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Dynamical description of strongly interacting parton-hadron matter

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PHSD

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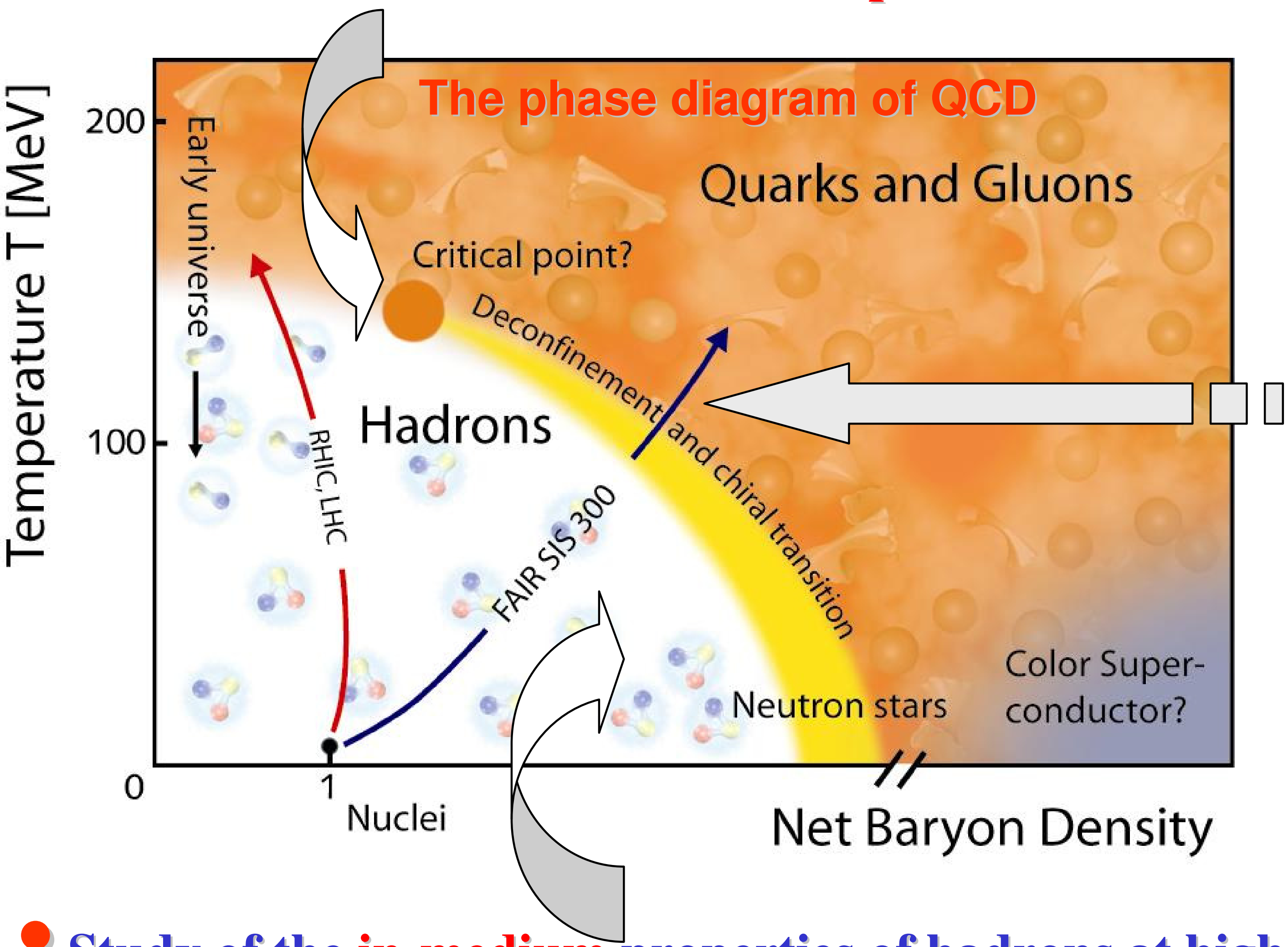
The holy grail of heavy-ion physics:

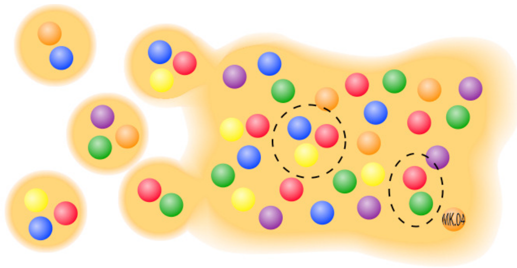
- Search for the critical point



- 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

From hadrons to partons



In order to study the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma – we need a consistent non-equilibrium (transport) model with

- explicit parton-parton interactions (i.e. between quarks and gluons) beyond strings!
- explicit phase transition from hadronic to partonic degrees of freedom
- lQCD EoS for partonic phase

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

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

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 :

$$\rho_i(\omega, T) = \frac{4\omega\Gamma_i(T)}{\left(\omega^2 - \vec{p}^2 - M_i^2(T)\right)^2 + 4\omega^2\Gamma_i^2(T)} \qquad (i = q, \bar{q}, g)$$

- **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:**

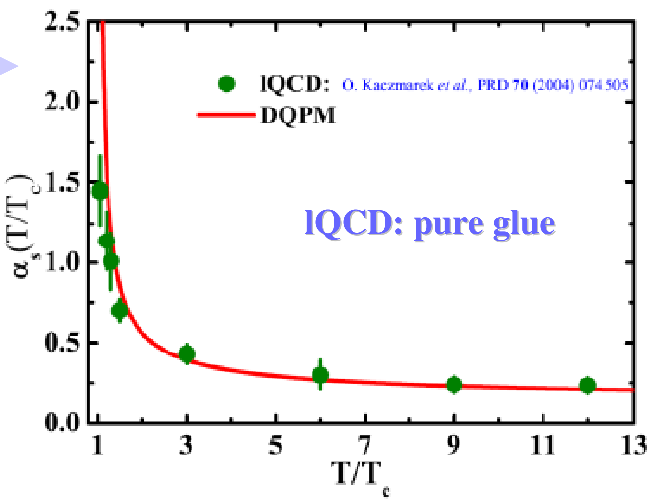
    $$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

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

    $N_c = 3$, 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)**

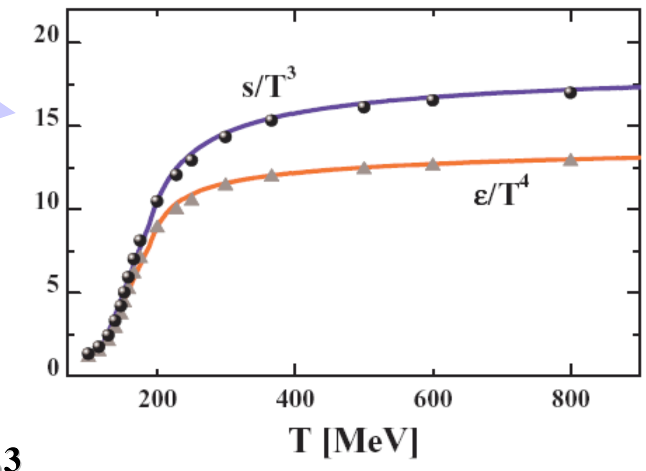
with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42
(for pure glue N_f=0)

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

The Dynamical QuasiParticle Model (DQPM)

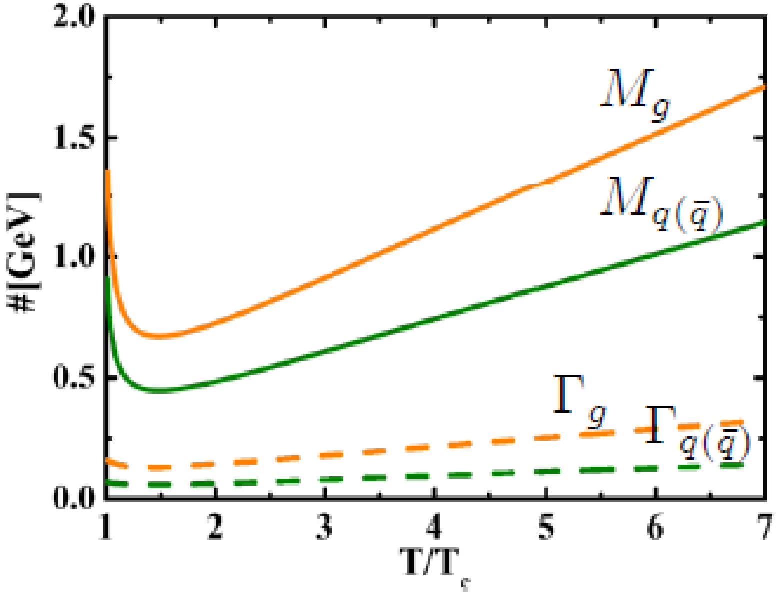
➢ **fit to lattice (lQCD) results** (e.g. entropy density)

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

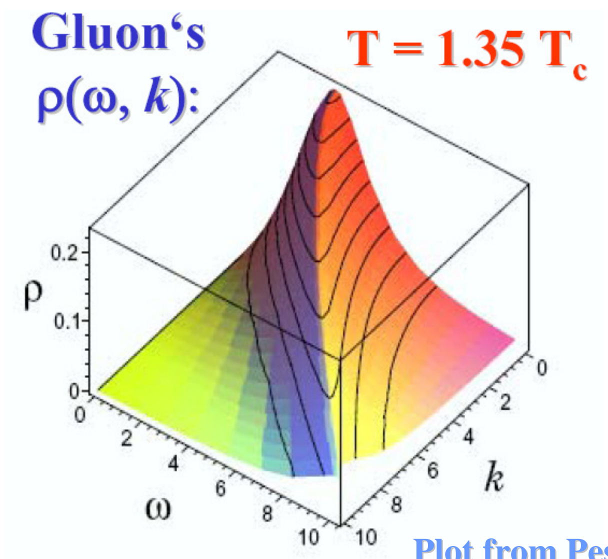


➔ **Quasiparticle properties:**

- **large width and mass for gluons and quarks**



T_C=158 MeV
ε_C=0.5 GeV/fm³

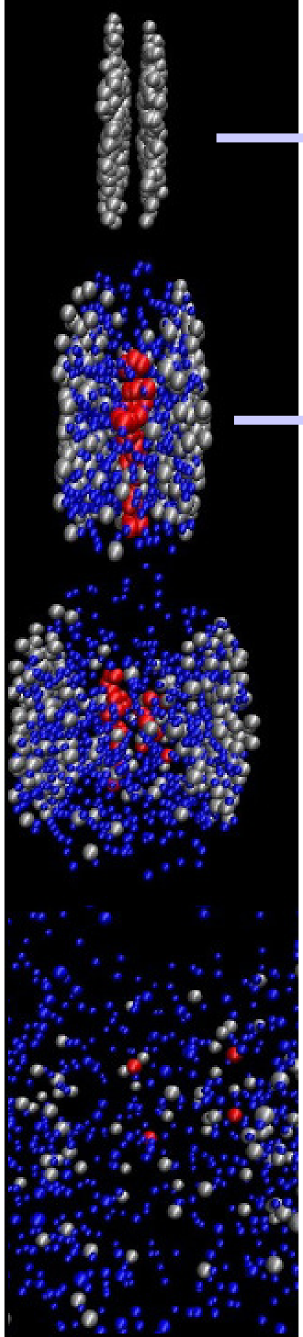


Plot from Peshier, PRD 70 (2004) 034016

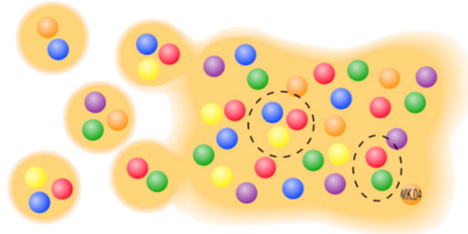
- **DQPM matches well lattice QCD**
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons → PHSD**

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

I. PHSD - basic concept



I. From hadrons to QGP:



- **Initial A+A collisions – as in HSD:**
  - string formation in primary NN collisions
  - string decay to pre-hadrons (*B* - baryons, *m* - mesons)

- **Formation of QGP stage by dissolution of pre-hadrons**
  (all new produced secondary hadrons)
  into massive colored quarks + mean-field energy

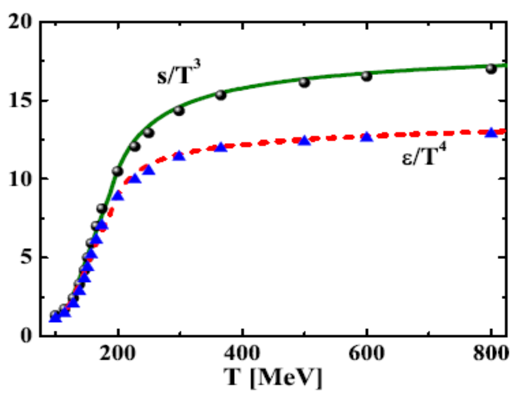
QGP phase:
$\varepsilon > \varepsilon_{critical}$

$$B \rightarrow qqq, \;\; m \rightarrow q\bar{q} \quad \forall \quad U_q$$

based on the **Dynamical Quasi-Particle Model (DQPM)** which defines quark spectral functions, i.e. masses $M_q(\varepsilon)$ and widths $\Gamma_q(\varepsilon)$

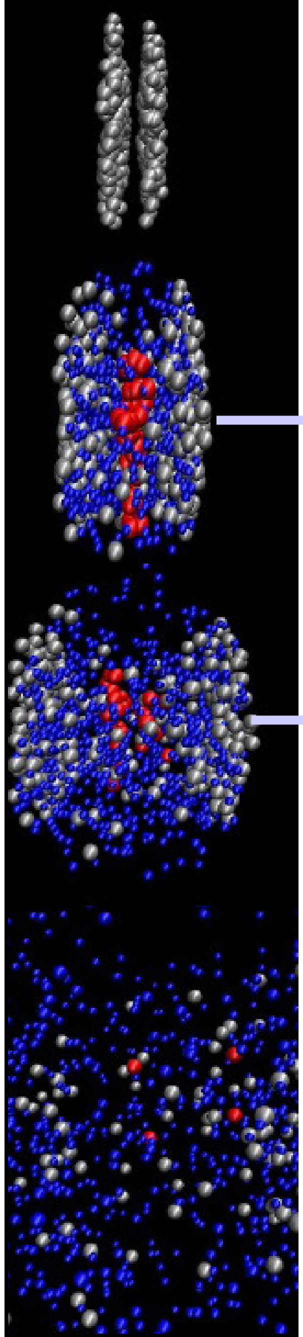
\+ mean-field potential U_q at given ε – local energy density

