FIAS Frankfurt Institute for Advanced Studies

HIC for FAIR Helmholtz International Center

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

The properties of parton-hadron matter from heavy-ion collisions

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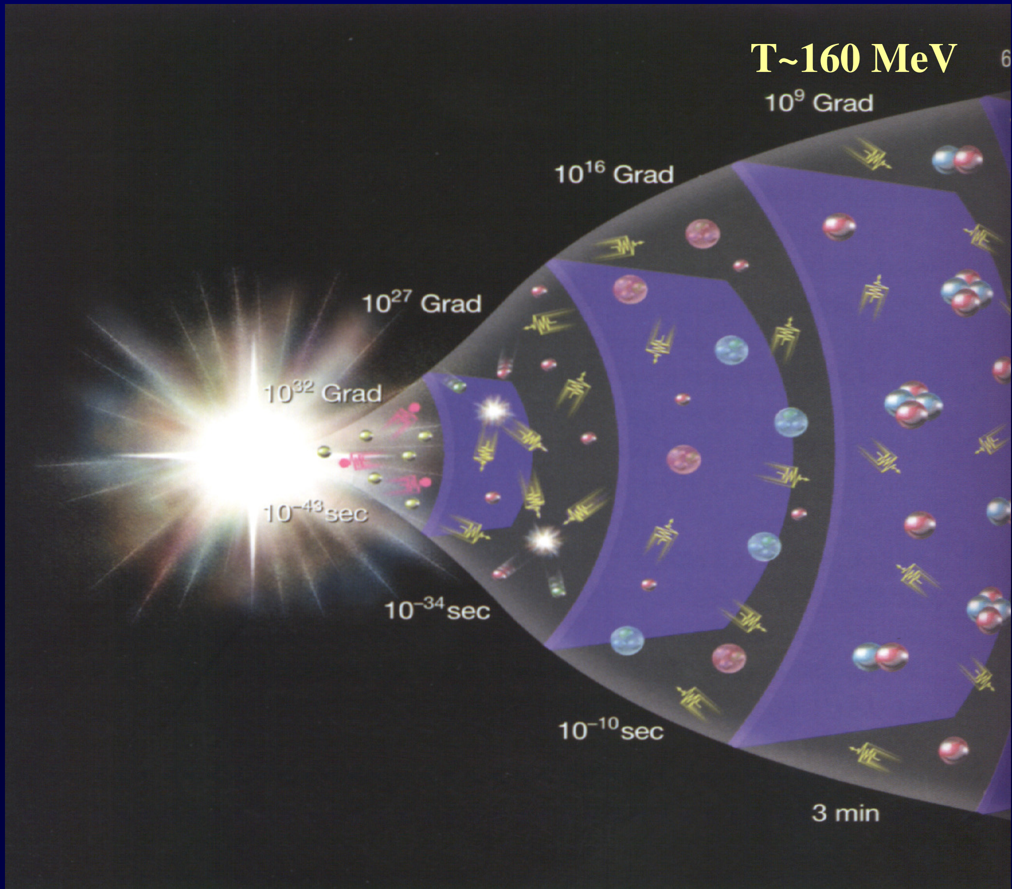
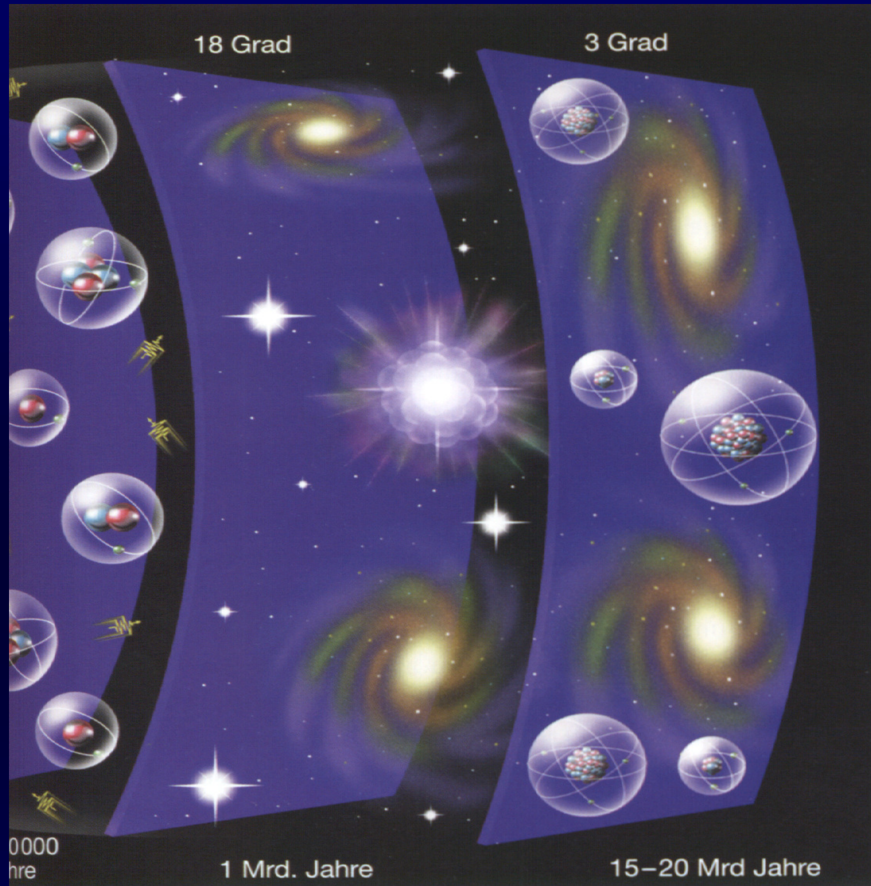
BLTP, 7 August, 2013

From Big Bang to Formation of the Universe



➔

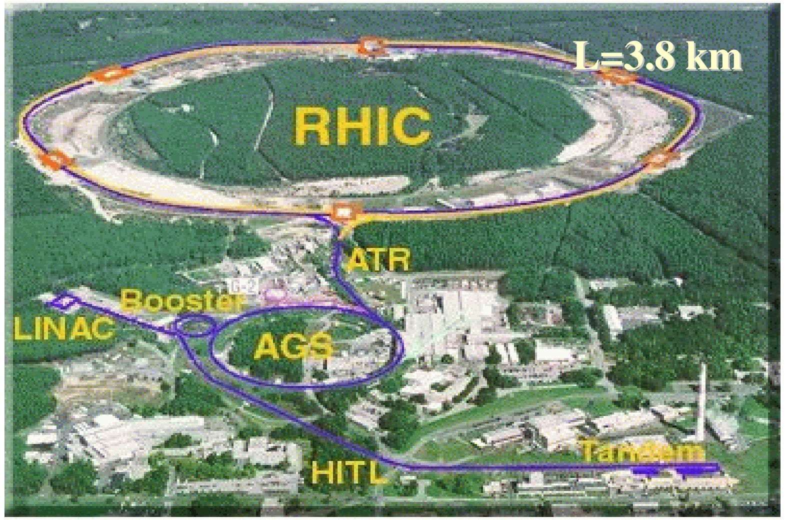


time	10^{-3}sec	3 min	300000 years	15 Mrd years
	quarks gluons photons	nucleons deuterons α–particles	atoms	our Universe

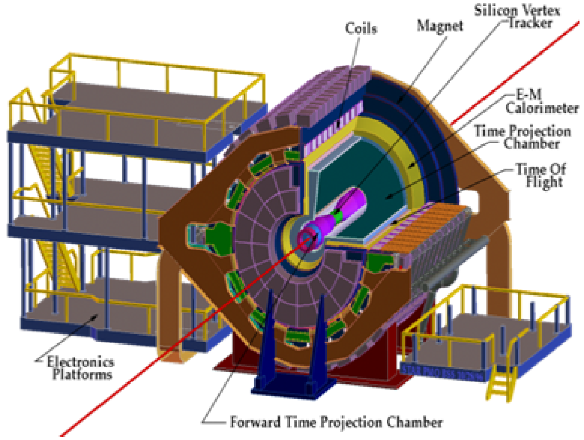
⟵ **Can we go back in time ?**

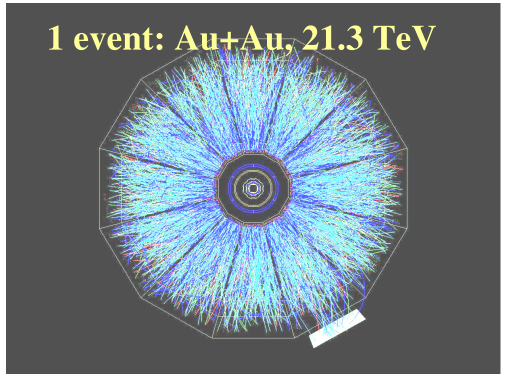
Heavy-ion accelerators

- **Relativistic-Heavy-Ion-Collider – RHIC - (Brookhaven): Au+Au at 21.3 A TeV**

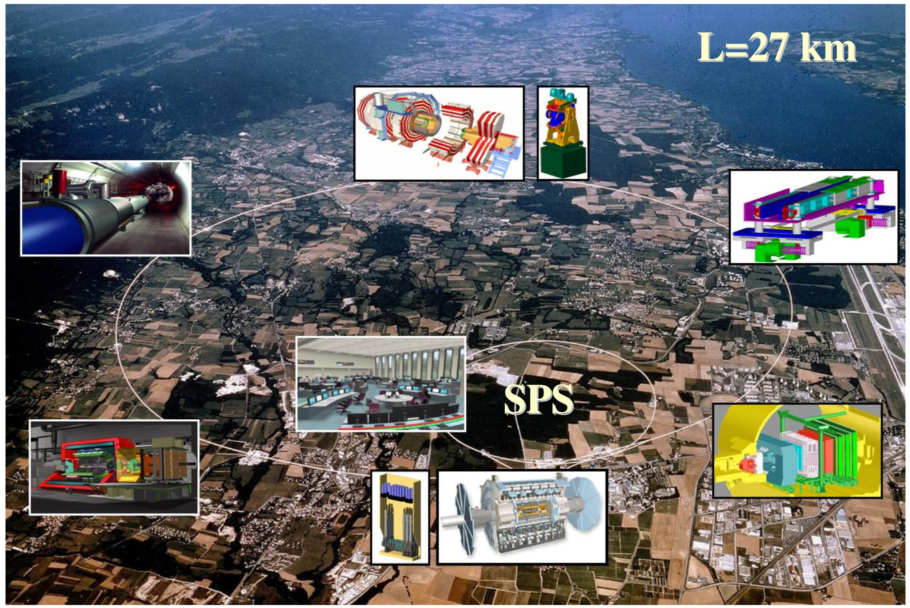


STAR detector at RHIC

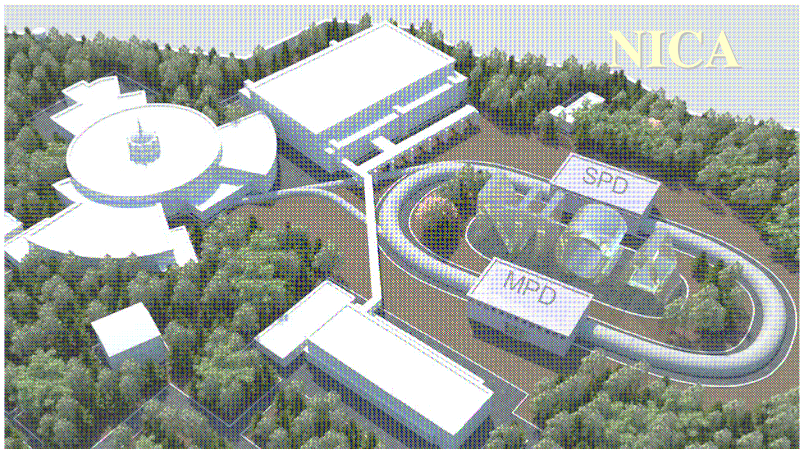




- **Large Hadron Collider - LHC - (CERN): Pb+Pb at 574 A TeV**



- **Future facilities: FAIR (GSI), NICA (Dubna)**

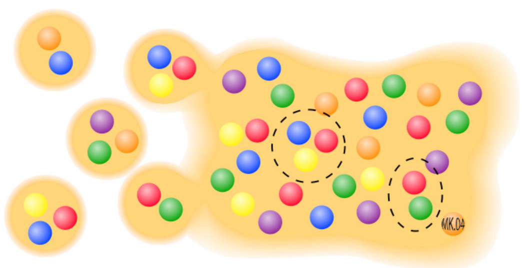


The QGP in Lattice QCD

Quantum Chromo Dynamics :

