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Transport properties of QCD within an effective approach

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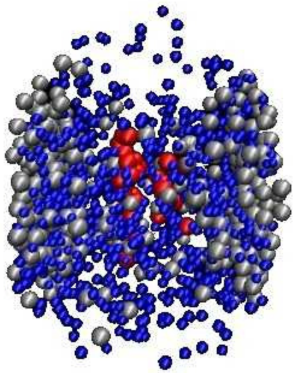
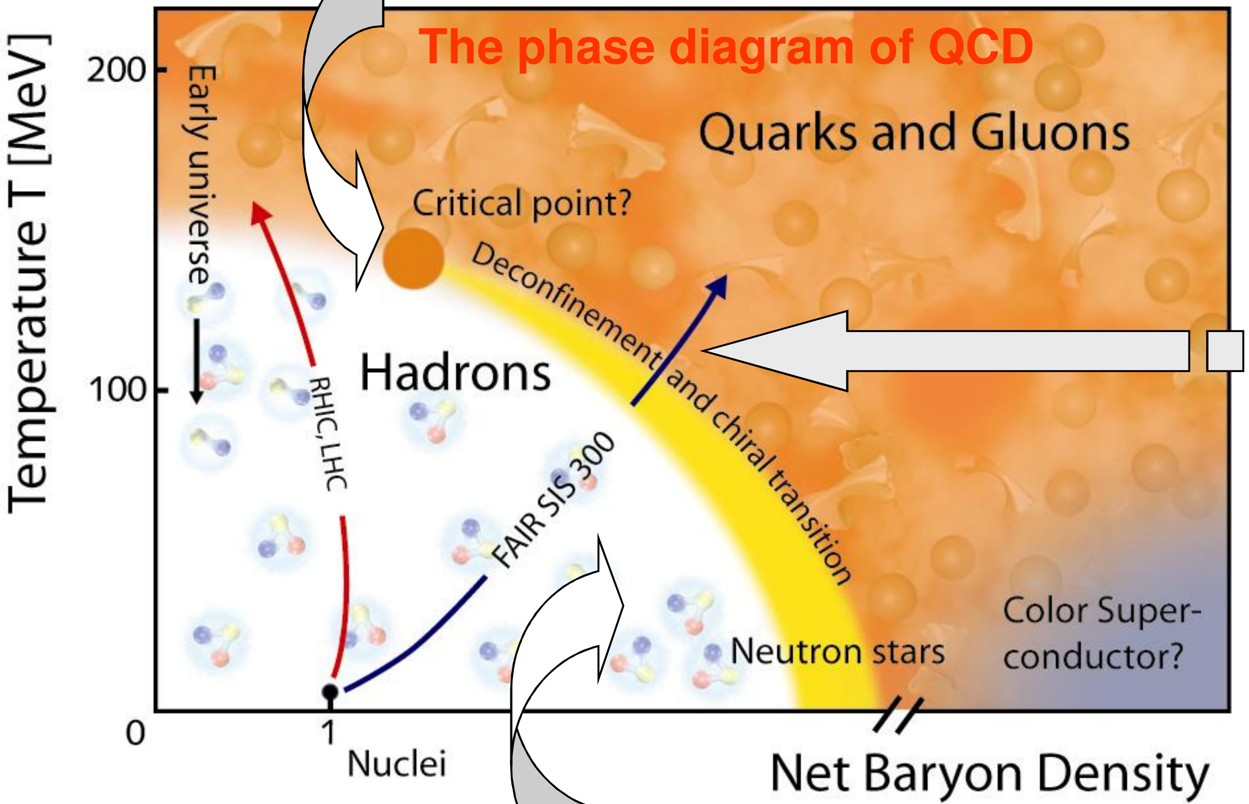


Erice, September 18th, 2015

PHSD

The holy grail of heavy-ion physics:

- Search for the critical point



- Study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma

- Study of the in-medium properties of hadrons at high baryon density and temperature → restoration of chiral symmetry

Semi-classical BUU equation


Ludwig Boltzmann

Boltzmann-Uehling-Uhlenbeck equation (non-relativistic formulation)
- propagation of particles in the **selfgenerated Hartree-Fock mean-field potential** *U(r,t)* with an on-shell **collision term:**

$$\frac{\partial}{\partial t} f(\vec r,\vec p,t)+\frac{\vec p}{m}\vec\nabla_{\vec r}\, f(\vec r,\vec p,t)-\vec\nabla_{\vec r}U(\vec r,t)\,\vec\nabla_{\vec p} f(\vec r,\vec p,t)=\left(\frac{\partial f}{\partial t}\right)_{coll}$$

collision term: elastic and inelastic reactions

$f(\vec r,\vec p,t)$ is the **single particle phase-space distribution function**
- probability to find the particle at position *r* with momentum *p* at time *t*

❑ selfgenerated **Hartree-Fock mean-field potential:**

$$U(\vec r,t)=\frac{1}{(2\pi\hbar)^3}\sum_{\beta_{occ}}\int d^3r'\,d^3p\;\;V(\vec r-\vec r',t)\;f(\vec r',\vec p,t)\;+\;(Fock\;\;term)$$

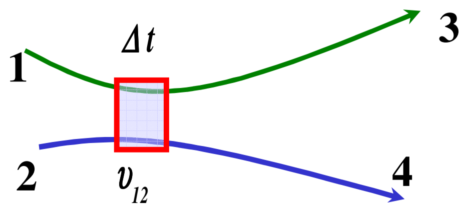
❑ **Collision term** for 1+2→3+4 (let's consider fermions) :

$$I_{coll}=\frac{4}{(2\pi)^3}\int d^3p_2\,d^3p_3\int d\Omega\;\;|v_{12}|\,\delta^3(\vec p_1+\vec p_2-\vec p_3-\vec p_4)\cdot\frac{d\sigma}{d\Omega}(1+2\rightarrow 3+4)\cdot P$$

Probability including **Pauli blocking of fermions:**

$$P=f_3f_4(1-f_1)(1-f_2)\;-\;f_1f_2(1-f_3)(1-f_4)$$

Gain term: 3+4→1+2 **Loss term: 1+2→3+4**



Dynamical description of strongly interacting systems

- **Semi-classical on-shell BUU:** applies for small collisional width, i.e. for a weakly interacting systems of particles

How to describe strongly interacting systems?!

- **Quantum field theory ➔**
Kadanoff-Baym dynamics for resummed single-particle Green functions $S^<$

(1962)

$$\hat{S}^{-1}_{0x} \, S^{<}_{xy} = \Sigma^{ret}_{xz} \odot S^{<}_{zy} + \Sigma^{<}_{xz} \odot S^{adv}_{zy}$$

Integration over the intermediate spacetime

Green functions $S^<$ / self-energies Σ:

$$iS^{<}_{xy} = \eta \langle \{ \Phi^{+}(y) \Phi(x) \} \rangle$$

$$iS^{>}_{xy} = \langle \{ \Phi(y) \Phi^{+}(x) \} \rangle$$

$$iS^{c}_{xy} = \langle T^{c} \{ \Phi(x) \Phi^{+}(y) \} \rangle \quad -causal$$

$$iS^{a}_{xy} = \langle T^{a} \{ \Phi(x) \Phi^{+}(y) \} \rangle \quad -anticausal$$

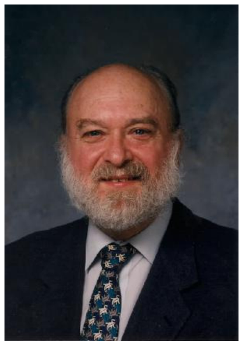
$$S^{ret}_{xy} = S^{c}_{xy} - S^{<}_{xy} = S^{>}_{xy} - S^{a}_{xy} \quad -retarded$$

$$S^{adv}_{xy} = S^{c}_{xy} - S^{>}_{xy} = S^{<}_{xy} - S^{a}_{xy} \quad -advanced$$

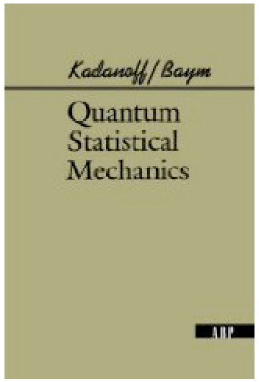
$$\hat{S}^{-1}_{0x} \equiv -(\partial^{\mu}_{x} \partial^{x}_{\mu} + M^{2}_{0})$$

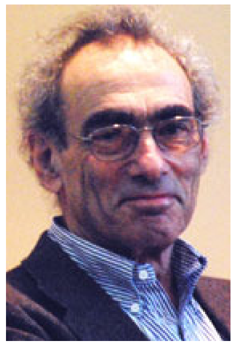
$$\eta = \pm 1 (bosons \,/\, fermions)$$

$$T^{a} (T^{c}) - (anti-) time-ordering \ operator$$



Leo Kadanoff





Gordon Baym

From Kadanoff-Baym equations to generalized transport equations

After the first order gradient expansion of the Wigner transformed Kadanoff-Baym equations and separation into the real and imaginary parts one gets:

Generalized transport equations (GTE):

drift term | Vlasov term | backflow term | collision term = ‚gain‘ - ‚loss‘ term

$$\diamond\{P^2 - M_0^2 - Re\Sigma^{ret}_{XP}\}\{S^<_{XP}\} - \diamond\{\Sigma^<_{XP}\}\{ReS^{ret}_{XP}\} = \frac{i}{2}\left[\Sigma^>_{XP}\,S^<_{XP} - \Sigma^<_{XP}\,S^>_{XP}\right]$$

Backflow term incorporates the off-shell behavior in the particle propagation
! vanishes in the quasiparticle limit $A_{XP} \to \delta(p^2-M^2)$

- GTE: Propagation of the Green‘s functions $iS^<_{XP}=A_{XP}N_{XP}$, which carry information not only on the number of particles (N_{XP}), but also on their properties, interactions and correlations (via A_{XP})

- Spectral function:

$$A_{XP} = \frac{\Gamma_{XP}}{(P^2 - M_0^2 - Re\Sigma^{ret}_{XP})^2 + \Gamma^2_{XP}/4}$$

$\Gamma_{XP} = -Im\,\Sigma^{ret}_{XP} = 2p_0\Gamma$ – ‚width‘ of spectral function
= reaction rate of particle (at space-time position X)

4-dimentional generalizaton of the Poisson-bracket:

$$\diamond\{F_1\}\{F_2\} := \frac{1}{2}\left(\frac{\partial F_1}{\partial X_\mu}\frac{\partial F_2}{\partial P^\mu} - \frac{\partial F_1}{\partial P_\mu}\frac{\partial F_2}{\partial X^\mu}\right)$$

- Life time $\tau = \frac{\hbar c}{\Gamma}$

W. Cassing , S. Juchem, NPA 665 (2000) 377; 672 (2000) 417; 677 (2000) 445

From SIS to LHC: from hadrons to partons

The goal: to study of the phase transition from hadronic to partonic matter and properties of the Quark-Gluon-Plasma from microscopic origin

➔ need a consistent non-equilibrium transport model

- ❑ with explicit parton-parton interactions (i.e. between quarks and gluons)
- ❑ explicit phase transition from hadronic to partonic degrees of freedom
- ❑ lQCD EoS for partonic phase (‚crossover' at μ_q=0)

❑ **Transport theory:** off-shell Kadanoff-Baym equations for the Green-functions $S^<_h(x,p)$ in phase-space representation for the partonic and hadronic phase

⇨ **Parton-Hadron-String-Dynamics (PHSD)**

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

A. Peshier, W. Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Dynamical QuasiParticle Model (DQPM) - Basic ideas:

DQPM describes QCD properties in terms of ‚resummed' single-particle Green's functions – in the sense of a two-particle irreducible (2PI) approach:

Gluon propagator: $\Delta^{-1} = P^2 - \Pi$ gluon self-energy: $\Pi = M_g^2 - i2\Gamma_g\omega$

Quark propagator: $S_q^{-1} = P^2 - \Sigma_q$ quark self-energy: $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

- the resummed properties are specified by complex self-energies which depend on temperature:
  -- the real part of self-energies (Σ_q, Π) describes a dynamically generated mass (M_q,M_g);
  -- the imaginary part describes the interaction width of partons (Γ_q, Γ_g)

- space-like part of energy-momentum tensor $T_{\mu\nu}$ defines the potential energy density and the mean-field potential (1PI) for quarks and gluons (U_q, U_g)

- 2PI framework guaranties a consistent description of the system in- and out-off equilibrium on the basis of Kadanoff-Baym equations with proper states in equilibrium

A. Peshier, W. Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

Properties of interacting quasi-particles:
massive quarks and gluons (g, q, q_{bar})
with Lorentzian spectral functions :

$$A_i(\omega,T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)}$$

$$(i = q, \bar{q}, g)$$

- Modeling of the quark/gluon masses and widths → HTL limit at high T

- quarks:

mass: $$M^2_{q(\bar{q})}(T) = \frac{N_c^2-1}{8N_c} g^2 \left(T^2 + \frac{\mu_q^2}{\pi^2}\right)$$

width: $$\Gamma_{q(\bar{q})}(T) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$$

- gluons:

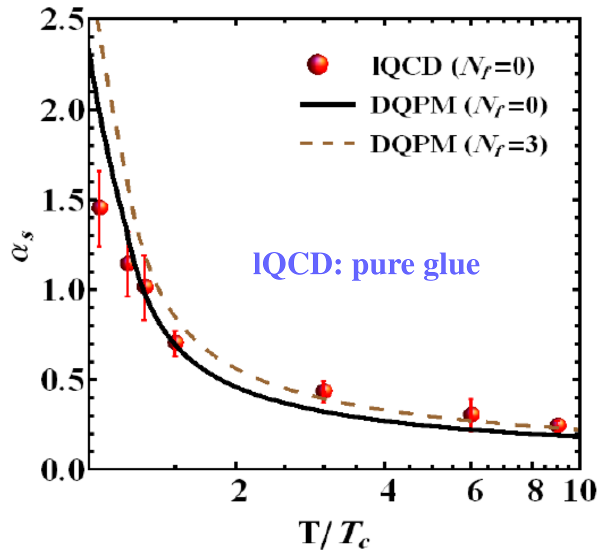
$$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

$$\Gamma_g(T) = \frac{1}{3}N_c\frac{g^2 T}{8\pi}\ln\left(\frac{2c}{g^2}+1\right)$$

$N_c = 3$, $N_f=3$

- running coupling (pure glue):

$$\alpha_s(T) = \frac{g^2(T)}{4\pi} = \frac{12\pi}{(11N_c - 2N_f)\ln[\lambda^2(T/T_c - T_s/T_c)^2]}$$



❑ fit to lattice (lQCD) results (e.g. entropy density)

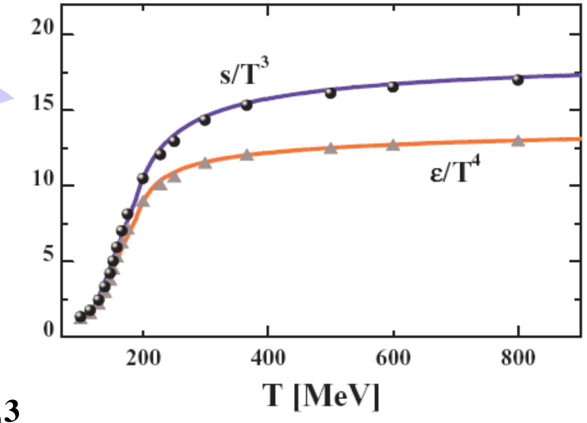
with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42
(for pure glue N_f=0)

DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

The Dynamical QuasiParticle Model (DQPM)

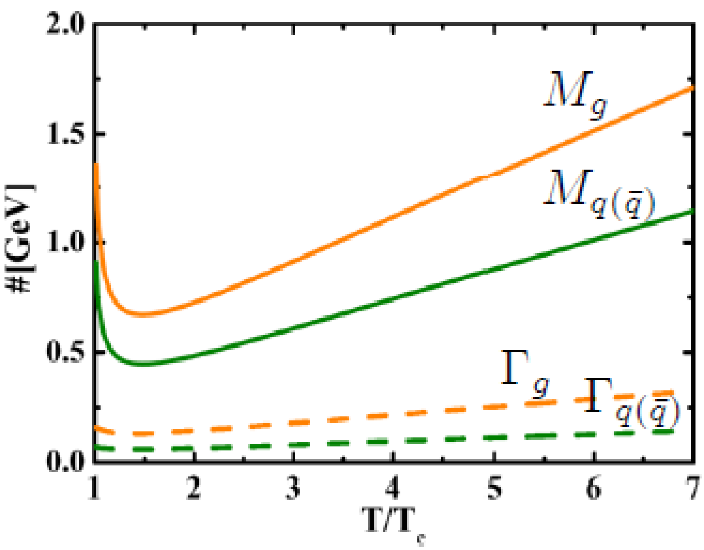
➢ fit to lattice (lQCD) results (e.g. entropy density)

* BMW lQCD data S. Borsanyi et al., JHEP 1009 (2010) 073



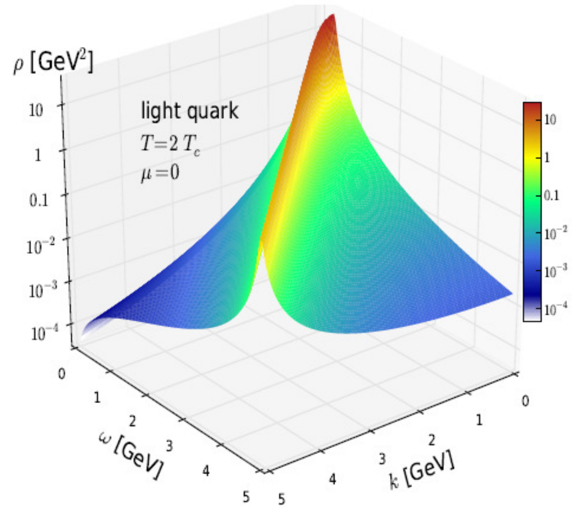
➔ Quasiparticle properties:

- large width and mass for gluons and quarks



T_C=158 MeV

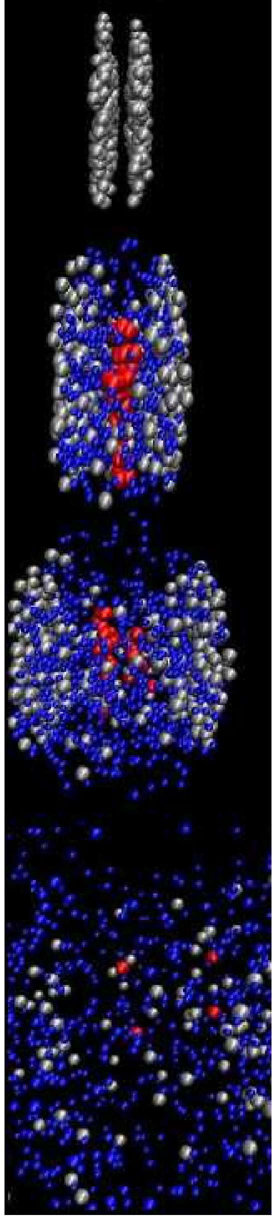
ε_C=0.5 GeV/fm^3



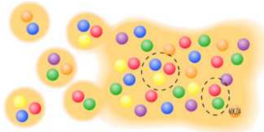
- DQPM matches well lattice QCD
- DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons → PHSD

Peshier, Cassing, PRL 94 (2005) 172301; Cassing, NPA 791 (2007) 365: NPA 793 (2007)

Parton Hadron String Dynamics

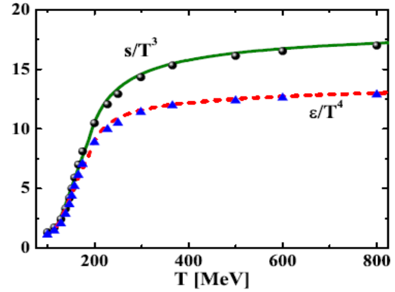


I. From hadrons to QGP:



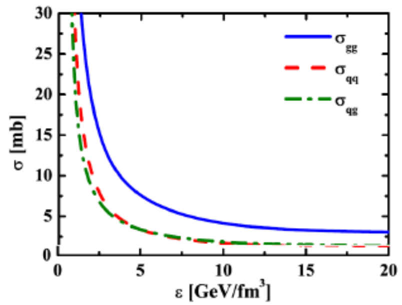
QGP phase:
$\varepsilon > \varepsilon_{critical}$

- Initial A+A collisions:
  - string formation in primary NN collisions
  - strings decay to pre-hadrons (*B* - baryons, *m* – mesons)
- Formation of QGP stage by dissolution of pre-hadrons into massive colored quarks + mean-field energy based on the Dynamical Quasi-Particle Model (DQPM) which defines quark spectral functions, masses $M_q(\varepsilon)$ and widths $\Gamma_q(\varepsilon)$ + mean-field potential U_q at given ε – local energy density (related by lQCD EoS to T - temperature in the local cell)



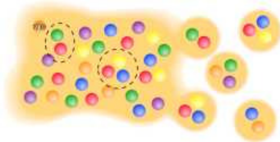
II. Partonic phase - QGP:

- quarks and gluons (= ‚dynamical quasiparticles') with off-shell spectral functions (width, mass) defined by the DQPM
- in self-generated mean-field potential for quarks and gluons U_q, U_g
- EoS of partonic phase: ‚crossover' from lattice QCD (fitted by DQPM)
- (quasi-) elastic and inelastic parton-parton interactions: using the effective cross sections from the DQPM



III. Hadronization: based on DQPM

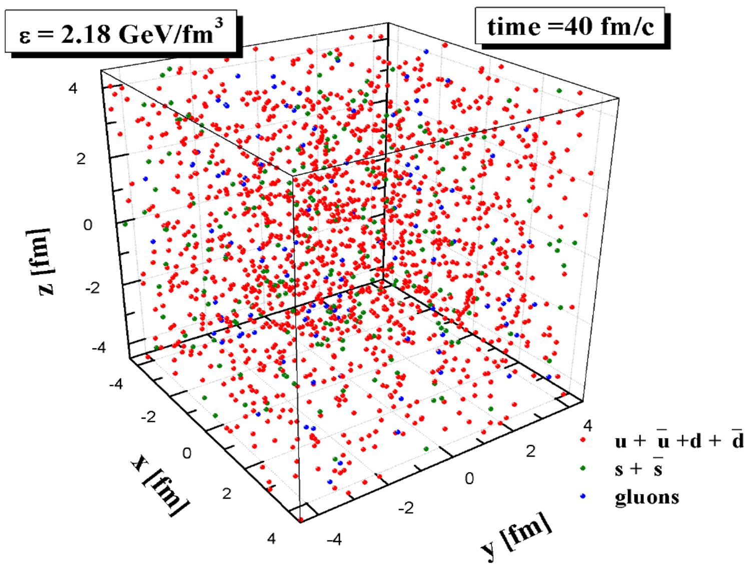
- massive, off-shell (anti-)quarks with broad spectral functions hadronize to off-shell mesons and baryons or color neutral excited states - ‚strings' (strings act as ‚doorway states' for hadrons)



IV. Hadronic phase: hadron-string interactions – off-shell HSD

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919; NPA831 (2009) 215; EPJ ST 168 (2009) 3; NPA856 (2011) 162.

Properties of the QGP in equilibrium using PHSD



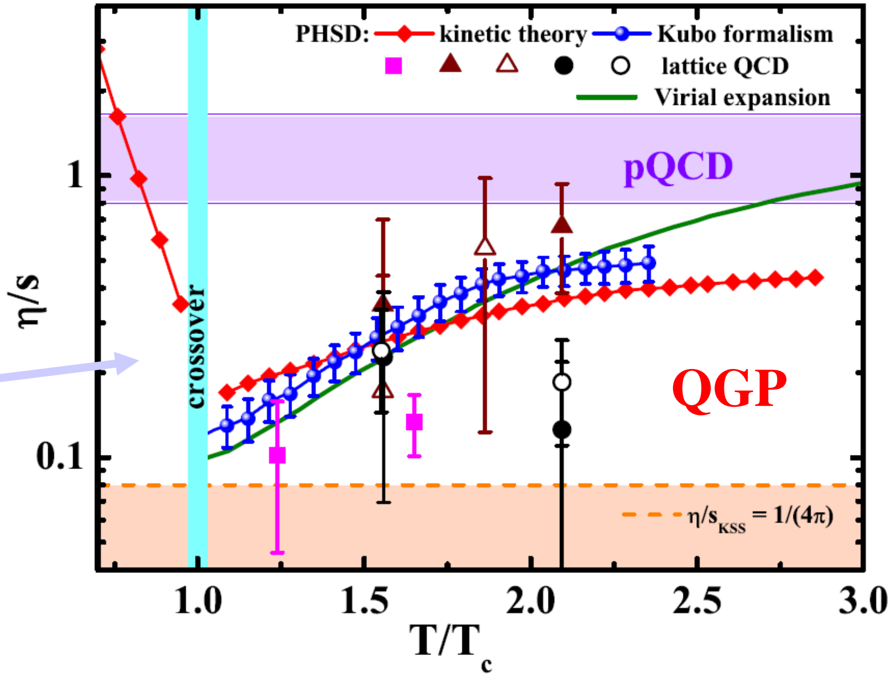
Properties of parton-hadron matter: shear viscosity

η/s using **Kubo formalism** and the **relaxation time approximation** (‚kinetic theory‘)

- ❑ $T=T_C$: η/s shows a minimum (~0.1) close to the critical temperature

- ❑ $T>T_C$: QGP - pQCD limit at higher temperatures

- ❑ $T<T_C$: fast increase of the ratio h/s for hadronic matter ➔
  - lower interaction rate of hadronic system
  - smaller number of degrees of freedom (or entropy density) for hadronic matter compared to the QGP



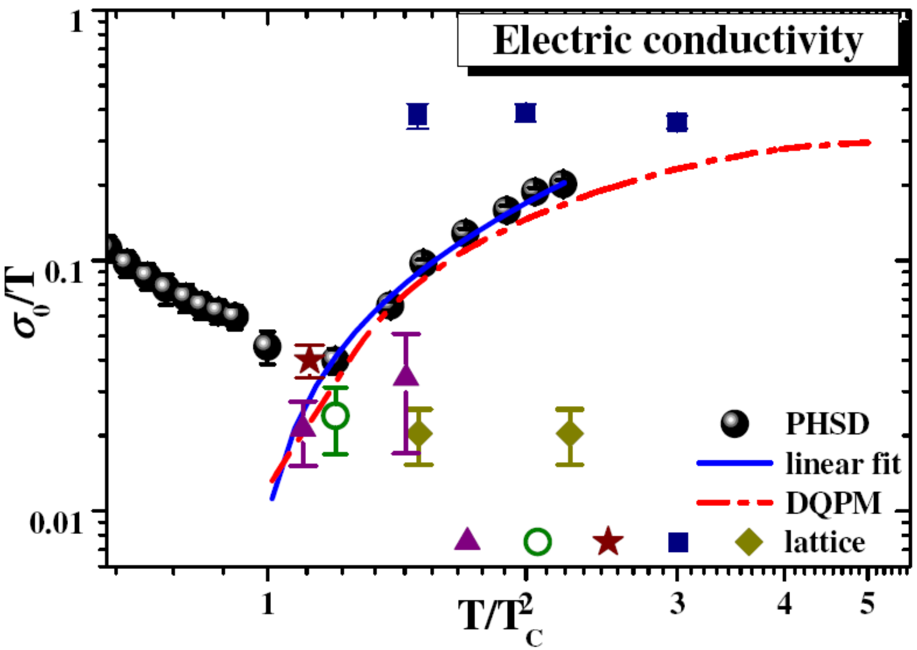
Virial expansion: S. Mattiello, W. Cassing, Eur. Phys. J. C 70, 243 (2010)

QGP in PHSD = strongly-interacting system

V. Ozvenchuk et al., PRC 87 (2013) 064903

Properties of parton-hadron matter: electric conductivity

- The response of the strongly-interacting system in equilibrium to an external electric field eE_z defines the electric conductivity σ_0:



$$\frac{\sigma_0}{T} = \frac{j_{eq}}{E_z T},$$

$$j_z(t) = \frac{1}{V} \sum_j eq_j \frac{p_z^j(t)}{M_j(t)};$$

➔ the QCD matter even at $T \sim T_c$ is a much better electric conductor than Cu or Ag (at room temperature) by a factor of 500 !