(ε related by lQCD EoS to T - temperature in the local cell)



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

II. PHSD - basic concept



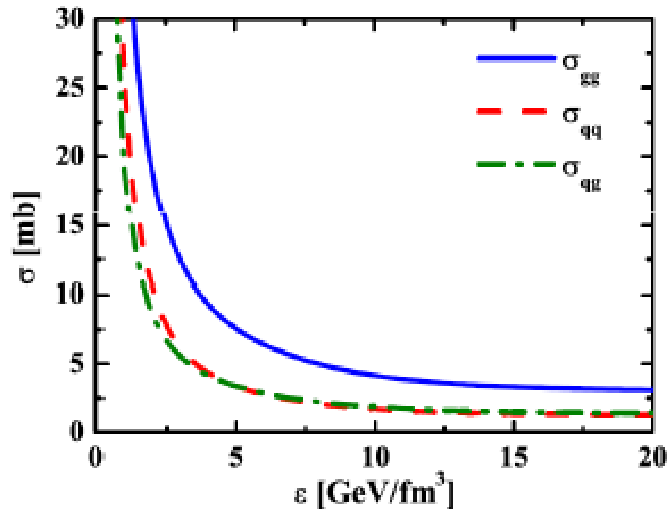
II. Partonic phase - QGP:

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 from the DQPM**
- **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

- **(quasi-) elastic collisions:**

$$q+q \to q+q \qquad g+q \to g+q$$
$$q+\bar{q} \to q+\bar{q} \qquad g+\bar{q} \to g+\bar{q}$$
$$\bar{q}+\bar{q} \to \bar{q}+\bar{q} \qquad g+g \to g+g$$

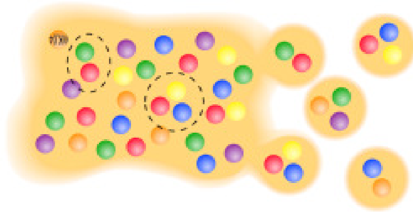


- **inelastic collisions:**
(Breight-Wigner cross sections)

$$\left\{ \begin{array}{l} q+\bar{q} \to g \\ g \to q+\bar{q} \end{array} \right.$$

$$\left. \begin{array}{l} q+\bar{q} \to g+g \\ g \to g+g \end{array} \right\}$$ **suppressed (<1%) due to the large mass of gluons**

III. PHSD - basic concept



III. Hadronization:

❑ **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)

$$g \rightarrow q + \bar{q}, \qquad q + \bar{q} \leftrightarrow meson \ ('string')$$

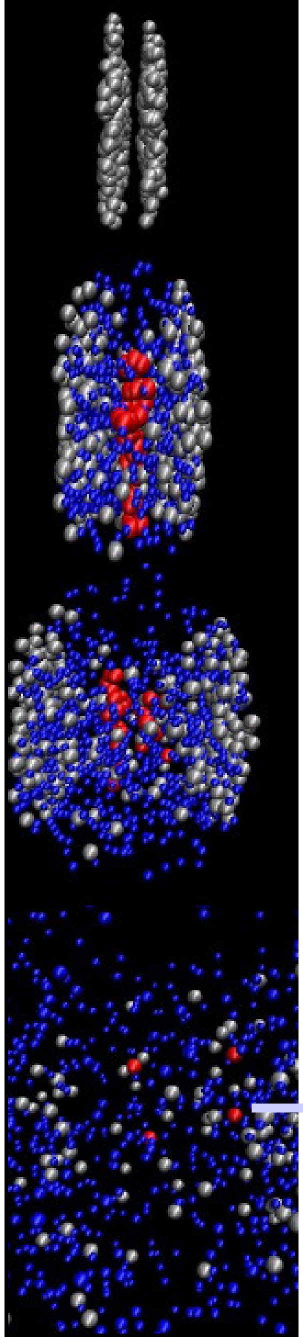
$$q + q + q \leftrightarrow baryon \ ('string')$$

- **Local covariant off-shell transition rate for q+qbar fusion**
  ➔ **meson formation:**

$$\frac{dN^{q+\bar{q}\rightarrow m}}{d^4x\, d^4p} = Tr_q Tr_{\bar{q}}\, \delta^4(p - p_q - p_{\bar{q}})\, \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right) \delta(flavor, color)$$

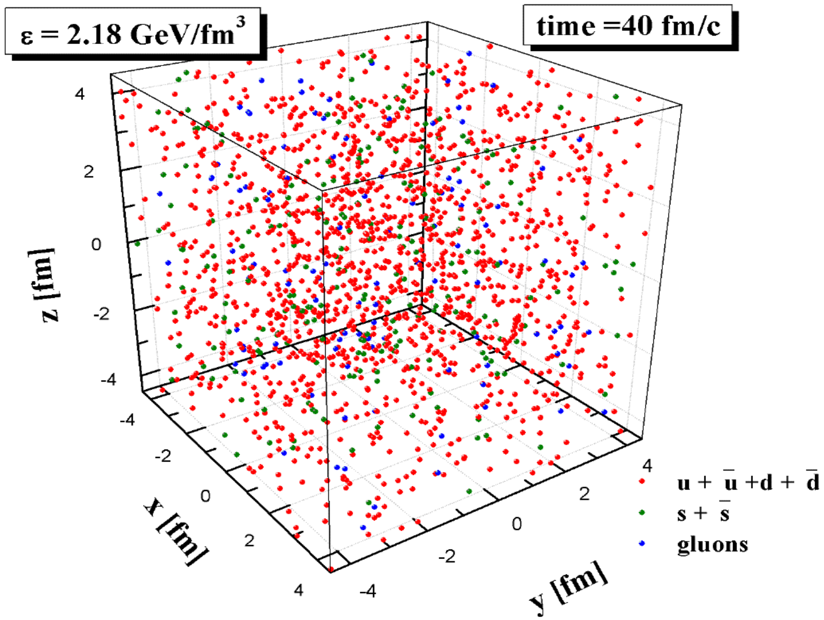
$$\cdot N_q(x_q, p_q) N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \cdot \omega_q \rho_q(p_q) \cdot \omega_{\bar{q}} \rho_{\bar{q}}(p_{\bar{q}}) \cdot |M_{q\bar{q}}|^2\, W_m\left(x_q - x_{\bar{q}}, p_q - p_{\bar{q}}\right)$$

- ❑ $N_j(x,p)$ is the phase-space density of parton j at space-time position x and 4-momentum p
- ❑ W_m is the phase-space distribution of the formed ‚pre-hadrons' (Gaussian in phase space)
- ❑ $|M_{qq}|^2$ is the effective quark-antiquark interaction from the DQPM



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

Properties of the QGP in-equilibrium using PHSD



Properties of parton-hadron matter in equilibrium

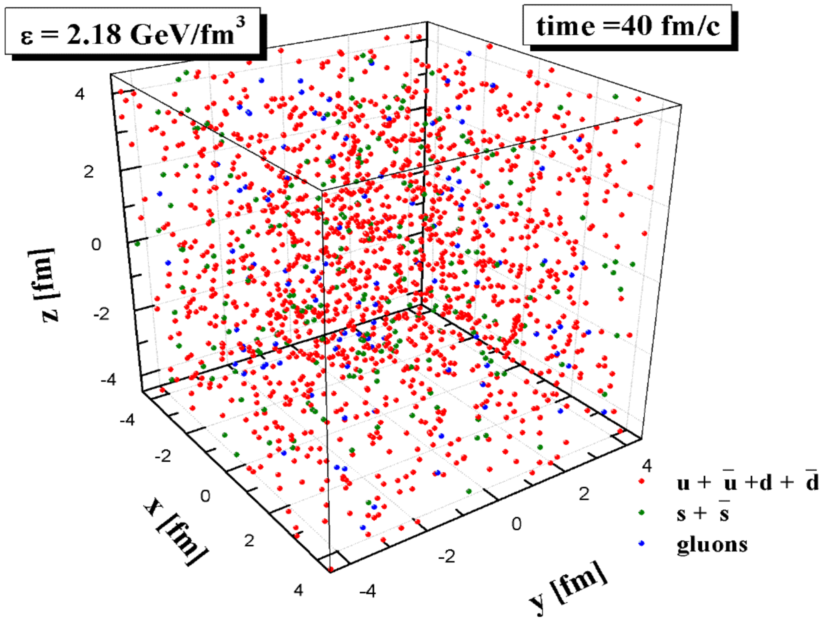
V. Ozvenchuk et al., PRC 87 (2013) 024901, arXiv:1203.4734
V. Ozvenchuk et al., PRC 87 (2013) 064903, arXiv:1212.5393

The goal:

- study of the dynamical equilibration of QGP within the non-equilibrium off-shell PHSD transport approach
- transport coefficients (shear and bulk viscosities) of strongly interacting partonic matter in equilibrium
- particle number fluctuations (scaled variance, skewness, kurtosis)

Realization:

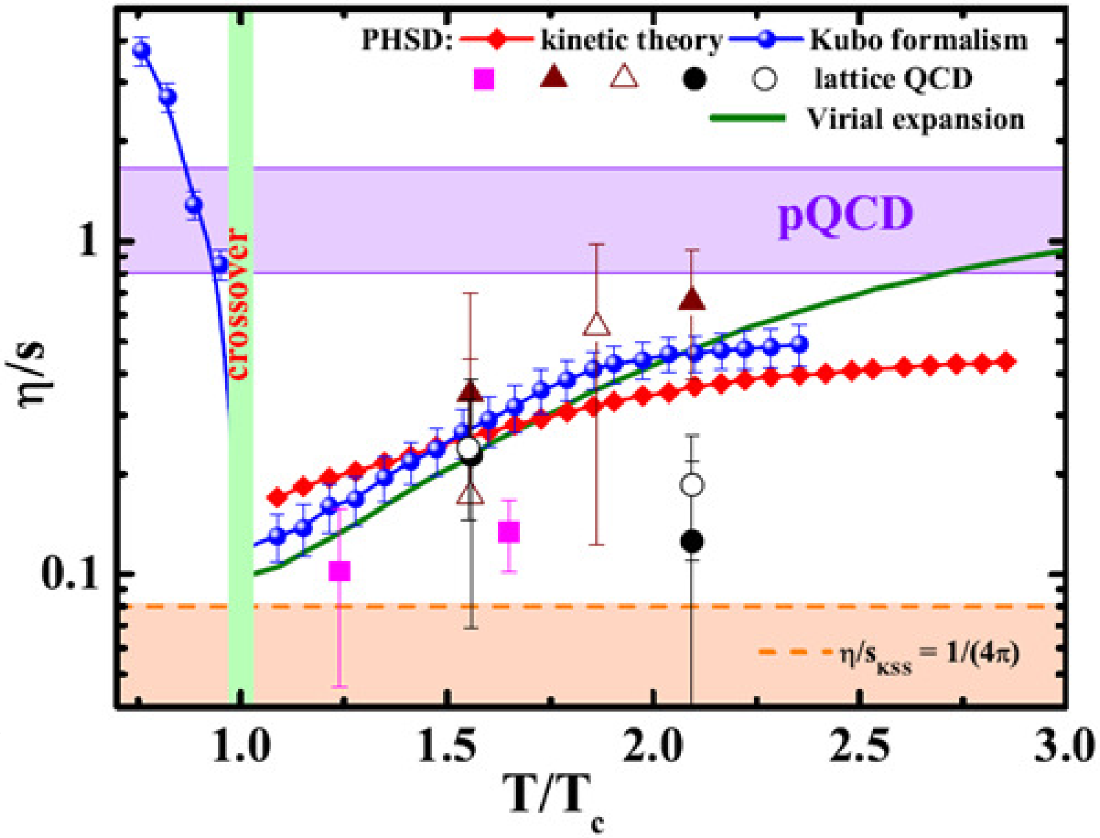
- Initialize the system in a finite box with periodic boundary conditions with some energy density ε and chemical potential μ_q
- Evolve the system in time until equilibrium is achieved



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 >3 Tc
- ❑ $T<T_C$: fast increase of the ratio η/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 liquid

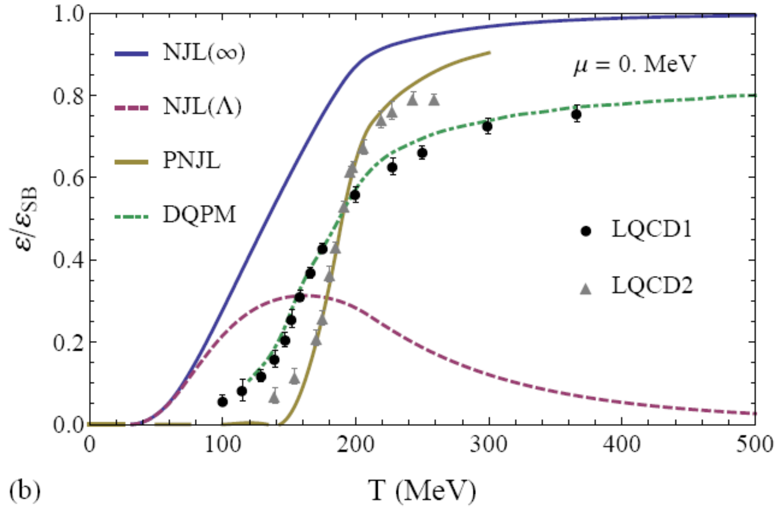
V. Ozvenchuk et al., PRC 87 (2013) 064903, arXiv:1212.5393

Transport coefficients from (P)NJL: shear viscosity

R. Marty, E.B., W. Cassing, J. Aichelin, H. Berrehrah, arXiv:1305.7180 [hep-ph]

- **NJL SU(3)$_f$ model** (from Nantes group)

