Simulations with the PHSD for NICA

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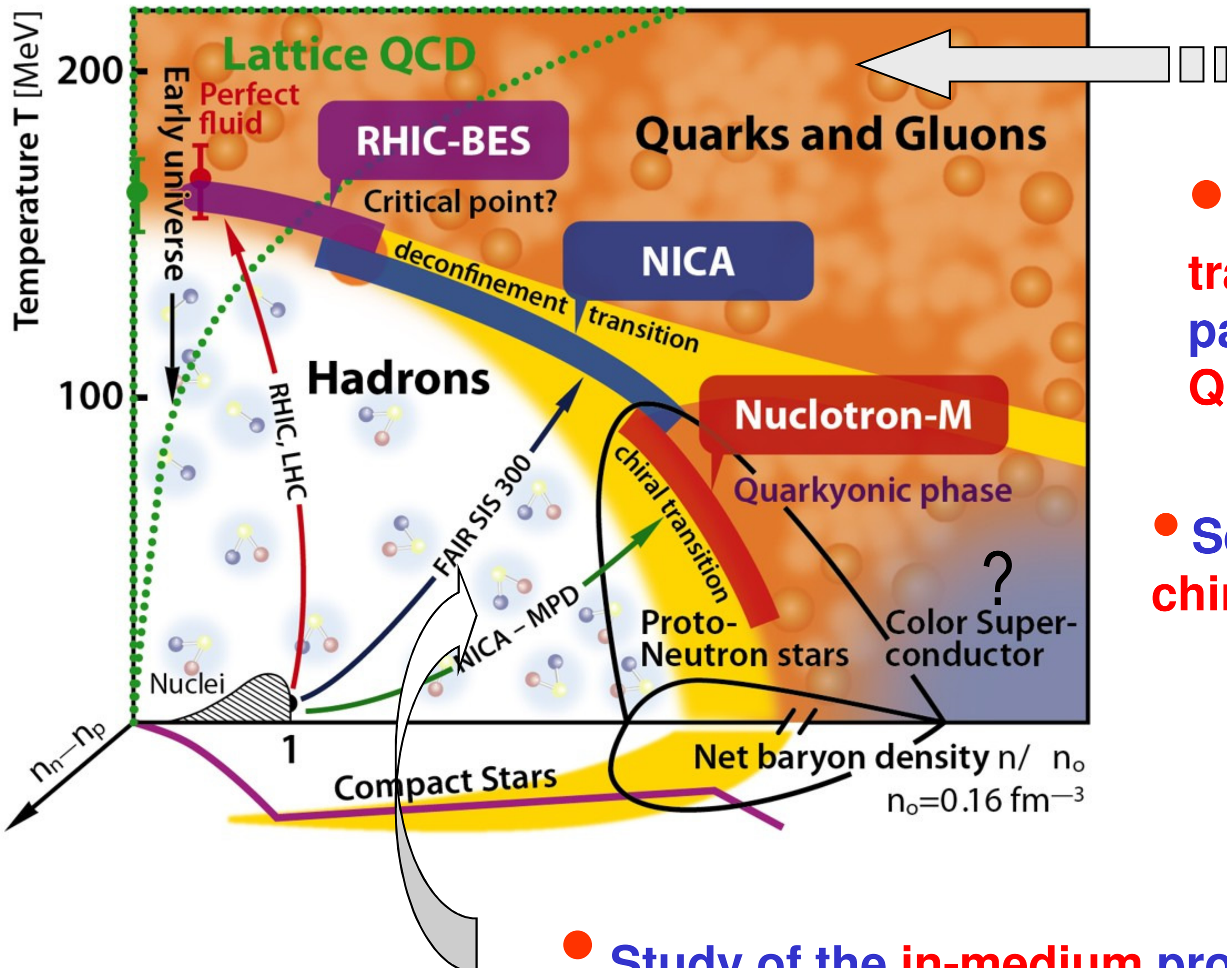
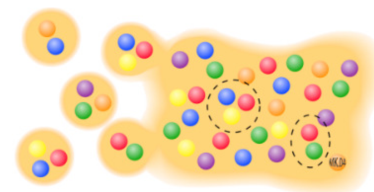
Mini-Workshop on Simulations of HIC for NICA energies,
Dubna, 10 – 12 April, 2017

The ‚holy grail‘ of heavy-ion physics:

The phase diagram of QCD



- Search for the critical point



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

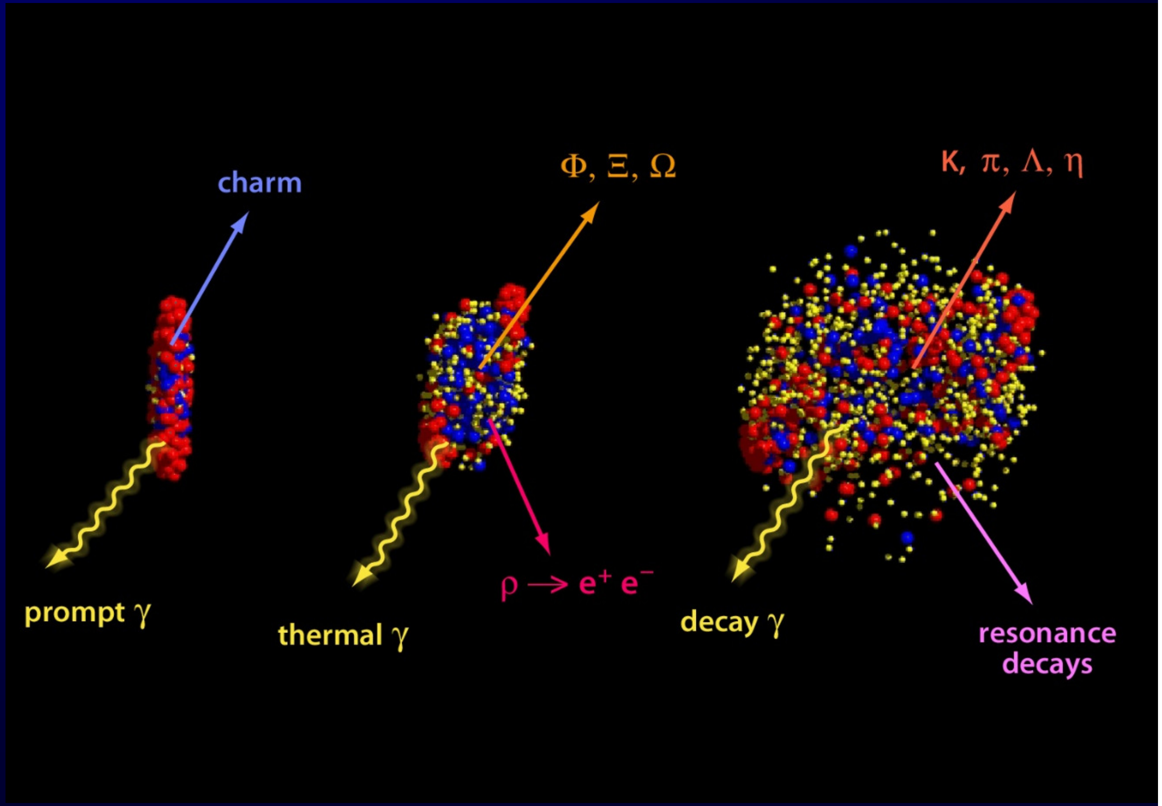
- Search for the signatures of chiral symmetry restoration

- Study of the in-medium properties of hadrons at high baryon density and temperature

Signals of the phase transition:

- Multi-strange particle enhancement in A+A
- Charm suppression
- Collective flow (v_1, v_2)
- Thermal dileptons
- Jet quenching and angular correlations
- High p_T suppression of hadrons
- Nonstatistical event by event fluctuations and correlations
- ...

Experiment: measures final hadrons and leptons



How to learn about physics from data?

Compare with theory!

Basic models for heavy-ion collisions

- **Statistical models:**

basic assumption: system is described by a (grand-) canonical ensemble of non-interacting fermions and bosons in thermal and chemical equilibrium

[- : no dynamics]

- **(Ideal) hydrodynamical models:**

basic assumption: conservation laws + equation of state; assumption of local thermal and chemical equilibrium

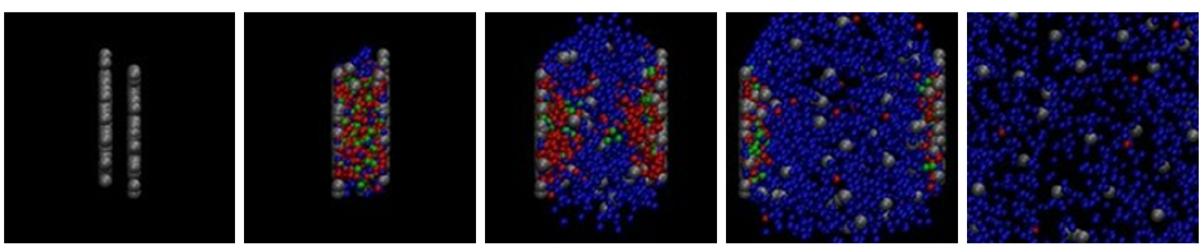
[- : simplified dynamics]

- **Transport models:**

based on transport theory of relativistic quantum many-body systems -
Actual solutions: Monte Carlo simulations

[+ : full dynamics | - : very complicated]

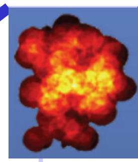
→ Microscopic transport models provide a unique dynamical description of nonequilibrium effects in heavy-ion collisions



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)

- 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)

History: Semi-classical BUU equation

Ludwig Boltzmann

Boltzmann-Uehling-Uhlenbeck equation (non-relativistic formulation here) - propagation of particles in the **self-generated 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***

- **self-generated Hartree-Fock mean-field potential:**

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

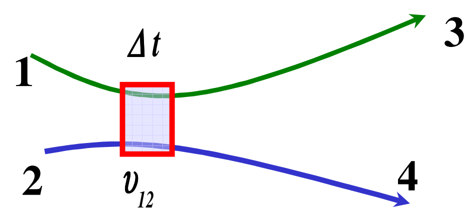
- **Collision term** for 1+2→3+4 (let's consider fermions) :

$$I_{coll} = \frac{4}{(2\pi)^3}\int d^3p_2\, d^3p_3 \int d\Omega\ \ |v_{12}|\,\delta^3(\vec{p}_1+\vec{p}_2-\vec{p}_3-\vec{p}_4)\cdot\frac{d\sigma}{d\Omega}(1+2\rightarrow 3+4)\cdot P$$

Probability including Pauli blocking of fermions:

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

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



Properties of matter created in HIC

❑ **Hadronic matter:**

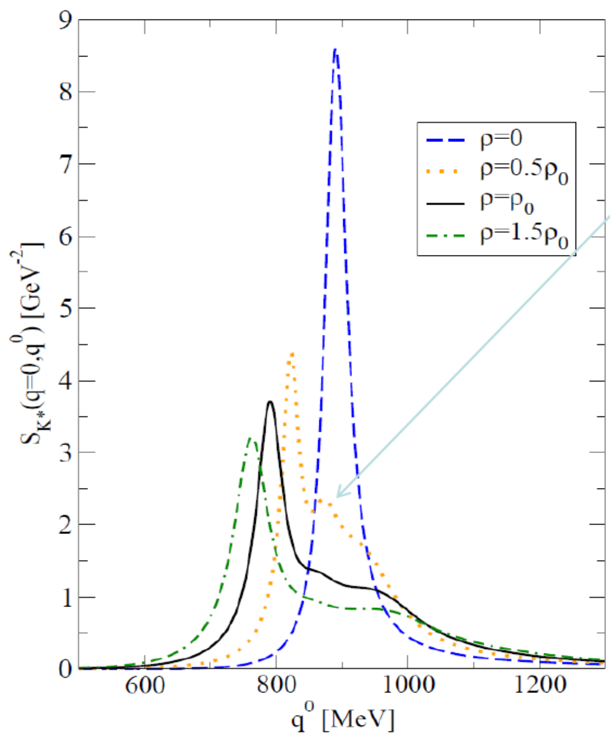
In-medium effects = changes of particle properties in the hot and dense hadronic medium;
example: vector mesons, strange mesons

❑ **QGP:**

Exp. data + lQCD: η/s near T_C is very small
➔ QGP is close to an ideal liquid, not a gas of weakly interacting quarks and gluons

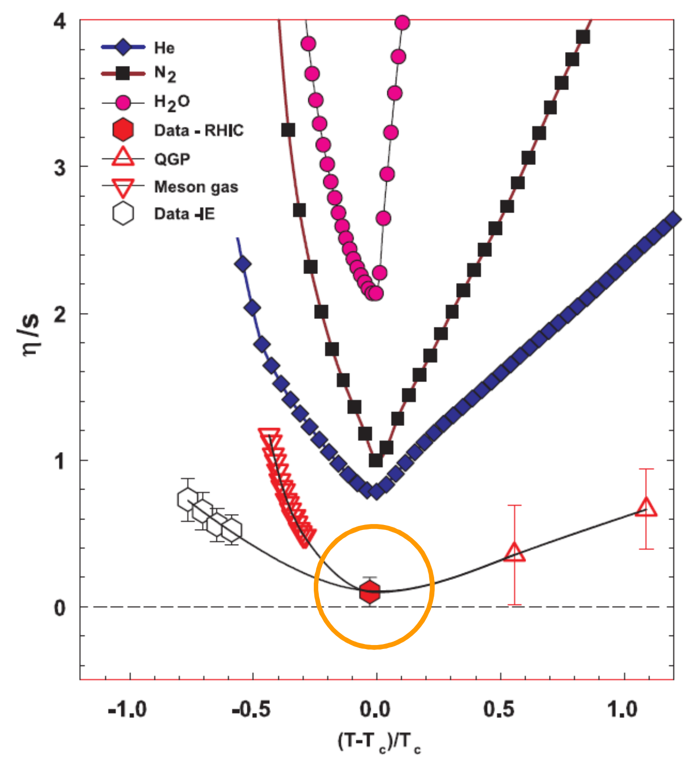
➔ QGP: strongly-interacting matter

Kbar* spectral function
Barcelona / Valencia group



$\Lambda(1783)N^{-1}$ and $\Sigma(1830)N^{-1}$ exitations

Compilation of the ratio of shear viscosity to entropy density for various substances



Theoretical description of strongly interacting systems

Many-body theory:
Strong interactions ➔ large width = short life-time
➔ broad spectral functions ➔ quantum objects

- **How to describe the dynamics of broad strongly interacting quantum states in transport theory?**

Mandatory for the description of strongly-interacting matter and in-medium effects!

- ❑ **semi-classical BUU**

First-order gradient expansion of quantum Kadanoff-Baym equations

- ❑ **generalized transport equations = off-shell transport approach!**

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 $S^<$

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

(1962)

Integration over the intermediate spacetime

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

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

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

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

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

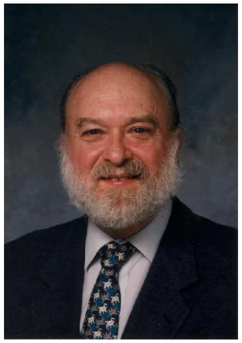
$$S^{ret}_{xy} = S^c_{xy} - S^<_{xy} = S^>_{xy} - S^a_{xy} \quad -retarded$$

$$S^{adv}_{xy} = S^c_{xy} - S^>_{xy} = S^<_{xy} - S^a_{xy} \quad -advanced$$

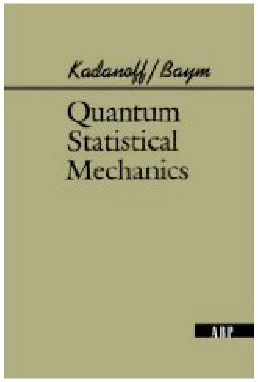
$$\hat{S}^{-1}_{0x} \equiv -(\partial^\mu_x \partial^x_\mu + M_0^2)$$

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

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



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 $A_{XP} \rightarrow \delta(p^2-M^2)$

- GTE: Propagation of the Green's function $iS^<_{XP}=A_{XP}N_{XP}$, which carries 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

General testparticle off-shell equations of motion

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

- Employ **testparticle Ansatz** for the real valued quantity $i\, S^{<}_{XP}$ -

$$F_{XP} = A_{XP} N_{XP} = i\, S^{<}_{XP} \sim \sum_{i=1}^{N} \delta^{(3)}(\vec{X} - \vec{X}_i(t))\ \delta^{(3)}(\vec{P} - \vec{P}_i(t))\ \delta(P_0 - \epsilon_i(t))$$

insert in generalized transport equations and determine equations of motion !