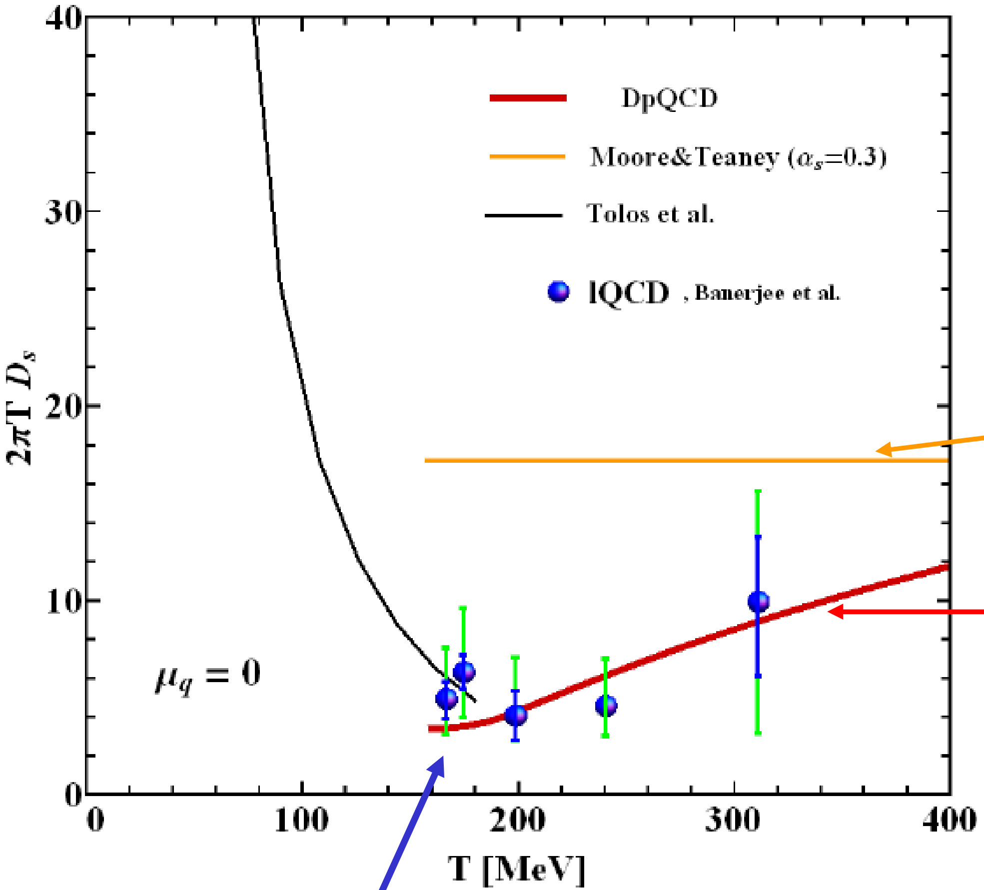
- Photon (dilepton) rates at $q_0 \to 0$ are related to electric conductivity σ_0
➔ Probe of electric properties of the QGP

$$q_0 \frac{dR}{d^4x\, d^3q}\bigg|_{q_0 \to 0} = \frac{T}{4\pi^3}\sigma_0$$

W. Cassing et al., PRL 110(2013)182301

Charm spatial diffusion coefficient D_s in the hot medium

- D_s for heavy quarks as a function of T for $\mu_q=0$



❑ T < T_c : hadronic D_s
L. Tolos , J. M. Torres-Rincon, Phys. Rev. D 88, 074019 (2013)

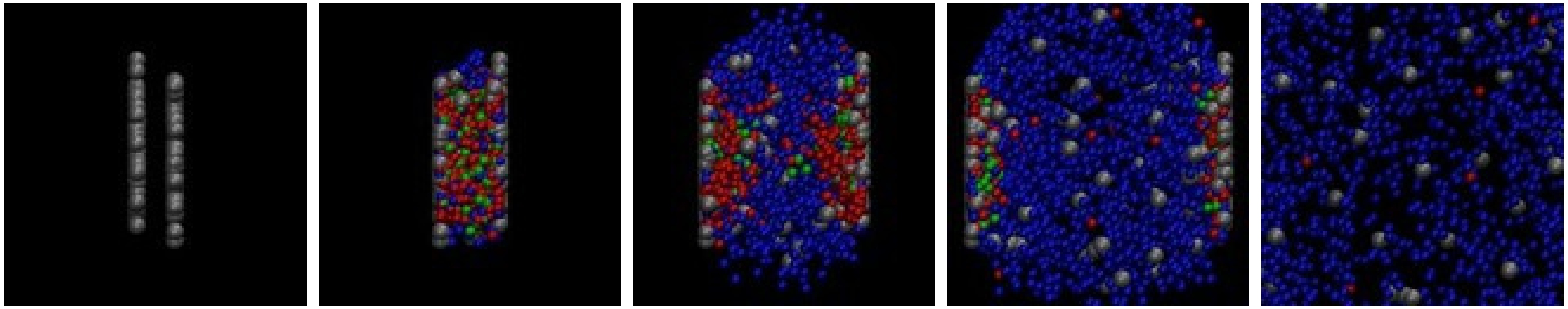
❑ T > T_c : QGP D_s

- pQCD - G. D. Moore, D. Teaney, Phys. Rev. C 71, 064904 (for α_s=0.3)
- DQPM - H. Berrehrah et al., Phys. Rev. C90 (2014) 051901
- lQCD - Banerjee et al., Phys. Rev. D 85, 014510 (2012).

→ Continuous transition !

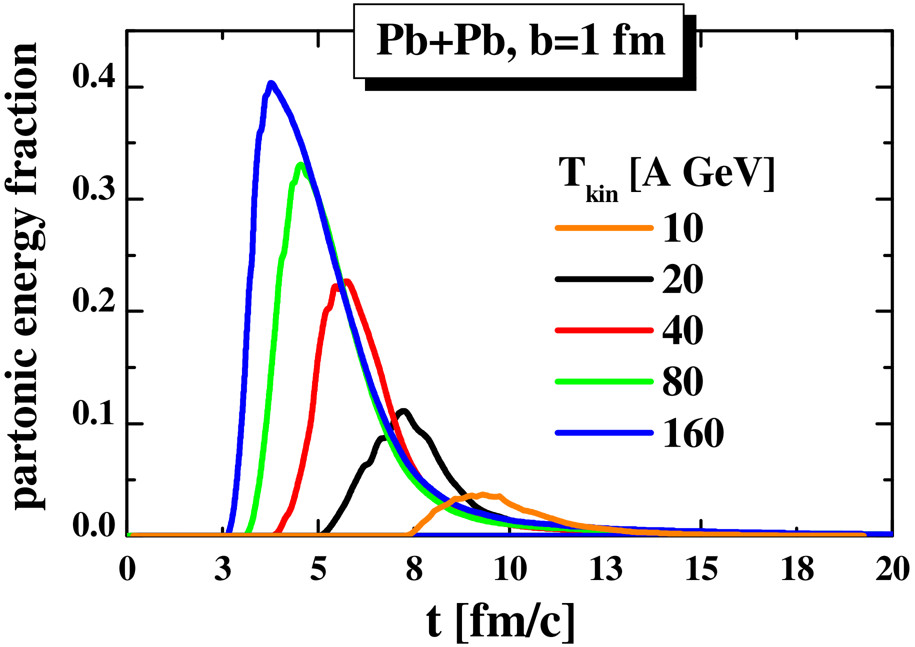
H. Berrehrah et al, Phys. Rev. C90 (2014) 051901