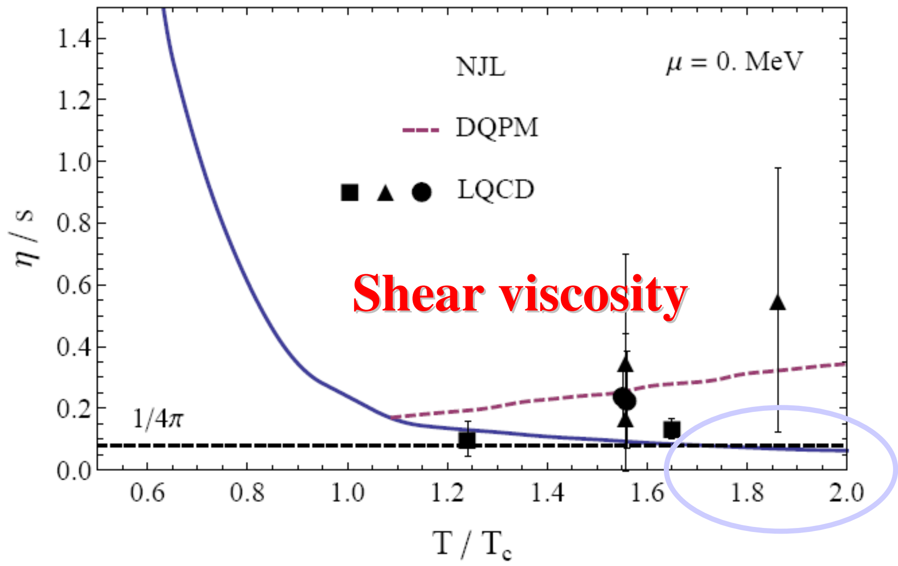
$$\mathscr{L}_{NJL} = \bar{\psi}\,(i\partial\!\!\!/ - m_0)\,\psi + G\sum_{a=0}^{8}\left[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2\right] - K\left[\det\bar{\psi}\,(1-\gamma_5)\,\psi + \det\bar{\psi}\,(1+\gamma_5)\,\psi\right]$$



- **masses:** $m_i = m_{0i} - 4G\langle\langle\bar{\psi}_i\psi_i\rangle\rangle + 2K\langle\langle\bar{\psi}_j\psi_j\rangle\rangle\langle\langle\bar{\psi}_k\psi_k\rangle\rangle$

- **quark condensate** in the mean field limit:

$$\langle\langle\bar{\psi}_i\psi_i\rangle\rangle = -2N_c\int_0^{\Lambda}\frac{d^3p}{(2\pi)^3}\frac{m_i}{E_{ip}}\left[1-f_q-f_{\bar{q}}\right]$$



- NJL: $\eta/s < 1/4\pi$ for $T > 1.7\,T_c$

➔ the applicability of the NJL model should be restricted to temperatures at least below 1.7 T_c

NJL: $T_c = T_{Mott} = 200$ MeV

LQCD1: S. Borsanyi, G. Endrodi, Z. Fodor, A. Jakovac, S. D. Katz, et al., JHEP 1011, 077 (2010)
LQCD2: M. Cheng, S. Ejiri, P. Hegde, F. Karsch, O. Kaczmarek, et al.,Phys. Rev. D 81, 054504 (2010)
PNJL: P. Costa, M. Ruivo, C. de Sousa, and H. Hansen, Symmetry 2, 1338 (2010)

Bulk viscosity (mean-field effects)

- bulk viscosity in relaxation time approximation with mean-field effects:

Chakraborty, Kapusta, Phys. Rev.C 83, 014906 (2011).

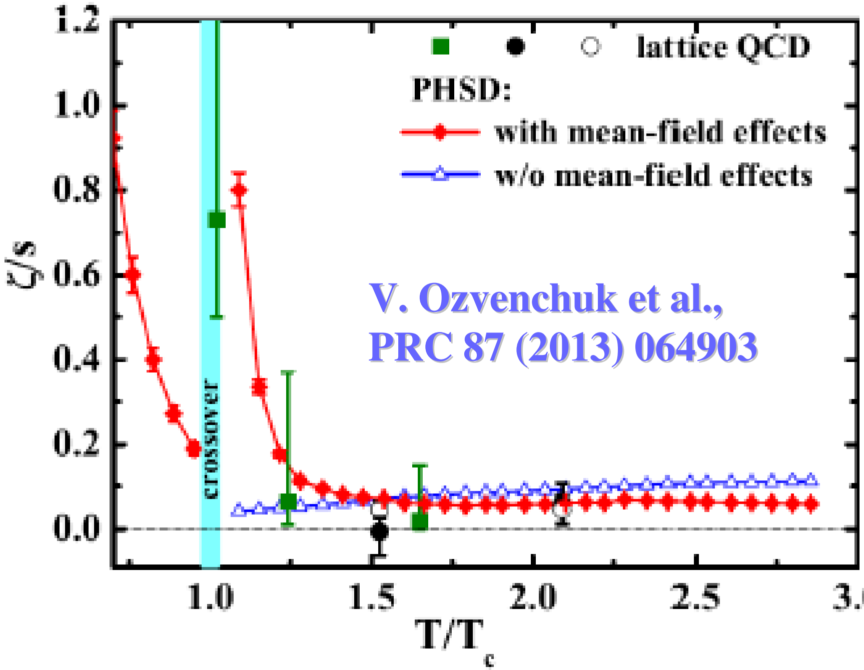
$$\zeta = \frac{1}{TV}\sum_{i=1}^{N}\frac{\Gamma_i^{-1}}{E_i^2}\left[\left(\frac{1}{3}-v_s^2\right)|\mathrm{p}|^2 - v_s^2\left(m_i^2 - T^2\frac{dm_i^2}{dT^2}\right)\right]^2$$

use DQPM results for masses for μ_q=0:

$$m_q^2 = \frac{1}{3}g^2T^2, \qquad m_g^2 = \frac{3}{4}g^2T^2$$

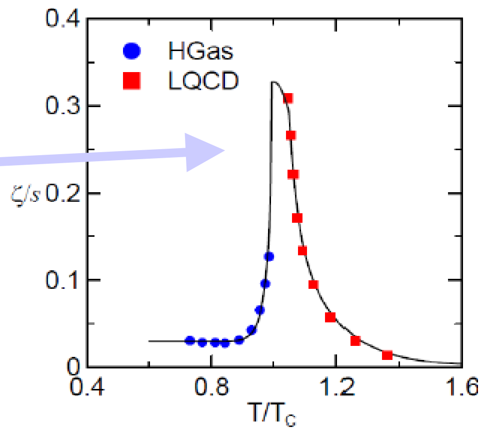
PHSD using the relaxation time approximation:

- significant rise in the vicinity of the critical temperature
- in line with the ratio from lQCD calculations



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

Cf. talk by Gabriel Denicol



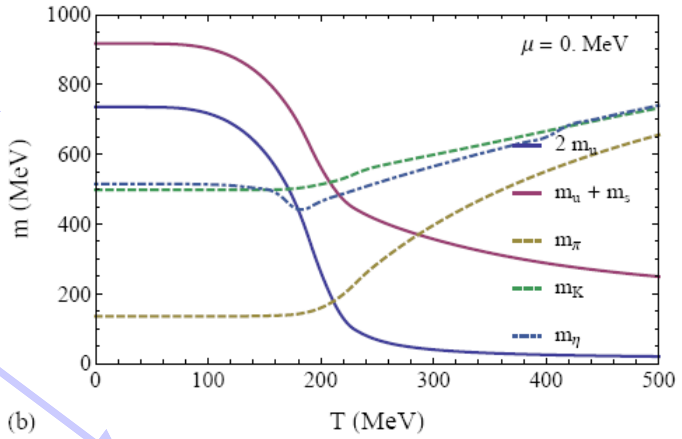
lQCD: Meyer, Phys. Rev. Lett. 100, 162001 (2008);
Sakai,Nakamura, Pos LAT2007, 221 (2007).

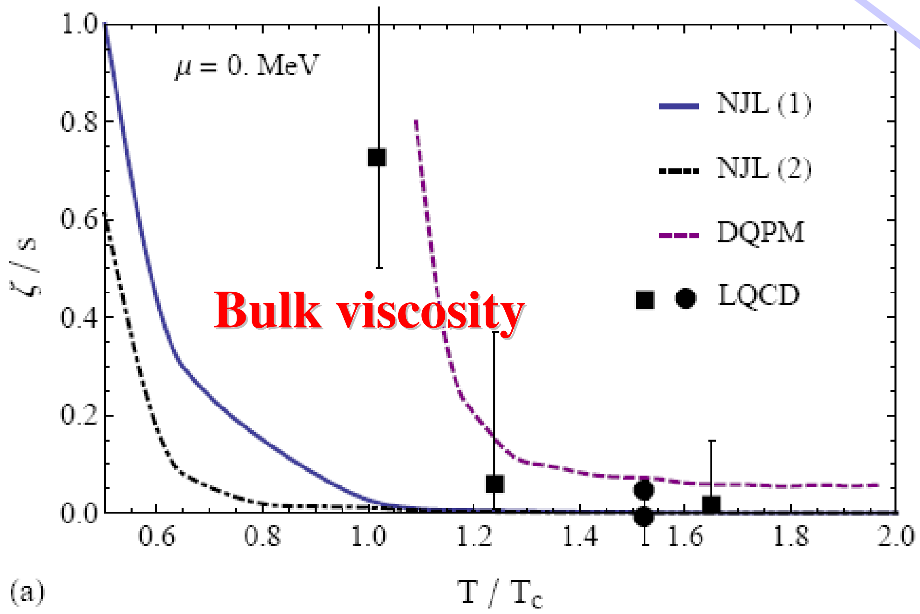
Transport coefficients from (P)NJL: bulk viscosity

R. Marty, E.B., W. Cassing, J. Aichelin, H. Berrehrah,   arXiv:1305.7180 [hep-ph]

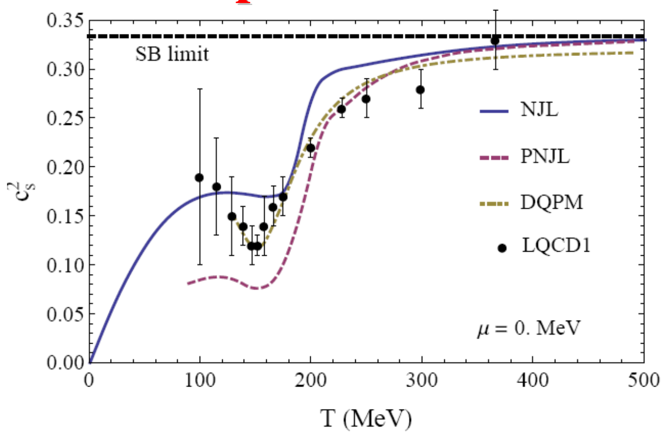
$$\zeta = \frac{1}{TV}\sum_{i=1}^{N}\frac{\Gamma_i^{-1}}{E_i^2}\left[\left(\frac{1}{3}-v_s^2\right)|\mathbf{p}|^2 - v_s^2\left(m_i^2 - T^2\frac{dm_i^2}{dT^2}\right)\right]^2$$

masses in NJL





Speed of sound



NJL (1): NJL using the RTA method Chakraborty, Kapusta, Phys. Rev.C 83, 014906 (2011)

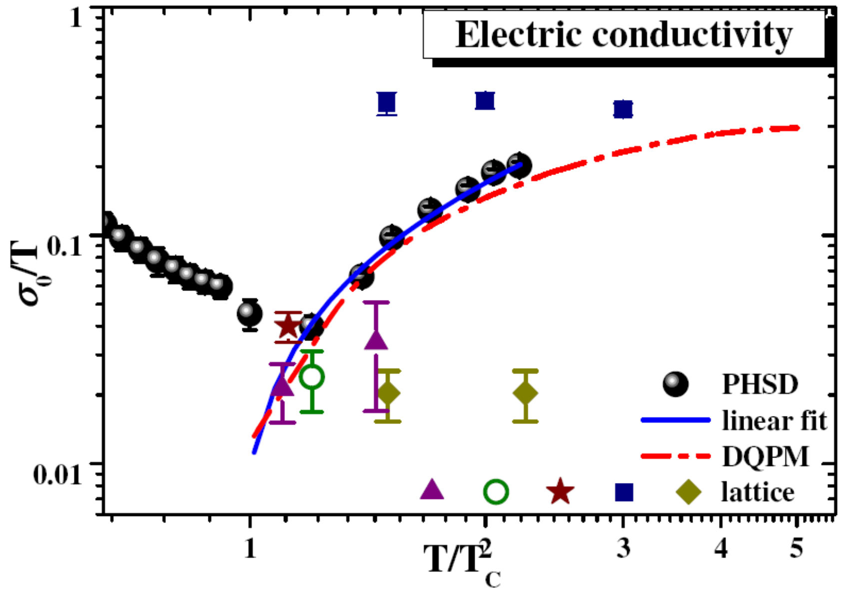
NJL (2): NJL model with method from Sasaki, Redlich, Phys.Rev. C79, 055207 (2009)

ζ/s from NJL is not consistent with the available lQCD data

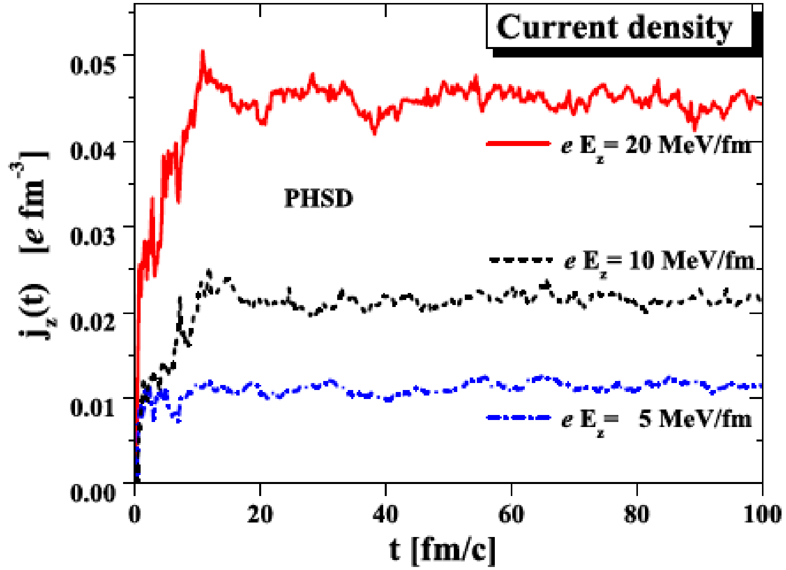
Properties of parton-hadron matter – electric conductivity