➔ **General testparticle Cassing's off-shell equations of motion for the time-like particles:**

$$\frac{d\vec{X}_i}{dt} = \frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[2\,\vec{P}_i + \vec{\nabla}_{P_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{P_i} \Gamma_{(i)} \right],$$

$$\frac{d\vec{P}_i}{dt} = -\frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[\vec{\nabla}_{X_i} Re\Sigma^{ret}_{i} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \vec{\nabla}_{X_i} \Gamma_{(i)} \right],$$

$$\frac{d\epsilon_i}{dt} = \frac{1}{1 - C_{(i)}} \frac{1}{2\epsilon_i} \left[\frac{\partial Re\Sigma^{ret}_{(i)}}{\partial t} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial \Gamma_{(i)}}{\partial t} \right],$$

with $F_{(i)} \equiv F(t, \vec{X}_i(t), \vec{P}_i(t), \epsilon_i(t))$

$$C_{(i)} = \frac{1}{2\epsilon_i} \left[\frac{\partial}{\partial \epsilon_i} Re\Sigma^{ret}_{(i)} + \frac{\epsilon_i^2 - \vec{P}_i^2 - M_0^2 - Re\Sigma^{ret}_{(i)}}{\Gamma_{(i)}} \frac{\partial}{\partial \epsilon_i} \Gamma_{(i)} \right]$$

Collision term in off-shell transport models

Collision term for reaction 1+2->3+4:

$$I_{coll}(X,\vec{P},M^2) = Tr_2 Tr_3 Tr_4 A(X,\vec{P},M^2) A(X,\vec{P}_2,M_2^2) A(X,\vec{P}_3,M_3^2) A(X,\vec{P}_4,M_4^2)$$

$$|G((\vec{P},M^2)+(\vec{P}_2,M_2^2) \rightarrow (\vec{P}_3,M_3^2)+(\vec{P}_4,M_4^2))|^2_{\mathcal{A},\mathcal{S}} \; \delta^{(4)}(P+P_2-P_3-P_4)$$

$$[N_{X\vec{P}_3M_3^2}\, N_{X\vec{P}_4M_4^2}\, \bar{f}_{X\vec{P}M^2}\, \bar{f}_{X\vec{P}_2M_2^2} \; - \; N_{X\vec{P}M^2}\, N_{X\vec{P}_2M_2^2}\, \bar{f}_{X\vec{P}_3M_3^2}\, \bar{f}_{X\vec{P}_4M_4^2}]$$

‚gain' term ‚loss' term

with $\bar{f}_{X\vec{P}M^2} = 1 + \eta\, N_{X\vec{P}M^2}$ and $\eta = \pm 1$ for bosons/fermions, respectively.

The trace over particles 2,3,4 reads explicitly

for fermions

$$Tr_2 = \sum_{\sigma_2,\tau_2} \frac{1}{(2\pi)^4} \int d^3P_2 \frac{dM_2^2}{2\sqrt{\vec{P}_2^2+M_2^2}}$$

for bosons

$$Tr_2 = \sum_{\sigma_2,\tau_2} \frac{1}{(2\pi)^4} \int d^3P_2 \frac{dP_{0,2}^2}{2}$$

additional integration

The transport approach and the particle spectral functions are fully determined once the in-medium transition amplitudes G are known in their off-shell dependence!

Example of in-medium transition rates: G-matrix approach

Need to know in-medium transition amplitudes G and their off-shell dependence

$$|G((\vec{P},M^2)+(\vec{P}_2,M_2^2)\rightarrow(\vec{P}_3,M_3^2)+(\vec{P}_4,M_4^2))|^2_{\mathcal{A},\mathcal{S}}$$

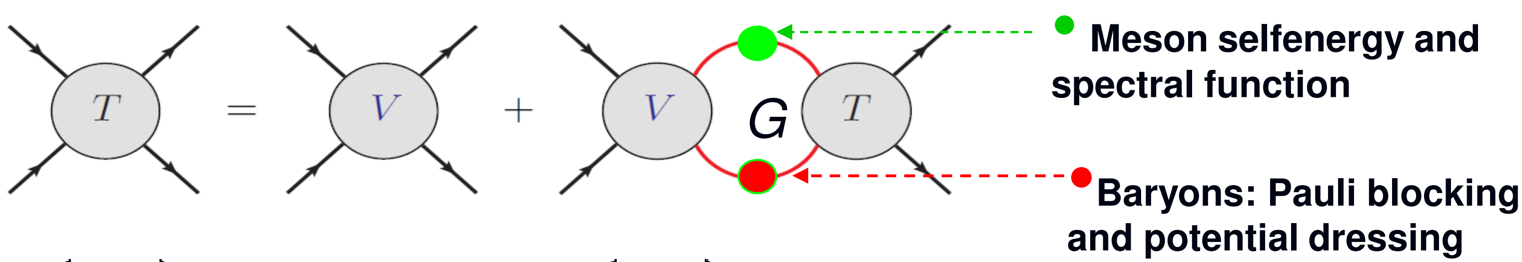
↓

Coupled-channel G-matrix approach

Transition probability :

$$P_{1+2\rightarrow 3+4}(s)=\int d\cos(\theta)\ \frac{1}{(2s_1+1)(2s_2+1)}\sum_i\sum_\alpha\ G^\dagger G$$

with G(p,ρ,T) - G-matrix from the solution of coupled-channel equations:



$$\mathcal{T}_{ij}(\rho,T)\ =\ V_{ij}\ +\ V_{il}\ G_l(\rho,T)\ \mathcal{T}_{lj}(\rho,T)$$

For strangeness:
D. Cabrera, L. Tolos, J. Aichelin, E.B., PRC90 (2014)055207; W. Cassing, L. Tolos, E.B., A. Ramos, NPA727 (2003) 59

Detailed balance on the level of 2<->n:
treatment of multi-particle collisions in transport approaches

W. Cassing, NPA 700 (2002) 618

Generalized collision integral for *n <->m* reactions:

$$I_{coll} = \sum_n \sum_m \; I_{coll}[n \leftrightarrow m]$$

$$I^i_{coll}[n \leftrightarrow m] =$$
$$\frac{1}{2} N^m_n \sum_\nu \sum_\lambda \left(\frac{1}{(2\pi)^4}\right)^{n+m-1} \int \left(\prod_{j=2}^{n} d^4p_j \;\; A_j(x,p_j)\right) \left(\prod_{k=1}^{m} d^4p_k \; A_k(x,p_k)\right)$$
$$\times A_i(x,p) \; W_{n,m}(p,p_j;i,\nu \mid p_k;\lambda) \; (2\pi)^4 \; \delta^4(p^\mu + \sum_{j=2}^{n} p^\mu_j - \sum_{k=1}^{m} p^\mu_k)$$
$$\times [\tilde{f}_i(x,p) \prod_{k=1}^{m} f_k(x,p_k) \prod_{j=2}^{n} \tilde{f}_j(x,p_j) - f_i(x,p) \prod_{j=2}^{n} f_j(x,p_j) \prod_{k=1}^{m} \tilde{f}_k(x,p_k)].$$

$\tilde{f} = 1 + \eta f$ **is Pauli-blocking or Bose-enhancement factors;**
η=1 for bosons and η=-1 for fermions

$W_{n,m}(p,p_j;i,\nu \mid p_k;\lambda)$ **is a transition probability**

Antibaryon production in heavy-ion reactions

Multi-meson fusion reactions

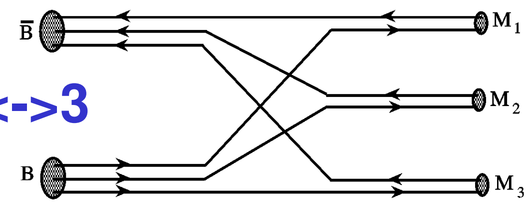
$m_1+m_2+...+m_n \leftrightarrow B+Bbar$

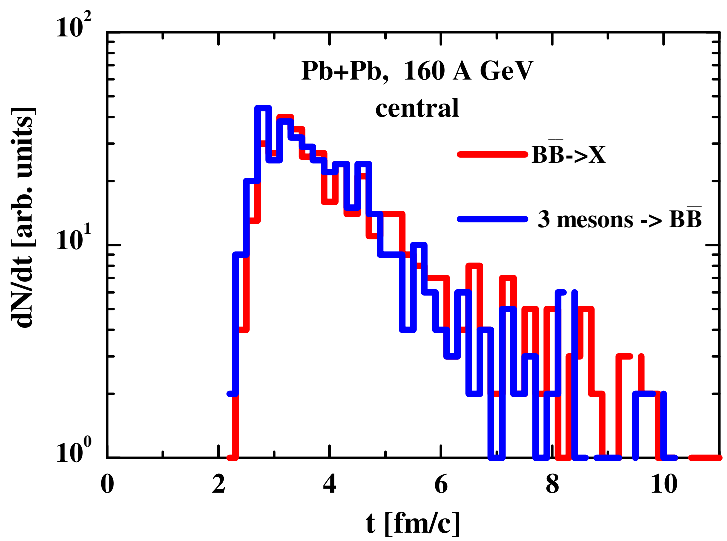
($m=\pi,\rho,\omega,..$)

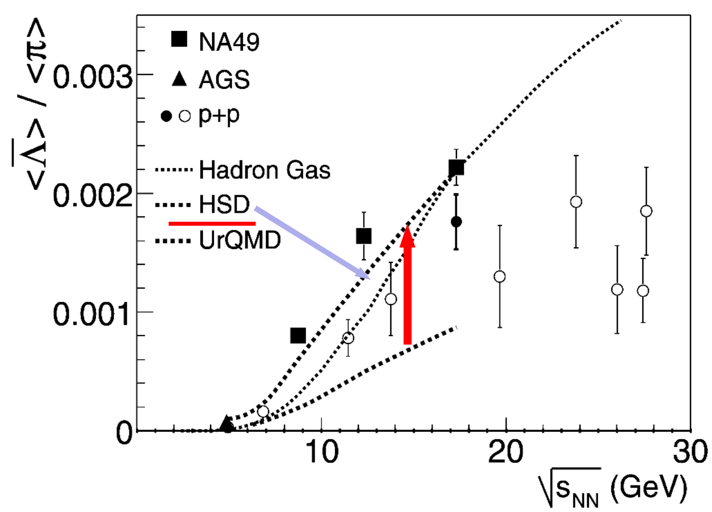
W. Casing, NPA 700 (2002) 618

- important for antiproton, antilambda dynamics !

2<->3







→ approximate equilibrium of annihilation and recreation

- 2017: Ph.D. Thesis of Eduard Seifert (Giessen Uni.)

Consider the light and strangeness sector ⇒ 2546 possible mass channels

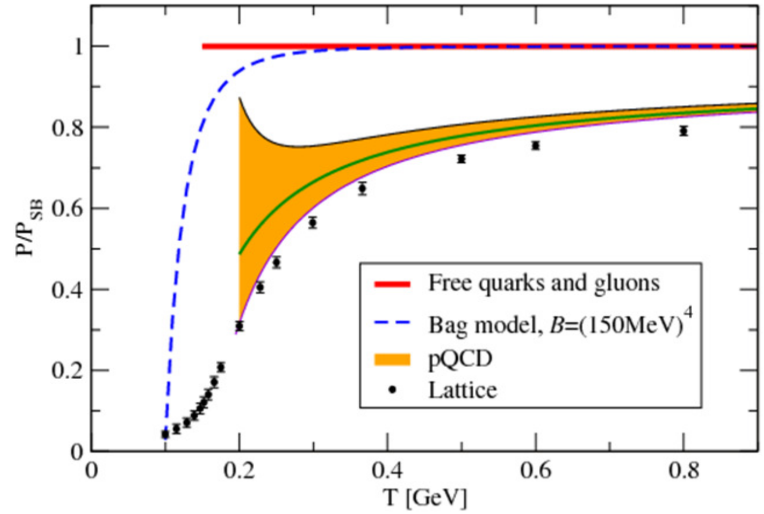
Baryons: N,Δ(1232),N(1440),N(1535),Λ,Σ,Σ*,Ξ,Ξ*,Ω (octett and decuplett)

Mesons: $\pi,\eta,\eta',K,K^*,\rho,\omega,\Phi,a_1$

Degrees-of-freedom of QGP

❖ lQCD gives QGP EoS ➔

! need to be interpreted in terms of degrees-of-freedom



Non-perturbative QCD ← pQCD

pQCD:

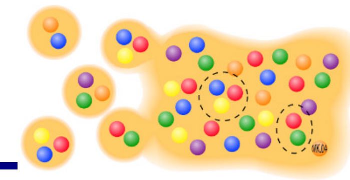
- weakly interacting system
- massless quarks and gluons

Thermal QCD = QCD at high parton densities:

- strongly interacting system
- massive quarks and gluons

❖ Effective degrees-of-freedom

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 on a **microscopic level**

➔ need a consistent non-equilibrium transport approach

- ❑ 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 (‚cross over' at μ_q=0)

❑ **Transport theory for strongly interacting systems:** **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)**

QGP phase is described by

Dynamical QuasiParticle Model (DQPM)

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

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 (propagators) – in the sense of a two-particle irreducible (2PI) approach:

gluon propagator: $\Delta^{-1} = P^2 - \Pi$ &	**quark propagator** $S_q^{-1} = P^2 - \Sigma_q$
gluon self-energy: $\Pi = M_g^2 - i2\Gamma_g\omega$ &	**quark self-energy:** $\Sigma_q = M_q^2 - i2\Gamma_q\omega$

(scalar approximation)

- **the resummed properties are specified by complex (retarded) 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 guarantees a consistent description of the system in- and out-of 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:**

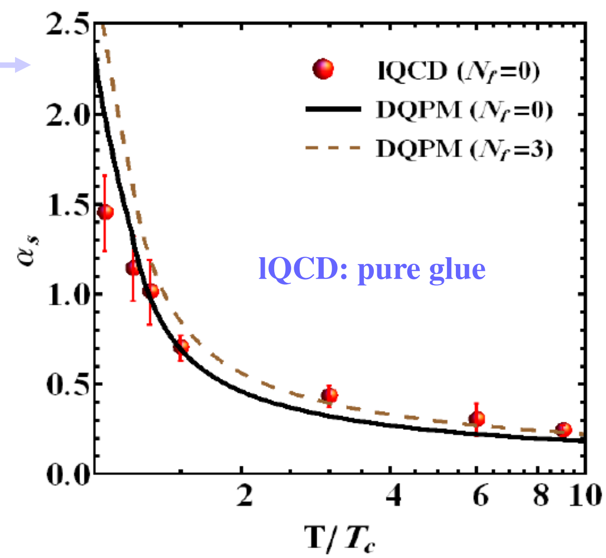
$$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

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

$N_c = 3$, $N_f=3$

- **running coupling: T-dependent $\alpha_S(T)$**

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



❑ **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)

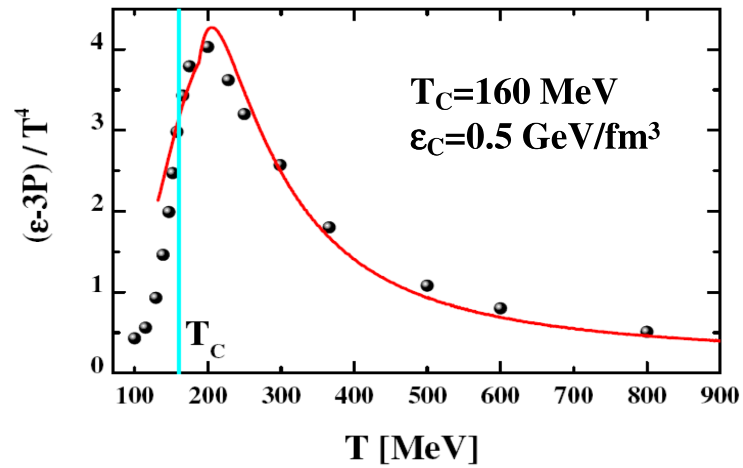
DQPM thermodynamics (N_f=3) and lQCD

entropy $s = \frac{\partial P}{dT}$ → pressure P

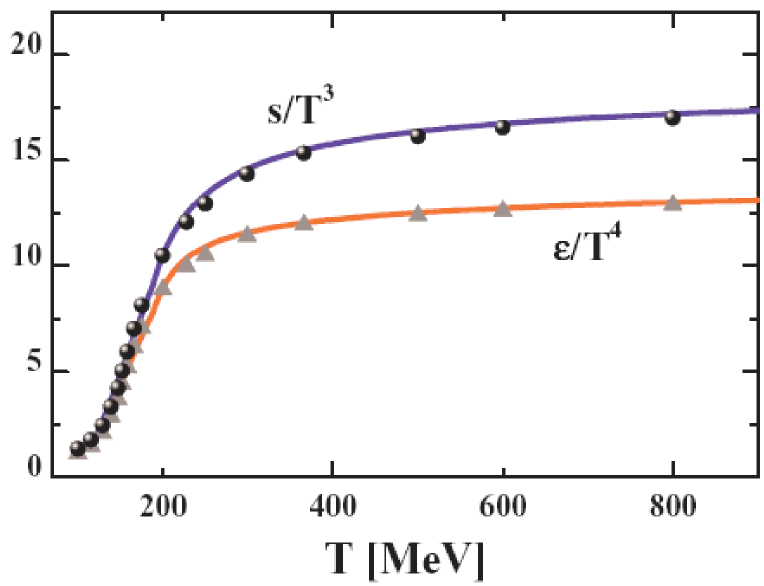
energy density: $\epsilon = Ts - P$

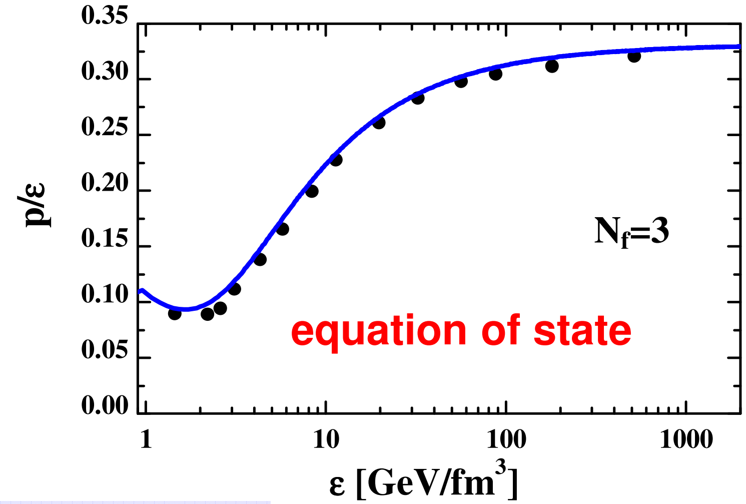
interaction measure:

$$W(T) := \epsilon(T) - 3P(T) = Ts - 4P$$



lQCD: Wuppertal-Budapest group
Y. Aoki et al., JHEP 0906 (2009) 088.