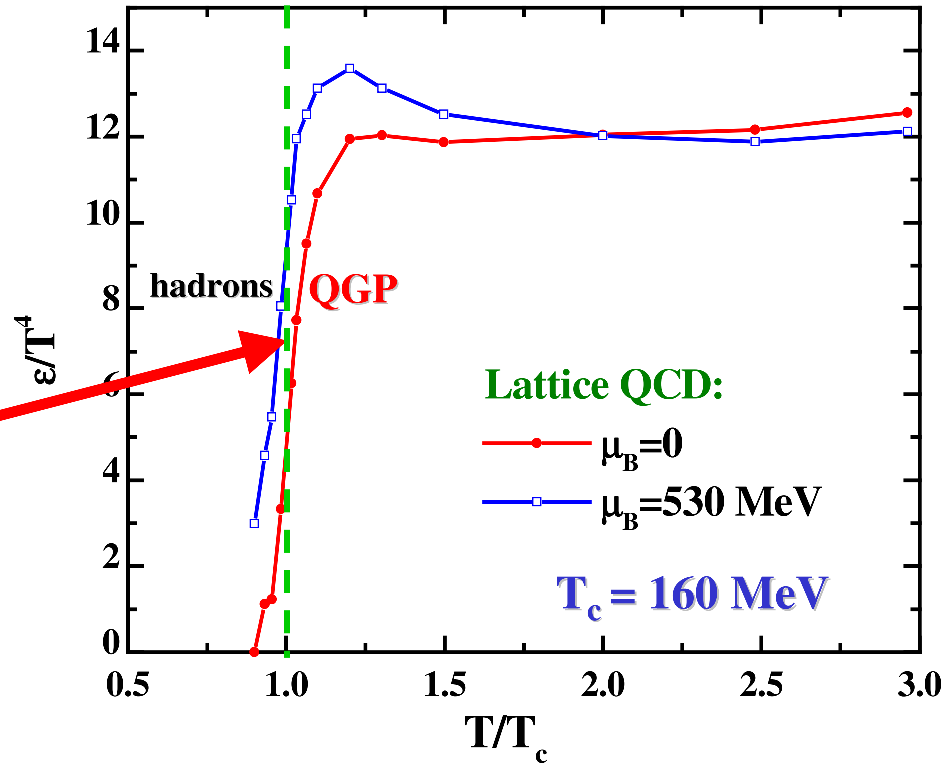
predicts strong increase of the energy density ε at a critical temperature T_C ~160 MeV

⇒ Possible phase transition from hadronic to partonic matter (quarks, gluons) at critical energy density ε_C ~0.5 GeV/fm³



Lattice QCD:

energy density versus temperature

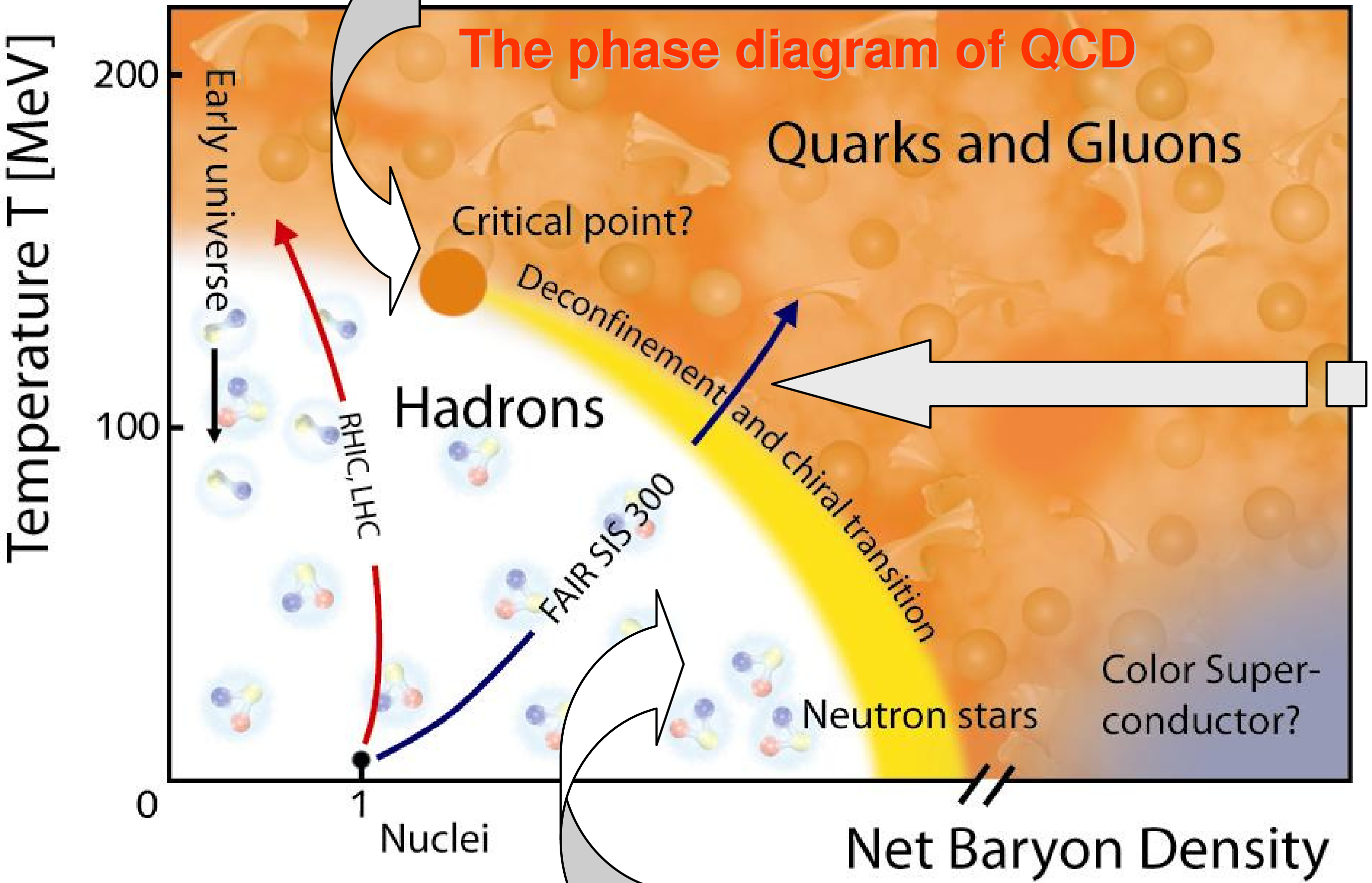


Z. Fodor et al., PLB 568 (2003) 73

Critical conditions - ε_C ~0.5 GeV/fm³ , T_C ~160 MeV - can be reached in heavy-ion experiments at bombarding energies > 5 GeV/A

The holy grail of heavy-ion physics:

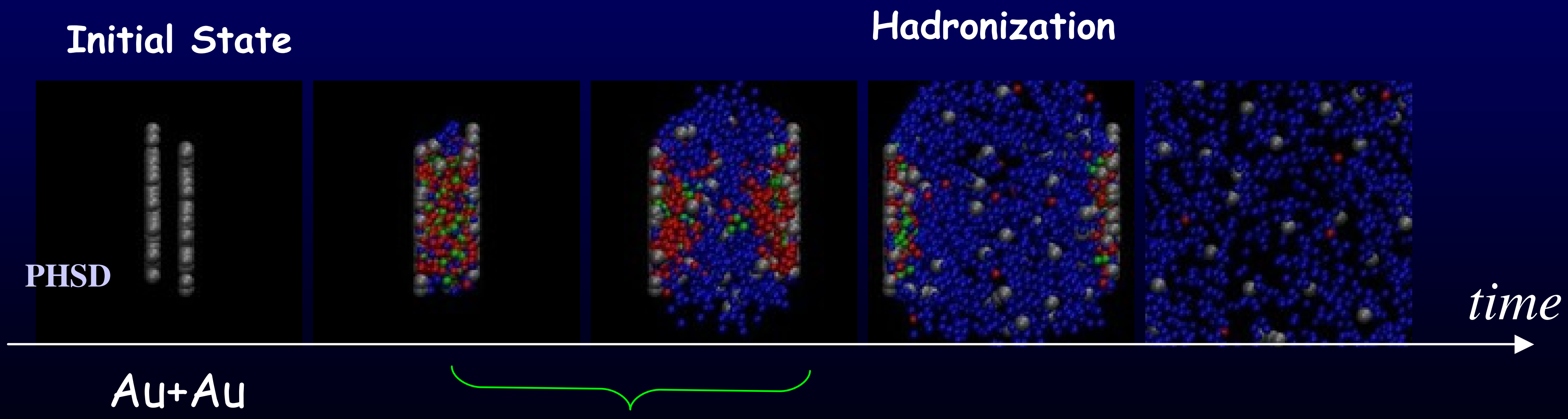
- Search for the critical point



- 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

‚Little Bangs‘ in the Laboratory



Quark-Gluon-Plasma ?

hadron degrees of freedom → quarks and gluons → hadron degrees of freedom

How can we prove that an equilibrium QGP has been created in central heavy-ion collisions ?!

