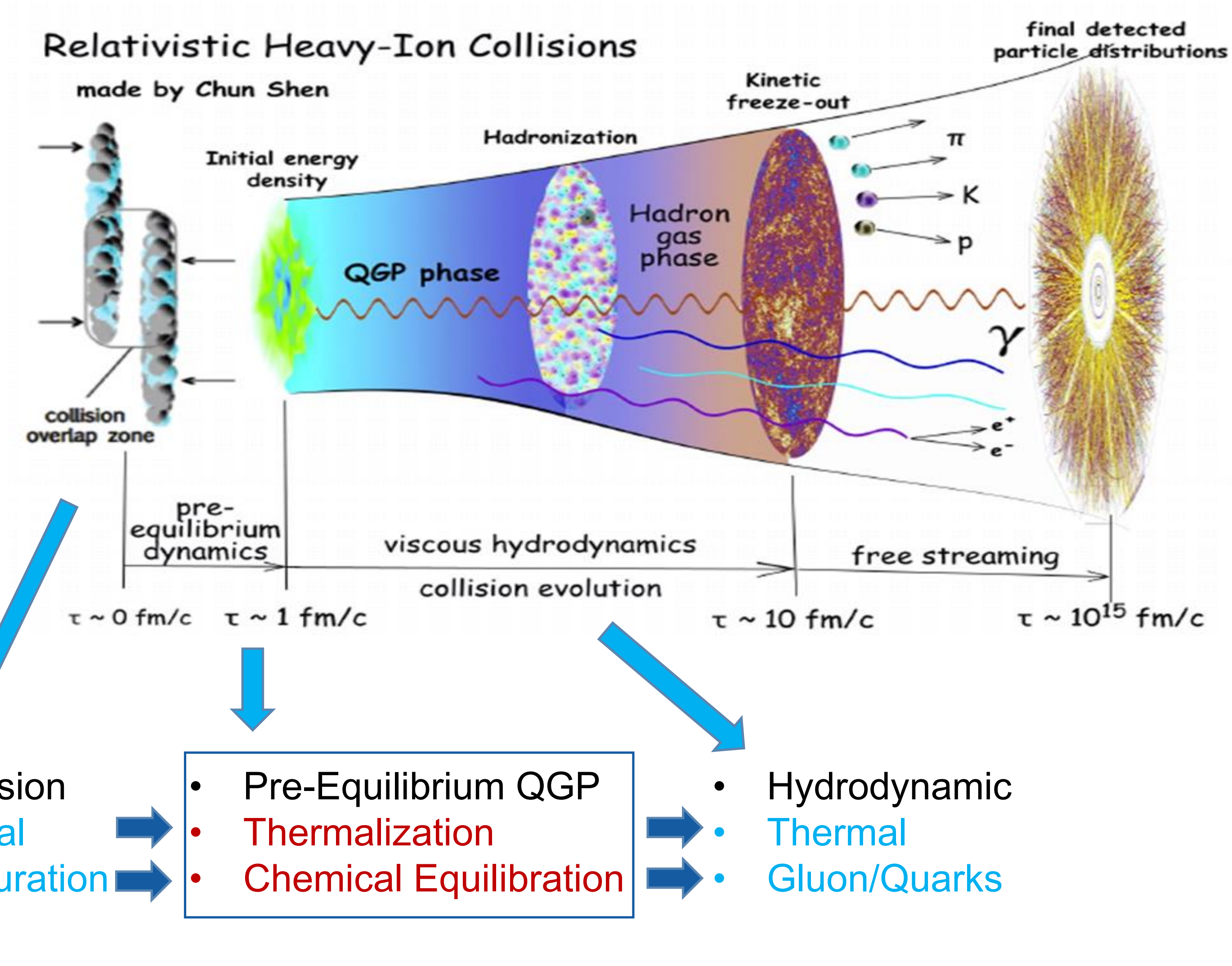
UNIVERSITÄT BIELEFELD

CRC-TR 211
Strong-interaction matter under extreme conditions

Pre-Equilibration Quark-Gluon Plasma



- Initial Collision
- Off-Thermal
- Gluon Saturation

- Pre-Equilibrium QGP
- Thermalization
- Chemical Equilibration

- Hydrodynamic
- Thermal
- Gluon/Quarks

Effective Kinetic QCD

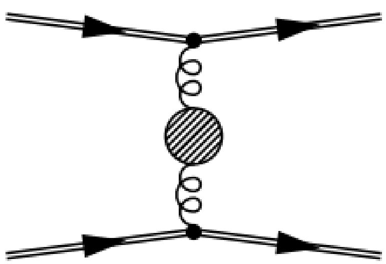
Effective Kinetic Theory (Arnold, Moore, Yaffe) at LO

AMY,JHEP01 (2003) 030
AMY,JHEP0206(2002)030
Kurkela, Mazeliauskas,PRD99 (2019) 054018