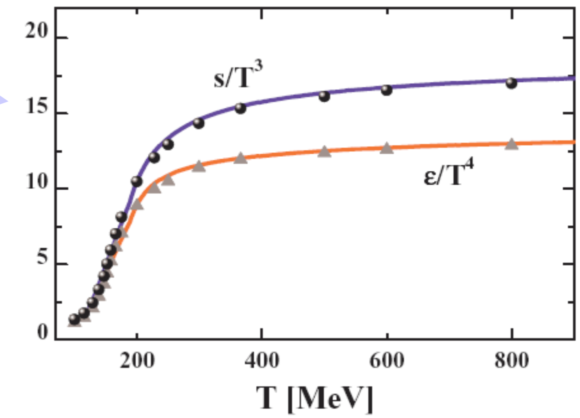




DQPM gives a good description of lQCD results !

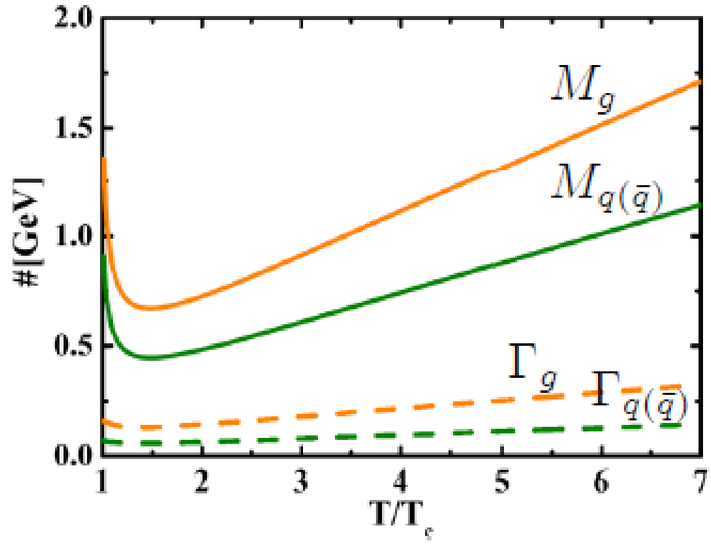
The Dynamical QuasiParticle Model (DQPM)

- **fit to lattice (lQCD) results (e.g. entropy density)**
  - **BMW lQCD data S. Borsanyi et al., JHEP 1009 (2010) 073**

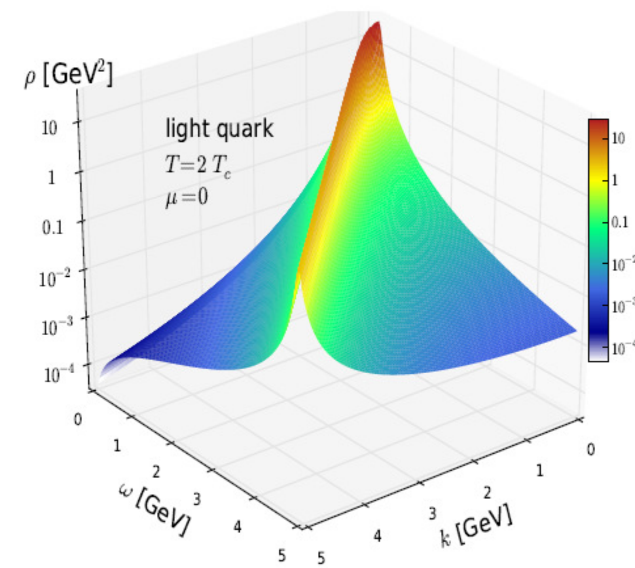


➔ Quasiparticle properties:

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



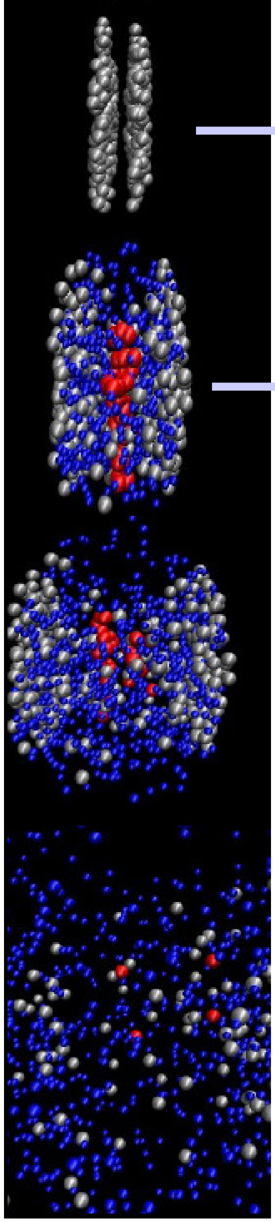
T_C=158 MeV
ε_C=0.5 GeV/fm³



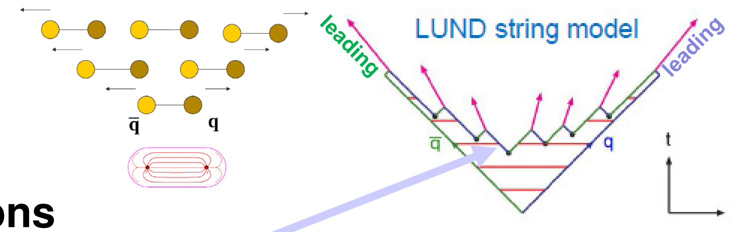
- **DQPM matches well lattice QCD**
- **DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)**
- **DQPM gives transition rates for the formation of hadrons → PHSD**

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

I. PHSD - basic concept



I. From hadrons to QGP:

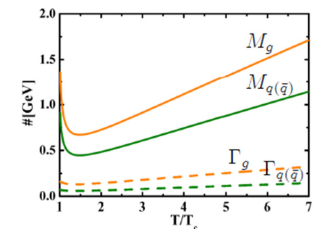


❑ **Initial A+A collisions – as in HSD:**
- **string formation in primary NN collisions**
- **string decay to pre-hadrons (= new produced secondary hadrons: *B* - baryons, *m* - mesons)** ➔ **‚flavor chemistry' from strings**

❑ **Formation of initial QGP stage - if local energy density $\varepsilon > \varepsilon_c$ =0.5 GeV/fm^3:**

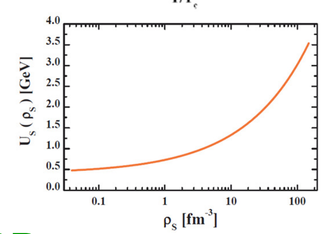
I. Dynamical Quasi-Particle Model (DQPM) defines:

1) **properties of quasiparticles in equilibrium,**
   i.e. masses $M_q(T)$ and widths $\Gamma_q(T)$ (T➔ε by lQCD EoS)



2) **‚chemistry' of ‚initial state' of QGP: number of q, qbar, g**

3) **‚energy balance' , i.e. the fraction of mean-field quark and gluon potentials U_q, U_g from the energy density ε**

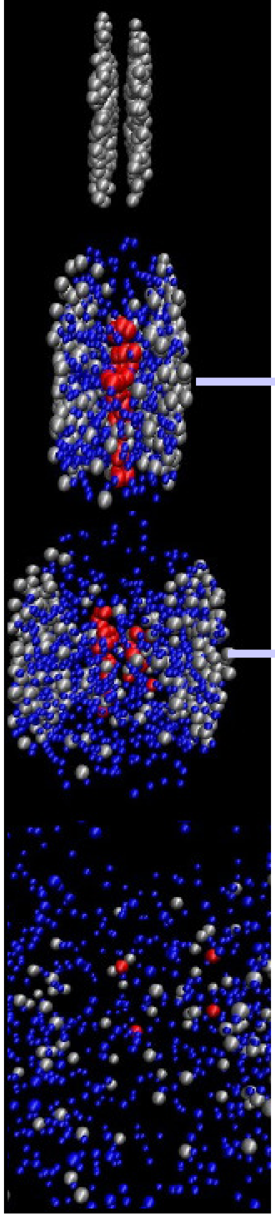


II. Realization of the initial QGP stage from DQPM in the PHSD:
by dissolution of pre-hadrons (keep ‚leading' hadrons!) into massive colored quarks (and gluons) + mean-field energy

$$B \rightarrow qqq, \quad \tilde{m} \rightarrow q\bar{q}, \quad (q\bar{q}) \Rightarrow g \quad \forall \quad U_q, U_g$$

➔ **allows to keep initial non-equilibrium momentum anisotropy !**

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



II. PHSD - basic concept

II. Partonic phase - QGP:

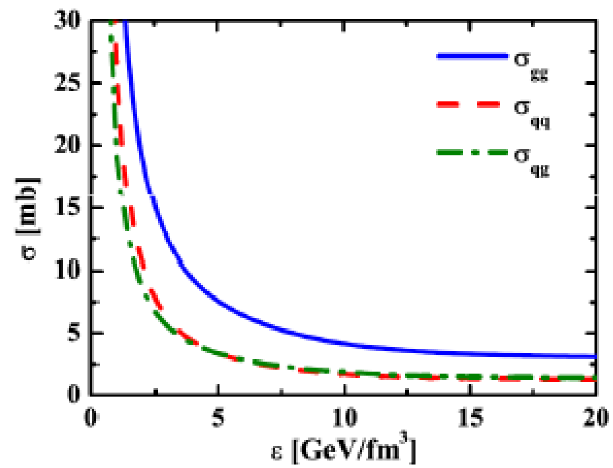
- **Propagation of quarks and gluons (= ‚dynamical quasiparticles') with off-shell spectral functions (width, mass) defined by the DQPM in self-generated mean-field potential for quarks and gluons U_q, U_g**

- **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**

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

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

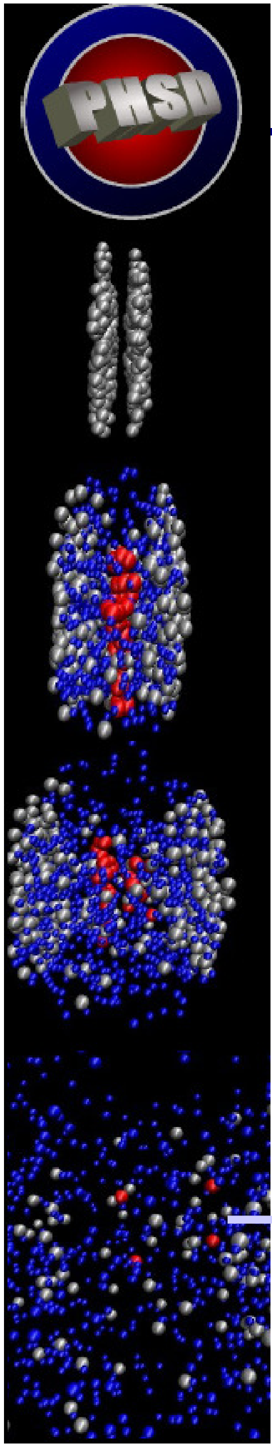


  - **inelastic collisions:**
    (Breight-Wigner cross sections)

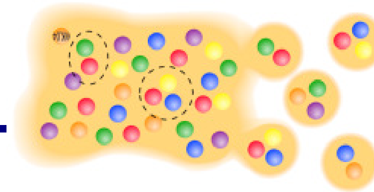
$$\left\{ \begin{array}{l} q+\bar{q} \to g \\ g \to q+\bar{q} \end{array} \right.$$

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

suppressed (<1%) due to the large mass of gluons



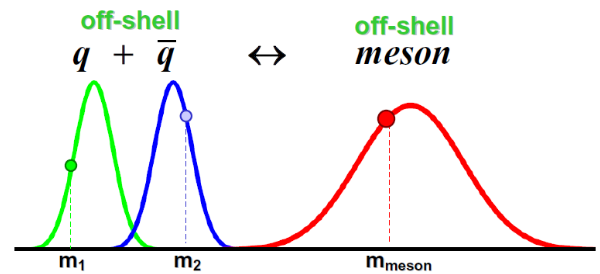
III. PHSD - basic concept



III. Hadronization (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)

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



- Local covariant off-shell transition rate for q+qbar fusion

➔ meson formation:

$$Tr_j = \sum_j \int d^4 x_j d^4 p_j / (2\pi)^4$$

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

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

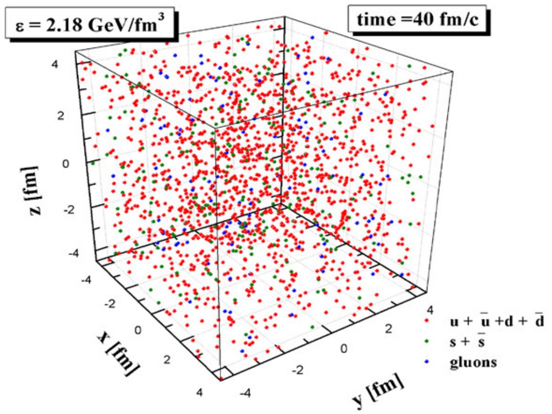
- $N_j(x,p)$ is the phase-space density of parton j at space-time position x and 4-momentum p
- W_m is the phase-space distribution of the formed ‚pre-hadrons‘ (Gaussian in phase space)
- $|M_{qq}|^2$ is the effective quark-antiquark interaction from the DQPM

➔ Strict 4-momentum and quantum number (flavour, color) conservation

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

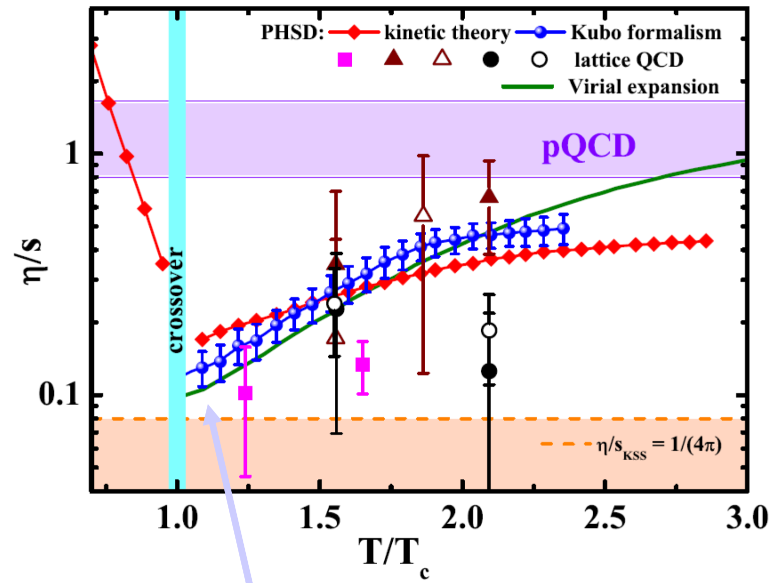
QGP in equilibrium: Transport properties at finite (T, μ_q): η/s

Infinite hot/dense matter = PHSD in a box:



Shear viscosity η/s at finite T

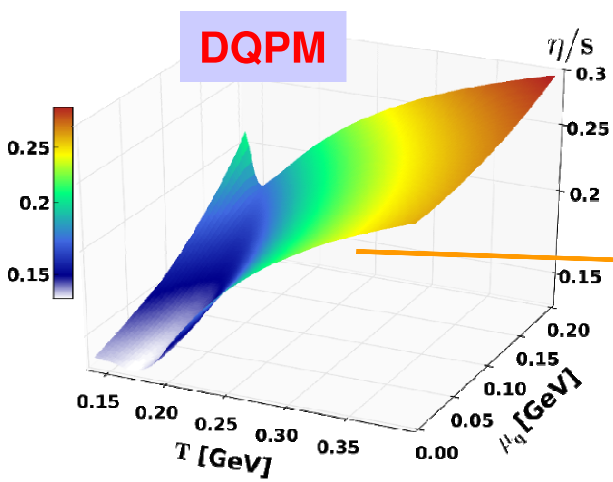
V. Ozvenchuk et al., PRC 87 (2013) 064903



Shear viscosity η/s at finite (T, μ_q)

lQCD:

$$\frac{T_c(\mu_q)}{T_c(\mu_q=0)} = \sqrt{1-\alpha\,\mu_q^2} \approx 1-\alpha/2\,\mu_q^2 + \cdots$$