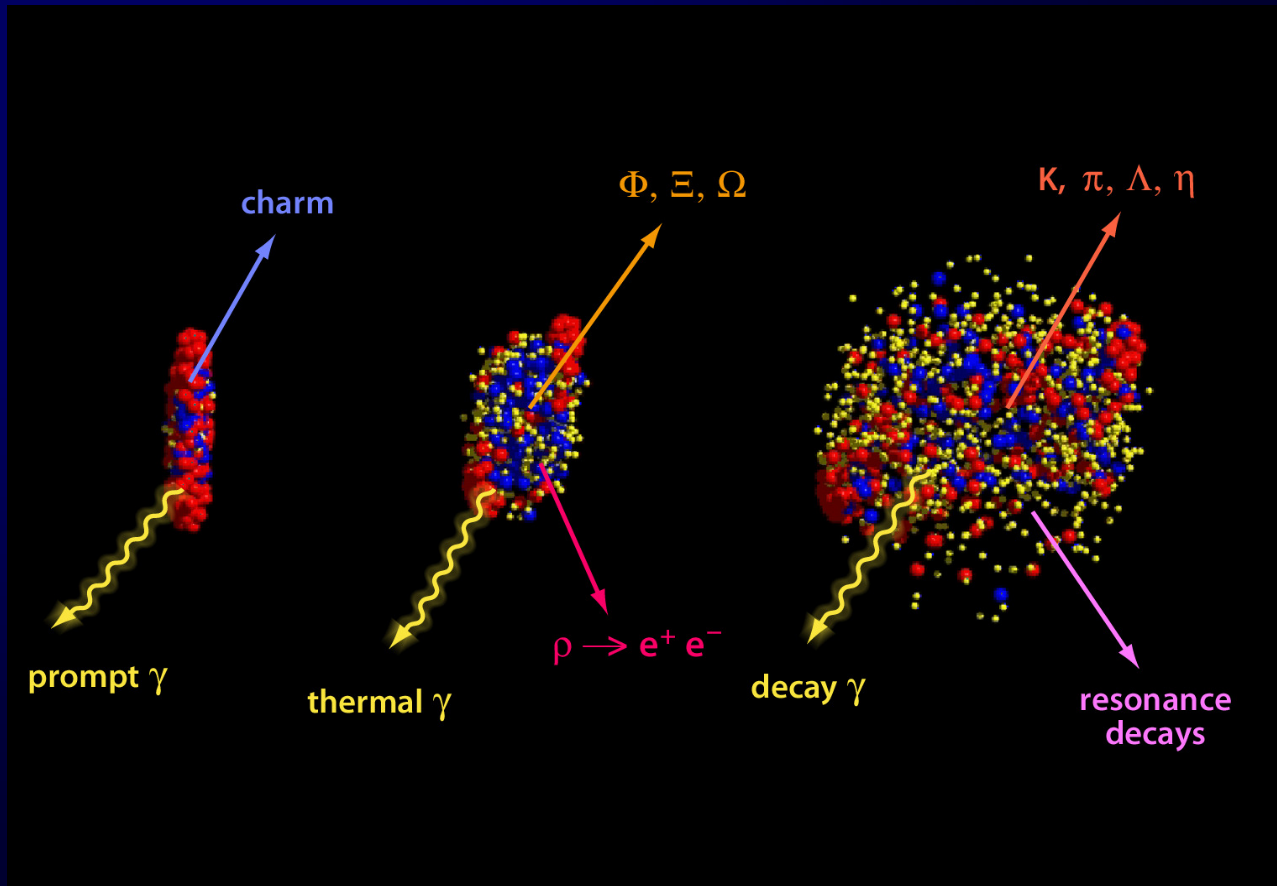
Signals of the phase transition:

- 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

Semi-classical BUU equation

Ludwig Boltzmann

Boltzmann -Uehling-Uhlenbeck equation (non-relativistic formulation)
- 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: eleastic 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:**

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

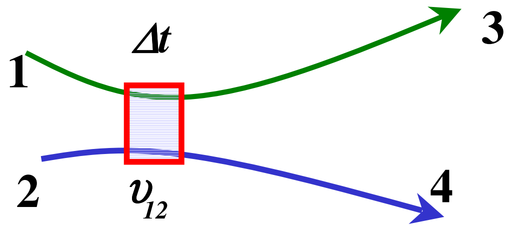
- **Collision term for 1+2→3+4 (let's consider fermions) :**

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

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**



Dynamical description of strongly interacting systems

- **Semi-classical BUU** ➔ solution for weakly interacting systems of particles

How to describe strongly interacting systems?!

- **Quantum field theory** ➔

Kadanoff-Baym dynamics for resummed(!) single-particle Green functions $S^<$

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

(1962)

Integration over the intermediate spacetime

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

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

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

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

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

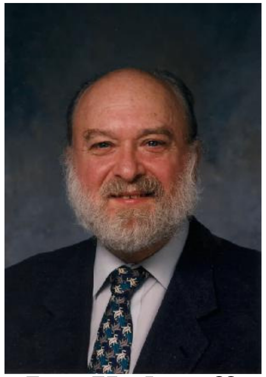
$$S_{xy}^{ret} = S_{xy}^{c} - S_{xy}^{<} = S_{xy}^{>} - S_{xy}^{a} \quad - retarded$$

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

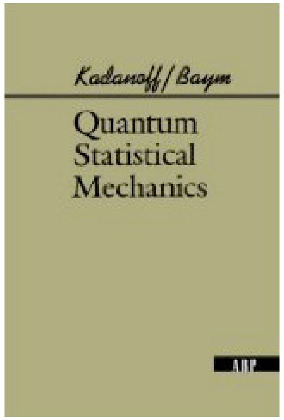
$$\hat{S}_{0x}^{-1} \equiv -(\partial_x^{\mu} \partial_{\mu}^{x} + M_0^2)$$

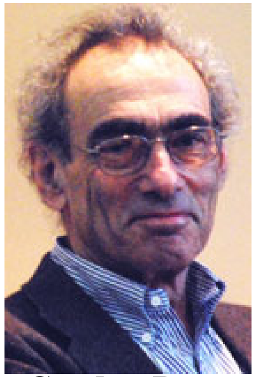
$$\eta = \pm 1 (bosons \,/\, fermions)$$

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



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 = ‚loss' term - ‚gain' term

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

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

$\Gamma_{XP} = -Im\,\Sigma^{ret}_{XP}$ – width of spectral function

= reaction rate of particle (at phase-space position XP)

4-dimentional generalizaton of the Poisson-bracket:

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

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

The baseline concepts of HSD

HSD – Hadron-String-Dynamics transport approach:

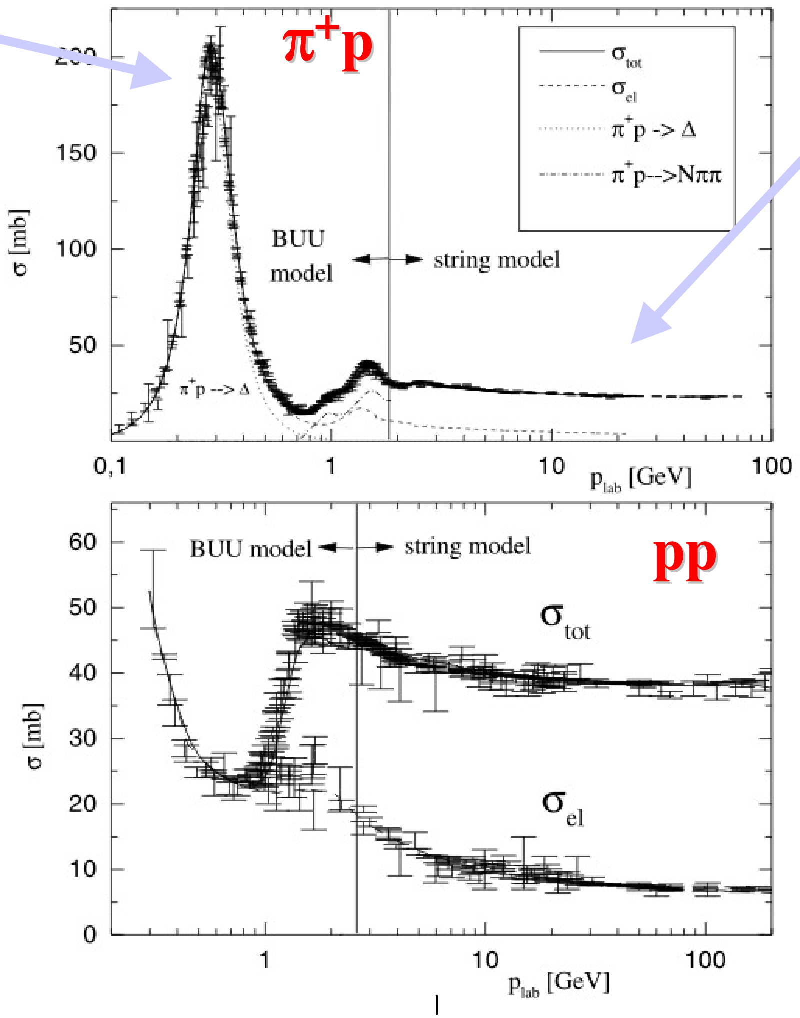
➔ solution of the generalized off-shell transport equations for the phase-space density $f_i(r,p,t)$ with collision terms I_{coll} describing:

Low energy collisions:

- binary 2<–>2 and 2<–>3 reactions
- 1<–>2 : formation and decay of baryonic and mesonic resonances

BB <–> B´B´
BB <–> B´B´m
mB <–> m´B´
mB <–> B´
mm <–> m´m´
mm <–> m´ . . .

Baryons:
B = p, n, Δ(1232), N(1440), N(1535), ...
Mesons:
M = π, η, ρ, ω, φ, ...



High energy collisions:
(above $s^{1/2}$~2.5 GeV)

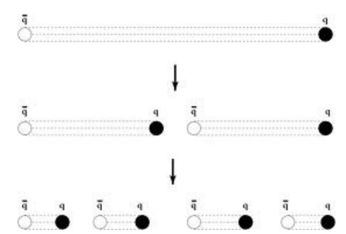
Inclusive particle production:

BB –> X , mB –>X

X =many particles

described by

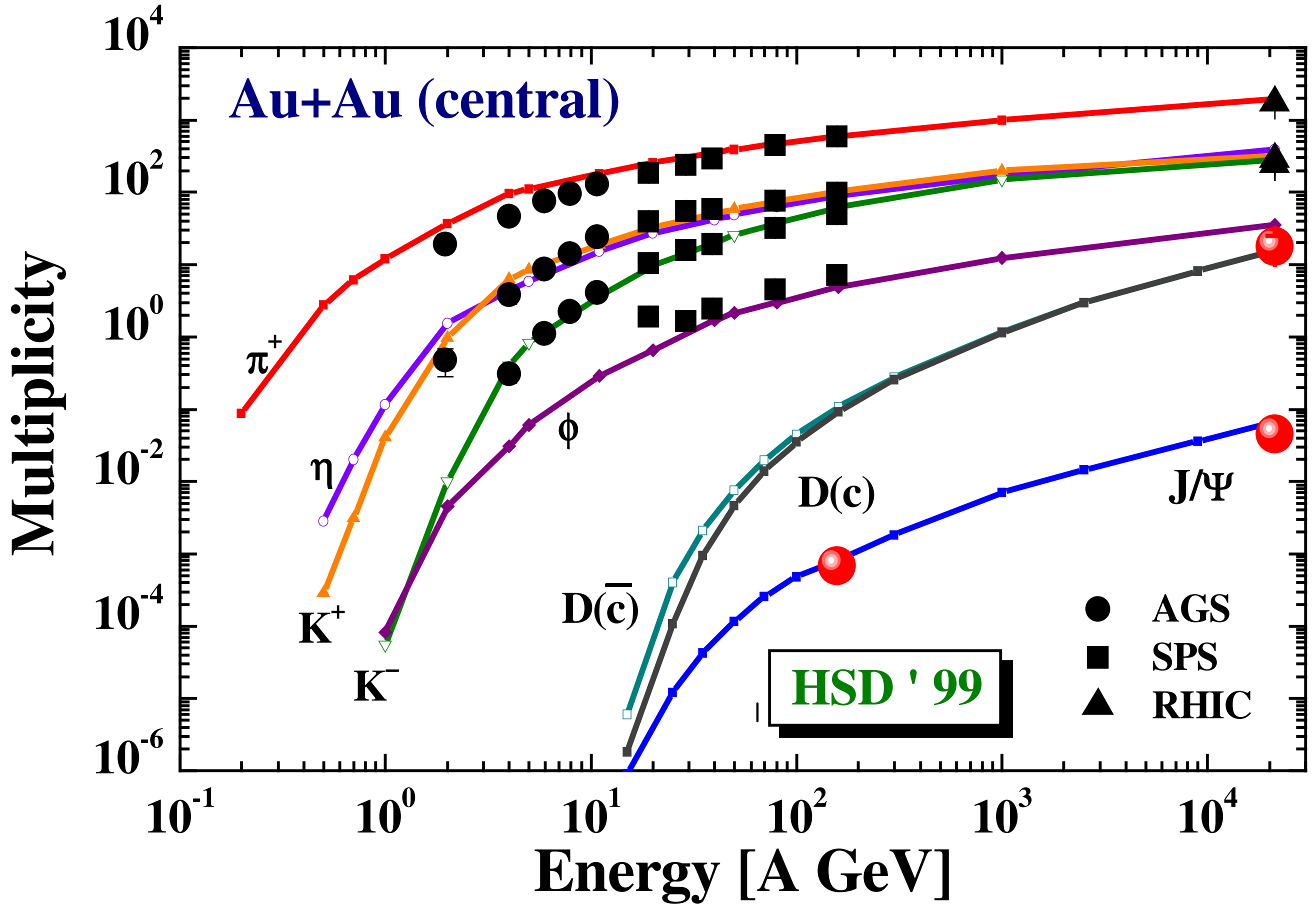
strings (= excited color singlet states *q-qq*, *q-qbar*) formation and decay



HSD is an open code: *http://www.th.physik.uni-frankfurt.de/~brat/hsd.html*

HSD – a microscopic off-shell transport model for heavy-ion reactions

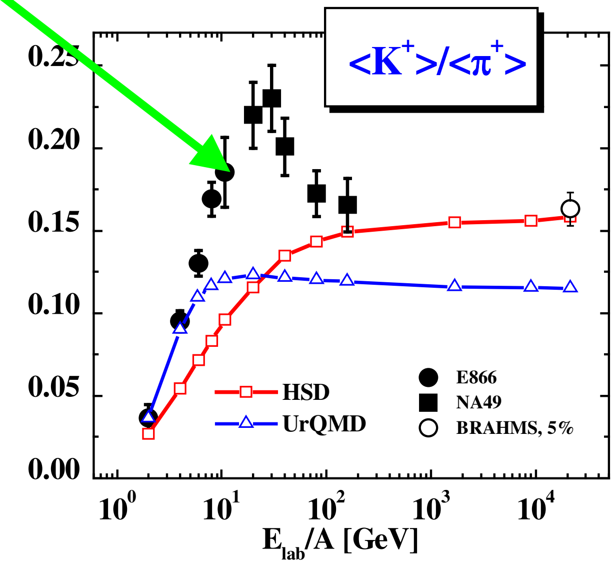
- very good description of particle production in pp, pA, πA, AA reactions
- unique description of nuclear dynamics from low (~100 MeV) to ultrarelativistic (>20 TeV) energies



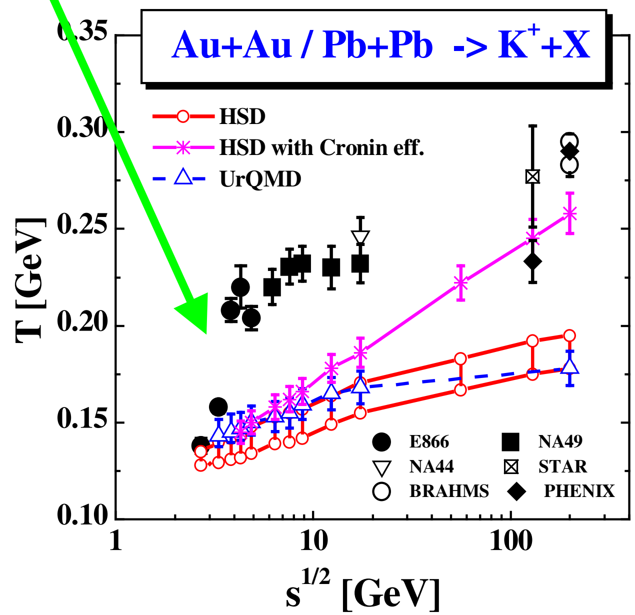
HSD predictions from 1999; data from the new millenium

Hadron-string transport models (HSD, UrQMD) versus observables

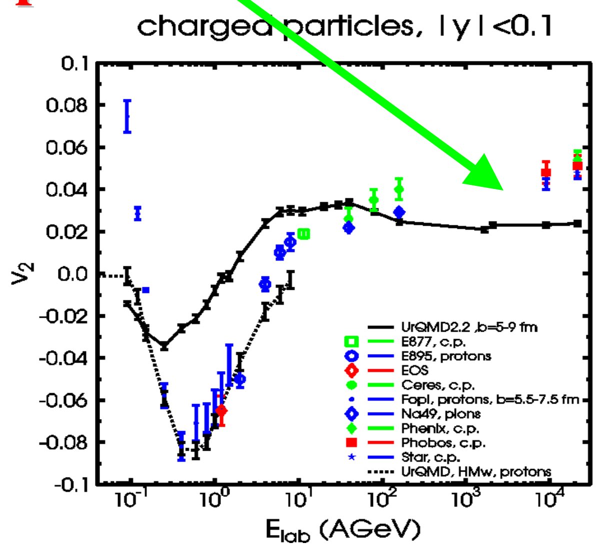
‚horn' in K^+/π^+



‚step' in slope T



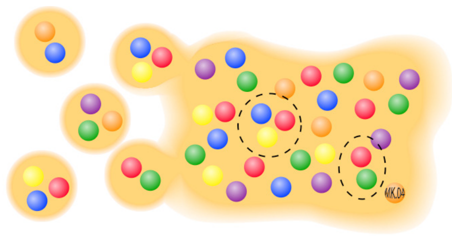
elliptic flow



Exp. data are not reproduced in terms of the hadron-string picture => evidence for partonic degrees of freedom

PRC 69 (2004) 032302

Goal: microscopic transport description of the partonic and hadronic phase



Problems:

- ❑ How to model a QGP phase in line with lQCD data?
- ❑ How to solve the hadronization problem?

Ways to go:

pQCD based models:

- QGP phase: pQCD cascade
- hadronization: quark coalescence

➔ AMPT, HIJING, BAMPS

‚Hybrid' models:

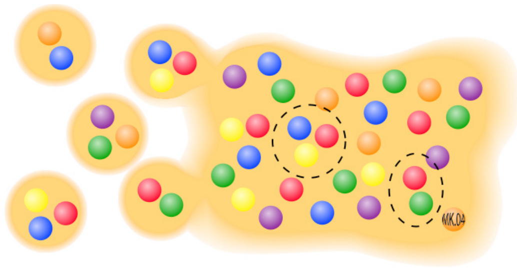
- QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model

➔ Hybrid-UrQMD

- microscopic transport description of the partonic and hadronic phase in terms of strongly interacting dynamical quasi-particles and off-shell hadrons

➔ PHSD

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-of 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 :

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

- **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:**

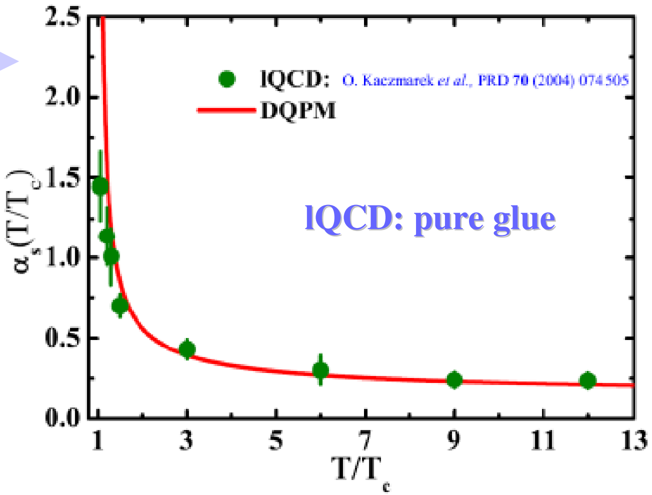
    $$M_g^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{N_f}{2}\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

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

$N_c = 3$, $N_f=3$

- **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)**

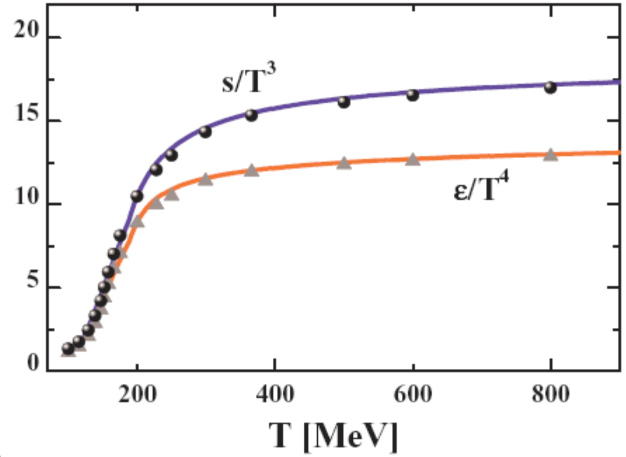
  with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42
  (for pure glue N_f=0)

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

The Dynamical QuasiParticle Model (DQPM)