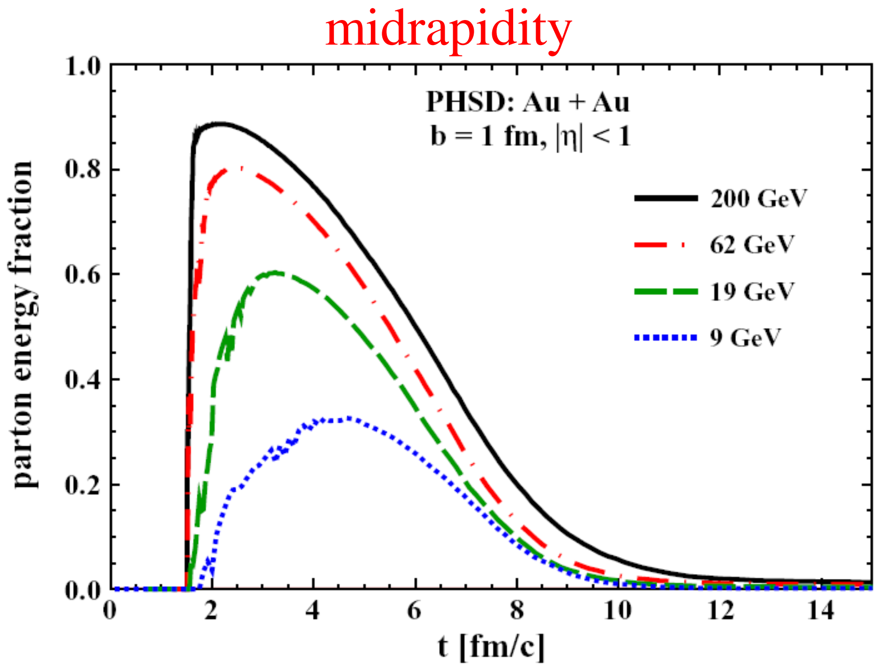
‚Bulk' properties in Au+Au



Partonic energy fraction in central A+A

Time evolution of the partonic energy fraction vs energy





- Strong increase of partonic phase with energy from AGS to RHIC

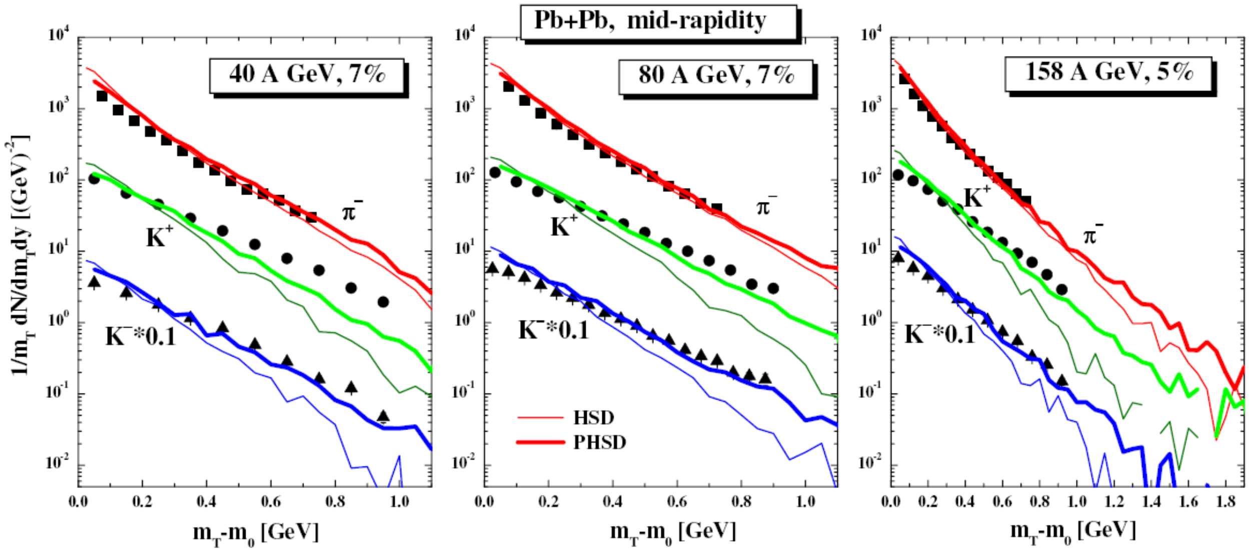
- SPS: Pb+Pb, 160 A GeV: only about 40% of the converted energy goes to partons; the rest is contained in the large hadronic corona and leading partons
- RHIC: Au+Au, 21.3 A TeV: up to 90% - QGP

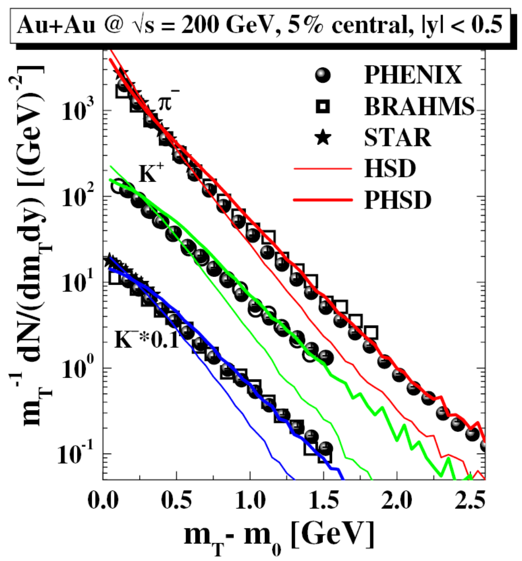
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
V. Konchakovski et al., Phys. Rev. C 85 (2012) 011902

Transverse mass spectra from SPS to RHIC

Central Pb + Pb at SPS energies

Central Au+Au at RHIC





- PHSD gives harder m_T spectra and works better than HSD (wo QGP) at high energies – RHIC, SPS (and top FAIR, NICA)
- however, at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases due to the decrease of the partonic fraction

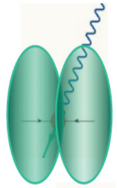
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

Direct photon flow puzzle

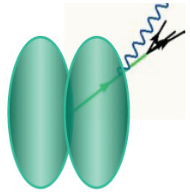
Production sources of photons in p+p and A+A

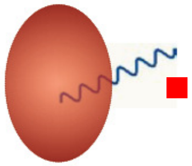
- **Decay photons** (in pp and AA):

$$m \rightarrow \gamma + X, \;\; m = \pi^0, \eta, \omega, \eta', a_1, \ldots$$

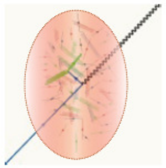


- **Direct photons:** (inclusive(=total) – decay) – measured experimentally
  - **hard photons**: (large p_T, in pp and AA)
    - **prompt** (pQCD; initial hard N+N scattering)
    - **jet fragmentation** (pQCD; qq, gq bremsstrahlung) (in AA can be modified by parton energy loss in medium)

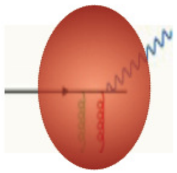




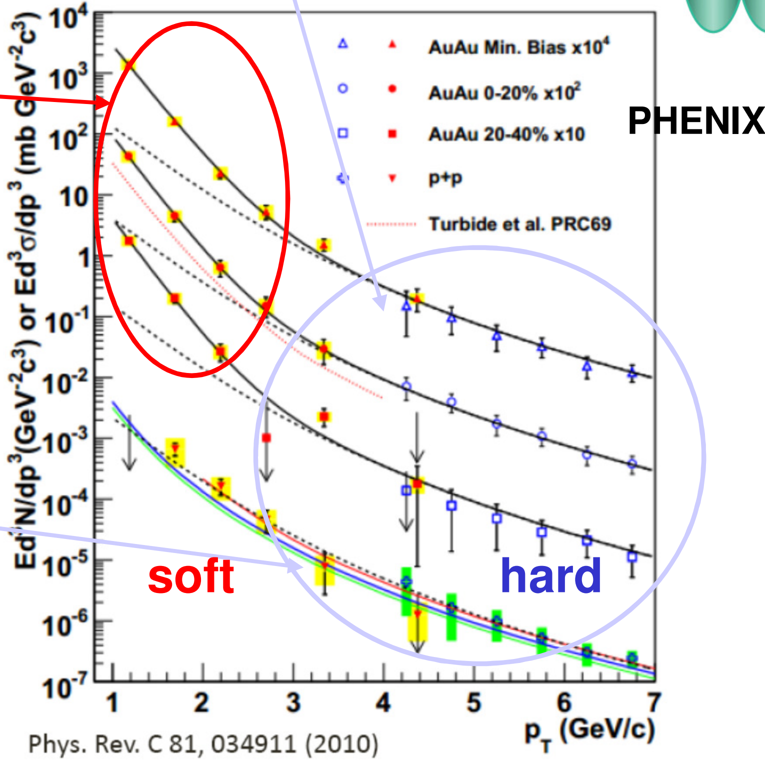
  - **thermal photons**: (low p_T, in AA)
    - QGP
    - Hadron gas



  - **jet-γ-conversion** in plasma (large p_T, in AA)



  - **jet-medium photons** (large p_T, in AA) - scattering of hard partons with thermalized partons $q_{hard}+g_{QGP} \rightarrow \gamma+q$,
$q_{hard}+\bar{q}_{QGP} \rightarrow \gamma+q$



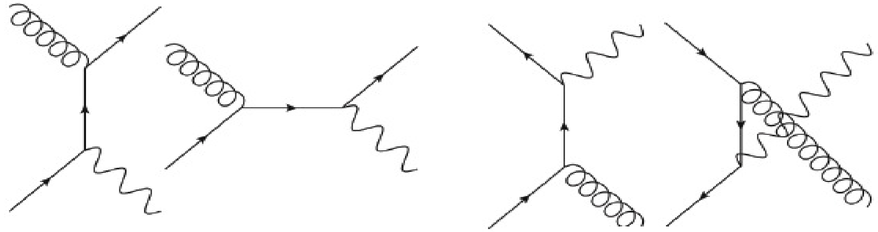
Phys. Rev. C 81, 034911 (2010)

Production sources of thermal photons

HTL program (Klimov (1981), Weldon (1982),
Braaten & Pisarski (1990); Frenkel & Taylor (1990), ...)