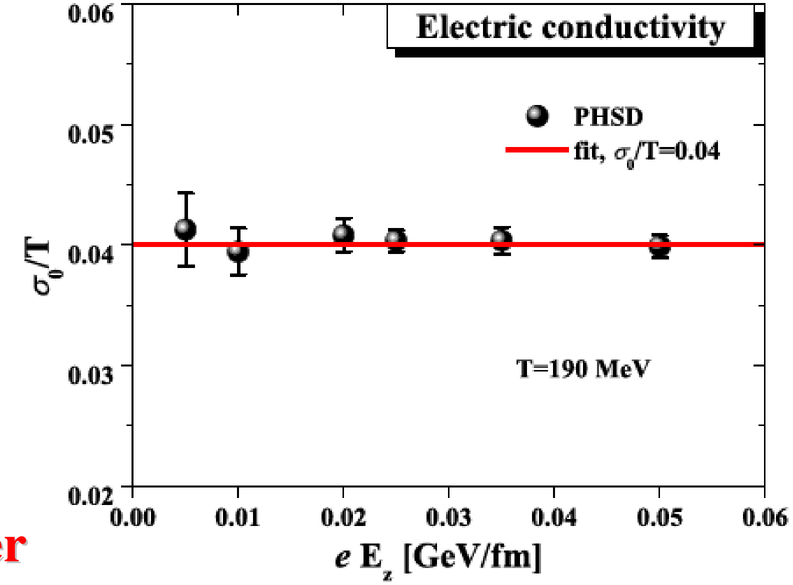
- The response of the strongly-interacting system in equilibrium to an external electric field eE_z defines the electric conductivity σ_0:

$$\frac{\sigma_0}{T} = \frac{j_{eq}}{E_z T}, \quad j_z(t) = \frac{1}{V}\sum_j eq_j \frac{p_z^j(t)}{M_j(t)};$$



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





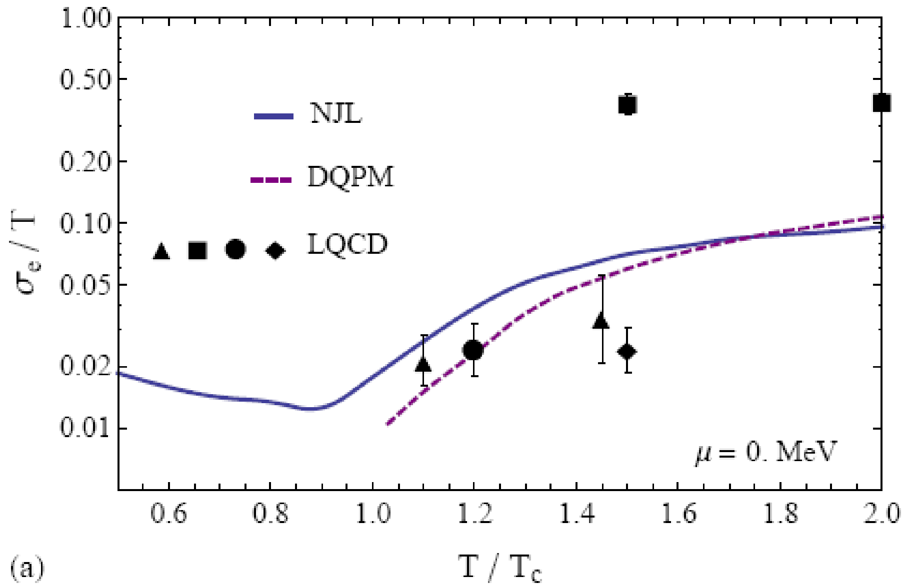
W. Cassing et al., PRL 110 (2013) 182301

Transport coefficients from NJL: electric and heat conductivity

R. Marty, E.B., W. Cassing, J. Aichelin, H. Berrehrah, arXiv:1305.7180 [hep-ph]

Electric conductivity

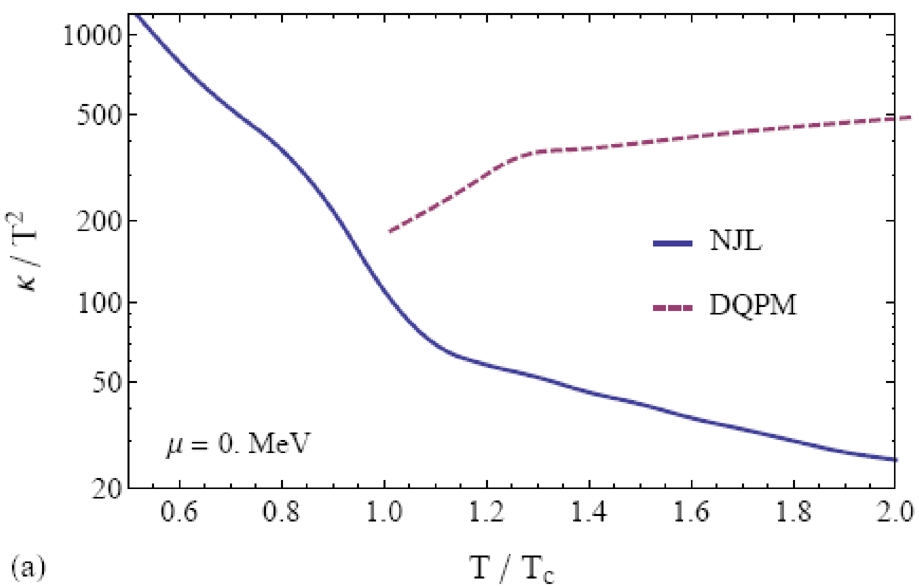
$$\sigma_e(T,\mu) = \sum_q \frac{e_q^2\, n_q(T,\mu)\ \tau_q(T,\mu)}{m_q(T,\mu)} \qquad q = u,d,s,\bar{u},\bar{d},\bar{s},$$



Heat conductivity

$$\kappa(T,\mu) = \frac{1}{3} v_{\rm rel}\ c_V(T,\mu) \sum_f \tau_f(T,\mu)$$

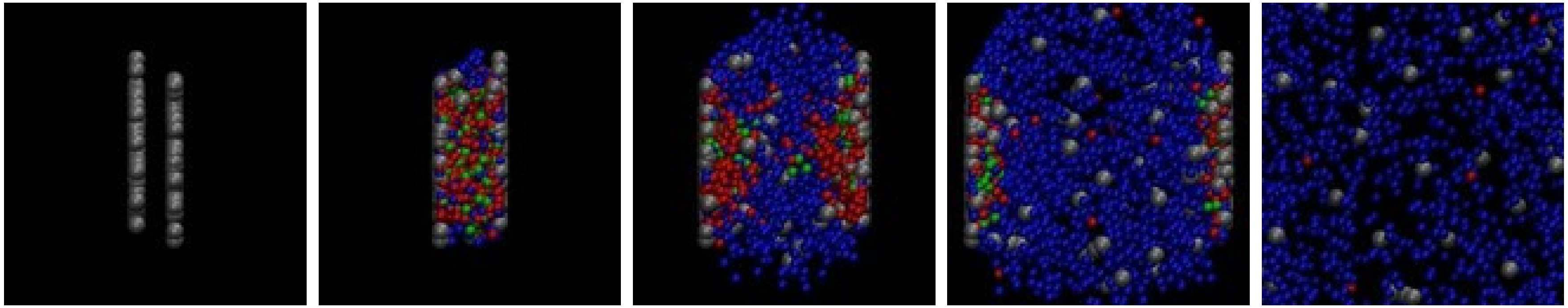
specific heat — relaxation time



For T>T$_c$:

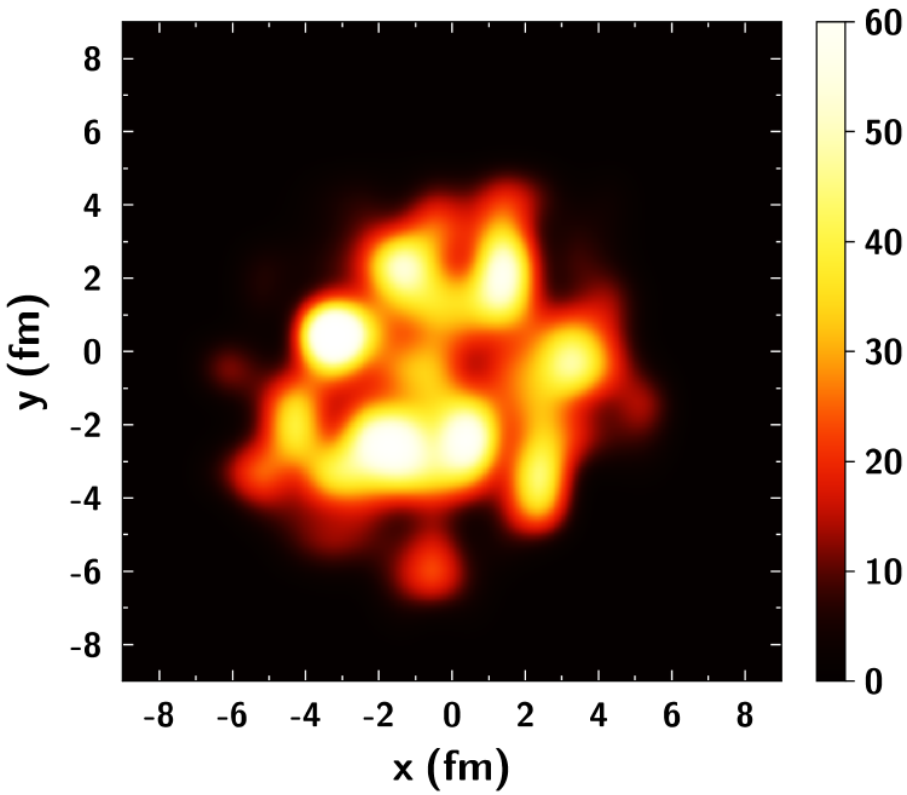
- **electric conductivity from NJL and DQPM agree roughly with lQCD**
- **heat conductivity from NJL and DQPM show very different behavior**
  => lQCD data are needed !

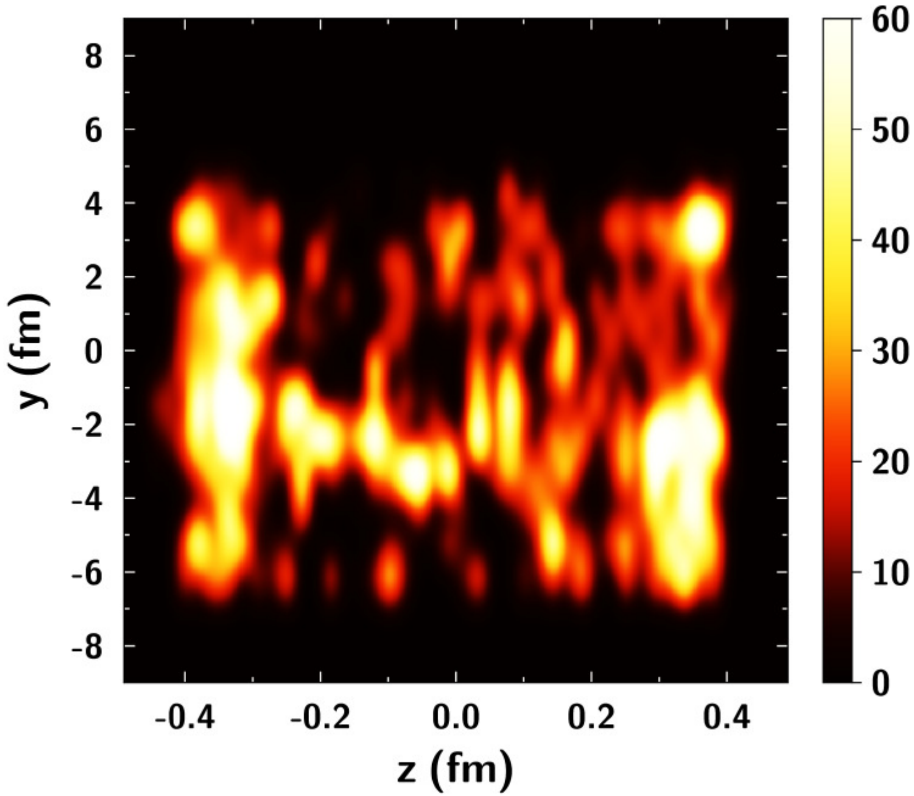
Properties of the QGP out-off equilibrium using PHSD



PHSD for HIC

Energy density ε(GeV/fm²) for Au+Au at $s^{1/2}$ = 200 GeV with impact parameter b = 2 fm in the rest frame