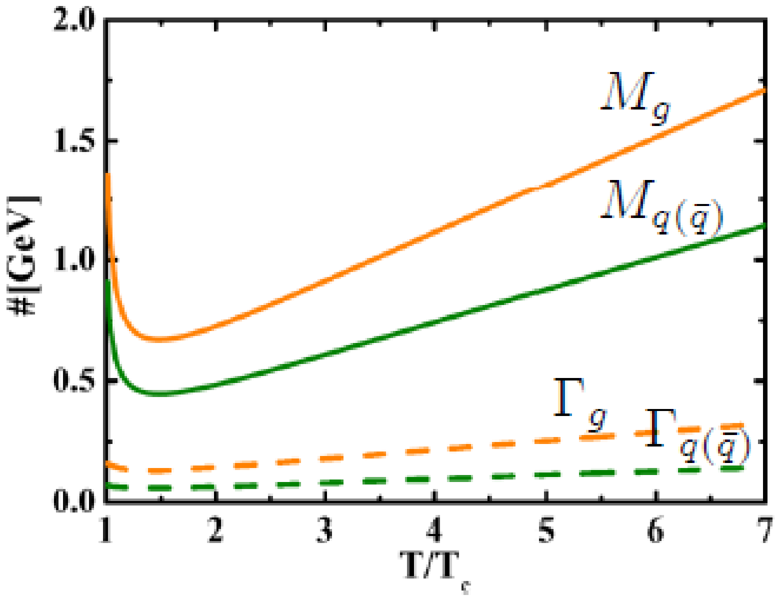
➢ fit to lattice (lQCD) results (e.g. entropy density)

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



➔ Quasiparticle properties:

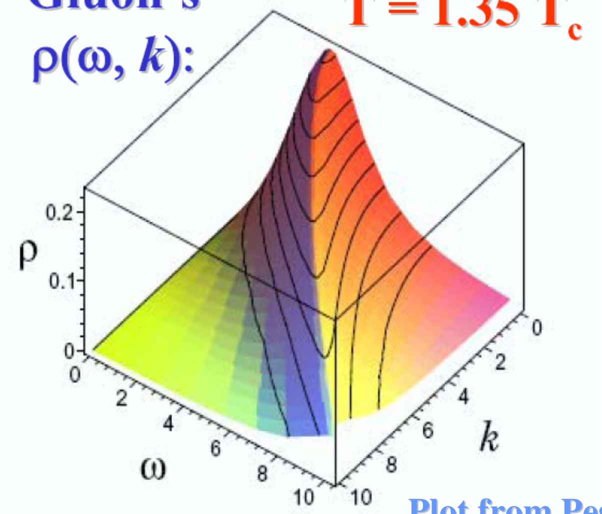
- large width and mass for gluons and quarks



T_C=158 MeV
ε_C=0.5 GeV/fm^3

Gluon's $\rho(\omega, k)$:

T = 1.35 T_c

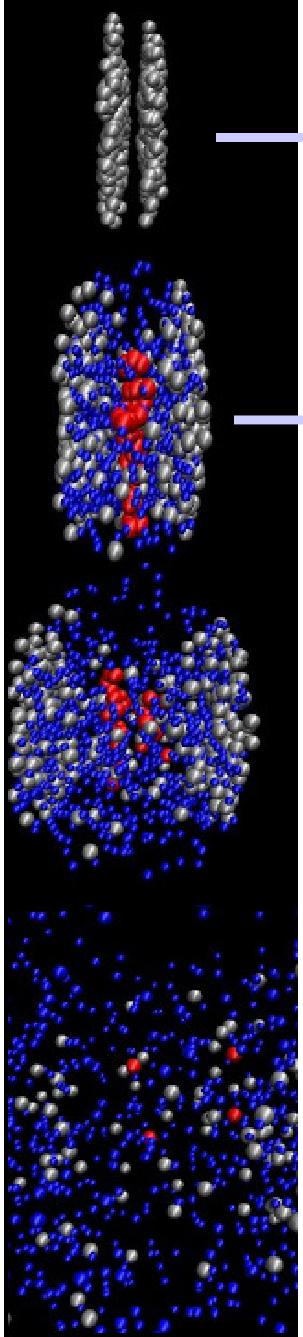


Plot from Peshier, PRD 70 (2004) 034016

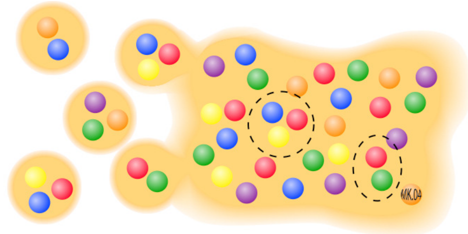
- DQPM matches well lattice QCD
- DQPM provides mean-fields (1PI) for gluons and quarks as well as effective 2-body interactions (2PI)
- DQPM gives transition rates for the formation of hadrons → PHSD

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**

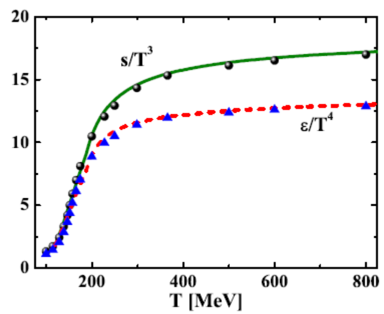
QGP phase: $\varepsilon > \varepsilon_{critical}$

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

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

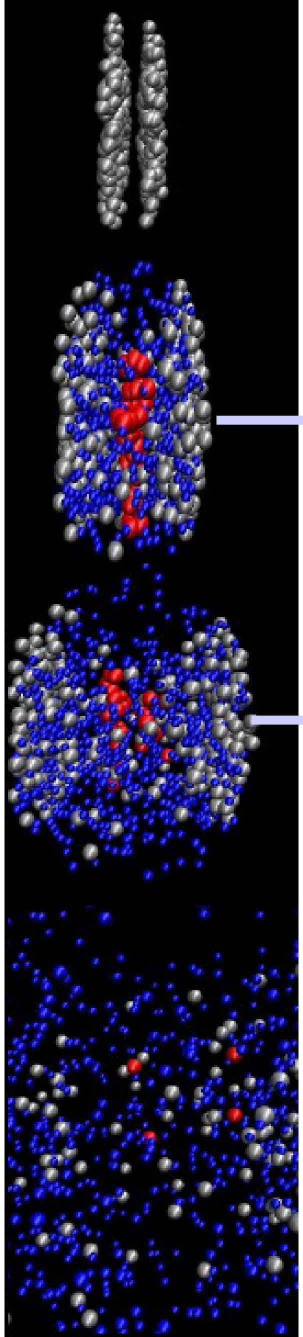
+ mean-field potential U_q at given ε – local energy density

(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:

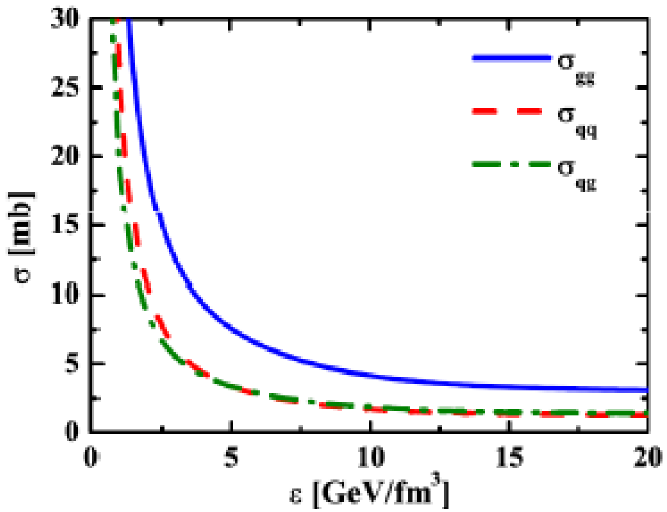
quarks and gluons (= ‚dynamical quasiparticles')
with off-shell spectral functions (width, mass) defined by the DQPM

- **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:**

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



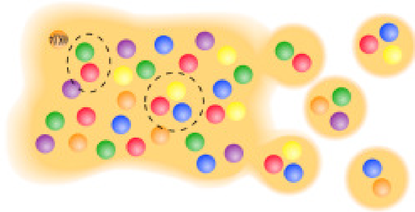
- **inelastic collisions:**

(Breit-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**

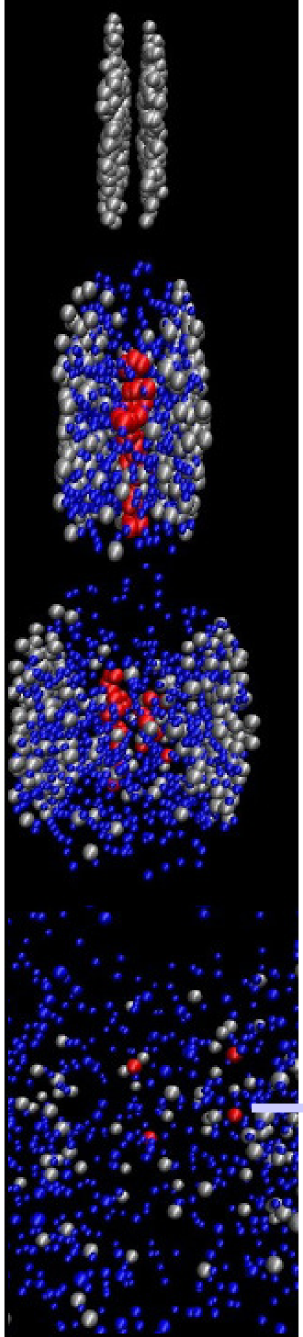
III. PHSD - basic concept



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)

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



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

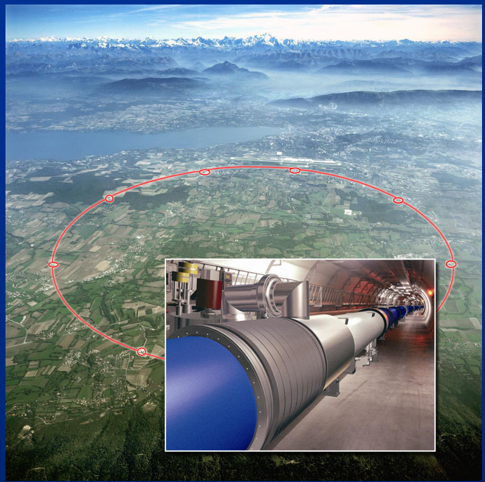
➔ **meson formation:**

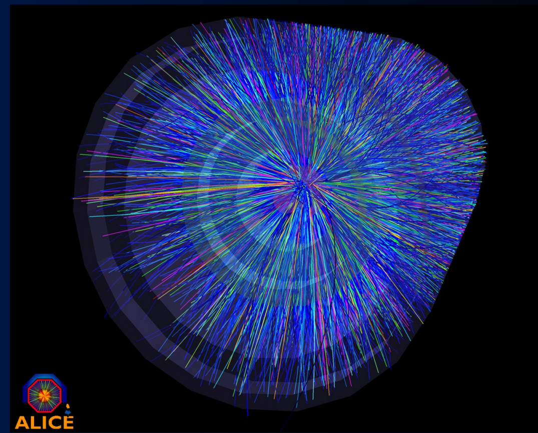
$$\frac{dN^{q+\bar{q}\to m}}{d^4x\, d^4p} = Tr_q Tr_{\bar{q}}\, \delta^4(p-p_q-p_{\bar{q}})\, \delta^4\left(\frac{x_q+x_{\bar{q}}}{2}-x\right) \delta(flavor, color)$$
$$\cdot N_q(x_q,p_q) N_{\bar{q}}(x_{\bar{q}},p_{\bar{q}}) \cdot \omega_q \rho_q(p_q) \cdot \omega_{\bar{q}} \rho_{\bar{q}}(p_{\bar{q}}) \cdot |M_{q\bar{q}}|^2\, W_m\left(x_q-x_{\bar{q}}, p_q-p_{\bar{q}}\right)$$