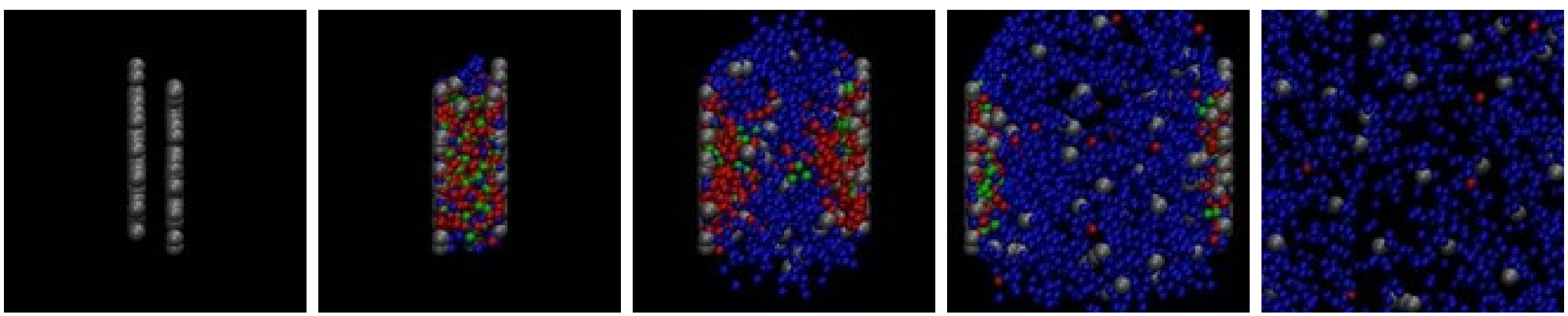


QGP in PHSD = strongly-interacting liquid-like system

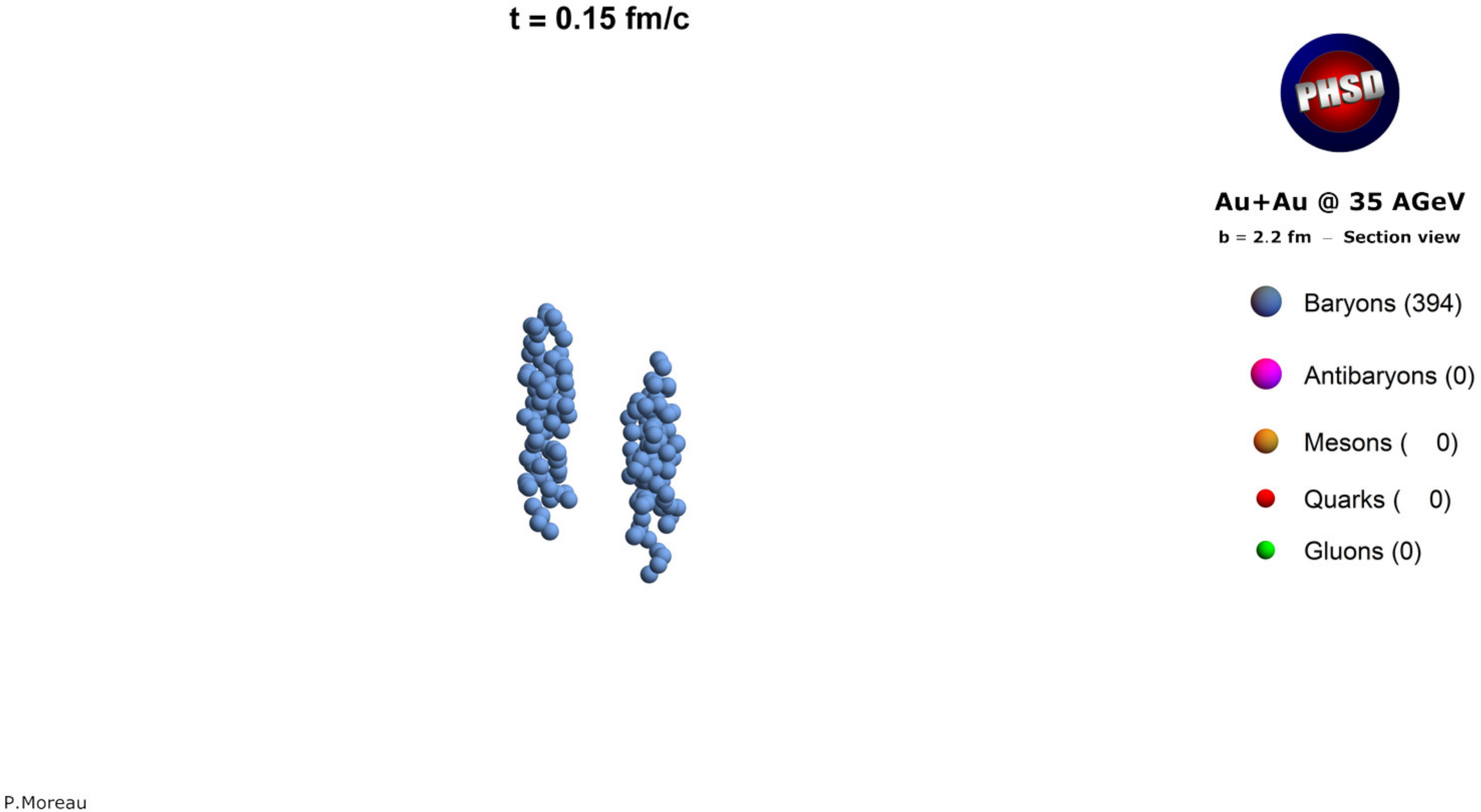
η/s: μ_q=0 ➔ finite μ_q: smooth increase as a function of (T, μ_q)

Review: H. Berrehrah et al. Int.J.Mod.Phys. E25 (2016) 1642003

‚Bulk‘ properties in Au+Au

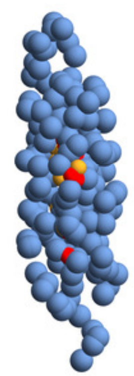


Au+Au collision at NICA energies



Au+Au collision at NICA energies

t = 2.55 fm/c



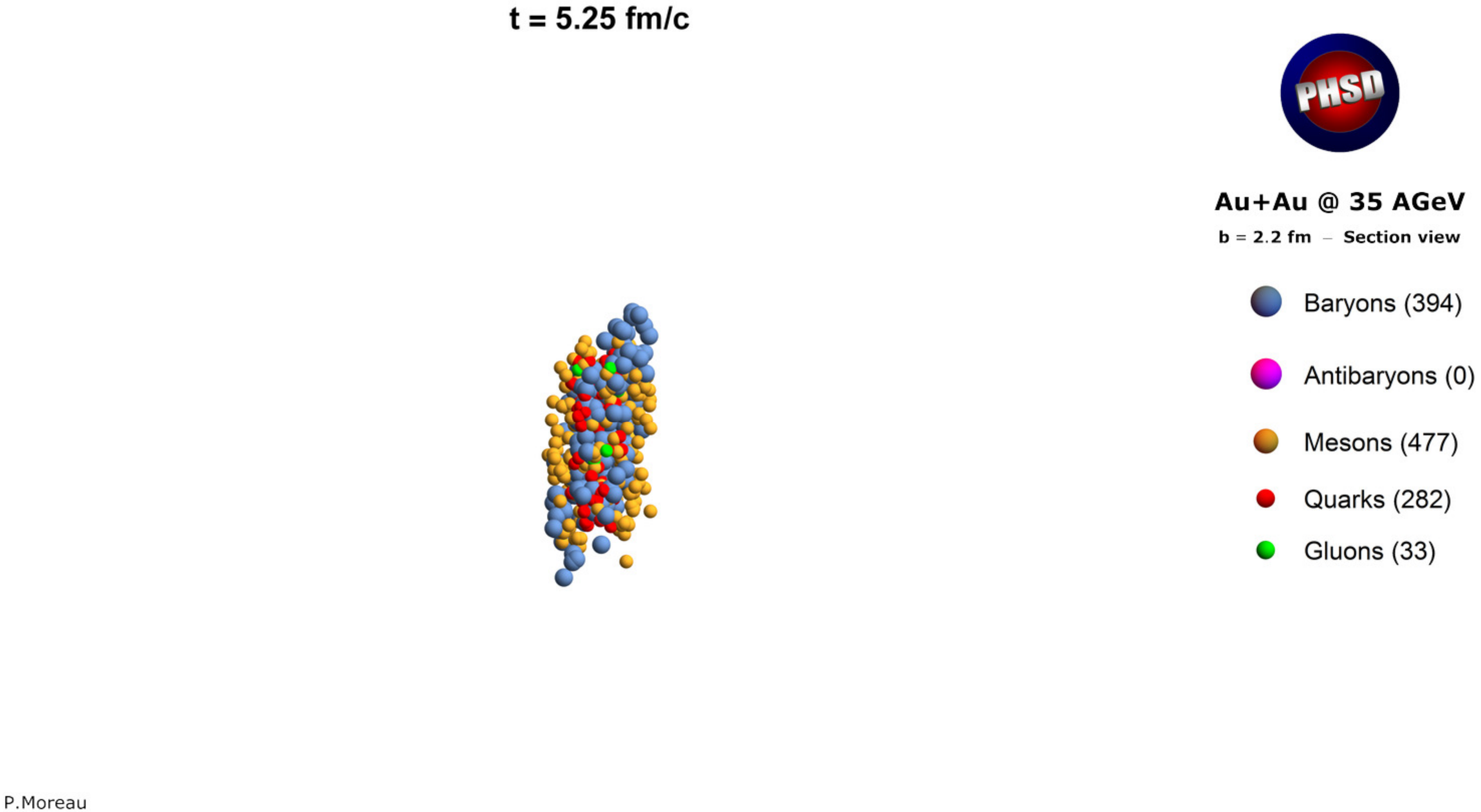
Au+Au @ 35 AGeV

b = 2.2 fm – Section view

- Baryons (394)
- Antibaryons (0)
- Mesons (93)
- Quarks (54)
- Gluons (0)

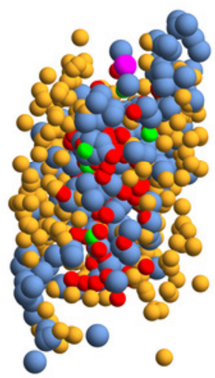
P.Moreau

Au+Au collision at NICA energies



Au+Au collision at NICA energies

t = 6.55001 fm/c



Au+Au @ 35 AGeV

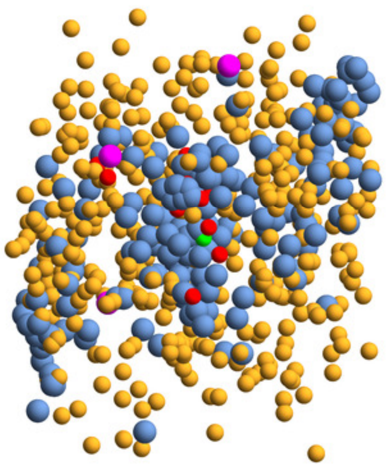
b = 2.2 fm – Section view

- Baryons (397)
- Antibaryons (3)
- Mesons (554)
- Quarks (199)
- Gluons (20)

P.Moreau

Au+Au collision at NICA energies

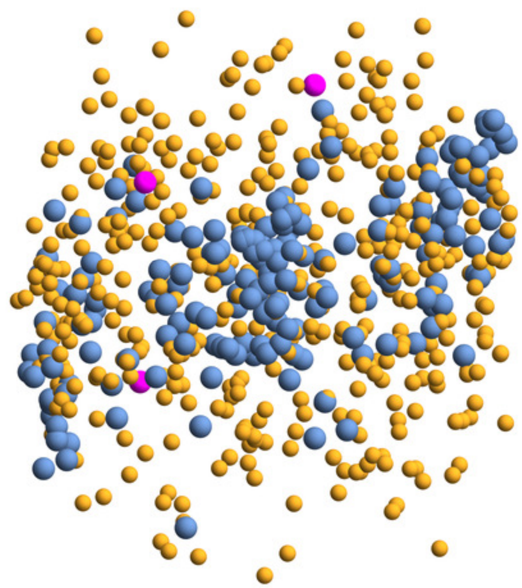
t = 10.45 fm/c



P.Moreau

Stages of a collision in PHSD

t = 13.55 fm/c



Au+Au @ 35 AGeV

b = 2.2 fm – Section view

Baryons (399)

Antibaryons (5)

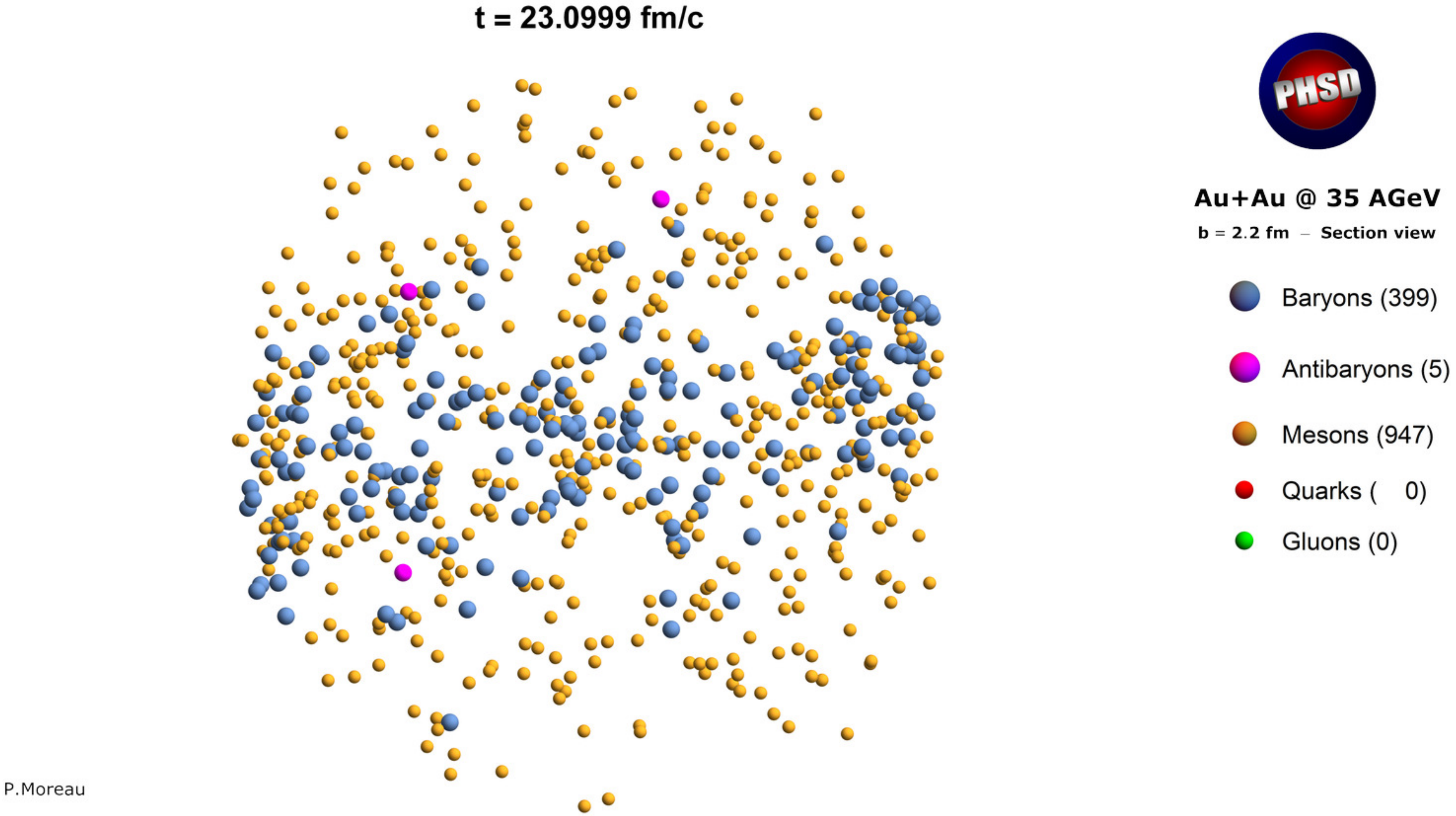
Mesons (817)

Quarks (0)