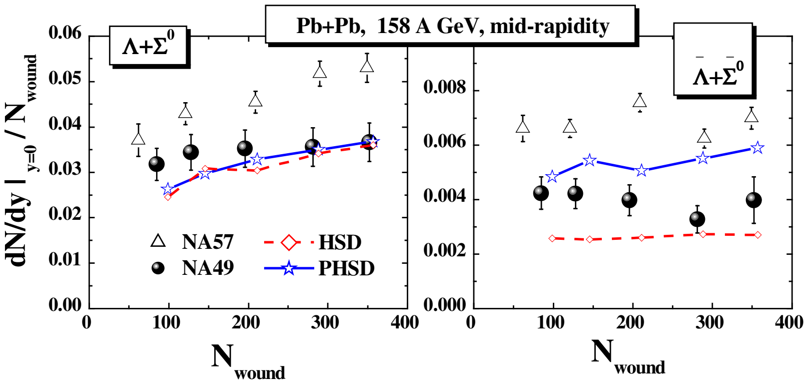


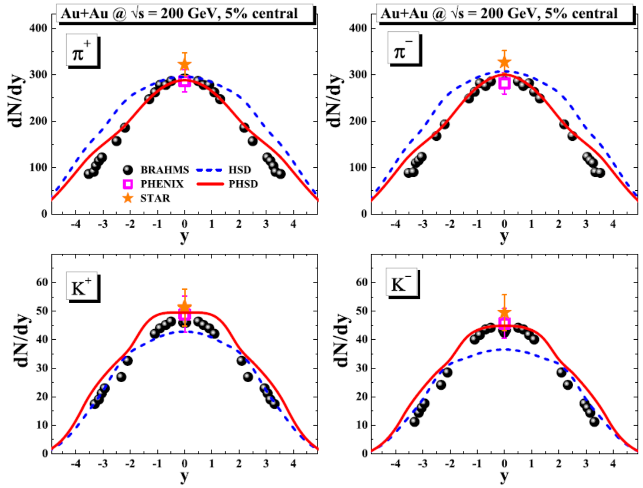


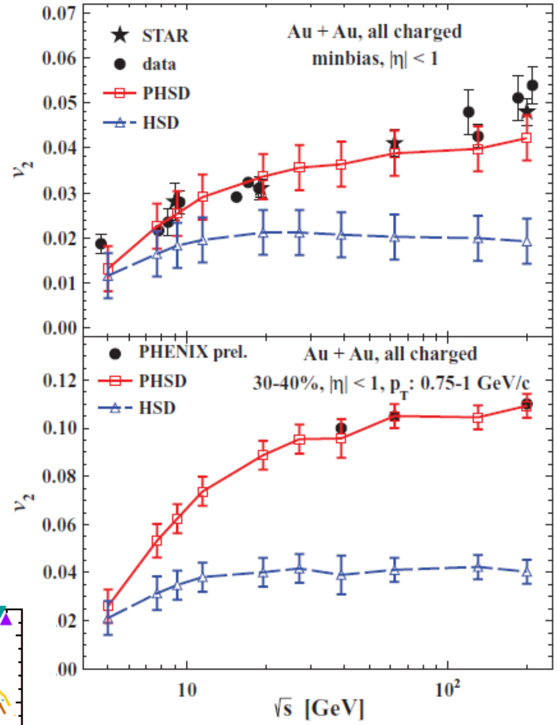
Fluctuating energy density ε(GeV/fm³) in PHSD

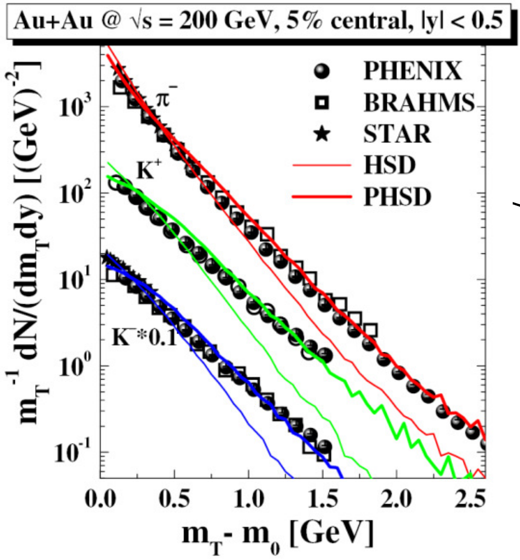
Rudy Marty et al.

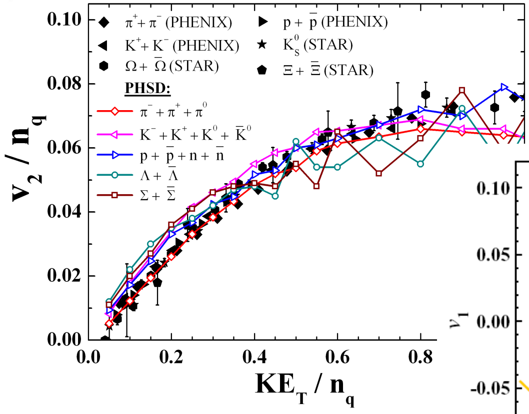
PHSD for HIC (highlights)

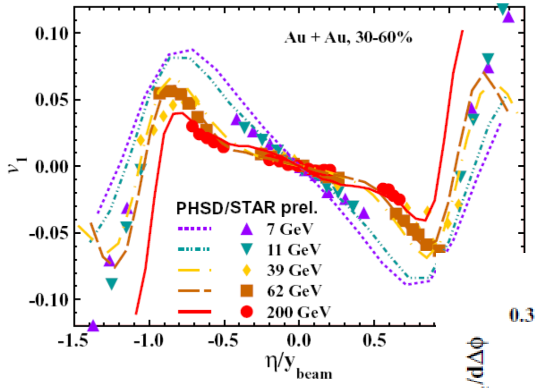


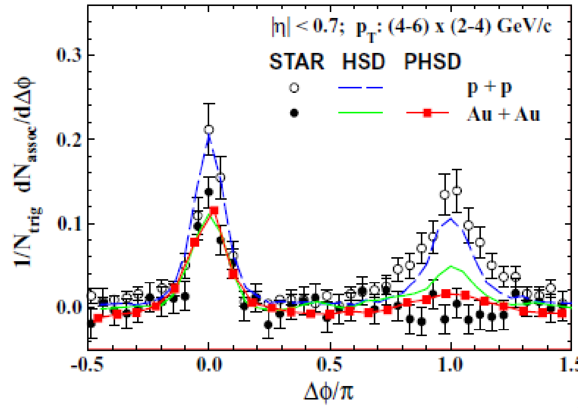






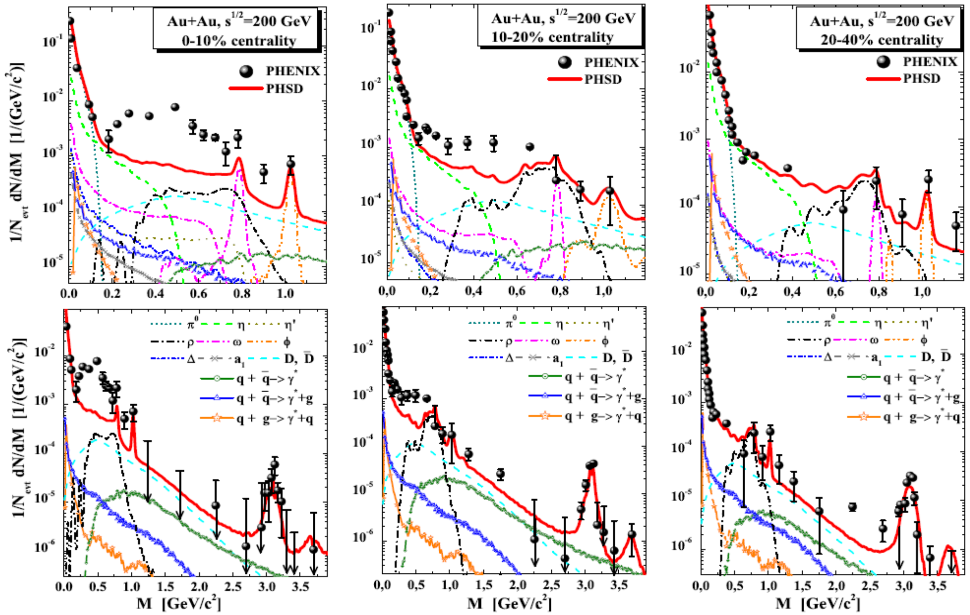




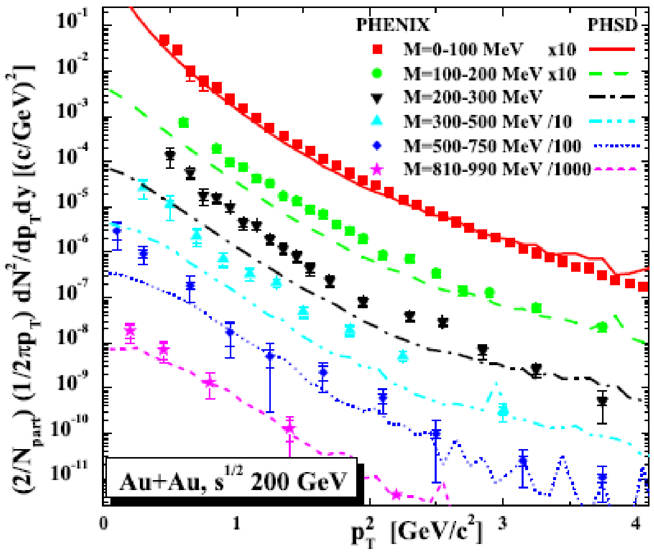


- **PHSD** provides a consistent description of HIC dynamics from AGS to RHIC energies

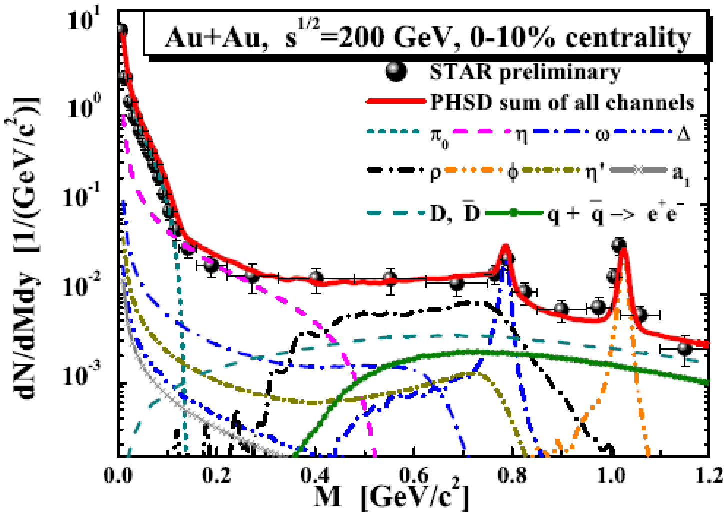
PHENIX, STAR dilepton spectra

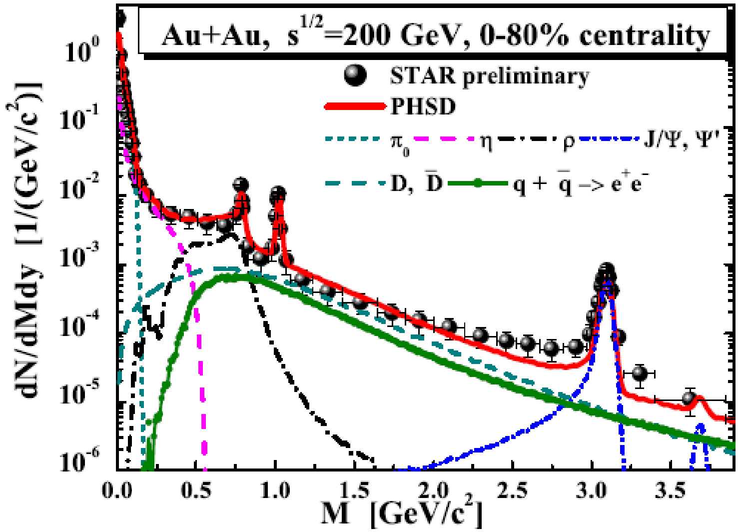


(a)0-10% centrality (b)10-20% centrality (c)20-40% centrality



▪PHENIX: Peripheral collisions (and pp) are well described, however, central fail!





▪ STAR data are well described!

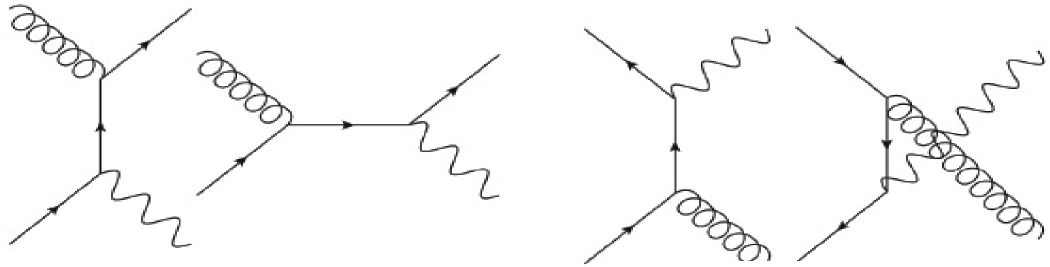
O. Linnyk et al., PRC 85 (2012) 024910

Photons from the hot and dense medium

Photon sources:

- **from the QGP via partonic interactions:**

Compton scattering **q-qbar annihilation**



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

- **from hadronic sources:**

• **decays of mesons:**

$$\pi \rightarrow \gamma + \gamma,\ \eta \rightarrow \gamma + \gamma,\ \omega \rightarrow \pi + \gamma$$
$$\eta' \rightarrow \rho + \gamma,\ \phi \rightarrow \eta + \gamma,\ a_1 \rightarrow \pi + \gamma$$

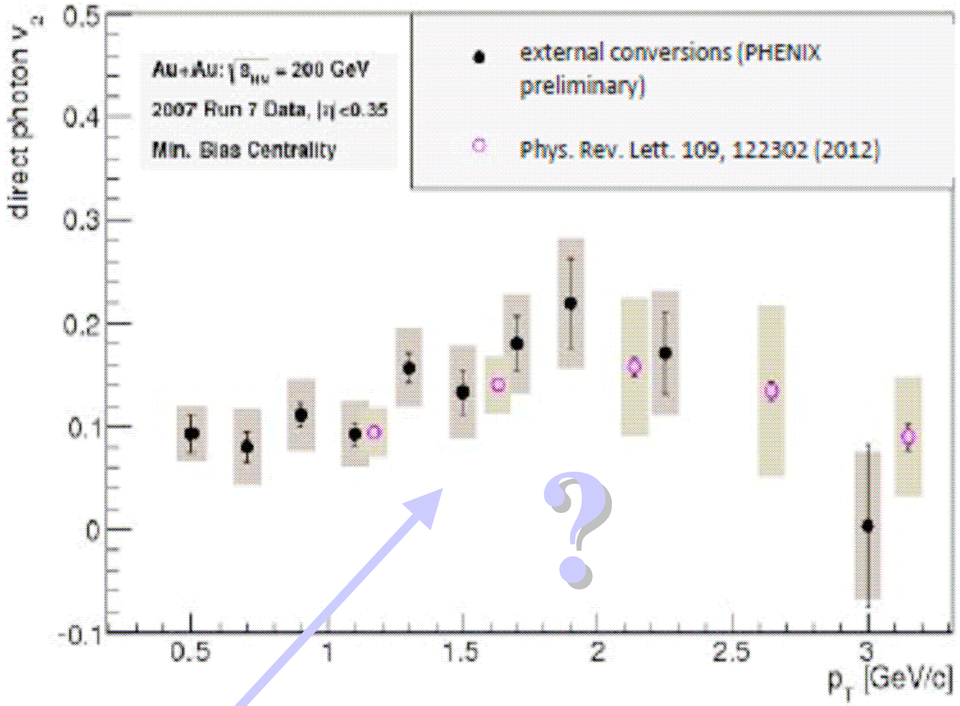
• **secondary meson interactions:** $\pi + \pi \rightarrow \rho + \gamma,\ \rho + \pi \rightarrow \pi + \gamma$