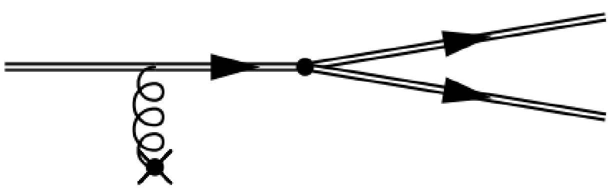
$$\frac{\partial}{\partial t} f_a(\vec{p},t) = -C_a^{2\leftrightarrow 2}[f](\vec{p},t) - C_a^{1\leftrightarrow 2}[f](\vec{p},t)$$

$$s = g, u, \bar{u}, d, d, s, \bar{s}$$

Explicitly solve Boltzmann equation for massless gluon and 3 light quarks/anti-quarks
as an integro-differential equation
including 2-2 elastic processes and 1-2 inelastic processes



2-2: Color screening by Debye mass fit to HTL calculation

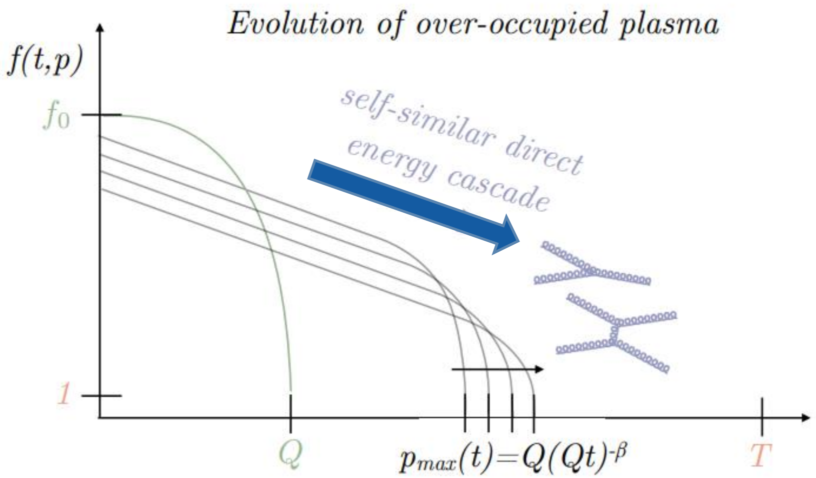


1-2: Collinear radiation including LPM effect via effective vertex resummation

Kinetic and Chemical Equilibration without Long. Expansion

Turbulence in Quark-Gluon Plasma

Weak-Coupling Thermalization



Over-occupied systems

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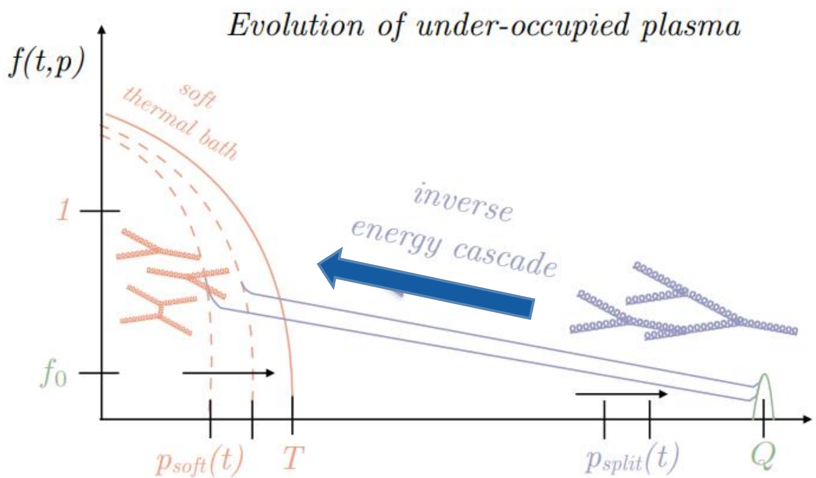
Direct energy cascade