- $N_j(x,p)$ 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

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

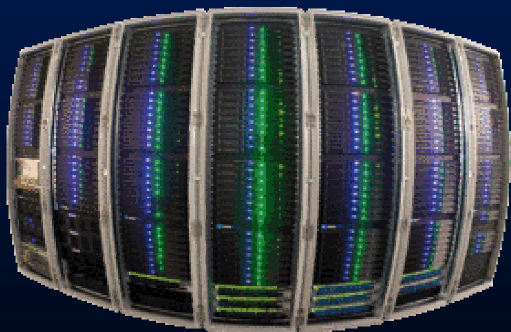
PHSD – ‚femto‘ accelerator

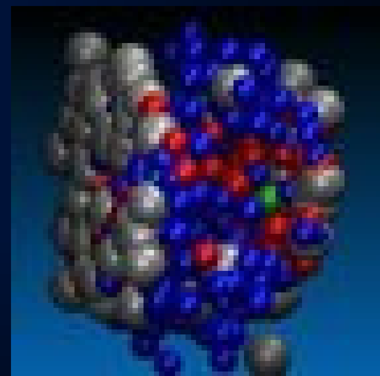




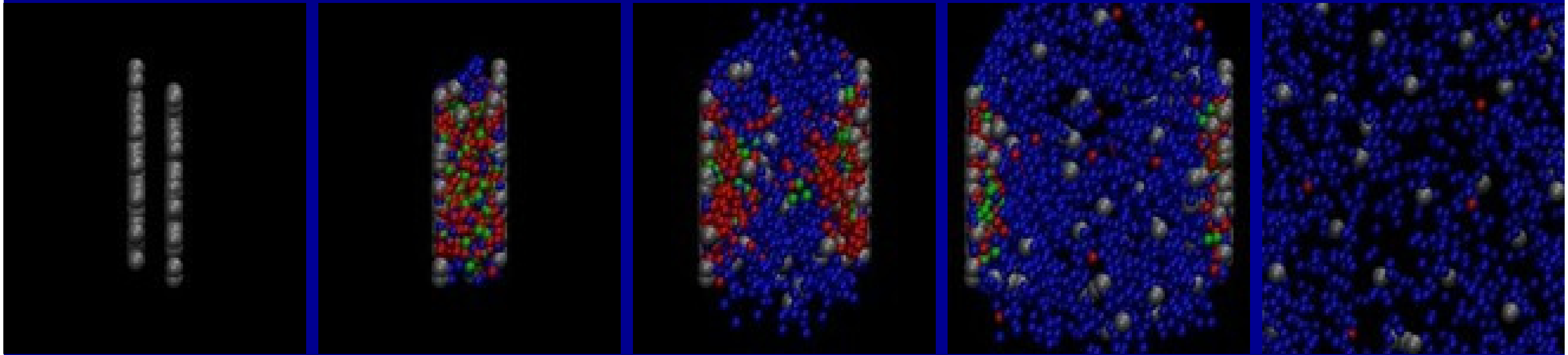
PHSD

Center for Scientific Computing Frankfurt

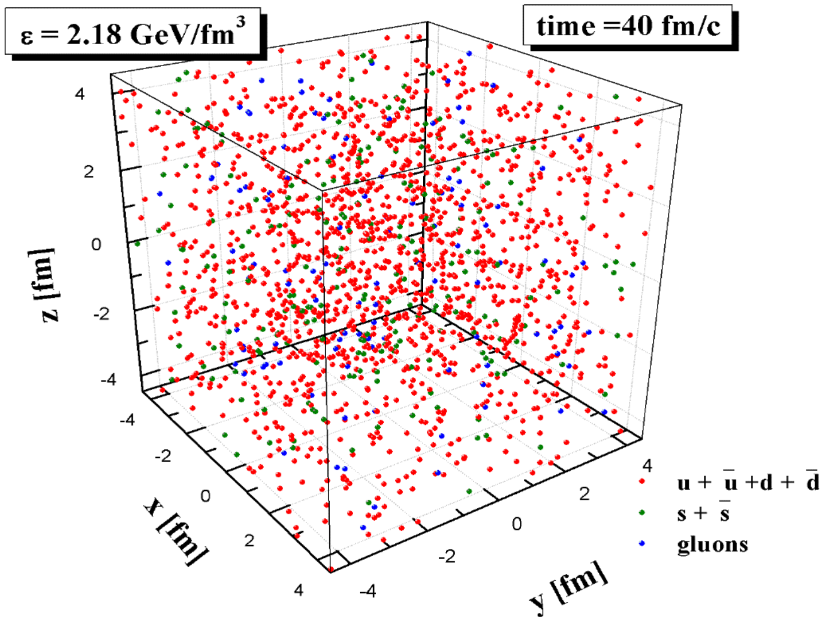




Au+Au, 21.3 TeV, central



Properties of QGP in-equilibrium using PHSD



Properties of parton-hadron matter in-equlibrium

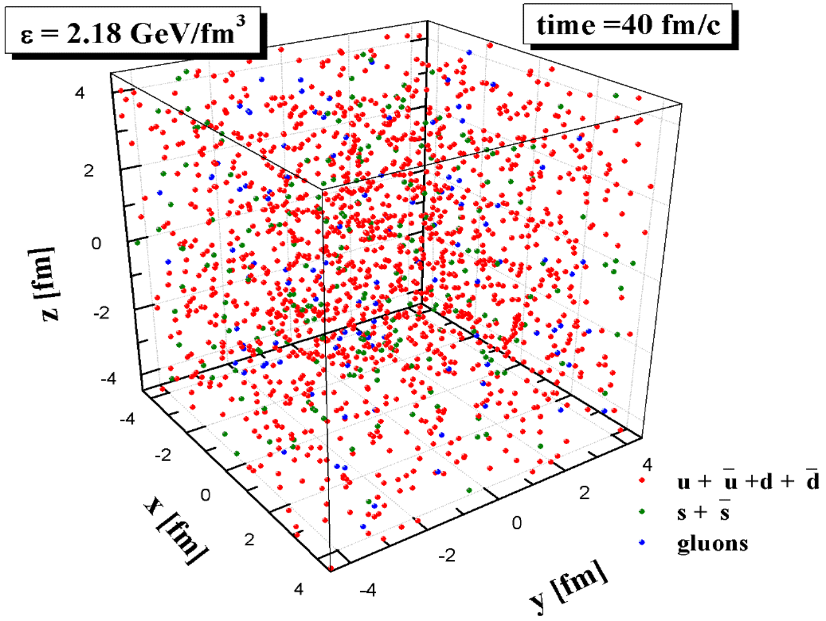
V. Ozvenchuk et al., PRC 87 (2013) 024901, arXiv:1203.4734
V. Ozvenchuk et al., PRC 87 (2013) 064903, arXiv:1212.5393

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
- ❑ particle number fluctuations (scaled variance, skewness, kurtosis)

Realization:

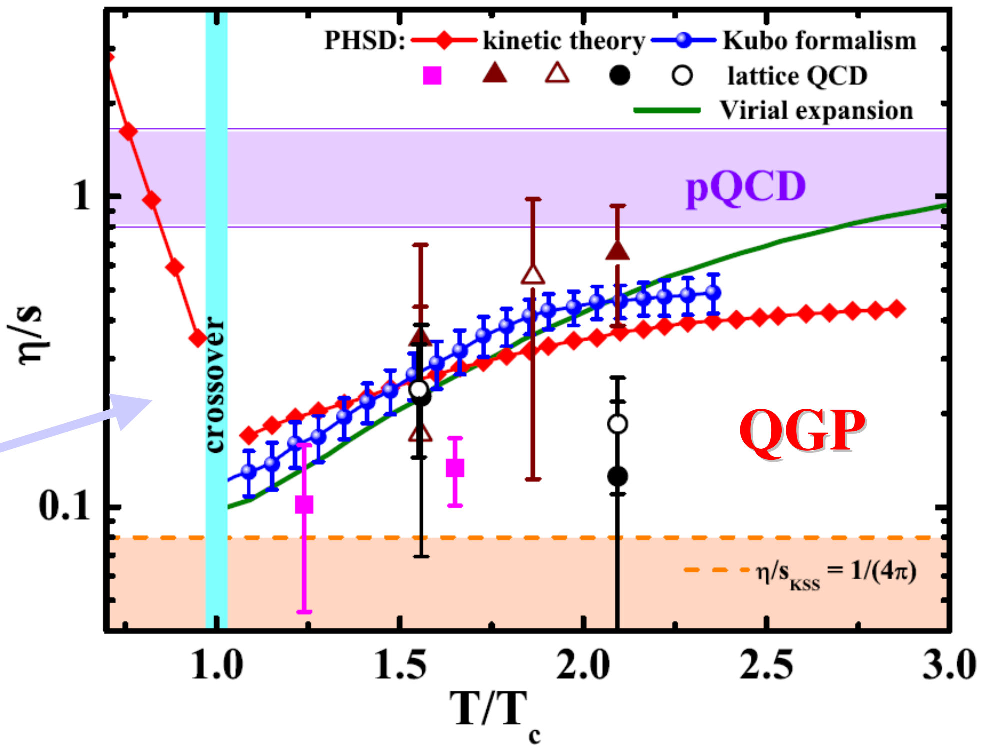
- ❑ Initialize the system in a finite box with periodic boundary conditions with some energy density ε and chemical potential μ_q
- ❑ Evolve the system in time until equilibrium is achieved



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
- ❑ $T<T_C$: 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).