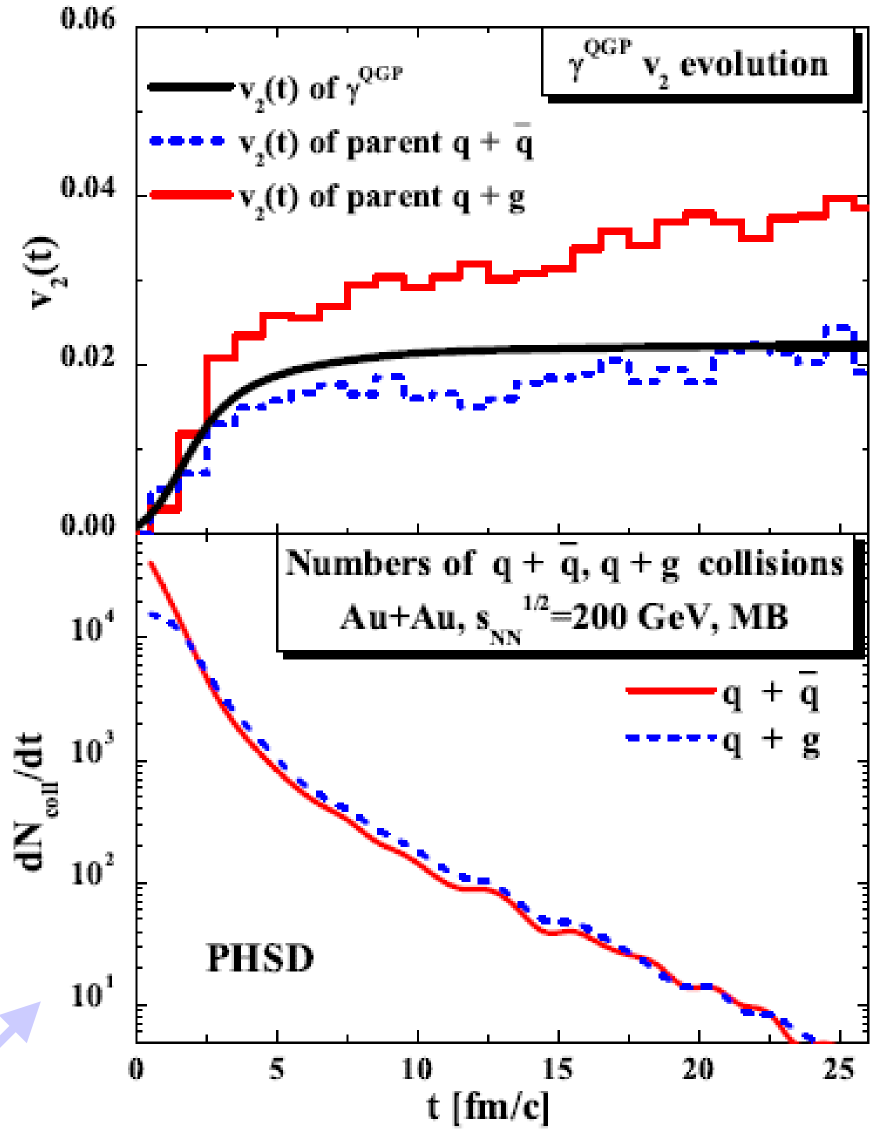
using the off-shell extension of Kapusta et al. in PRD44 (1991) 2774

• **meson-meson bremsstrahlung:** $m+m \rightarrow m+m+\gamma,\ m=\pi,\eta,\rho,\omega,K,K^*,\ldots$

using the soft-photon approximation

Photon elliptic flow





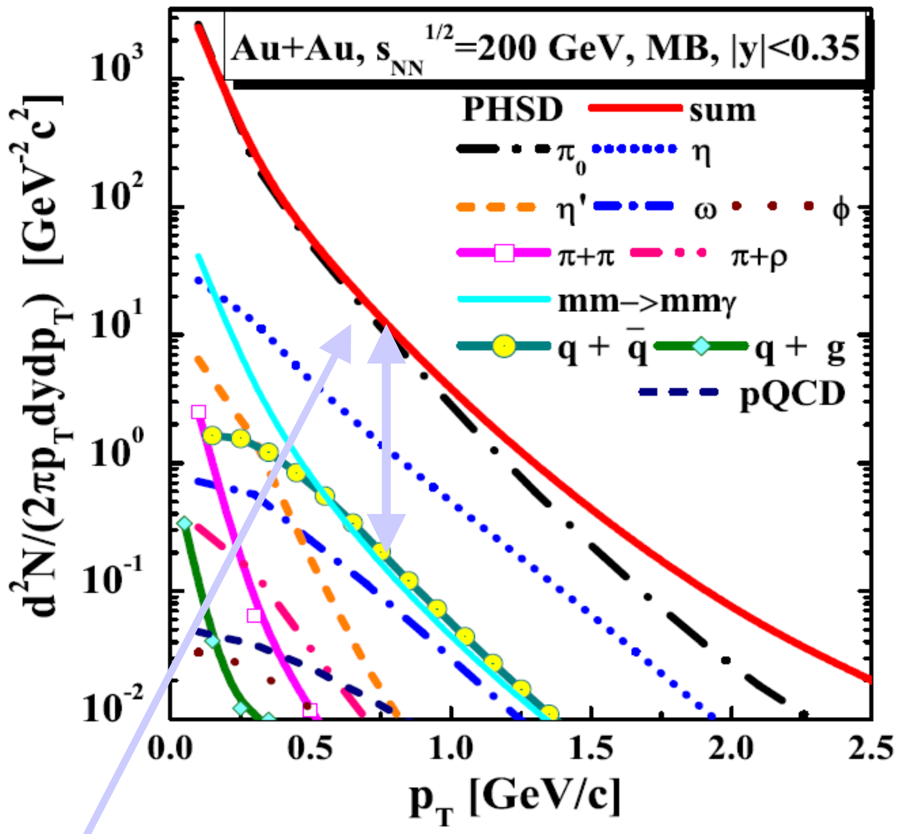
- **Strong elliptic flow of photons seen by PHENIX is surprising, if the origin should be the QGP !**

- **QGP radiation occurs at early times when the flow is not yet developed!**

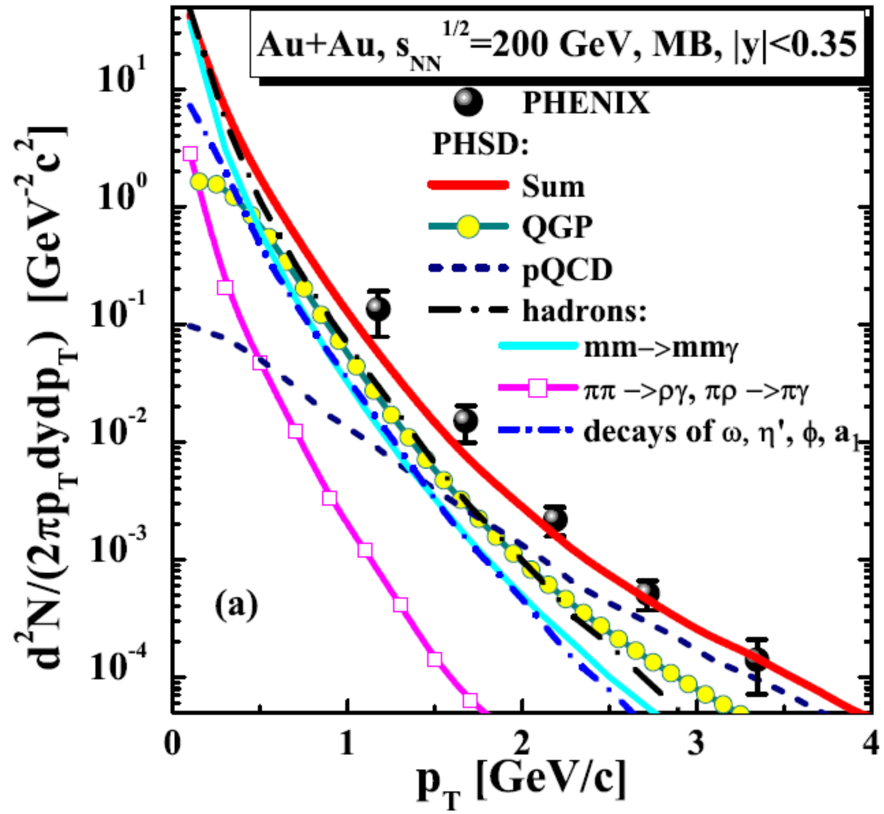
Olena Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Photon spectra at RHIC

- Inclusive photon spectrum



- π^0 and η subtracted photon spectrum



- **π^0 and η decays dominate the low p_T spectra**
- **QGP sources mandatory to explain the spectrum (~50%), but hadronic sources are considerable, too !**

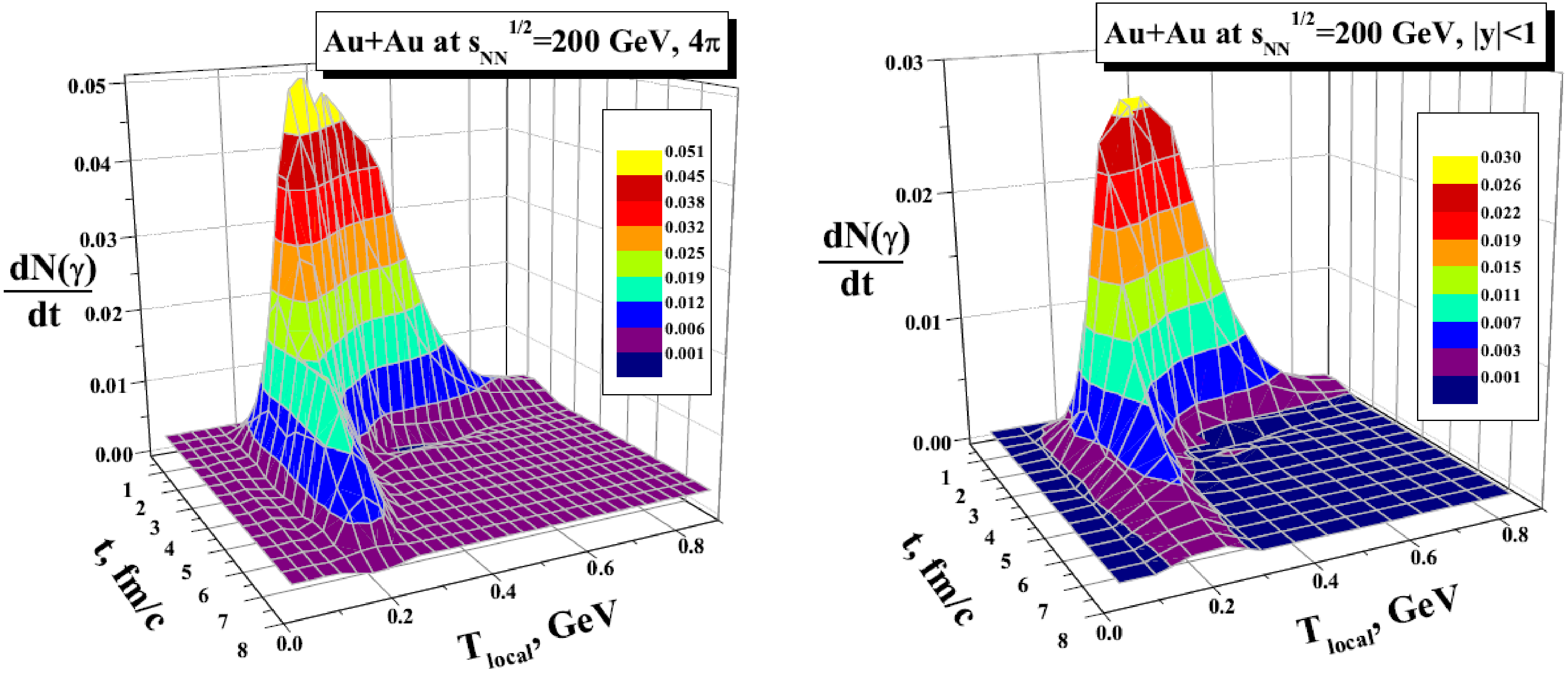
- **The 'effective temperature' T_{eff}:**

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

O. Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Time evolution of the photon production rate vs. T

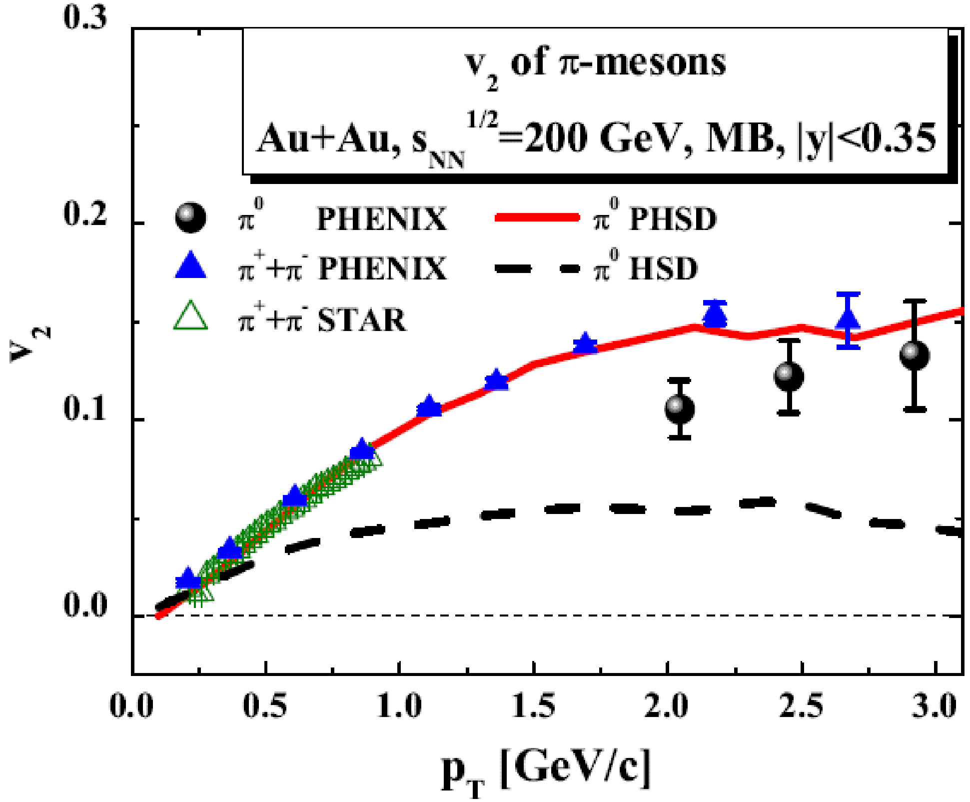
- The photon production rate versus time and the local 'temperature' at the production point in 4π and mid-rapidity Au+Au collisions:

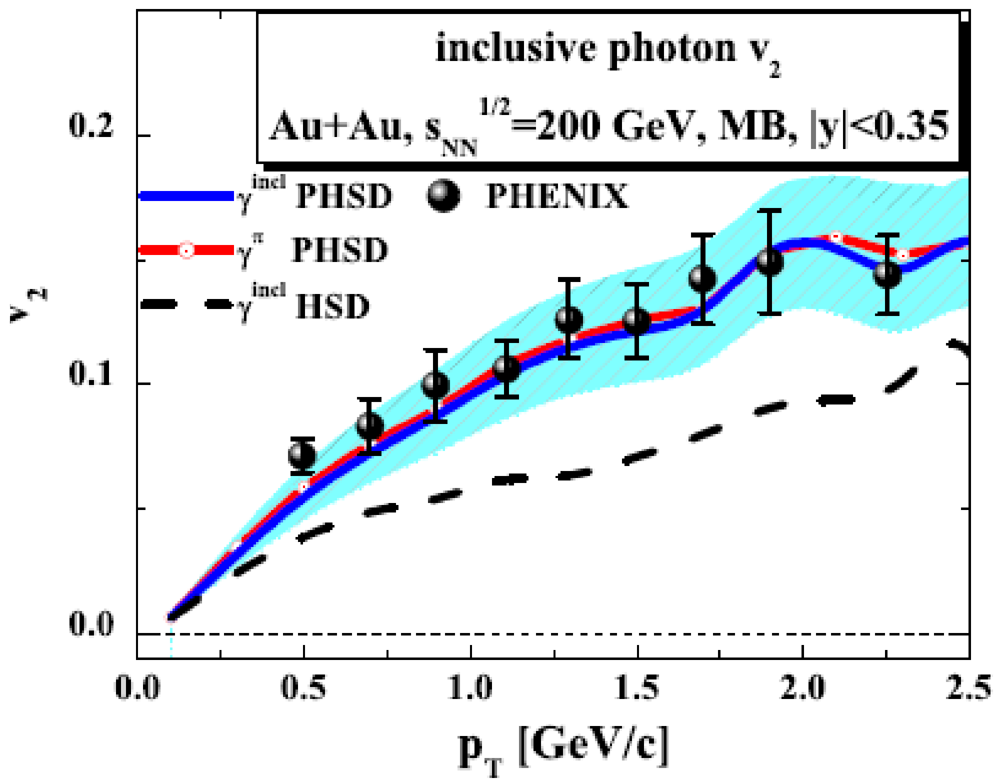


- Broad distribution of 'temperatures' → no universal 'temperature' can be assigned to the whole volume of the QGP - even in the mid-rapidity region !

Olena Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Inclusive photon elliptic flow





- Pion elliptic flow is reproduced in PHSD and underestimated in HSD (i.e. without partonic interactions)

- → large inclusive photon v_2 - comparable to that of hadrons - is reproduced in PHSD, too, because the inclusive photons are dominated by the photons from pion decay

O. Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Elliptic flow from direct photons: method I

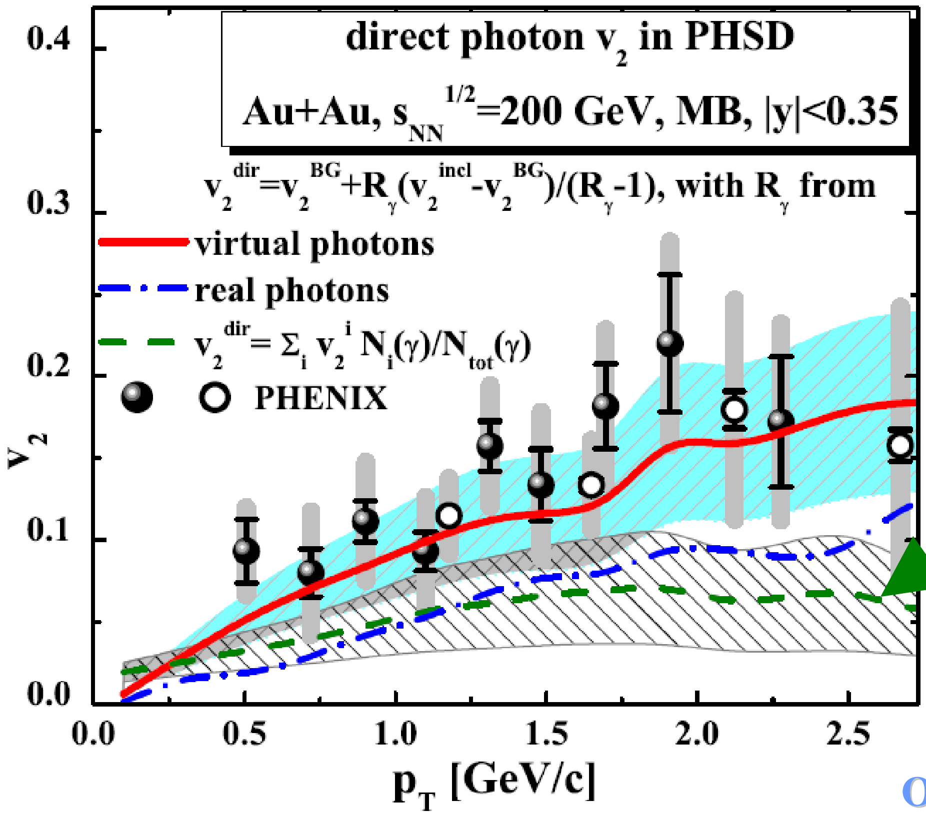
- ‚Weighted' method (theor. way):

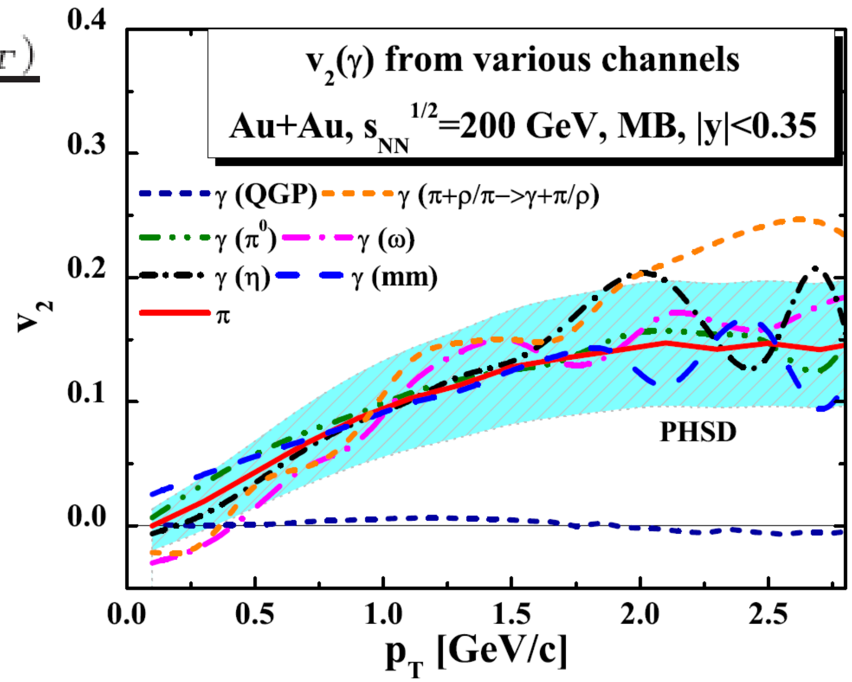
direct photon v_2 (in PHSD) = sum of v_2 of the individual channels, using their contributions to the spectrum as the relative p_T -dependent weights $w_i(p_T)$:

$$v_2(\gamma^{dir}) = \sum_i v_2(\gamma^i) w_i(p_T) = \frac{\sum_i v_2(\gamma^i) N_i(p_T)}{\sum_i N_i(p_T)}$$

$$i = (q\bar{q} \to g\gamma, qg \to q\gamma, \pi\pi/\rho \to \rho/\pi\gamma, mm \to mm\gamma, \mathrm{pQCD})$$

QGP





- **v_2 of direct photons in PHSD - as evaluated by the weighted average of direct photon channels – underestimates clearly the exp. data !**

O. Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Elliptic flow from direct photons: method II

- ‚Background' subtraction method (exp. way):

$$v_2(\gamma^{dir}) = \frac{R_\gamma v_2(\gamma^{incl}) - v_2(\gamma^{BG})}{R_\gamma - 1} = v_2(\gamma^{BG}) + \frac{R_\gamma}{R_\gamma - 1}(v_2(\gamma^{incl}) - v_2(\gamma^{BG}))$$

$$R_\gamma = N^{incl}/N^{BG}$$

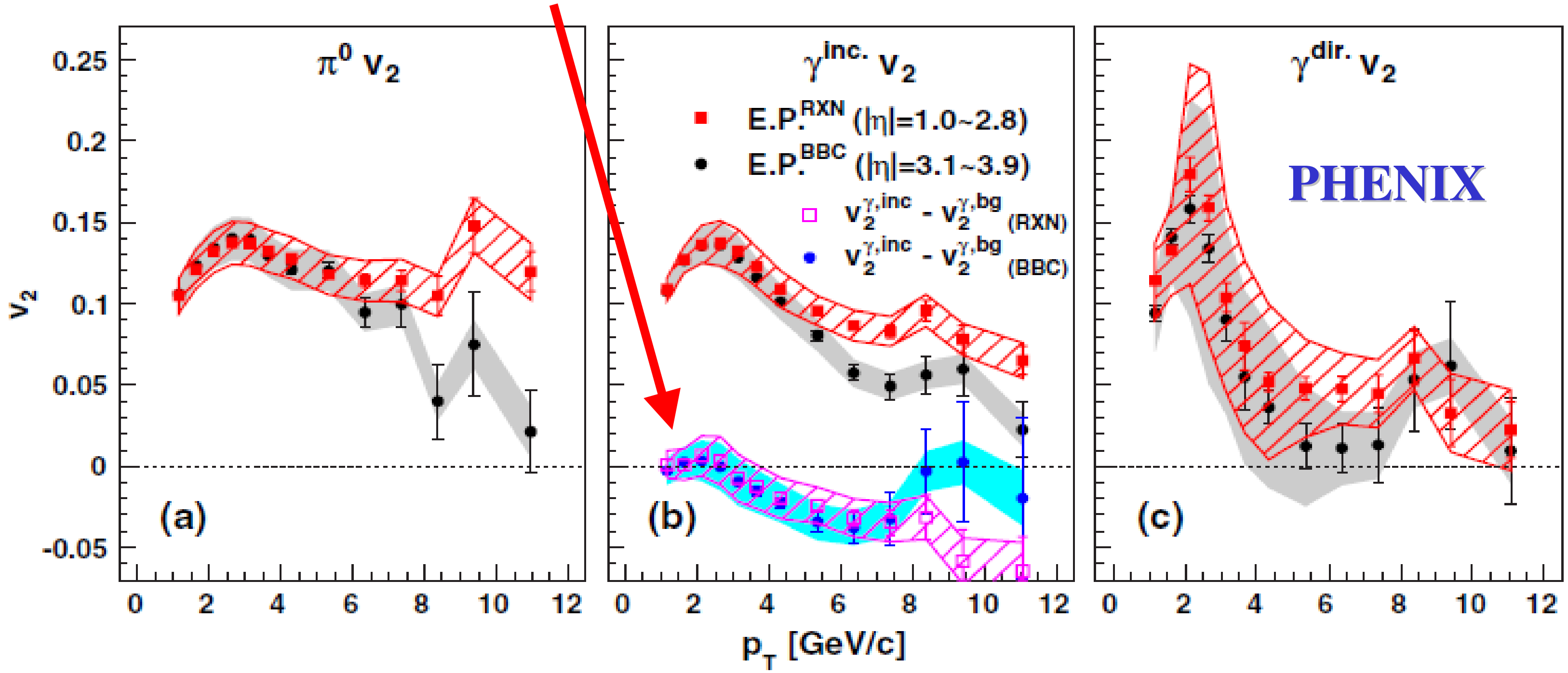
N^{incl} - number of inclusive photons

N^{BG} – number of photons attributed to hadron decays

➔ Problem: $v_2(\gamma^{BG})$ and R_γ – ?