Far from equilibrium

Large separation of scales



Under-occupied systems

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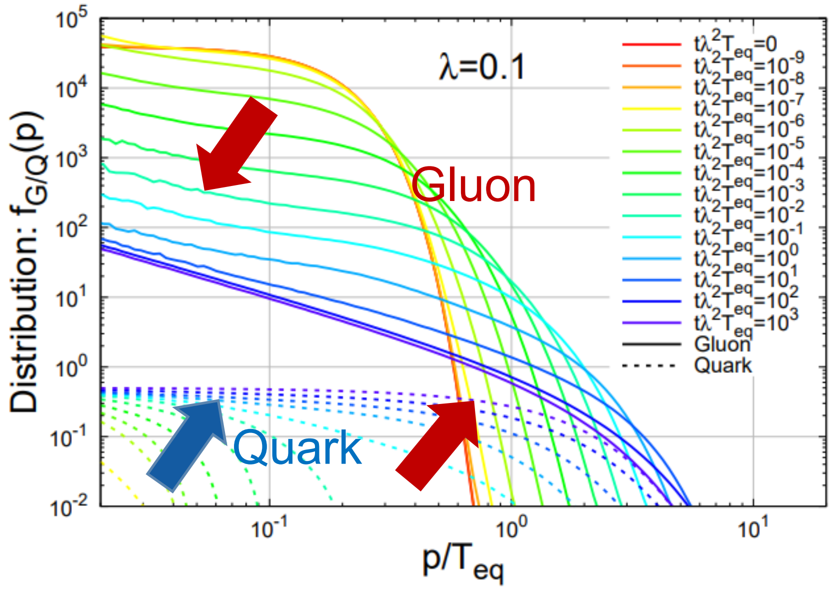
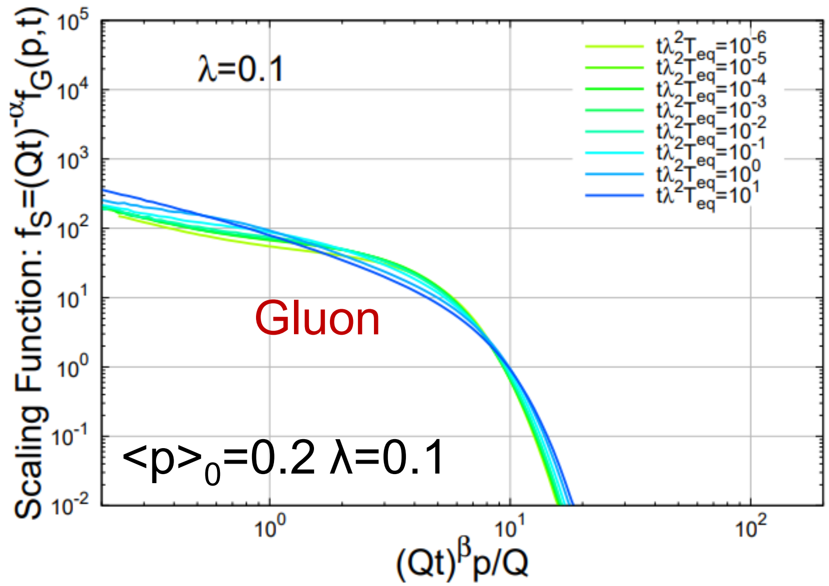
Inverse energy cascade

Schlichting, Teaney, Ann. Rev. of Nuc & Part. Sci. 69:447 (2019)

Over-Occupied Plasma





Self-similar Turbulence

$$f_G(p,t) = (Qt)^{\alpha} f_S\left((Qt)^{\beta}\frac{p}{Q}\right)$$

Universal Scaling Function

$$f_S\left((Qt)^{\beta}\frac{p}{Q}\right)$$

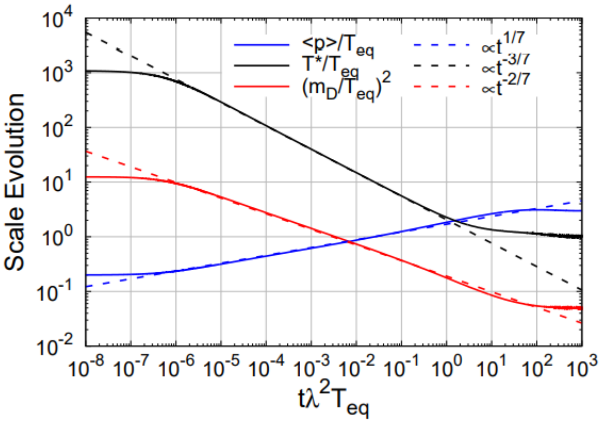
Scaling Exponents from pure Yang-Mills plasma α=-4/7, β=-1/7

Also work for QCD plasma: Gluon domination

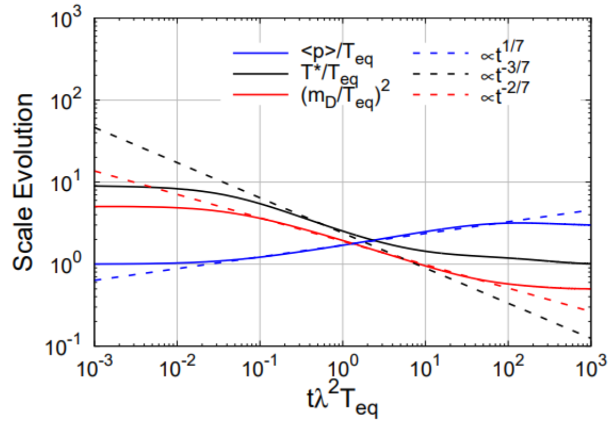
Quark spectra are following gluon spectrum

Berges, Boguslavski, Schlichting, Venugopalan, PRD89(2014)114007
Abraao York, Kurkela, Lu, Moore, PED89(2014)074036