❑ Thermal QGP:

Compton scattering q-qbar annihilation



+ soft ...

$$q(\bar{q}) + g \rightarrow q(\bar{q}) + \gamma \qquad q + \bar{q} \rightarrow g + \gamma$$

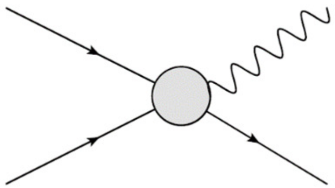
- in PHSD - rates beyond pQCD: off-shell massive q, g

O. Linnyk, JPG 38 (2011) 025105

❑ Hadronic sources:

(1) secondary mesonic interactions:

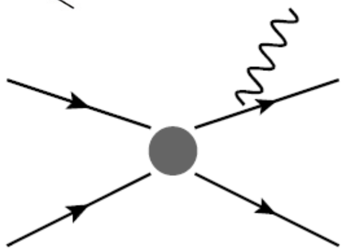
$\pi + \pi \rightarrow \rho + \gamma,\ \rho + \pi \rightarrow \pi + \gamma,\ \pi + K \rightarrow \rho + \gamma, \ldots$



(2) meson-meson and meson-baryon bremsstrahlung:

$m + m \rightarrow m + m + \gamma, \quad m + B \rightarrow m + B + \gamma,$

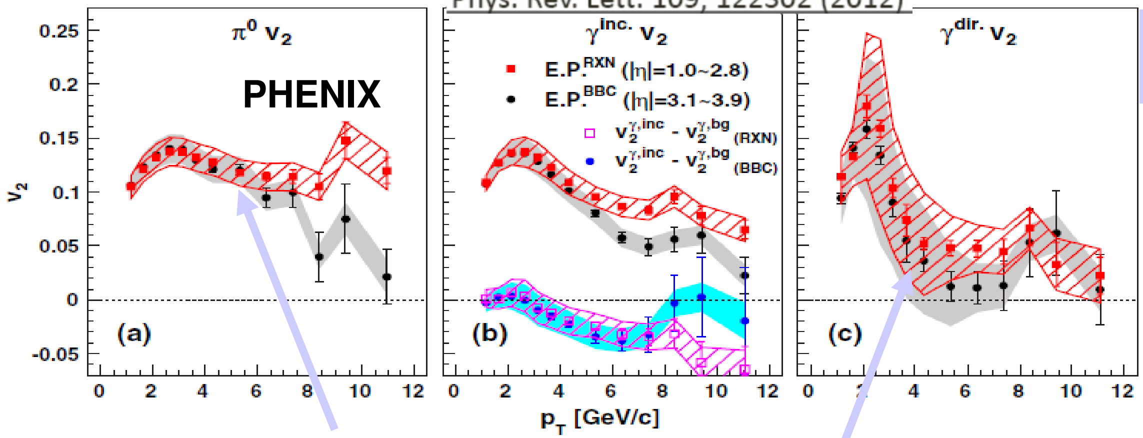
$m = \pi, \eta, \rho, \omega, K, K^*, \ldots, \ B = p, \Delta, \ldots$



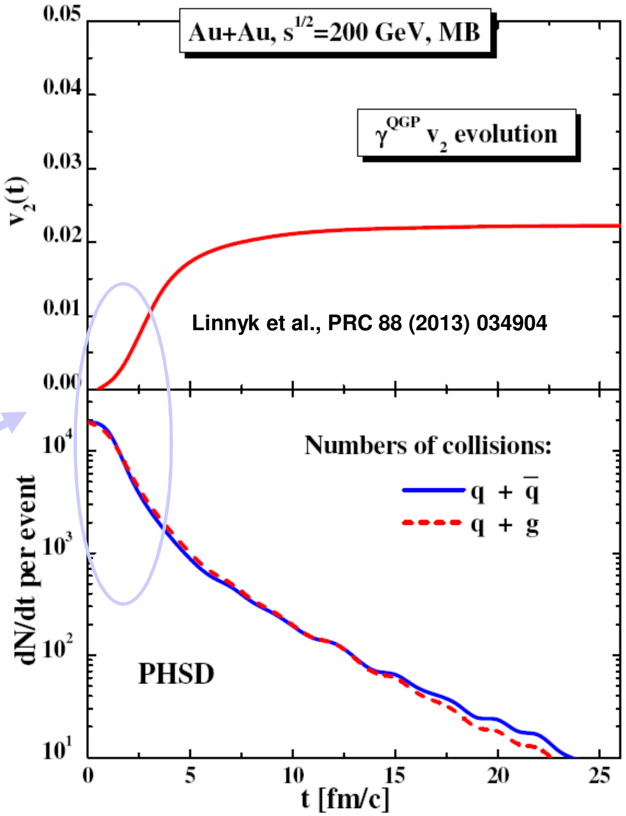
Models: chiral models, OBE, SPA ...

PHENIX: Photon v_2 puzzle

Phys. Rev. Lett. 109, 122302 (2012)



$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + 2\sum_{n\geq 1} v_n \cos\left(n(\phi - \Psi_n^{RP})\right)\right)$$



!

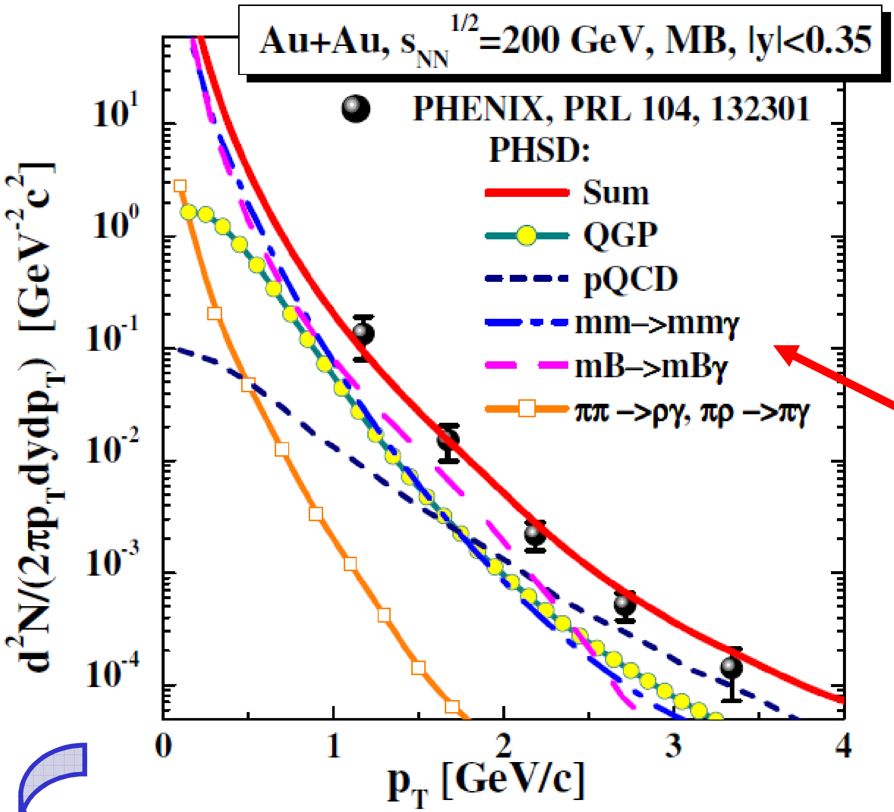
- PHENIX (also now ALICE): strong elliptic flow of photons $v_2(\gamma^{dir}) \sim v_2(\pi)$
- Result from a variety of models: $v_2(\gamma^{dir}) << v_2(\pi)$
- Problem: QGP radiation occurs at early times when elliptic flow is not yet developed ➔ expected $v_2(\gamma^{QGP}) \rightarrow 0$
- v_2 = weighted average $v_2 = \frac{\sum_i N^i \cdot v_2^i}{\sum_i N^i}$ ➔ a large QGP contribution gives small $v_2(\gamma^{QGP})$

- NEW (QM'2014): PHENIX, ALICE experiments - large photon v_3 !

⇨ **Challenge for theory – to describe spectra, v_2, v_3 simultaneously !**

PHSD: photon spectra at RHIC: QGP vs. HG ?

- **Direct photon spectrum (min. bias)**



The slope parameter T_{eff} (in MeV)			
PHSD			PHENIX
QGP	hadrons	Total	[38]
260 ± 20	200 ± 20	220 ± 20	233 ± 14 ± 19

Measured Teff > ‚true' T → ‚blue shift' due to the radial flow!

Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908

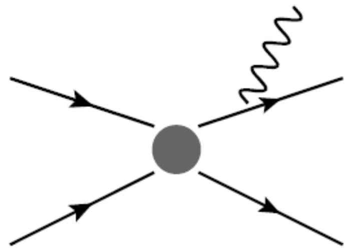
PHSD:

- **QGP gives up to ~50% of direct photon yield below 2 GeV/c**

! sizeable contribution from hadronic sources – meson-meson (mm) and meson-Baryon (mB) bremsstrahlung

$m+m \rightarrow m+m+\gamma,$

$m+B \rightarrow m+B+\gamma,$



$m=\pi,\eta,\rho,\omega,K,K^*,\ldots$

$B=p$

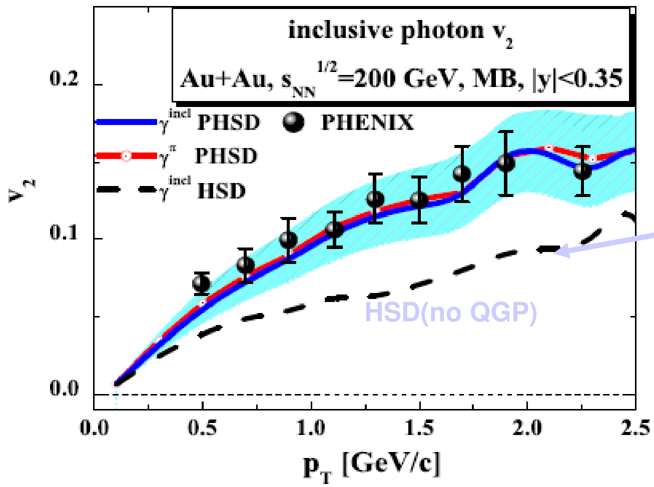
!!! mm and mB bremsstrahlung channels can not be subtracted experimentally !

Cf. Hydro: Shen et al., PRC89 (2014) 044910

Are the direct photons a barometer of the QGP?

- Do we see the QGP pressure in $v_2(\gamma)$ if the photon productions is dominated by hadronic sources?

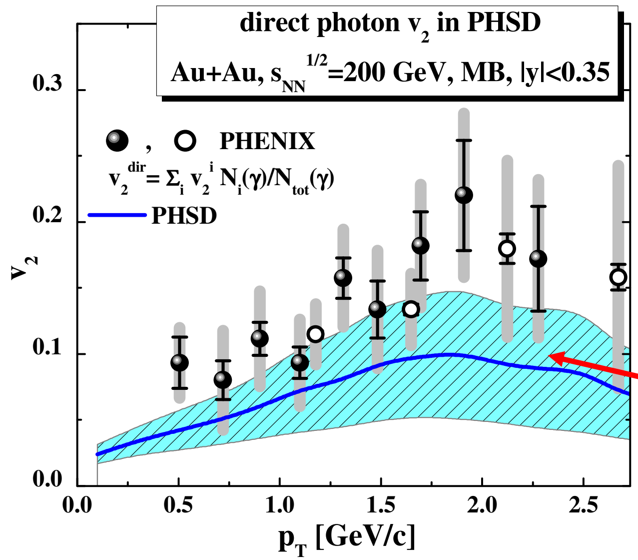
PHSD: Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908



1) $v_2(\gamma^{incl}) = v_2(\pi^0)$ - inclusive photons mainly come from π^0 decays

- HSD (without QGP) underestimates v_2 of hadrons and inclusive photons by a factor of 2, wheras the PHSD model with QGP is consistent with exp. data

➔ The QGP causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of final hadrons due to the partonic interactions



Direct photons (inclusive(=total) – decay):

2) $v_2(\gamma^{dir})$ of direct photons in PHSD underestimates the PHENIX data :

$v_2(\gamma^{QGP})$ is very small, but QGP contribution is up to 50% of total yield ➔ lowering flow

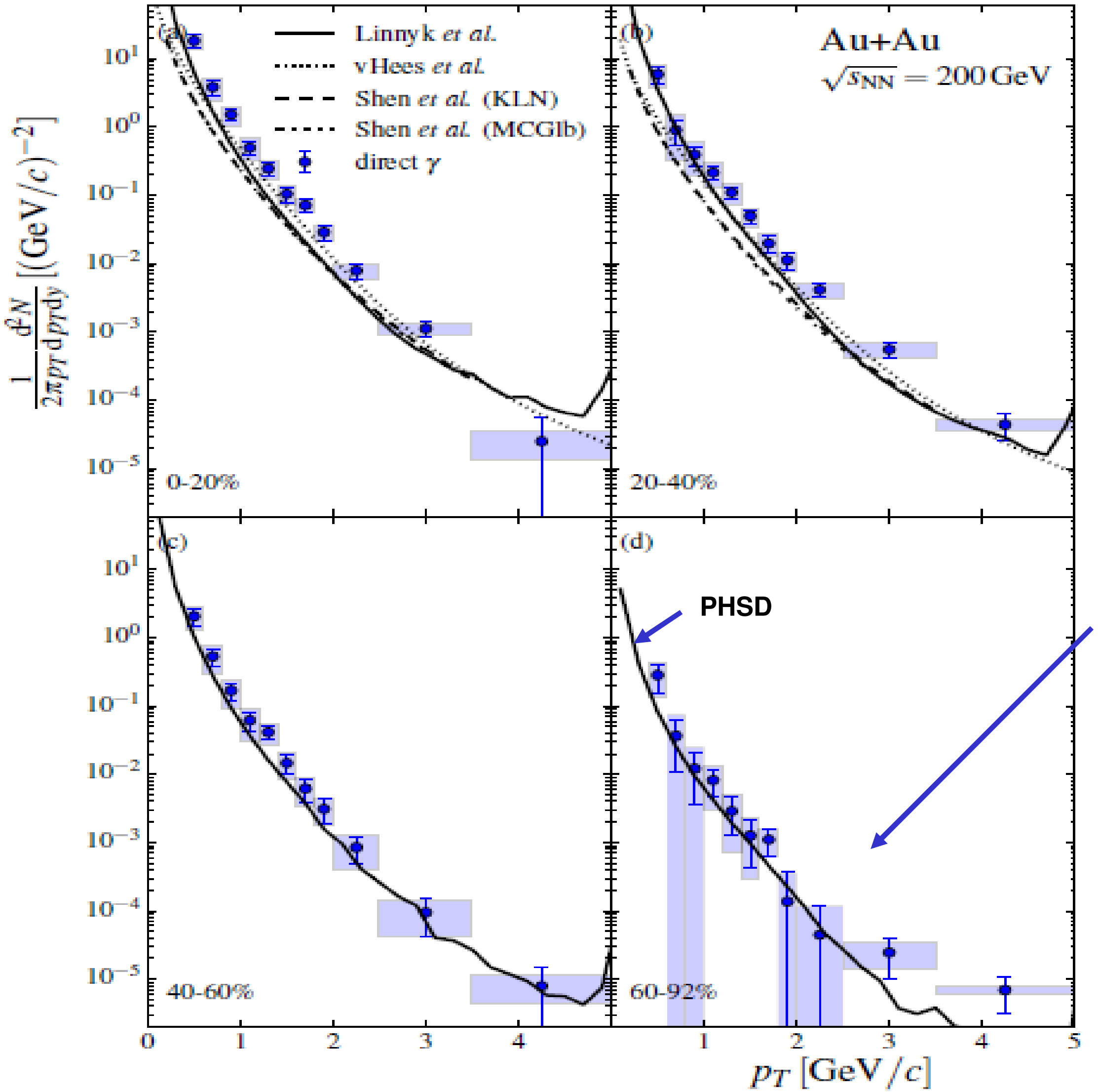
➔PHSD: $v_2(\gamma^{dir})$ comes from mm and mB bremsstrahlung !