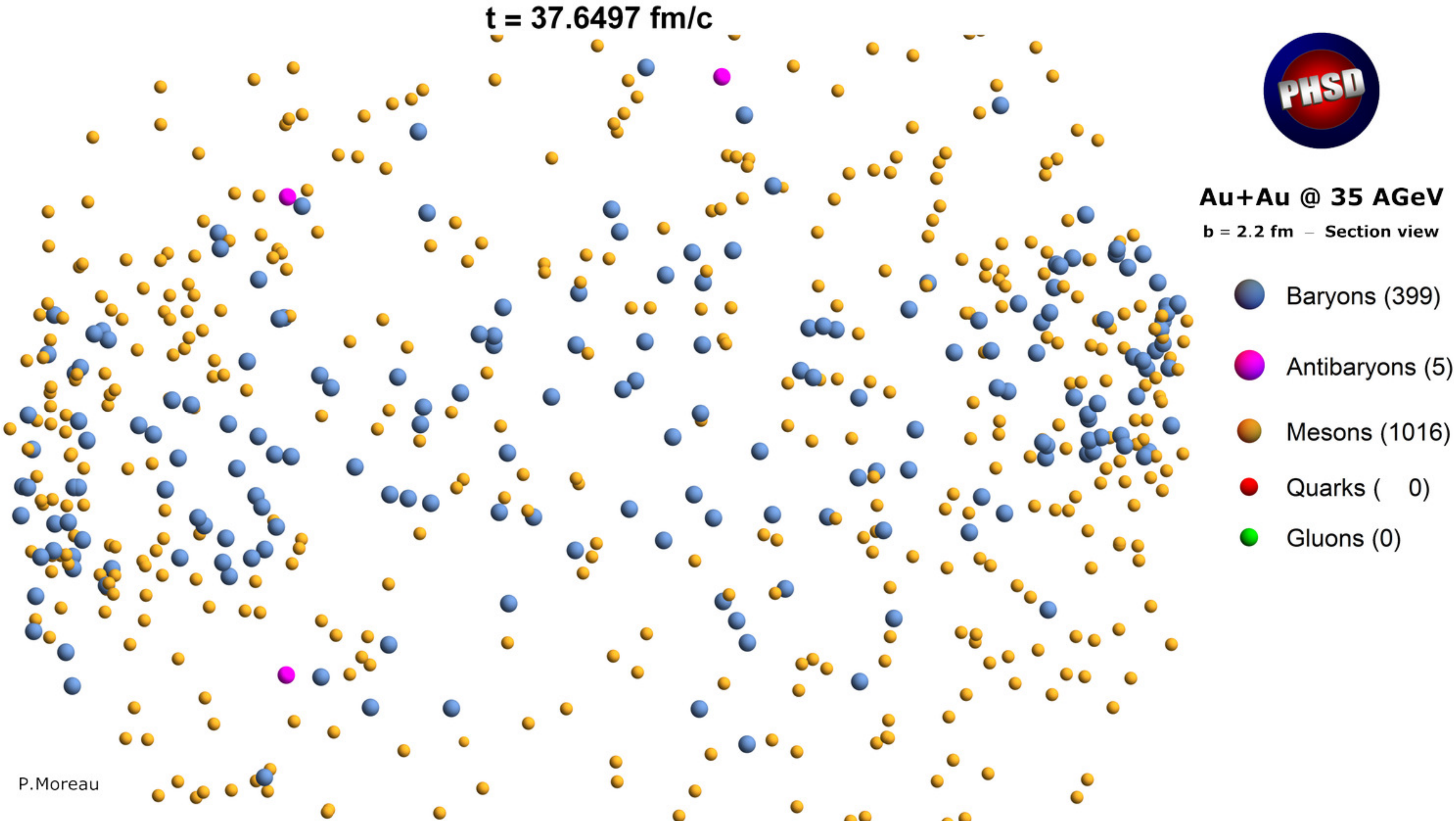
Gluons (0)

P.Moreau

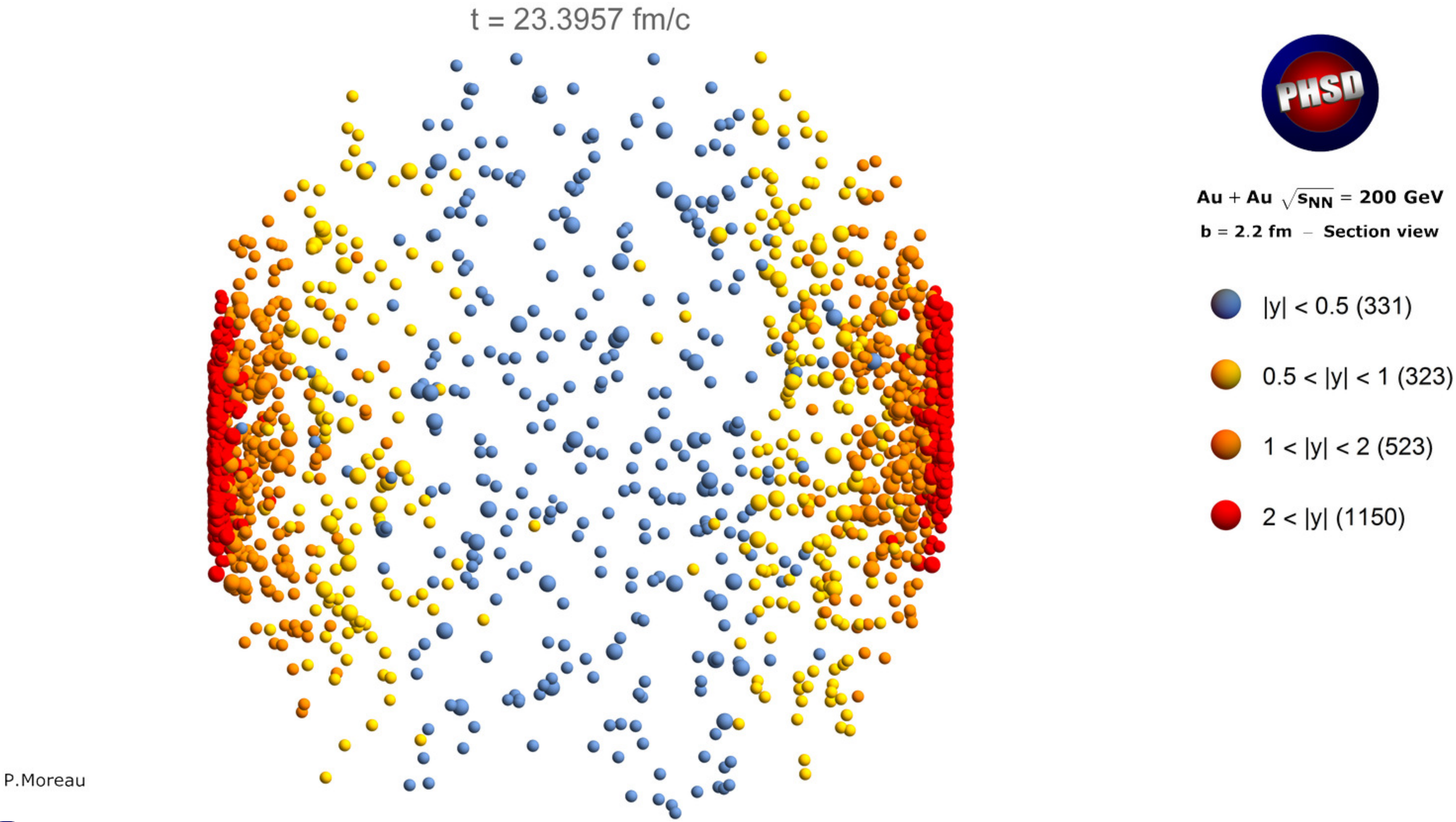
Au+Au collision at NICA energies



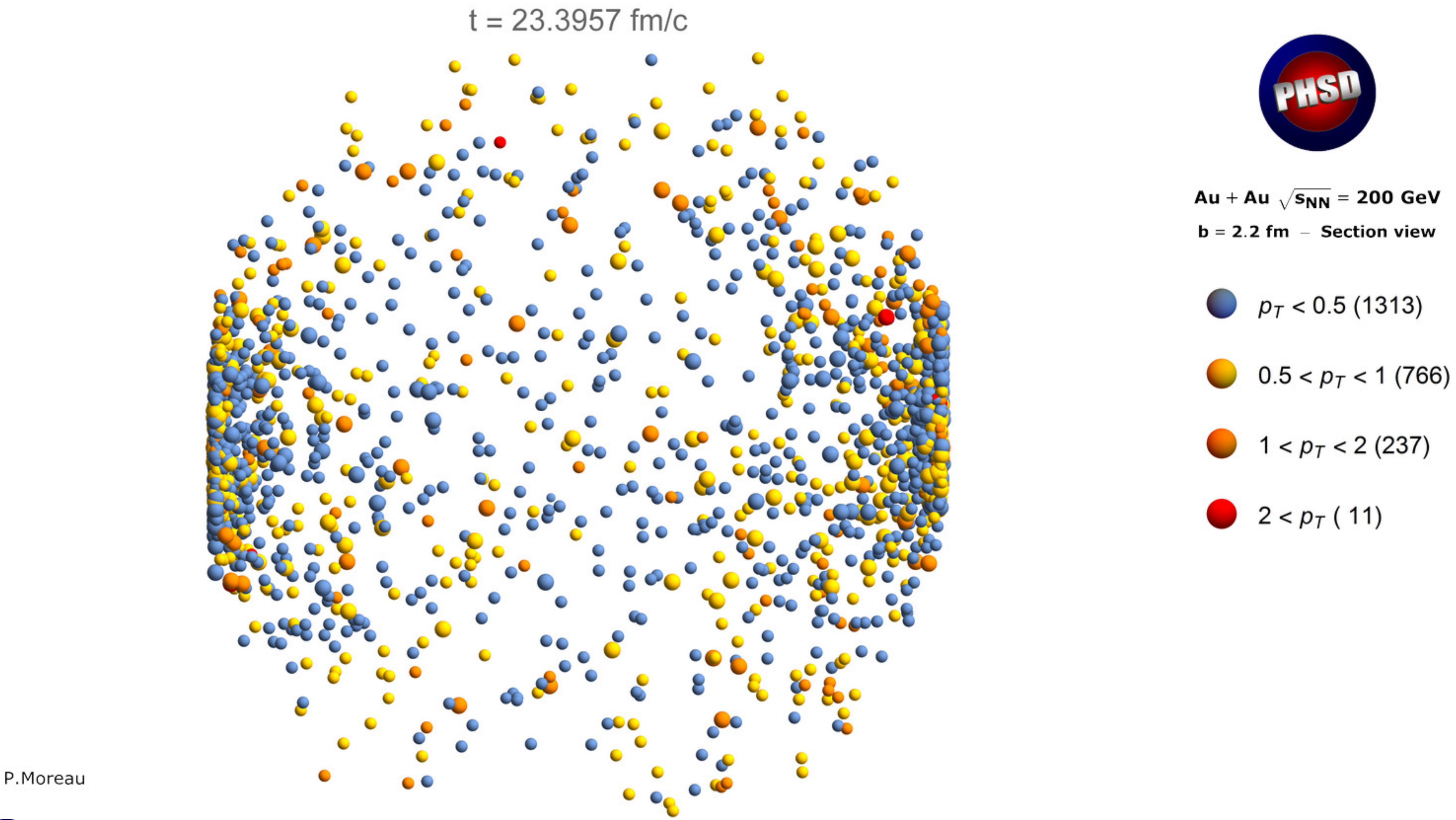
Au+Au collision at NICA energies



Distribution in rapidity – Au+Au, 200 GeV

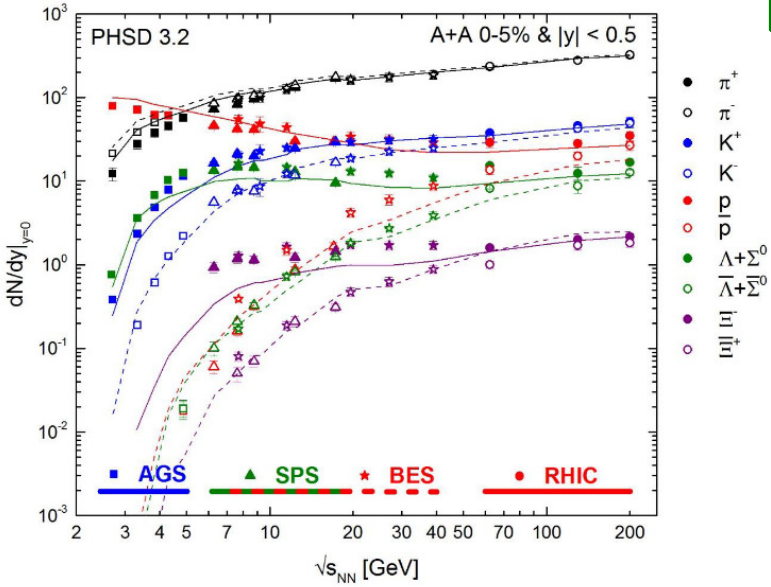


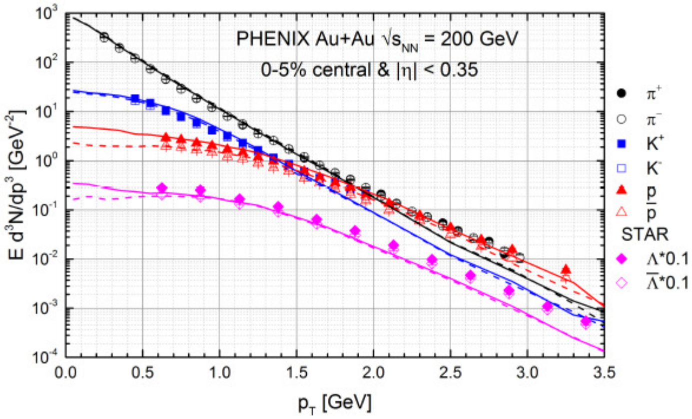
Distribution in p_T – Au+Au, 200 GeV



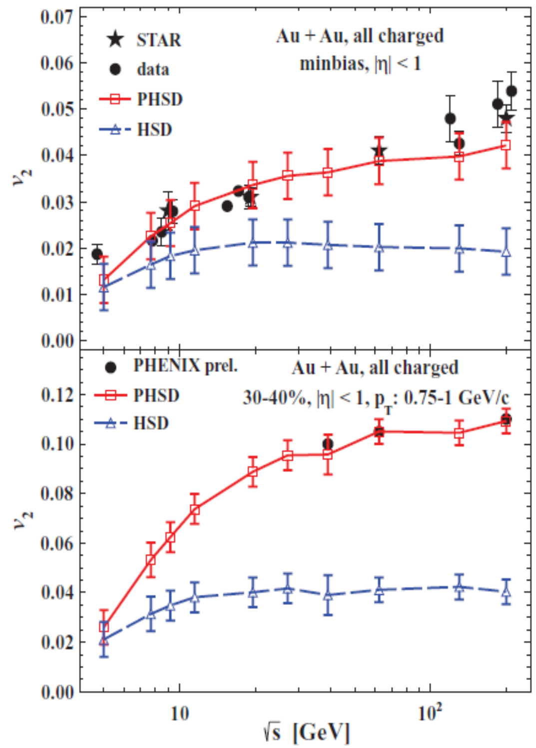
Non-equilibrium dynamics: description of A+A with PHSD

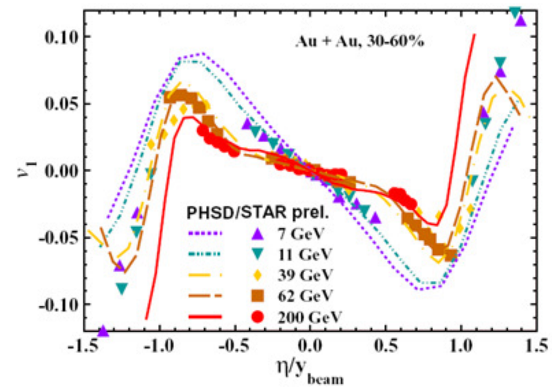
❑ **PHSD: highlights**

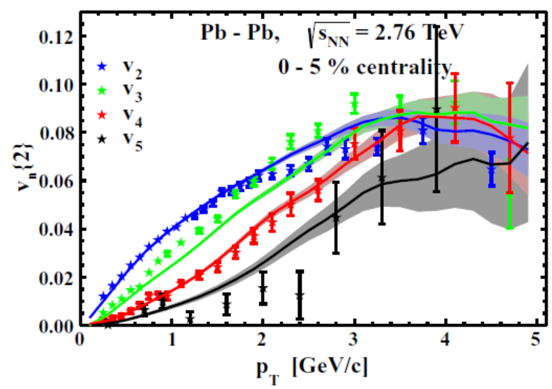




PHSD: P. Moreau





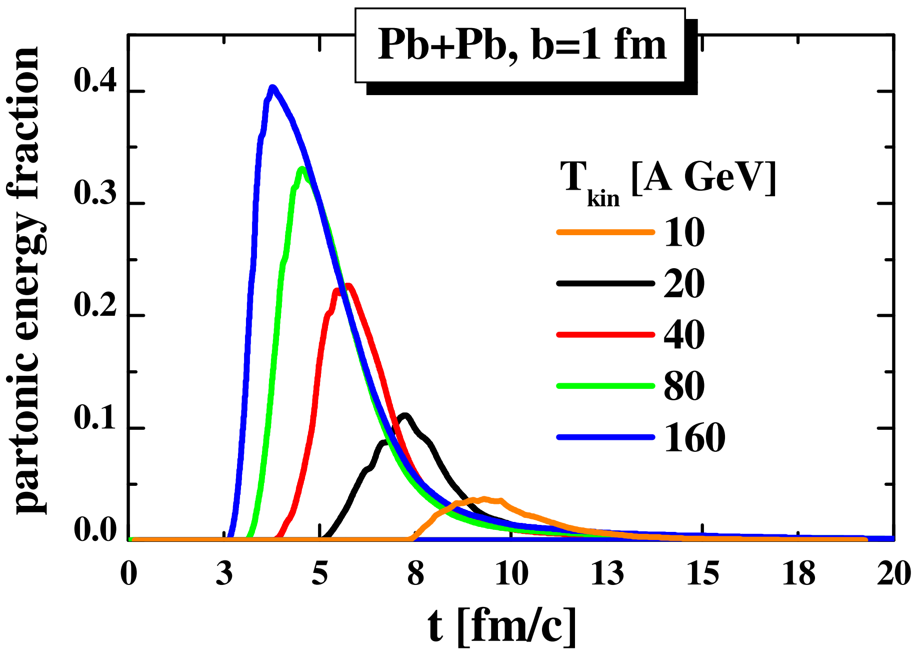


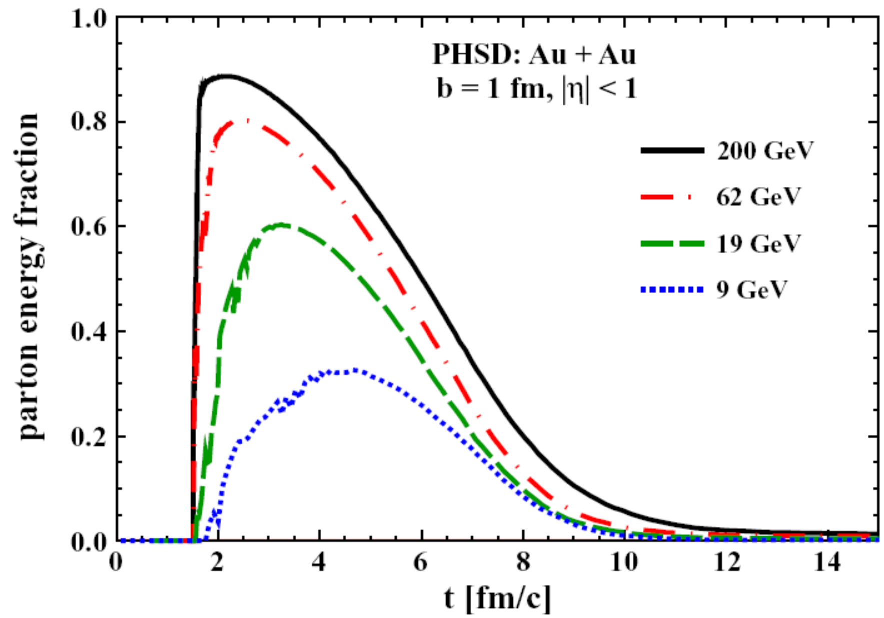
V. Konchakovski et al.,
PRC 85 (2012) 011902; JPG42 (2015) 055106