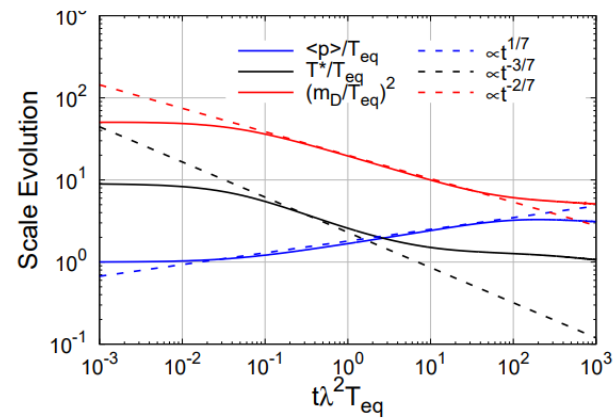
Over-Occupied Plasma



$\langle p\rangle_0$=0.2 λ=0.1



$\langle p\rangle_0$=1.0 λ=1.0



$\langle p\rangle_0$=1.0 λ=10.0

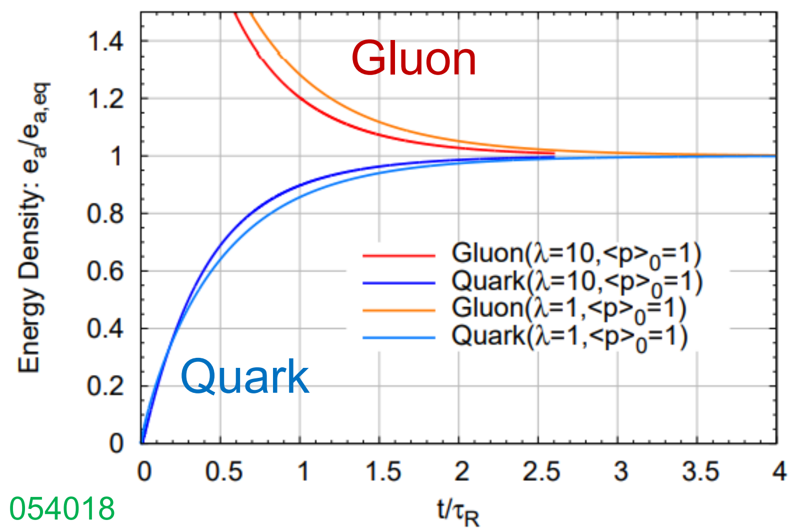
Self-similar Scaling: pow-law evolution

Not limited to pure Yang-Mills

Even work for stronger coupling

Chemical Equilibration

Later than kinetic equilibration



Equilibration relaxation time

$$\tau_R = \frac{4\pi\eta/s}{T_{eq}}$$

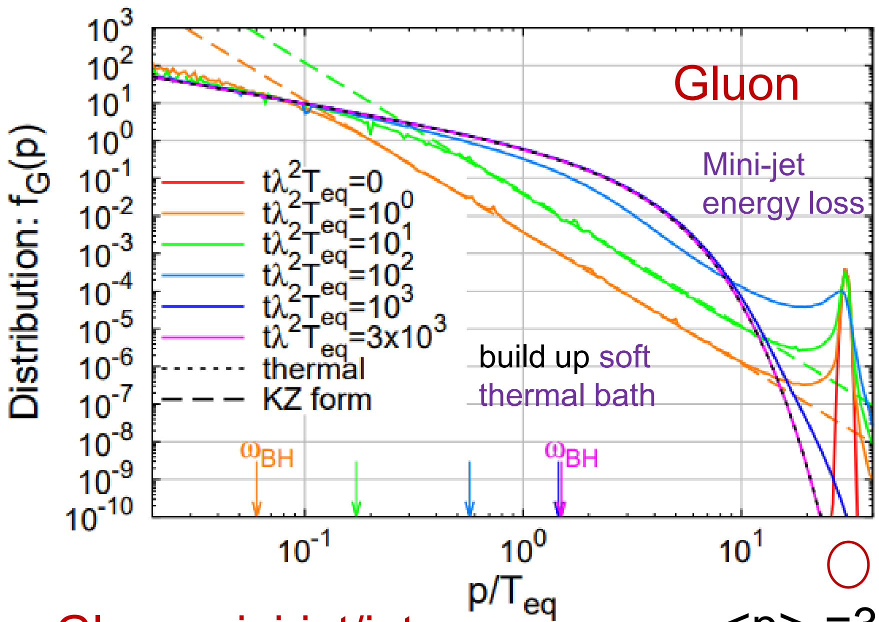
t'Hooft coupling

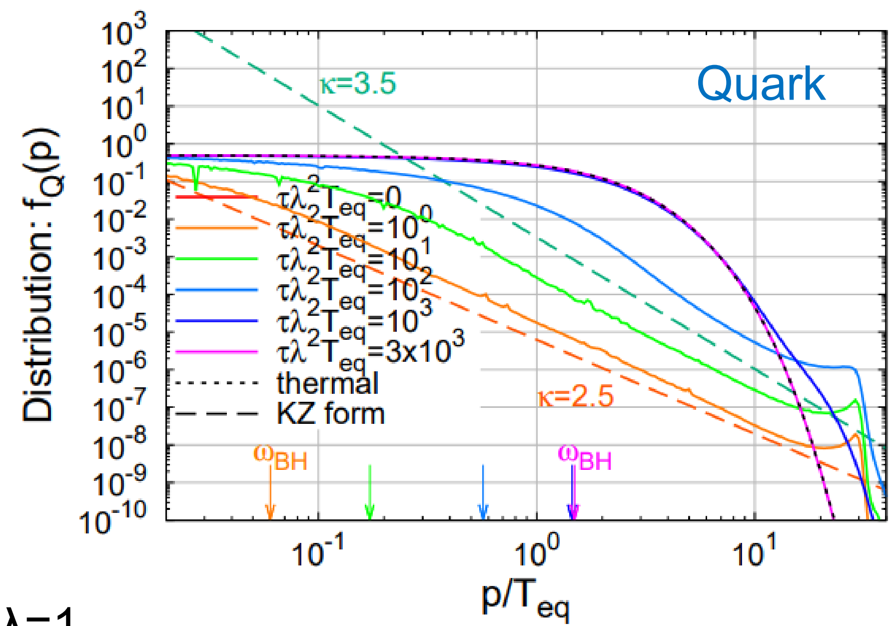
$$\lambda = 4\pi\alpha_s N_c$$

Kurkela, Mazeliauskas,PRD99 (2019) 054018