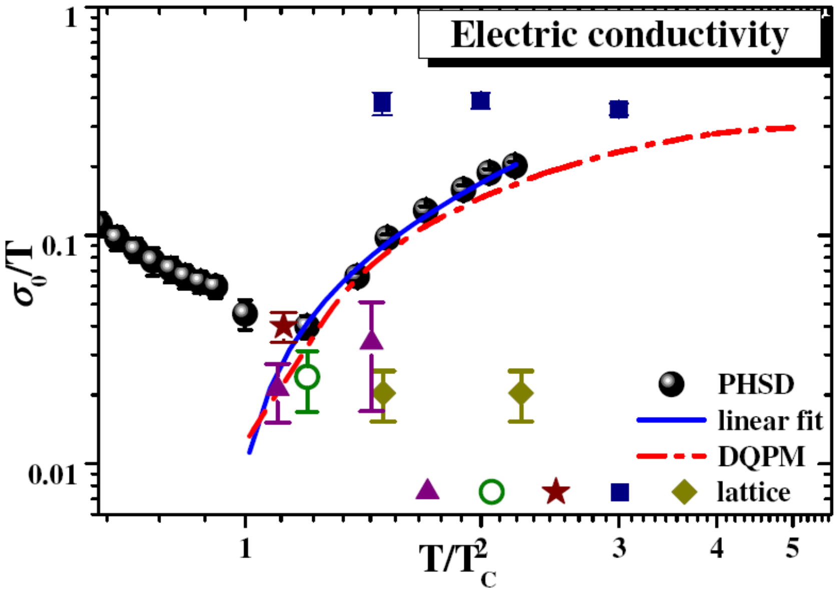
QGP in PHSD = strongly-interacting liquid

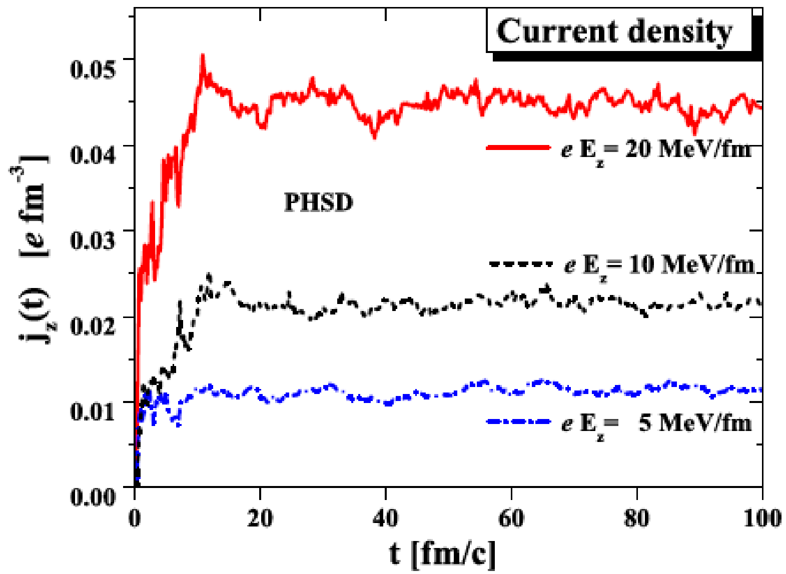
V. Ozvenchuk et al., PRC 87 (2013) 064903

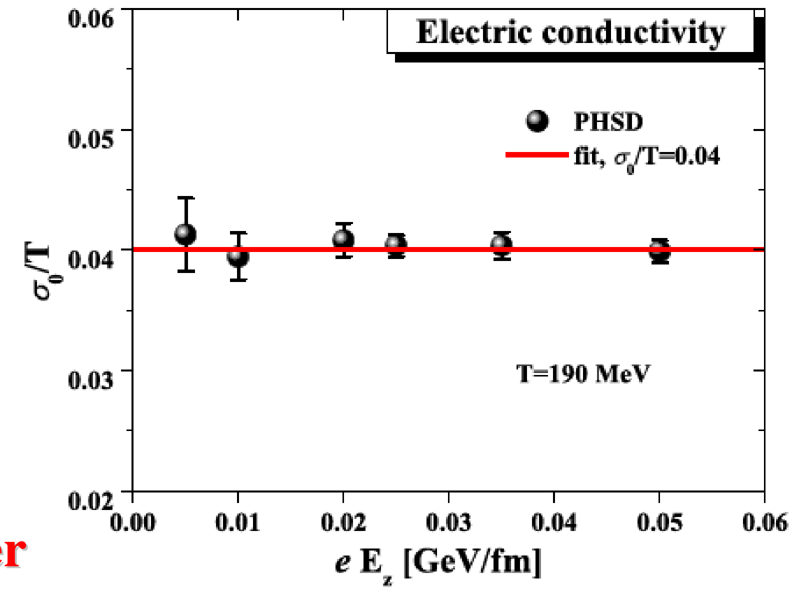
Properties of parton-hadron matter – electric conductivity

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

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



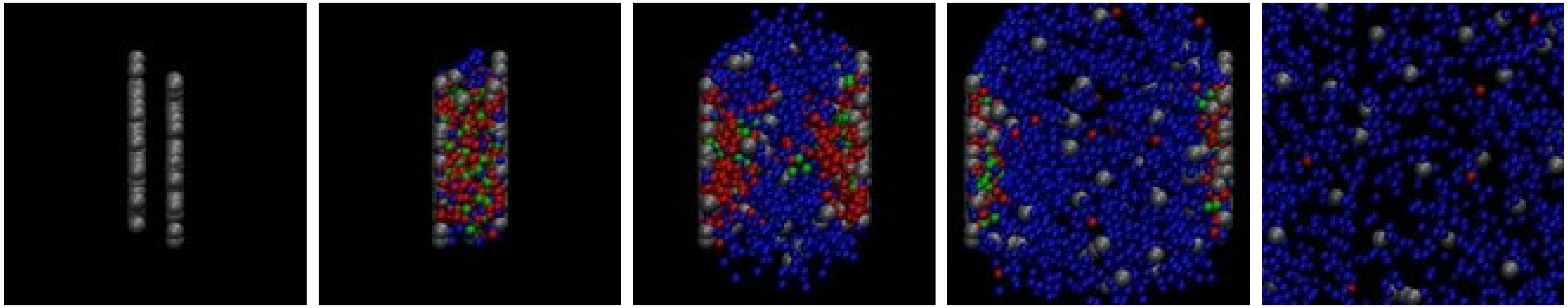




- the QCD matter even at T~ T_c is a much better electric conductor than Cu or Ag (at room temperature) by a factor of 500 !

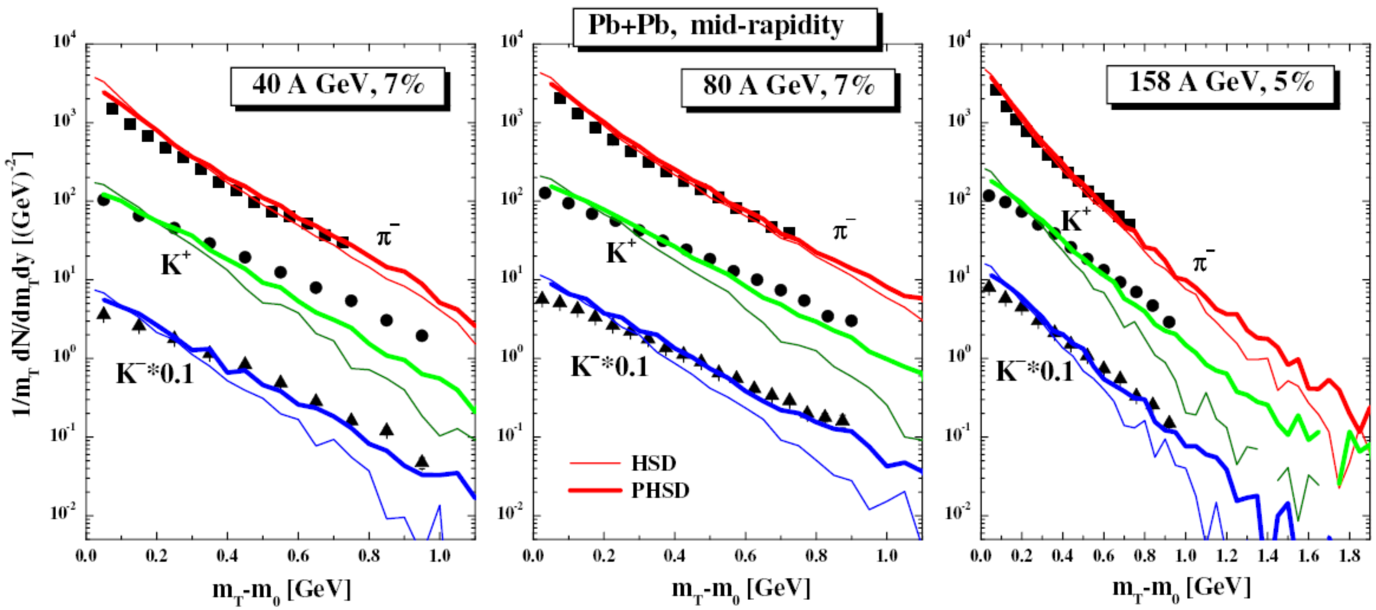
W. Cassing et al., PRL 110(2013)182301

Bulk properties: rapidity, m_T-distributions, multi-strange particle enhancement in Au+Au