- 1) $v_2(\gamma^{BG})$ from $v_2(\pi^0)$ using $KE_T=m_T-m$ scaling assumption ➔

$(v_2(\gamma^{incl}) - v_2(\gamma^{BG}))$ =0.01



Elliptic flow from direct photons: method II

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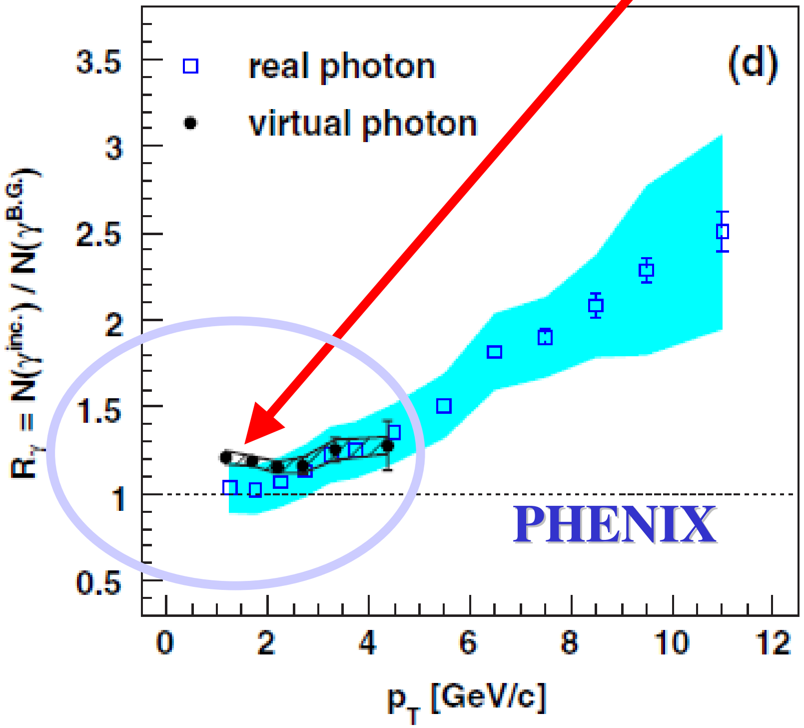
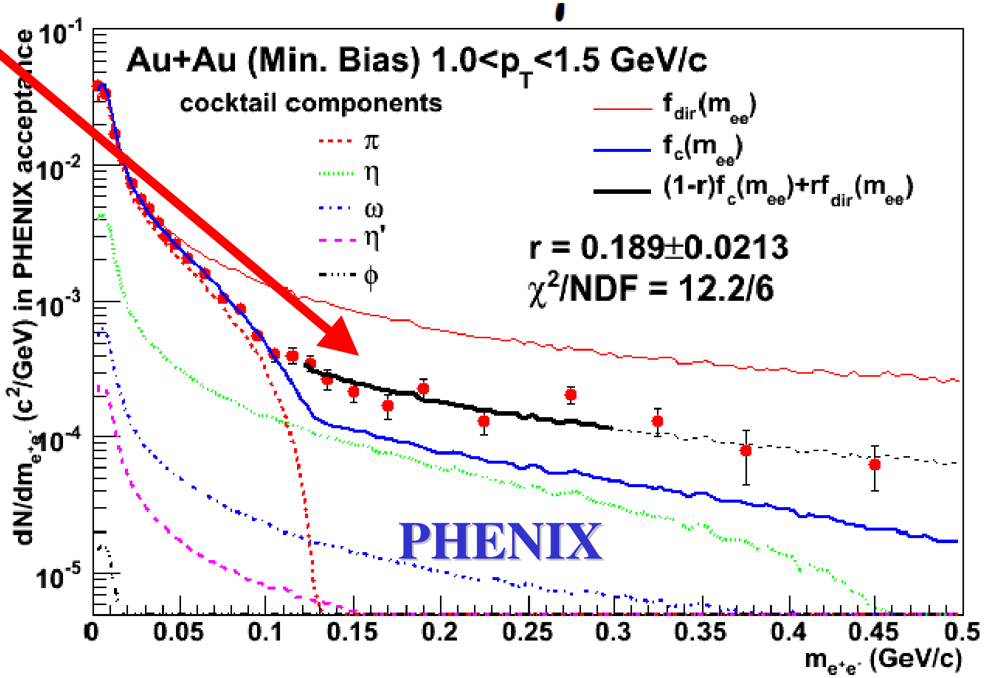
$$R_\gamma = N^{incl}/N^{BG}$$

N^{incl} - number of inclusive photons

N^{BG} – number of photons attributed to hadron decays

- 2) R_γ (p_T) for p_T<4 GeV/c from dilepton spectra at M=0.15-0.3 GeV ➔





Elliptic flow from direct photons: method II

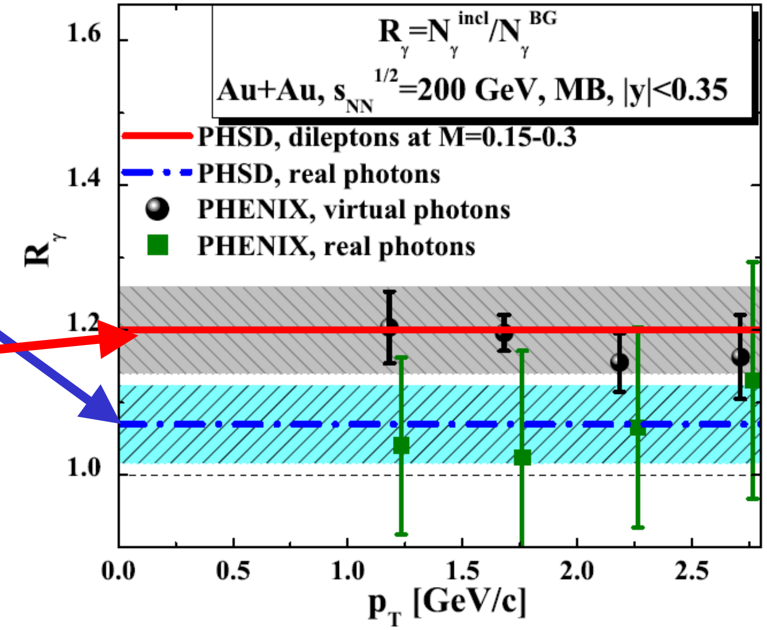
- ‚Background' subtraction method (exp. way):

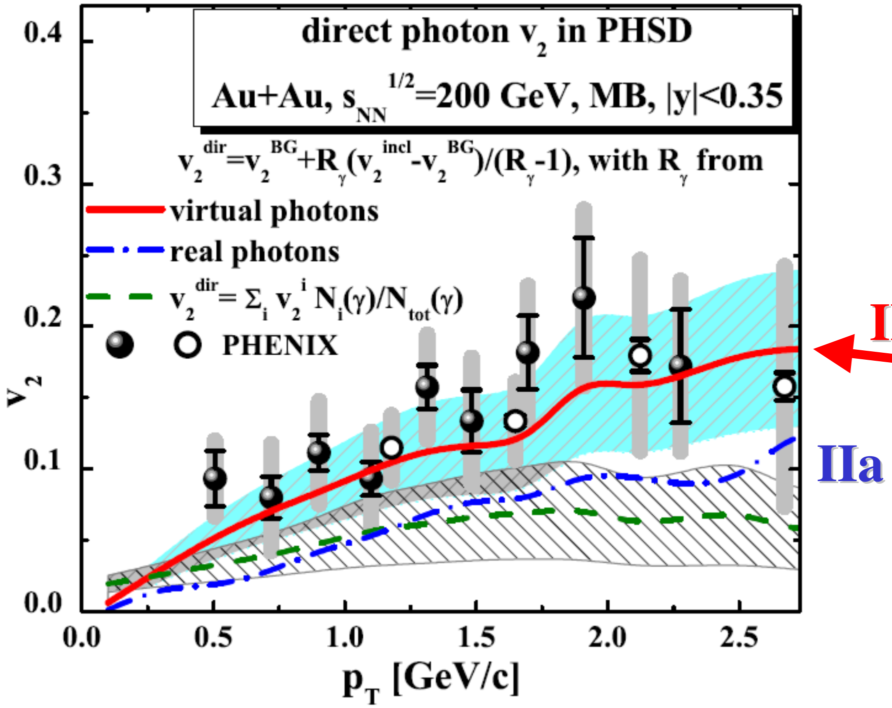
$$v_2(\gamma^{dir}) = \frac{R_\gamma v_2(\gamma^{incl}) - v_2(\gamma^{BG})}{R_\gamma - 1}$$

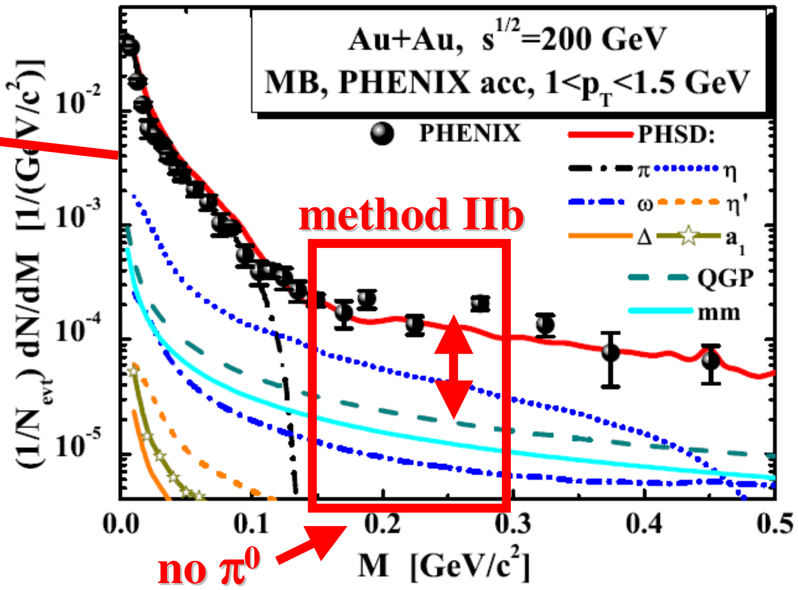
$$R_\gamma = N^{incl}/N^{BG}$$

IIa) from real photons $R_\gamma \sim 1.05$

IIb) from virtual photons $R_\gamma \sim 1.2$







- v_2 of direct photons in PHSD - as evaluated by the ‚background' subtraction method IIb - is consistent with PHENIX data!

O. Linnyk et al., PRC 88 (2013) 034904; arXiv:1304.7030

Summary

out-off equilibrium   in- equilibrium

- **PHSD provides a consistent description of off-shell parton dynamics in line with the lattice QCD equation of state**

❑ **minimum of η/s close to T_c**

➔ **QGP in PHSD behaves almost as a strongly-interacting liquid**

❑ **minimum of σ_0/T close to T_C**

➔ **the QCD matter is a good electric conductor**

- **PHSD for HIC:**

❑ **Direct photons: the photons produced in the QGP contribute about 50% to the observed spectrum but have small v_2**

❑ **The large measured 'direct photon v_2' – comparable to that of hadrons – is attributed to intermediate hadronic scattering channels and hadronic resonance decays not subtracted from the data;**
the value of v_2 is sensitive to the hadronic 'background' subtraction method!

❑ **The QGP phase causes the strong elliptic flow of photons indirectly by enhancing the v_2 of final hadrons due to the partonic interactions in terms of explicit parton collisions and the mean-field potentials!**

PHSD group

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Mark Gorenstein

Barcelona Univ.
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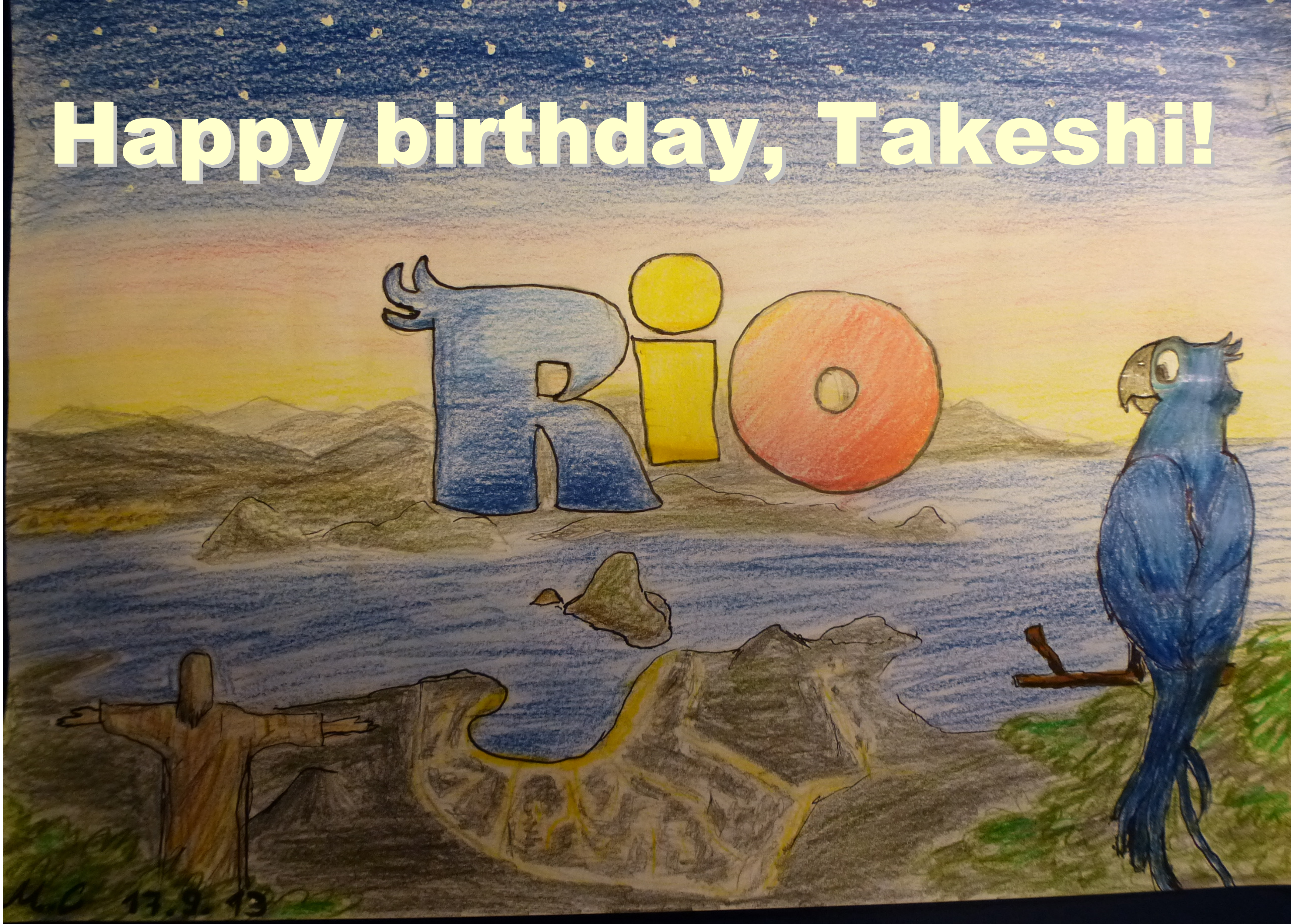
Non-equilibrium Dynamics
31 August - 3 September, 2011, Heraklion, Crete, Greece


approximated by noise ?
Fluid element
Undeterminancy of fluid elements


Happy birthday, Takeshi!
RiO