KOMPOST, PRC99 (2019) 034910

Under-Occupied Plasma



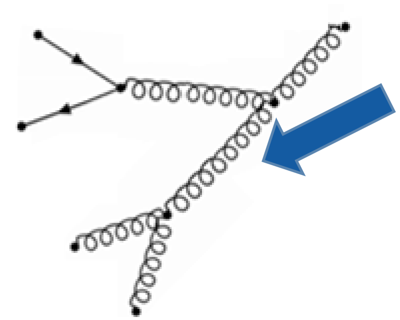


$\langle p\rangle_0=30, \lambda=1$

Gluon mini-jet/jet:

- Kolmogorov-Zakharov spectrum (exponent κ=7/2 for gluon)

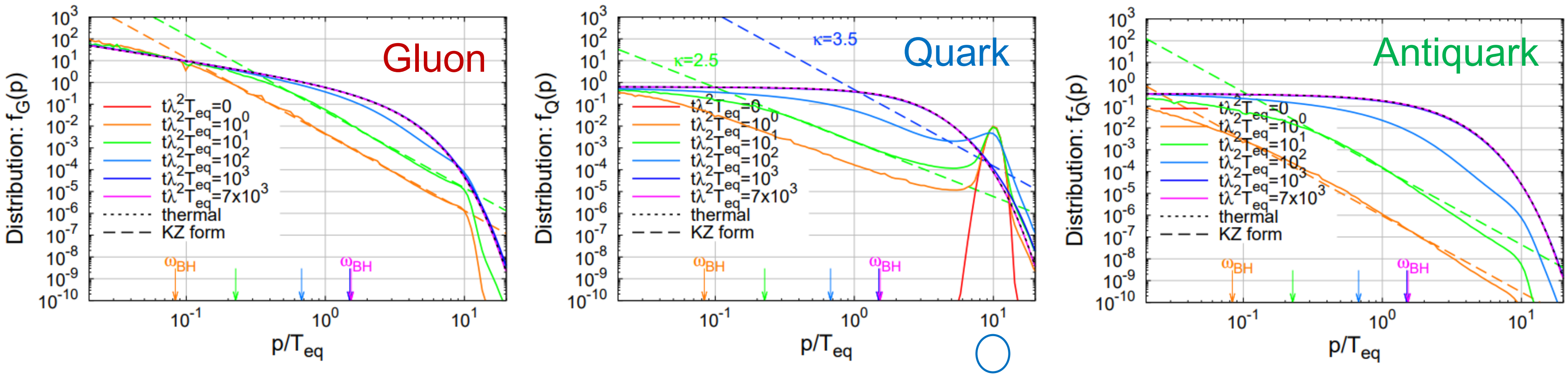
$$f_{KZ}(\vec{p},t)=\eta(t)\left(\frac{\langle p\rangle_0}{p}\right)^{\kappa}$$



- Bottom-up thermalization R. Baier, et al. PLB502(2001)51

1. Emission of (soft) quarks and gluons
2. Radiative breakup by multiple branchings -> build up soft thermal bath
3. Mini-jet energy loss -> heating up thermal bath

Under-Occupied Plasma



$\langle p\rangle_0=10$, $\lambda=1$

Quark mini-jet/jet:

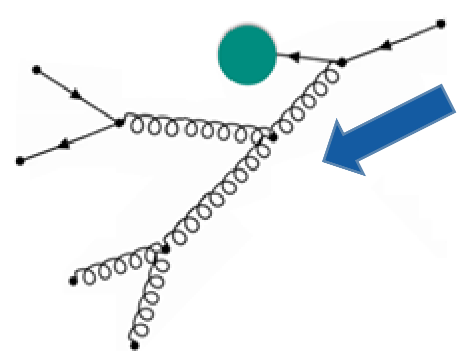
- Bottom up thermalization

- Kolmogorov-Zakharov spectrum

1. Quark follows κ=5/2 to κ=7/2
2. Gluon follows κ=7/2
3. Antiquark follows gluon (secondary production)

- Same pattern as for in-medium mini-jet/jet evolution with unified description of soft and hard sectors
- Equilibration of Jets

Soudi, Schlichting, 2008.04928

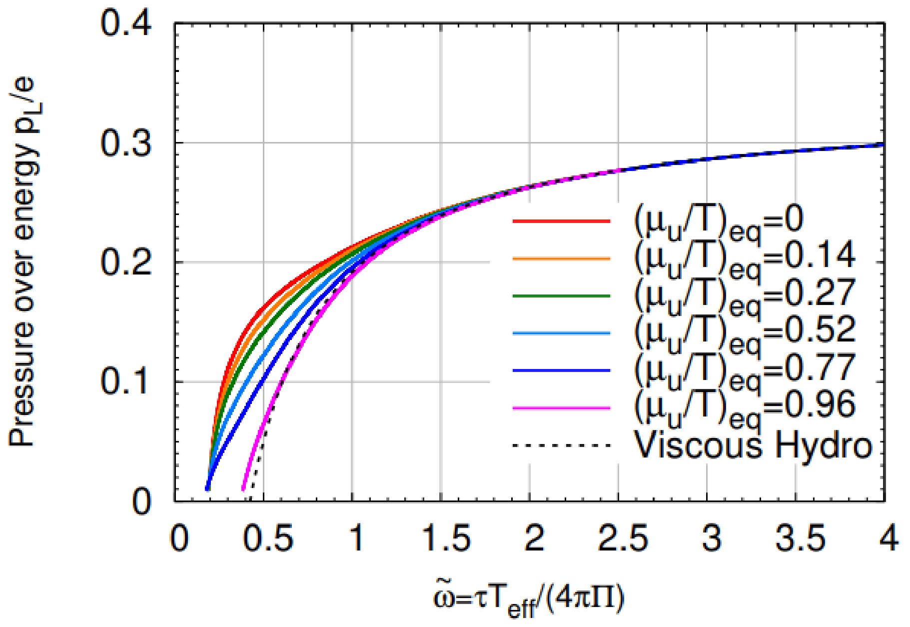


Kinetic and Chemical Equilibration with Long. Expansion

Hydrodynamic Attractor

Isotropization

System initially highly anisotropic with CGC inspired gluon dist. & finite charge density



Isotropization:

Larger chemical potential

⬇

Larger fraction of quarks

⬇

Slower isotropization

Ineffectiveness of quark interaction:

Color factor

Spin degeneracy

Quantum statistics

1[st]-order hydrodynamics near equilibrium

$$\frac{p_L}{e} = \frac{1}{3} - \frac{16}{9}\frac{\eta}{(e+p)\tau} = \frac{1}{3} - \frac{4}{9\pi}\left(\frac{\eta T_{\rm eff}}{e+p}\right)\frac{4\pi}{\tau T_{\rm eff}}$$