❑ **PHSD provides a good description of ‚bulk' observables (y-, p_T-distributions, flow coefficients v_n, …) from SIS to LHC**

Partonic energy fraction in central A+A

Time evolution of the partonic energy fraction vs energy at midrapidity





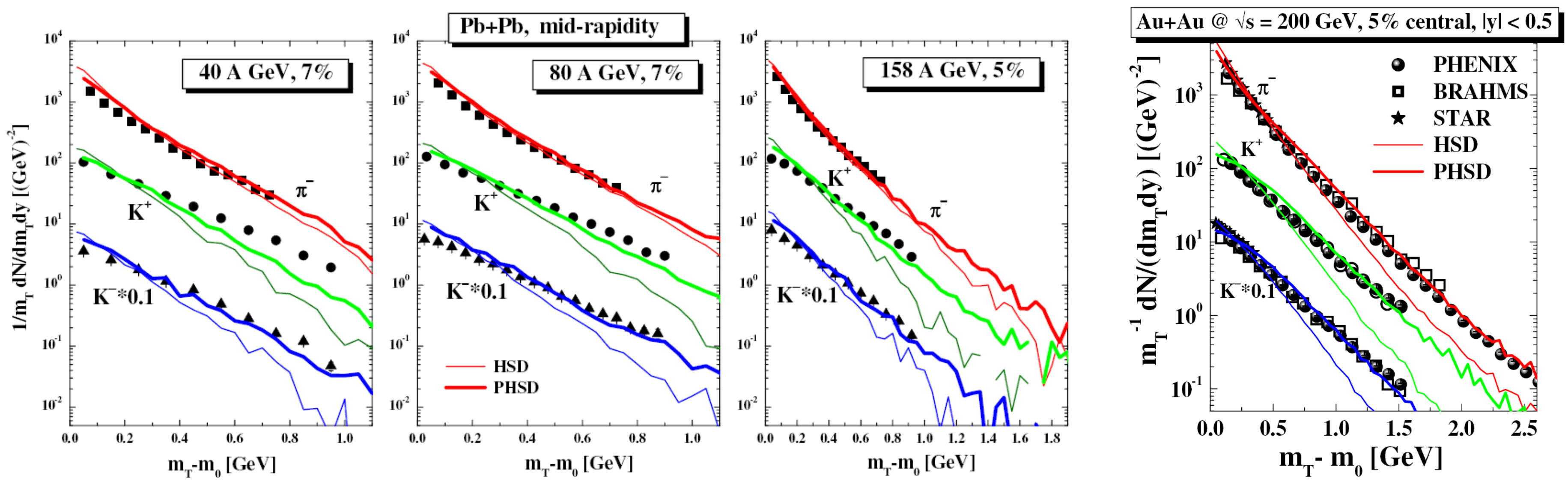
- ❑ Strong increase of partonic phase with energy from AGS to RHIC

- ❑ 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 particles
- ❑ 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

Traces of QGP in observables

Central Pb + Pb at SPS energies | **Central Au+Au at RHIC**



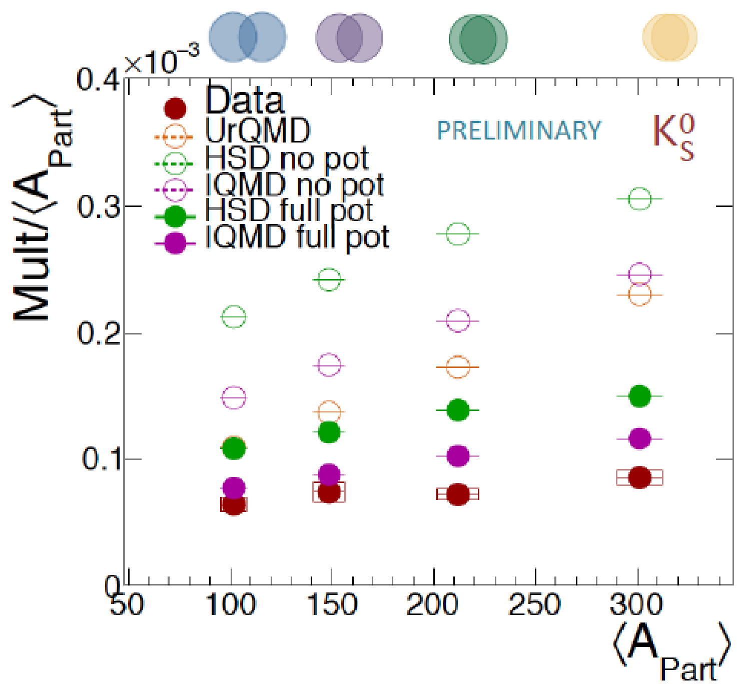
❑ PHSD gives harder m_T spectra and works better than HSD (wo QGP) at high energies – RHIC, SPS (and top FAIR, NICA)

❑ 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

In-medium effects in hadronic observables

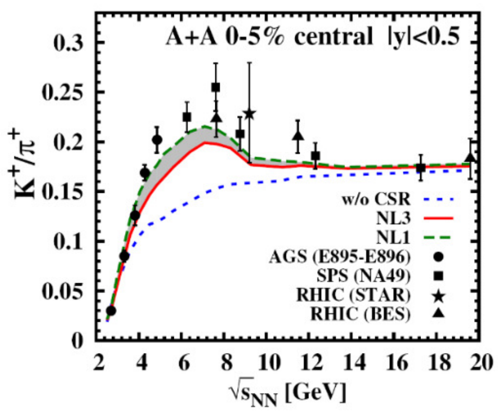
HADES data 2017 vs transport models



- Inclusion of repulsive KN potential reduces yield and <Apart> dependence
- Models w/o potential do not match low pt spectra
- Better description of kaon spectra with KN potential

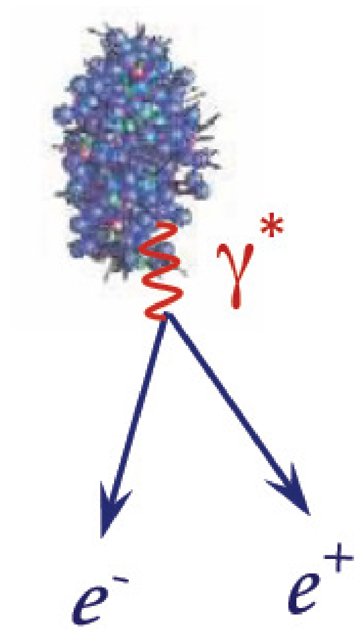
* Figures from the talk by Heidi Schuldes at QM-2017

Chiral symmetry restoration in heavy-ion collisions

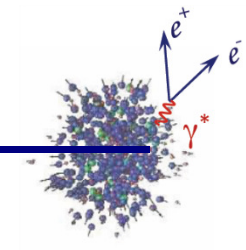


Talk by Alessia Palmese

Electromagnetic probes of the QGP and in-medium effects: dileptons and thermal photons

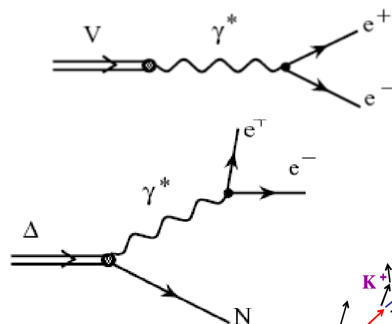


Dilepton sources

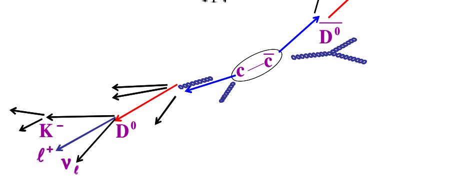


- **from the QGP via partonic (q,qbar, g) interactions:**

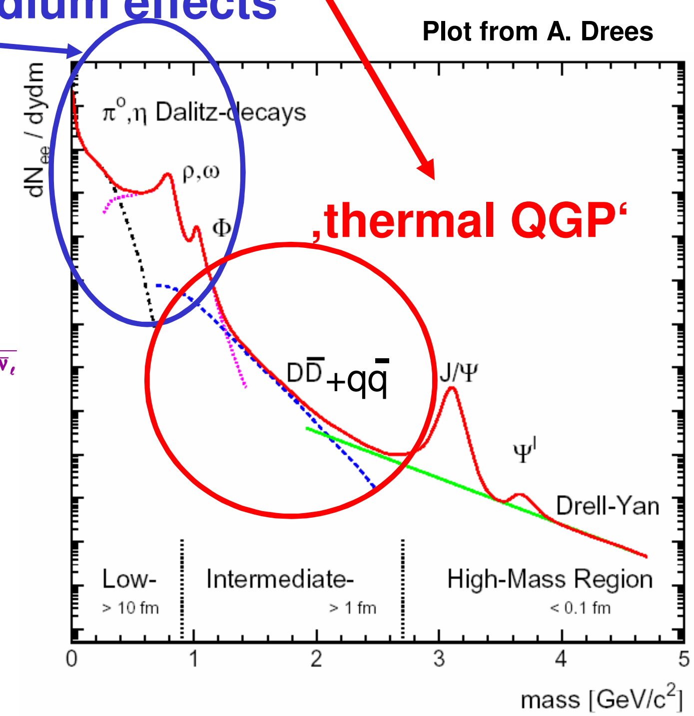
- **from hadronic sources:**



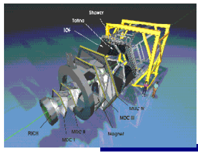
- **direct decay of vector mesons** ($\rho,\omega,\phi,J/\Psi,\Psi'$)
- **Dalitz decay of mesons and baryons** ($\pi^0,\eta,\Delta,\ldots$)
- **correlated D+Dbar pairs**



- **radiation from multi-meson reactions** ($\pi+\pi$, $\pi+\rho$, $\pi+\omega$, $\rho+\rho$, $\pi+a_1$) - ‚4π'



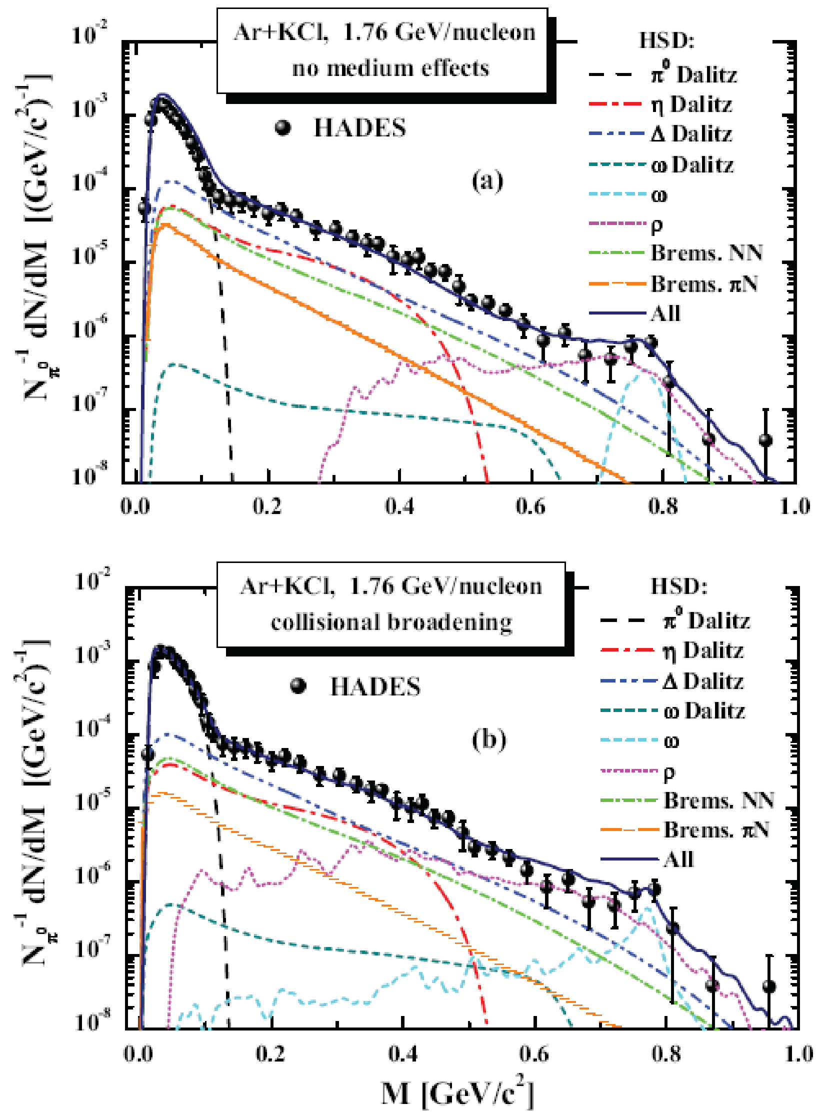
! Advantage of dileptons:
additional „degree of freedom" (*M*) allows to disentangle various sources



Dileptons at SIS energies - HADES

- **HADES:** **dilepton yield dN/dM scaled with the number of pions $N_{\pi 0}$**

- **Dominant hadronic sources at $M>m_{\pi}$:**
  - **η, Δ Dalitz decays**
  - **NN bremsstrahlung**
  - **direct ρ decay**



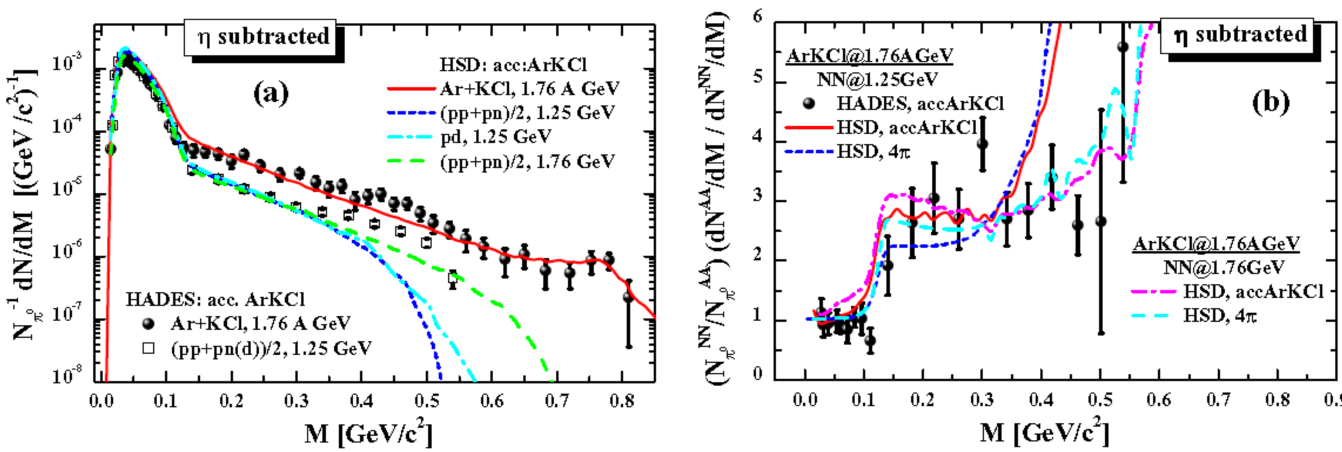
➢ **ρ meson = strongly interacting resonance**
strong collisional broadening of the ρ width

- **In-medium effects are more pronounced for heavy systems such as Ar+KCl than C+C**
- **The peak at M~0.78 GeV relates to ω/ρ mesons decaying in vacuum**