Photon p_T spectra at RHIC for different centralities

from talk by S. Mizuno at QM'2014

PHENIX data - arXiv:1405.3940

PHSD predictions:
O. Linnyk et al, Phys. Rev. C 89 (2014) 034908



- ❑ PHSD approximately reproduces the centrality dependence

- ❑ mm and mB bremsstrahlung is dominant for peripheral collisions

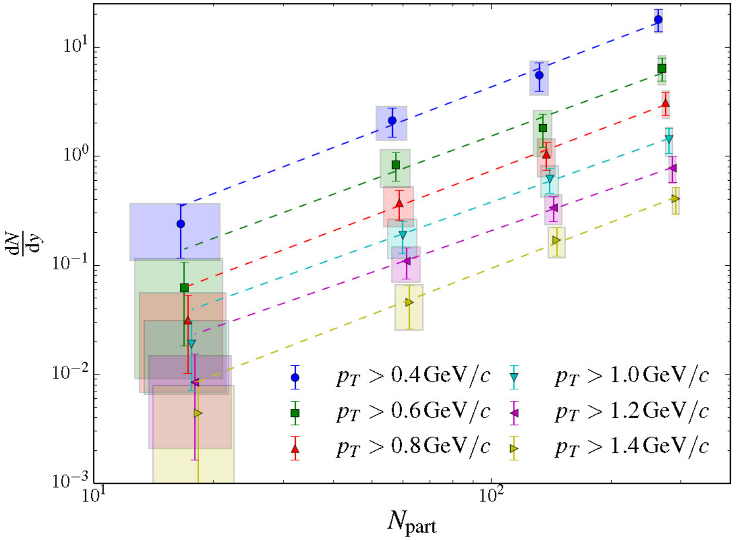
Centrality dependence of the ‚thermal‘ photon yield

O. Linnyk et al, Phys. Rev. C 89 (2014) 034908

PHENIX (arXiv:1405.3940):

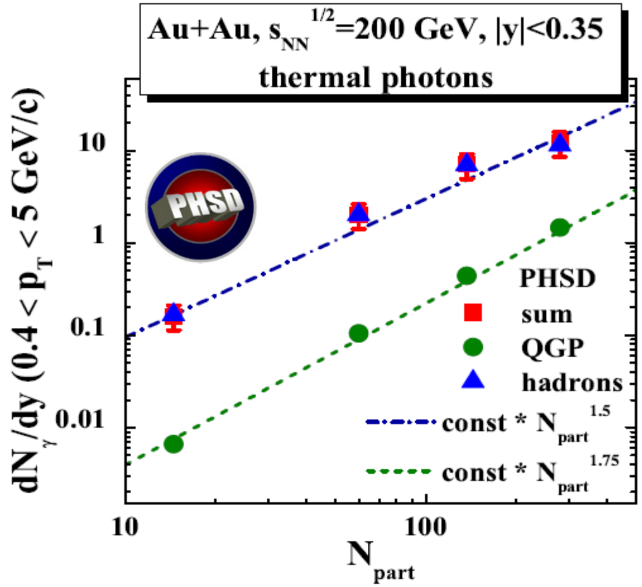
scaling of thermal photon yield vs centrality:
$dN/dy \sim N_{part}^{\alpha}$ with $\alpha \sim 1.48 \pm 0.08$

('Thermal' photon yield = direct photons - pQCD)



PHSD predictions:

- ❑ **Hadronic channels scale as ~ $N_{part}^{1.5}$**
- ❑ **Partonic channels scale as ~$N_{part}^{1.75}$**

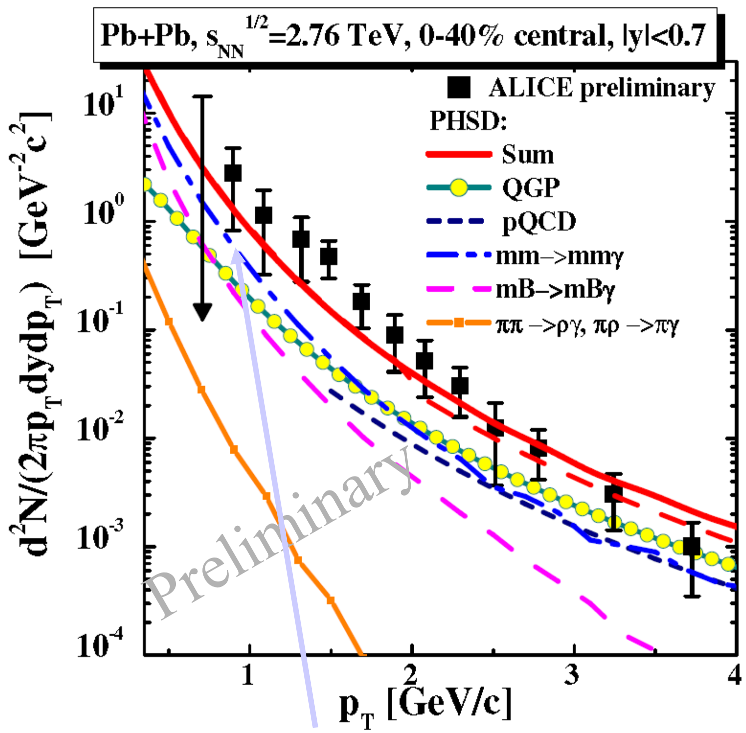


- ❑ **PHSD: scaling of the thermal photon yield with N_{part}^{α} with $\alpha \sim 1.5$**
- ❑ **similar results from viscous hydro:**
  (2+1)d VISH2+1: α(HG) ~1.46, α(QGP) ~2, α(total) ~1.7

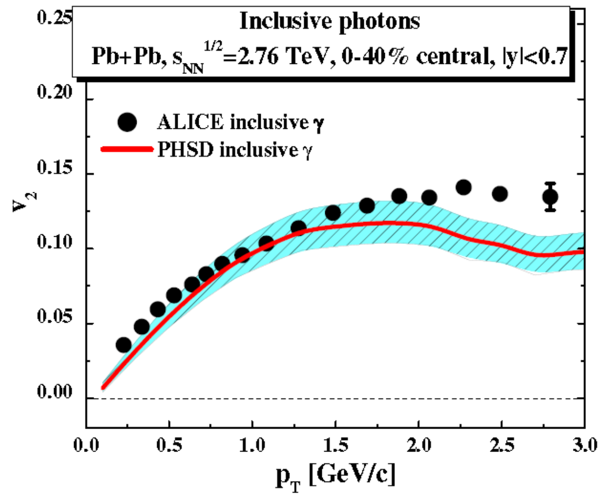
➔ What do we learn?
Indications for a dominant hadronic origin of thermal photon production?!

Photons from PHSD at LHC

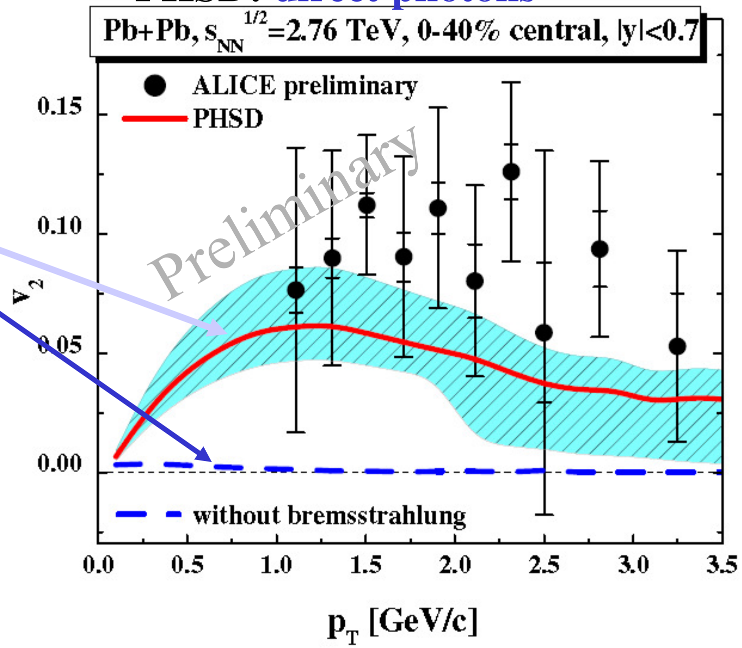
PHSD- preliminary: Olena Linnyk



PHSD: v_2 of inclusive photons



PHSD: direct photons



- Is the considerable elliptic flow of direct photons at the LHC also of hadronic origin as for RHIC?!
- The photon elliptic flow at LHC is lower than at RHIC due to a larger relative QGP contribution / longer QGP phase.

→ LHC (similar to RHIC): hadronic photons dominate spectra and v_2

Messages from the photon study

- sizeable contribution from hadronic sources - at RHIC and LHC hadronic photons dominate spectra and v_2

- meson-meson (mm) and meson-Baryon (mB) bremsstrahlung are important sources of direct photons

- mm and mB bremsstrahlung channels can not be subtracted experimentally !

- The QGP causes the strong elliptic flow of photons indirectly, by enhancing the v_2 of final hadrons due to the partonic interactions

Photons – one of the most sensitive probes for the early dynamics of HIC!

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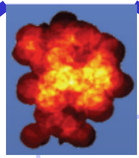
Thank you !

Dynamical models for HIC

Macroscopic

hydro-models:
- description of QGP and hadronic phase by hydrodanamical equations for fluid
- assumption of local equilibrium
- EoS with phase transition from QGP to HG
- initial conditions (e-b-e, fluctuating)



ideal
(Jyväskylä,SHASTA, TAMU, …)

viscous
(Romachkke,(2+1)D VISH2+1, (3+1)D MUSIC,…)

fireball models:
- no explicit dynamics: parametrized time evolution (TAMU)

‚Hybrid'
QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model

(‚hybrid'-UrQMD, EPOS, …)

Microscopic

Non-equilibrium microscopic transport models – based on many-body theory

Hadron-string models
(UrQMD, IQMD, HSD, QGSM …)

Partonic cascades
pQCD based
(Duke, BAMPS, …)

Parton-hadron models:
- QGP: pQCD based cascade
- massless q, g
- hadronization: coalescence

(AMPT, HIJING)

PHSD
- QGP: lQCD EoS
- massive quasi-particles
(q and g with spectral functions) in self-generated mean-field
- dynamical hadronization
- HG: off-shell dynamics
(applicable for strongly interacting systems)