const. Π

Non-equilibrium attractors from kinetic theory

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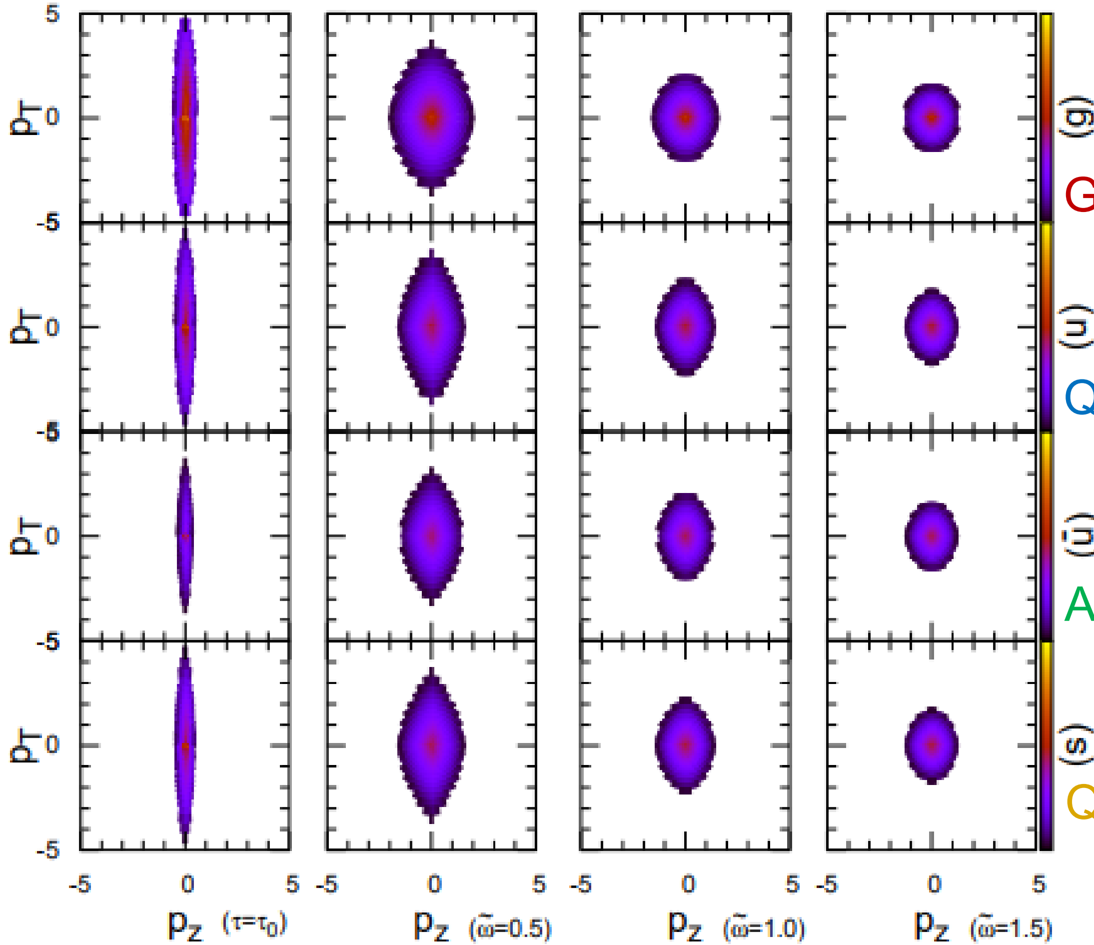
effective constitutive relations far-from equilibrium

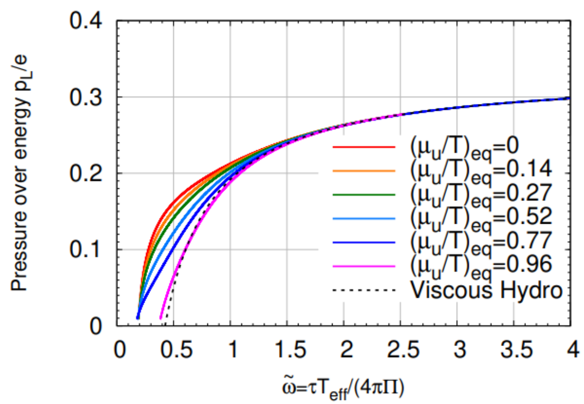
Isotropization



Gluon isotropy faster
Quarks isotropy slower

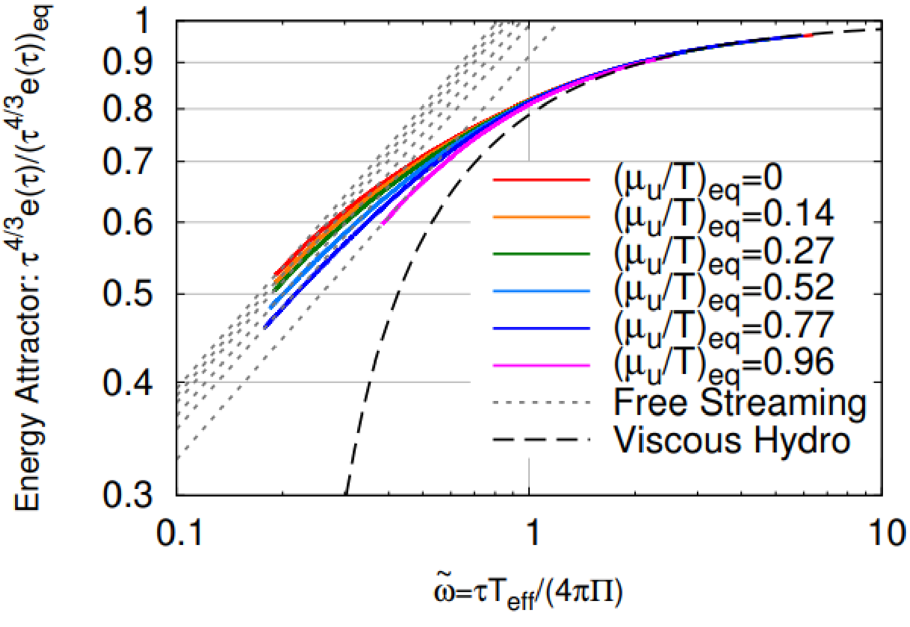
Systems eventually isotropy

hydrodynamization
~2 kinetic equilibration time



μ/T=0.14

Energy Attractor



Energy attractor

$$\mathcal{E}\left(\tilde{\omega} = \frac{T_{\rm eff}\tau}{4\pi\Pi}\right) = \frac{\tau^{\frac{4}{3}}e}{\left(\tau^{\frac{4}{3}}e\right)_{eq}}$$