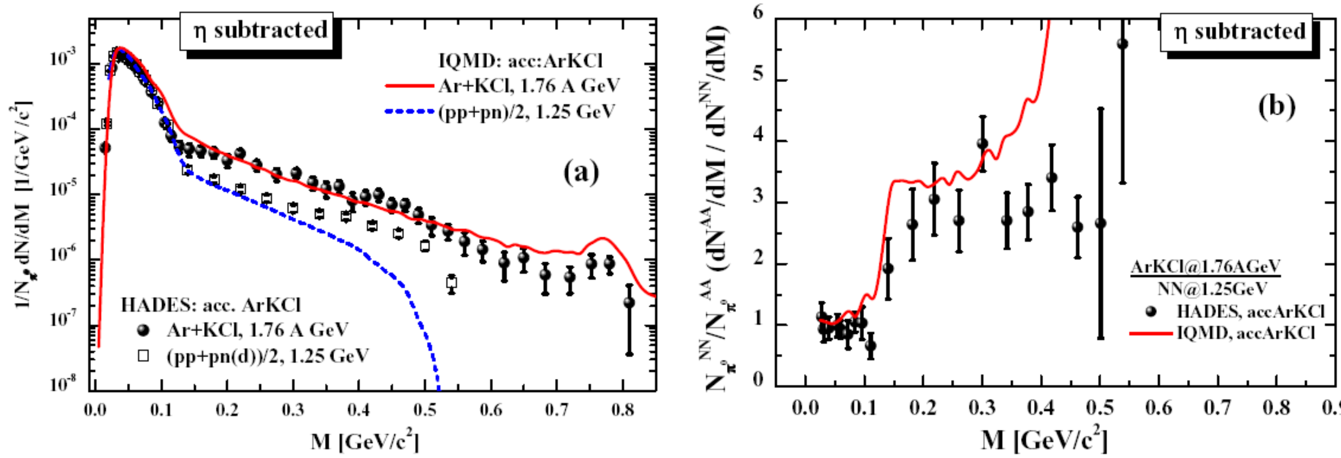
E.Bratkovskaya., J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (2013) 064907

Dileptons at SIS energies: A+A vs. N+N

- **ratio of AA/NN spectra** (scaled by $N_{\pi 0}$) after subtracted η contribution



▪HSD



▪IQMD

➔ **Strong enhancement of dilepton yield in A+A vs. NN is reproduced by HSD and IQMD for C+C at 1.0, 2.0 A GeV and Ar+KCl at 1.75 A GeV**

E.B., J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (2013) 064907

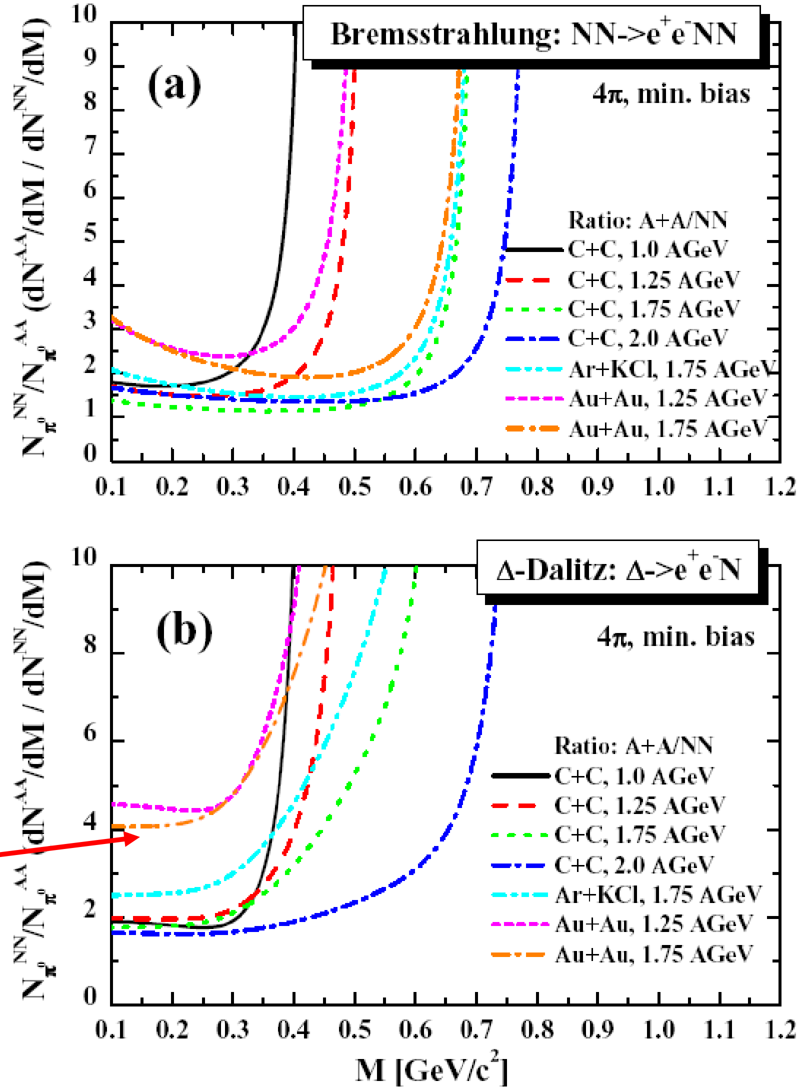
Dileptons at SIS (HADES): A+A vs NN

- **Two contributions to the enhancement of dilepton yield in A+A vs. NN**

1) the pN bremsstrahlung which scales with the number of collisions and not with the number of participants, i.e. pions;

2) the multiple Δ regeneration – dilepton emission from intermediate Δ's which are part of the reaction cycles Δ→πN; πN →Δ and NN→NΔ; NΔ→NN

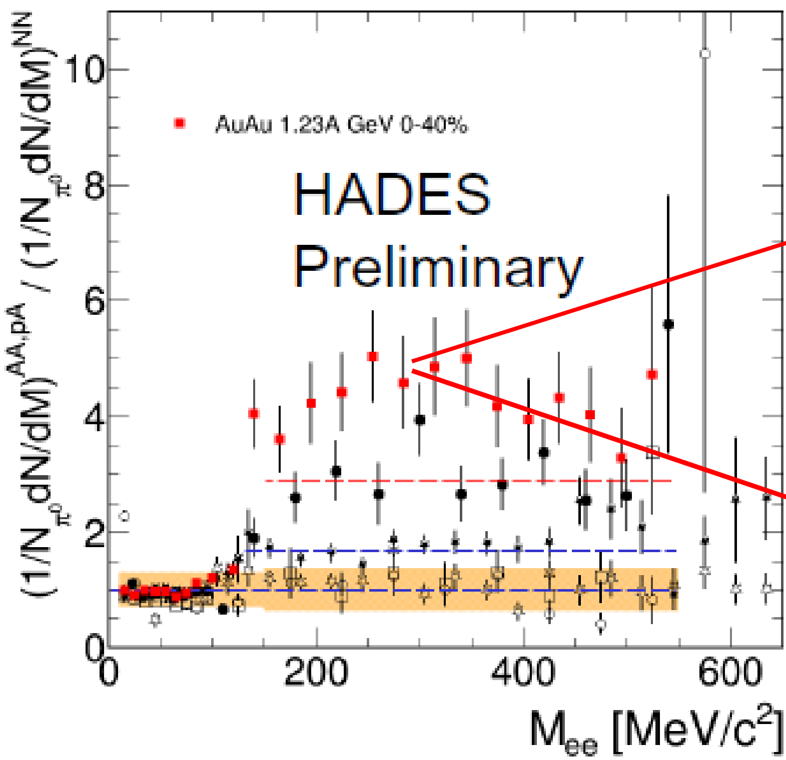
- **Enhancement of dilepton yield in A+A vs. NN increases with the system size!**



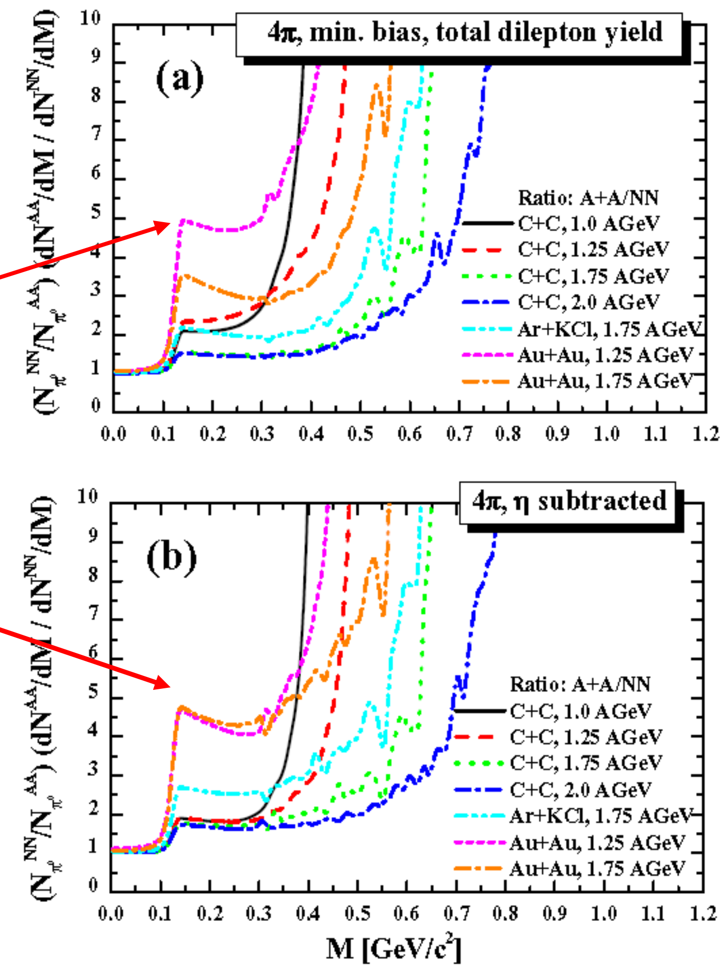
E.B., J. Aichelin, M. Thomere, S. Vogel, and M. Bleicher, PRC 87 (2013) 064907

Dileptons at SIS (HADES): Au+Au

CPOD-2016:
HADES preliminary: Au+Au, 1.23 A GeV



- **HSD predictions (2013)**

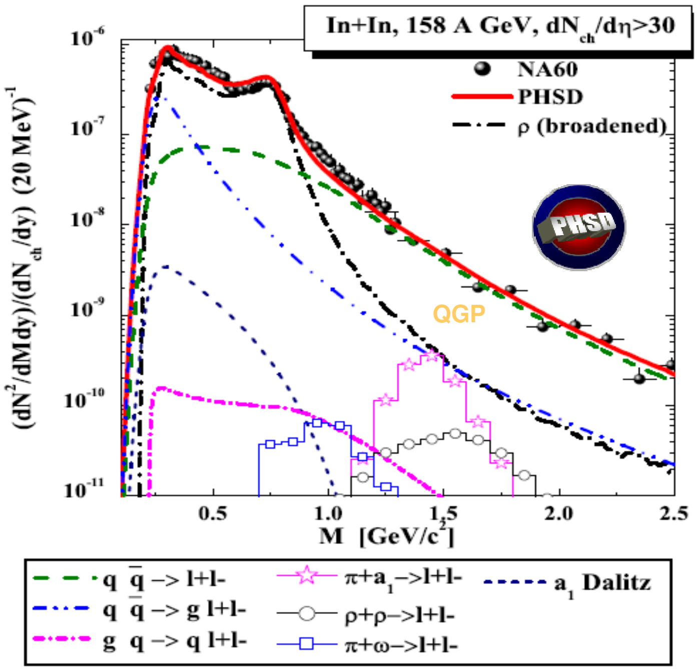


- **Strong in-medium enhancement of dilepton yield in Au+Au vs. NN**
  ➔ related to Δ regeneration and pN bremsstrahlung

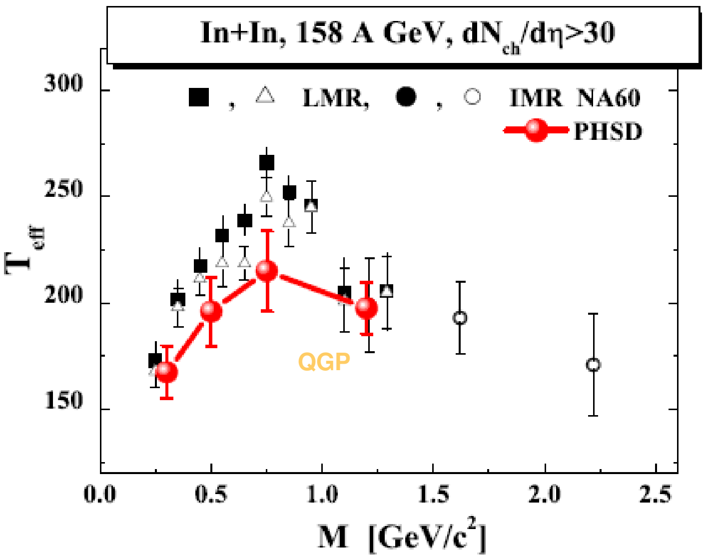
E.B., J. Aichelin, M. Thomere, S. Vogel, M. Bleicher, PRC 87 (2013) 064907

Lessons from SPS: NA60

❑ **Dilepton invariant mass spectra:**



❑ **Inverse slope parameter T_{eff}:**
spectrum from QGP is softer than from hadronic phase since the QGP emission occurs dominantly before the collective radial flow has developed

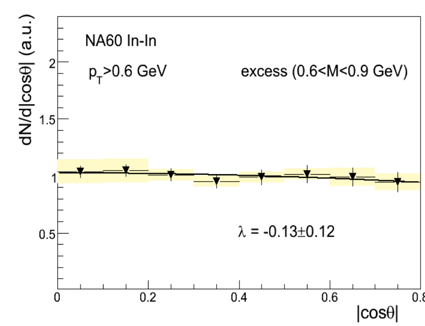


NA60: Eur. Phys. J. C 59 (2009) 607

PHSD:
Linnyk et al, PRC 84 (2011) 054917

Message from SPS: (based on NA60 and CERES data)

1) **Low mass spectra** - evidence for the **in-medium broadening of ρ-mesons**
2) Intermediate mass **spectra above 1 GeV** - dominated by **partonic radiation**
3) The rise and fall of **T_{eff}** – evidence for the thermal **QGP radiation**
4) **Isotropic angular distribution** – indication for a **thermal origin of dimuons**

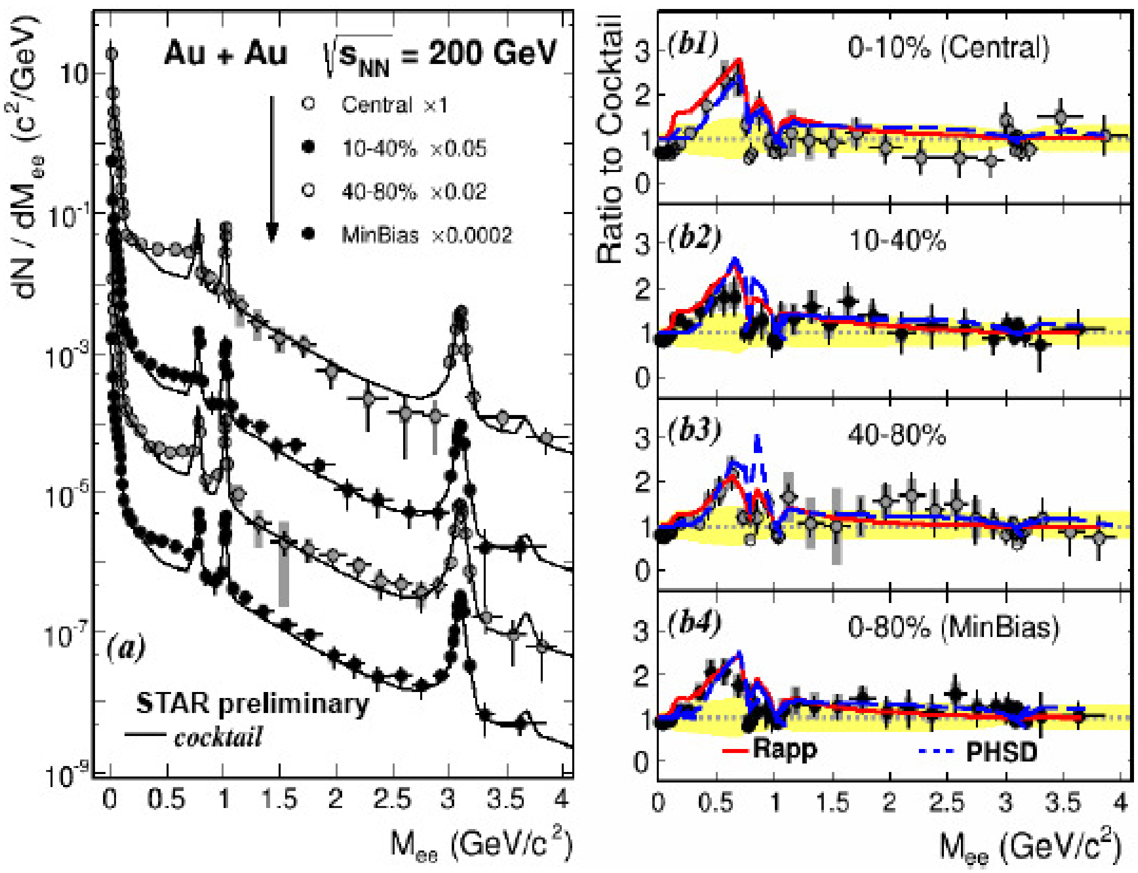


PRL 102 (2009) 222301

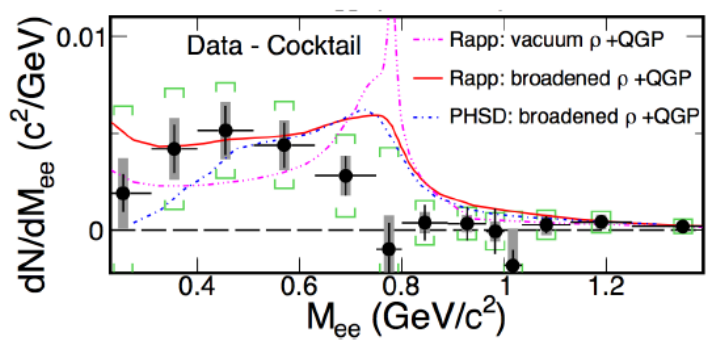
Dileptons at RHIC: STAR data vs model predictions