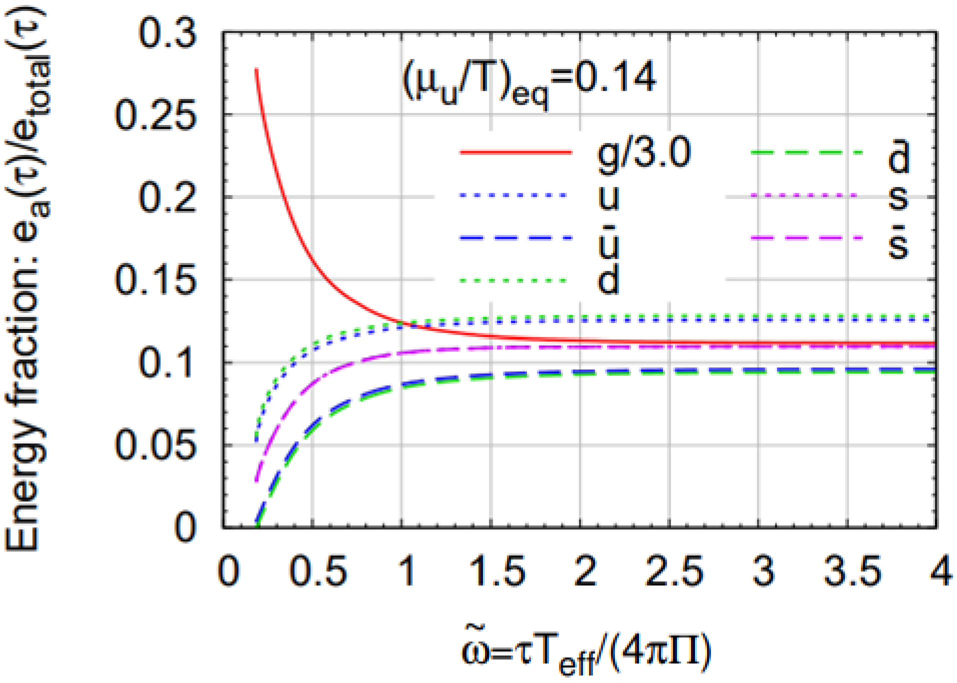
Overall Universal attractor

From conservation laws, connecting initial state to hydrodynamics

$$\left(\tau^{\frac{4}{3}}e\right)_{\tilde{\omega}} = \frac{\mathcal{E}\left(\tilde{\omega}\right)}{\mathcal{E}\left(\tilde{\omega}_0\right)}\left(\tau^{\frac{4}{3}}e\right)_0 \simeq \mathcal{E}\left(\tilde{\omega}\right)C_\infty\left(\frac{4\pi\Pi}{T_{0,\rm eff}\tau_0}\right)^{\frac{4}{9}}\left(\tau^{\frac{4}{3}}e\right)_0$$

$$\left(\tau\Delta n_f\right)_{\tilde{\omega}} = \left(\tau\Delta n_f\right)_0$$

Realistic Matching



Match

net baryon density/chemical potential

charged particle multiplicity

$$\left(\frac{\mu_f}{T}\right)_{\tilde{\omega}} \simeq \frac{6\left(\tau\Delta n_f\right)_0\left(\frac{\pi^2}{30}\nu_{\rm eff}\right)^{\frac{2}{3}}}{\nu_Q C_\infty^{\frac{3}{4}}\mathcal{E}\left(\tilde{\omega}\right)^{\frac{3}{4}}\left(4\pi\Pi\right)^{\frac{1}{3}}\left(\tau e\right)_0^{\frac{2}{3}}}$$

$$\mu_u = \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q$$

$$\mu_d = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q$$

$$\mu_s = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S$$

$$\left(s\tau\right)_{\rm eq} = \frac{\left(e + p - \sum_f \mu_f \Delta n_f\right)\tau}{T}$$

Realistic matching to hydrodynamics at finite density
(lower energy heavy-ion collisions, forward rapidity, etc…)

Chemical equilibration ~ 2 kinetic equilibration

Summary

- Turbulent Nature of Quark-Gluon Plasma
  - Over-occupied system follows a self-similar universal scaling, not limited to pure Yang-Mills theory, even for moderately strongly coupled system
  - Under-occupied system follows a bottom-up thermalization
  - Radiations dominate the energy cascade
- Hydrodynamic Attractor at zero and finite charge density.
  - Ineffectiveness of quarks in isotropization / equilibration
  - Universal attractor towards hydrodynamics
  - Validation of hydrodynamics ~ kinetic equilibration time << isotropization time
  - Realistic matching to hydrodynamics at finite density by fixing certain scales (entropy, baryon density, etc..)

Thank you!