PRC 92 (2015) 024912

Centrality dependence of dilepton yield



Excess in low mass region, min. bias



Models:

- **Fireball model – R. Rapp**
- **PHSD**

Low masses:

collisional broadening of ρ

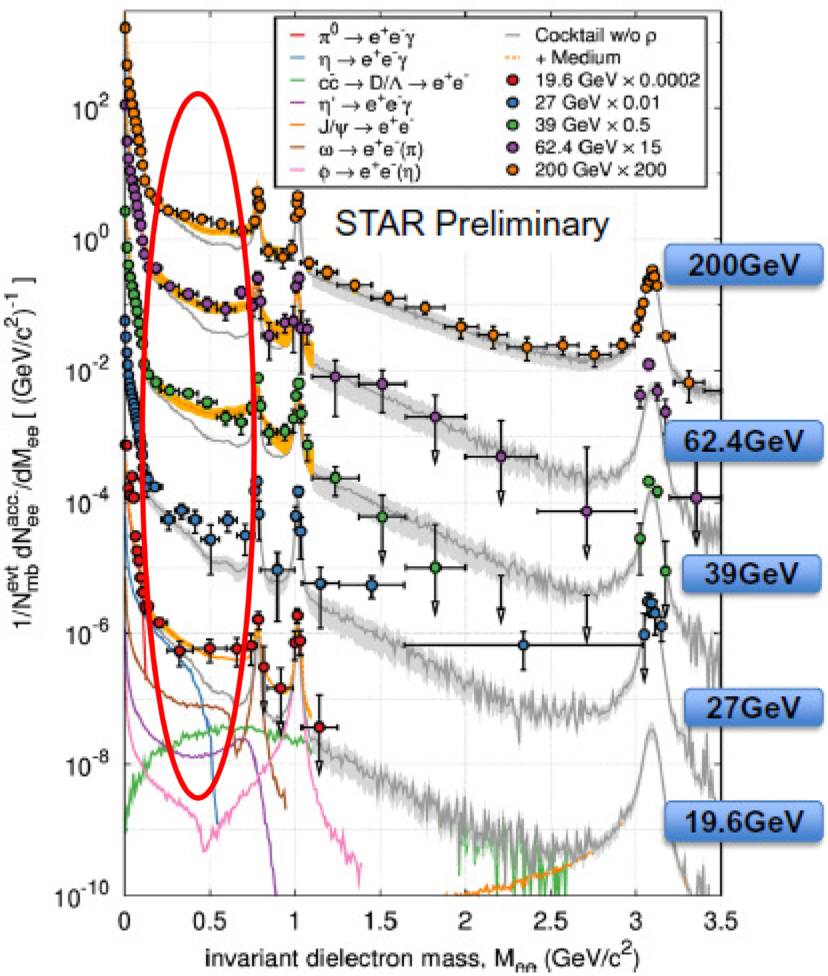
Intermediate masses:

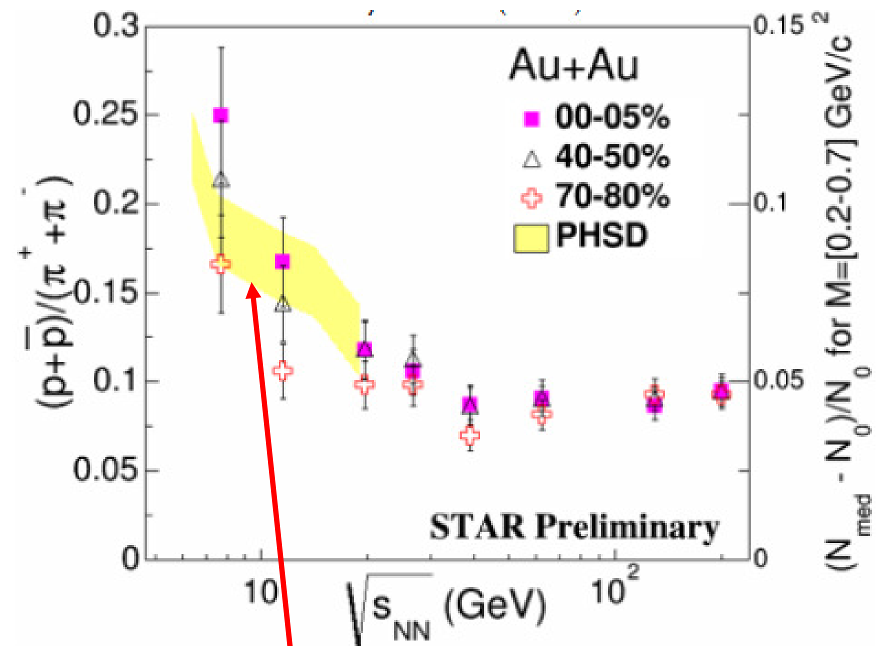
QGP dominant

Message: **STAR data are described by models within a collisional broadening scenario for the vector meson spectral function + QGP**

Dileptons from RHIC BES: STAR

(Nu Xu in 2014)



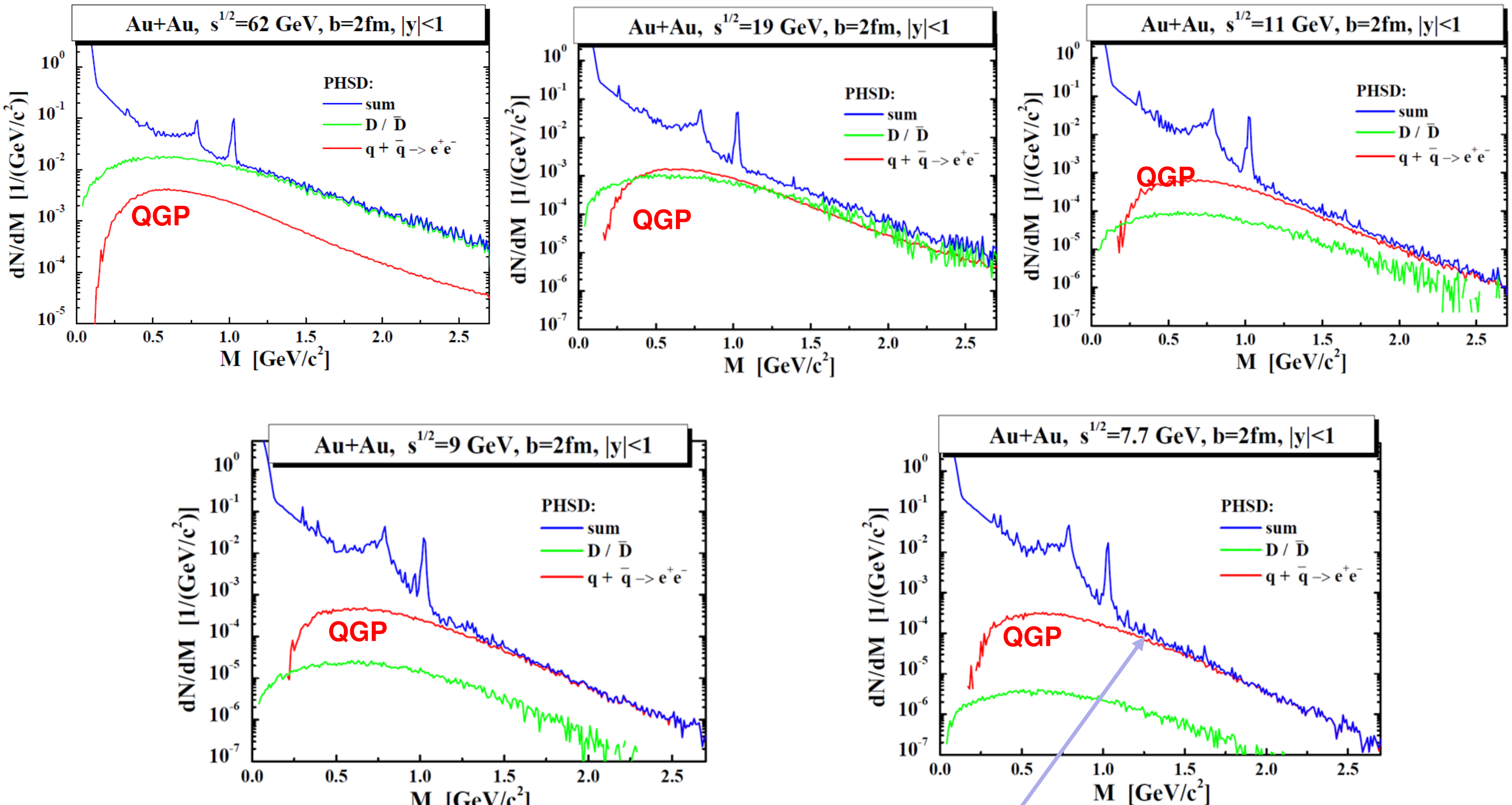


Message:

- **BES-STAR data show a constant low mass excess (scaled with $N(\pi^0)$) within the measured energy range**
- **PHSD: excess increasing with decreasing energy due to a longer ρ-propagation in the high baryon density phase**

➔ Good perspectives for future experiments – CBM(FAIR) / MPD(NICA)

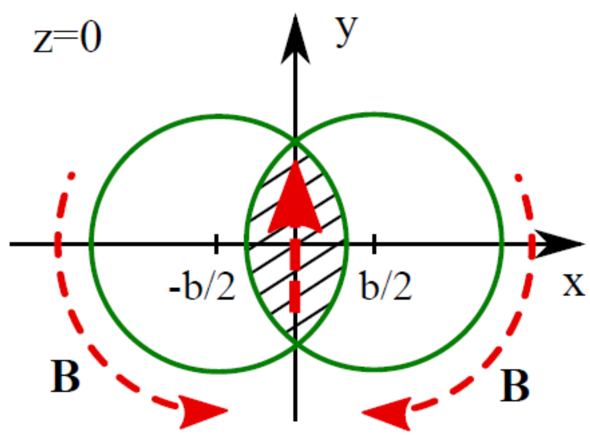
Dileptons at NICA/FAIR energies: predictions



Relative contribution of QGP versus charm increases with decreasing energy!
Good perspectives for NICA!

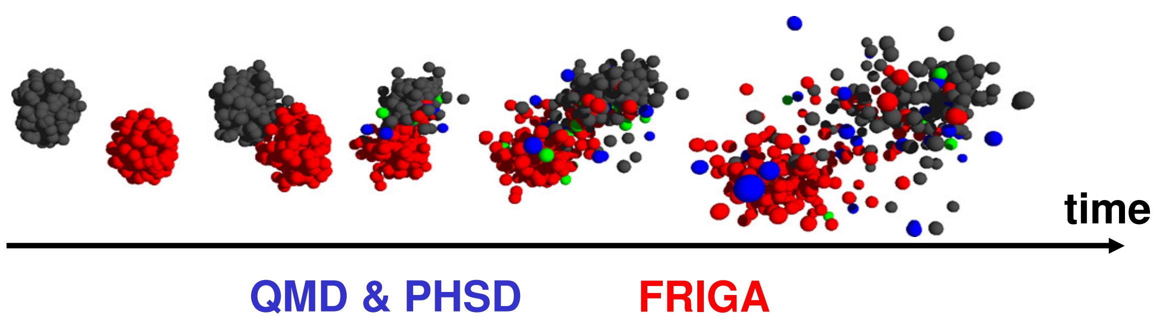
* **Dynamical description of charm degrees of freedom in the PHSD (T. Song, 2015)**

Chiral magnetic effect and evolution of the electromagnetic field in relativistic heavy-ion collisions



Talk by Vadim Voronyuk

Cluster and hypernuclei formation within PHQMD+FRIGA



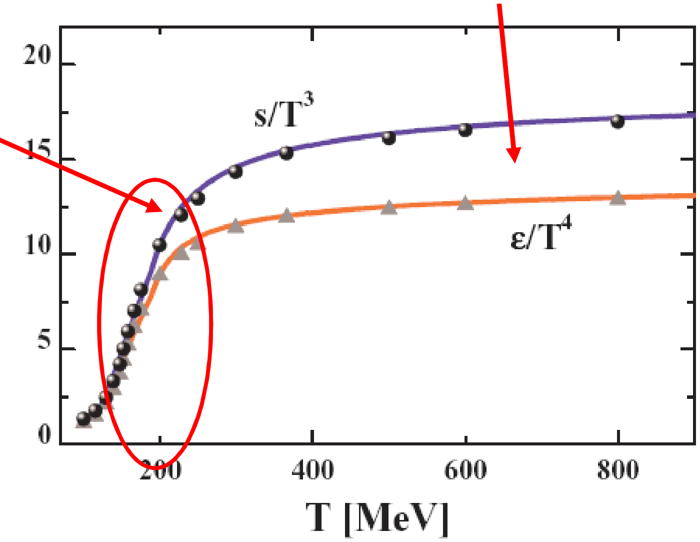
Talks by Jörg Aichelin and Viktar Kireyev

Outlook

What is the stage of matter close to T_c and large μ:

- ❑ **1st order phase transition?**
- ❑ **,Mixed' phase = interaction of partonic and hadronic degrees of freedom?**

Lattice EQS for μ=0
➔ ,crossover' , T > T_c



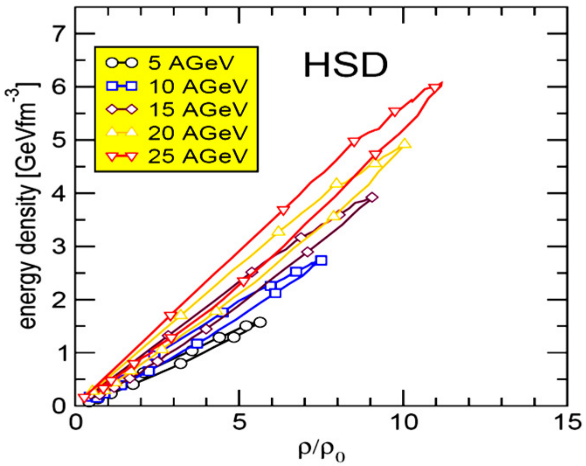
Open problems:

- **How to describe a first-order phase transition in transport models?**
- **How to describe parton-hadron interactions in a ,mixed' phase?**

Physics at NICA & BM@N

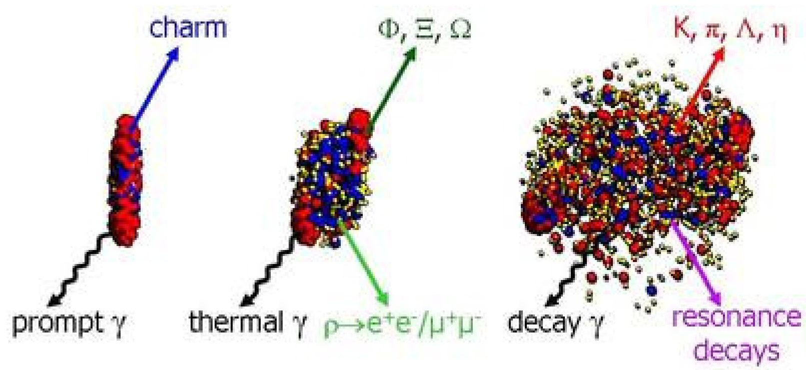
NICA & BM@N energies are well suited to study dense and hot nuclear matter :

- a phase transition to QGP
- in-medium effects of hadrons
- chiral symmetry restoration



Way to study:

Experimental energy scan of different observables in order to find an ‚anomalous' behavior by comparison with theory



➔ Dynamical models of HIC!

Thanks to: PHSD group -2017

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Daniel Cabrera

Barcelona University:
Laura Tolos
Angel Ramos

Duke University:
Steffen Bass

GSI
GOETHE UNIVERSITÄT FRANKFURT AM MAIN
FIAS Frankfurt Institute for Advanced Studies
HIC for FAIR Helmholtz International Center
HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research
Bundesministerium für Bildung und Forschung
DFG Deutsche Forschungsgemeinschaft
DAAD
PHSD
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN
Subatech
TEXAS A&M UNIVERSITY
JINR
UAB Universitat Autònoma de Barcelona
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