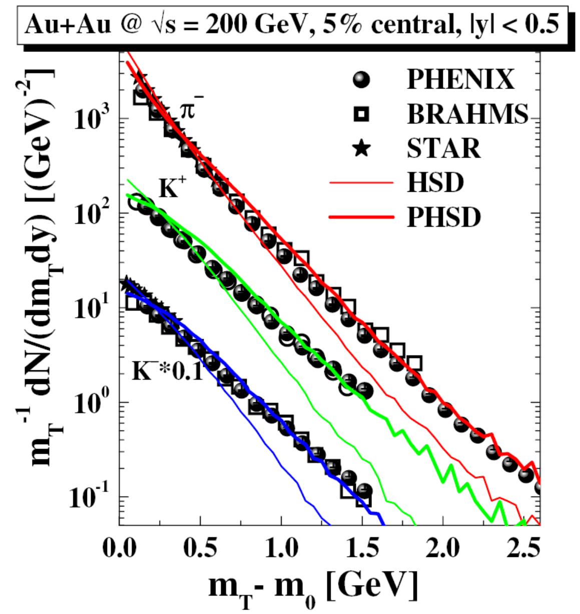


PHSD: Transverse mass spectra

Central Pb + Pb at SPS energies



Central Au+Au at RHIC

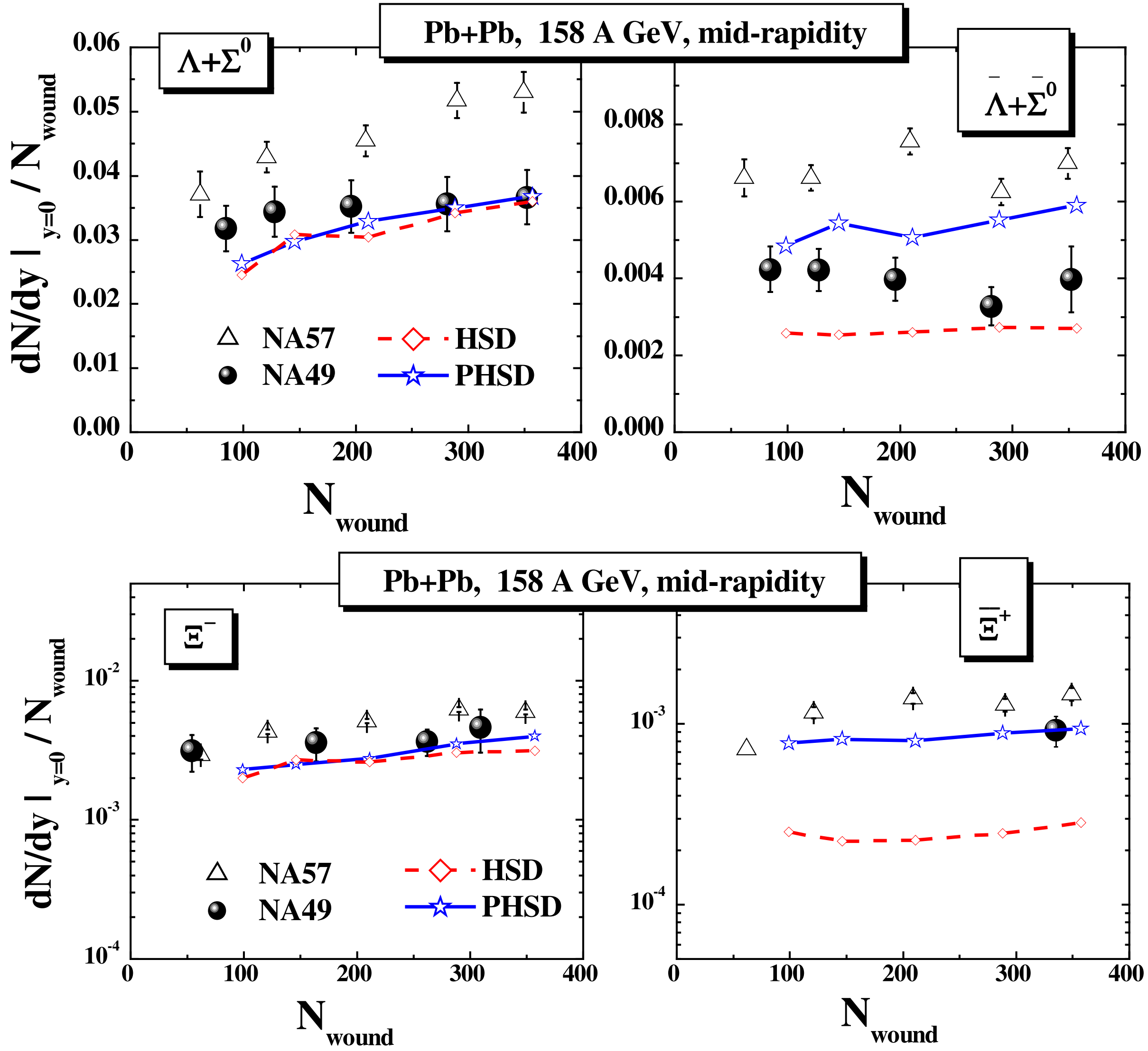


- PHSD gives harder m_T spectra and works better than HSD at high energies – RHIC, SPS (and top FAIR, NICA)
- however, at low SPS (and low FAIR, NICA) energies the effect of the partonic phase decreases due to the decrease of the partonic fraction

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

Centrality dependence of (multi-)strange (anti-)baryons

strange baryons $\Lambda+\Sigma^0$



strange antibaryons $\bar{\Lambda}+\bar{\Sigma}^0$

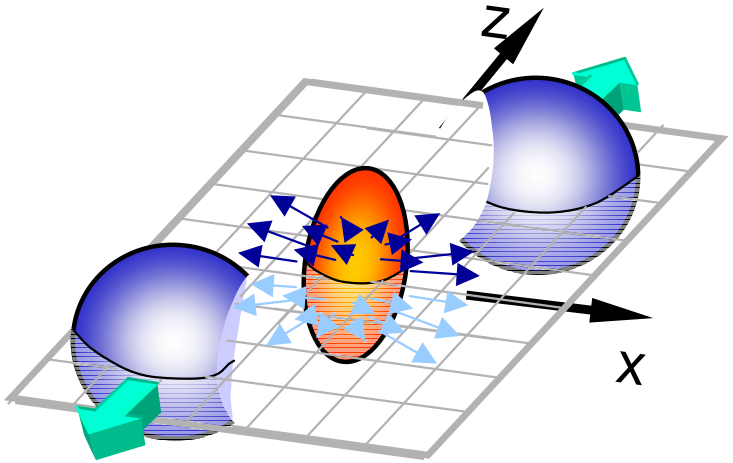
multi-strange baryon Ξ^-

multi-strange antibaryon $\bar{\Xi}^+$

➔ enhanced production of (multi-) strange antibaryons in PHSD relative to HSD

Cassing & Bratkovskaya, NPA 831 (2009) 215

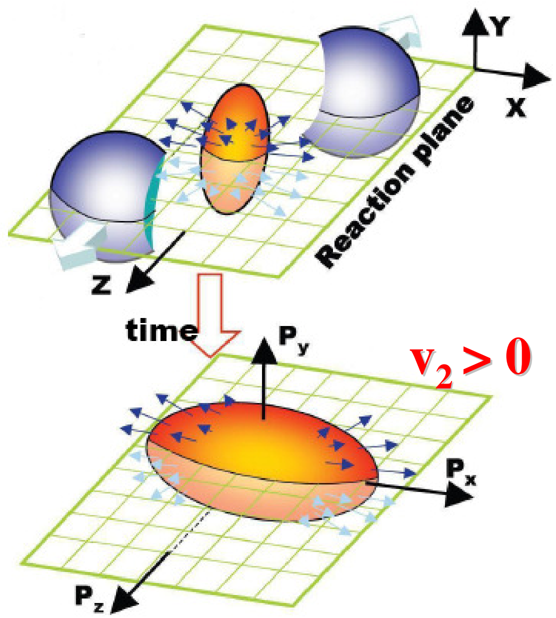
Collective flow:
anisotropy coefficients (v_1, v_2, v_3, v_4)
in A+A



Anisotropy coefficients

Non central Au+Au collisions :

- interaction between constituents leads to a **pressure gradient** => spatial asymmetry is converted to an asymmetry in momentum space => **collective flow**



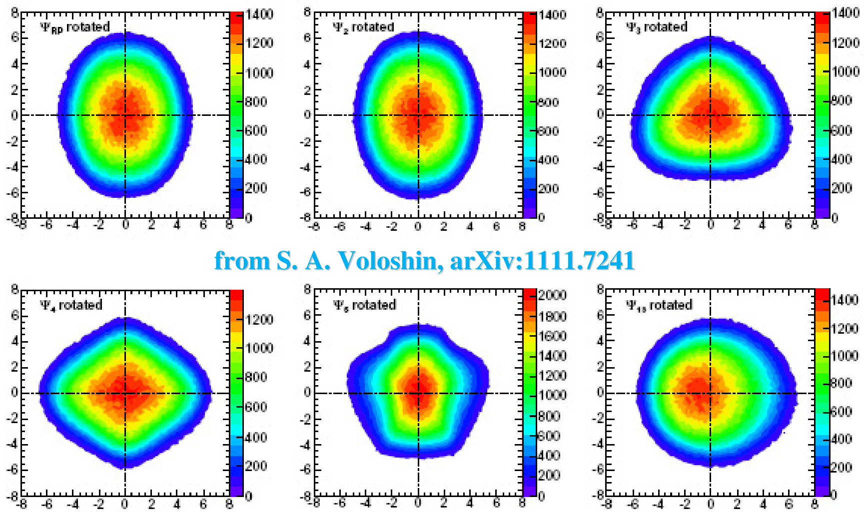
$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{+\infty} v_n \cos[n(\varphi - \psi_n)]\right)$$

$$v_n = \langle \cos n(\varphi - \psi_n) \rangle, \quad n = 1,2,3..,$$

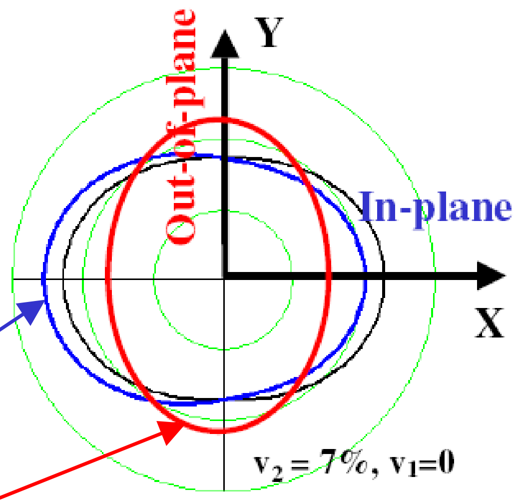
v_1: directed flow

v_2: elliptic flow

v_3: triangular flow…..



from S. A. Voloshin, arXiv:1111.7241

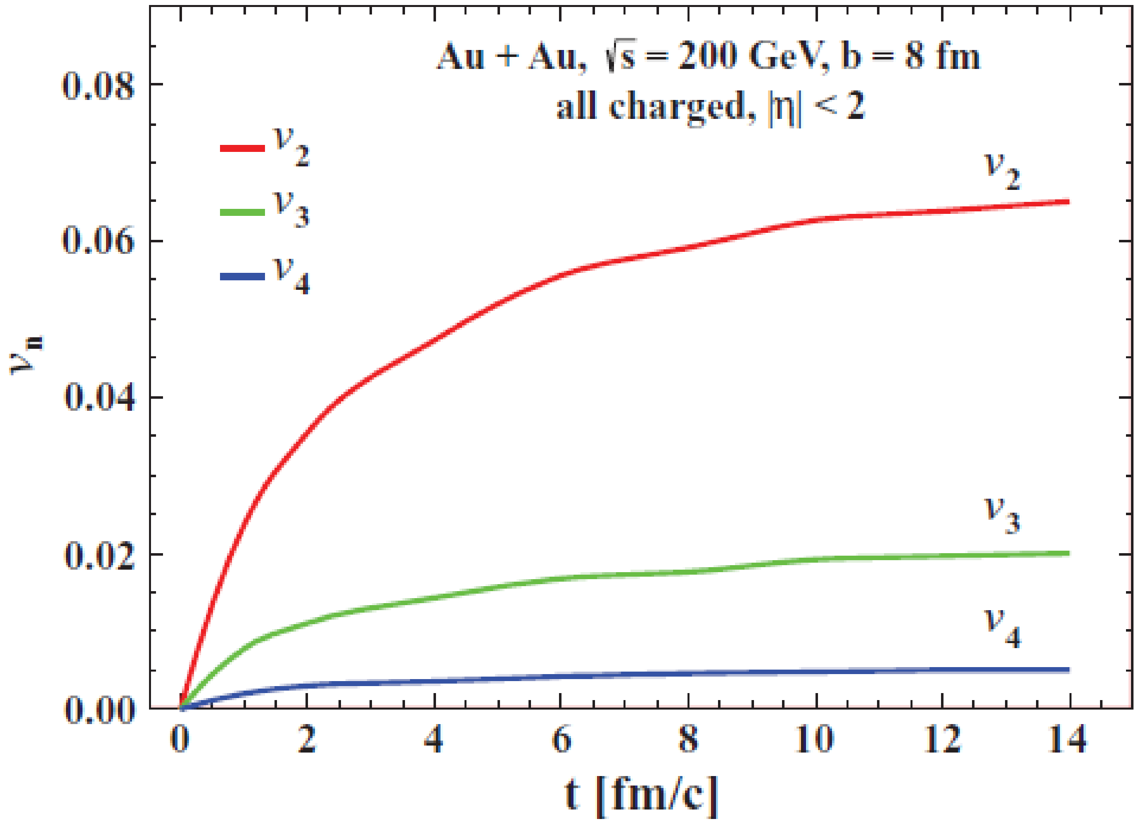


$v_2 > 0$ indicates **in-plane** emission of particles

$v_2 < 0$ corresponds to a **squeeze-out** perpendicular to the reaction plane (**out-of-plane** emission)

Development of azimuthal anisotropies in time

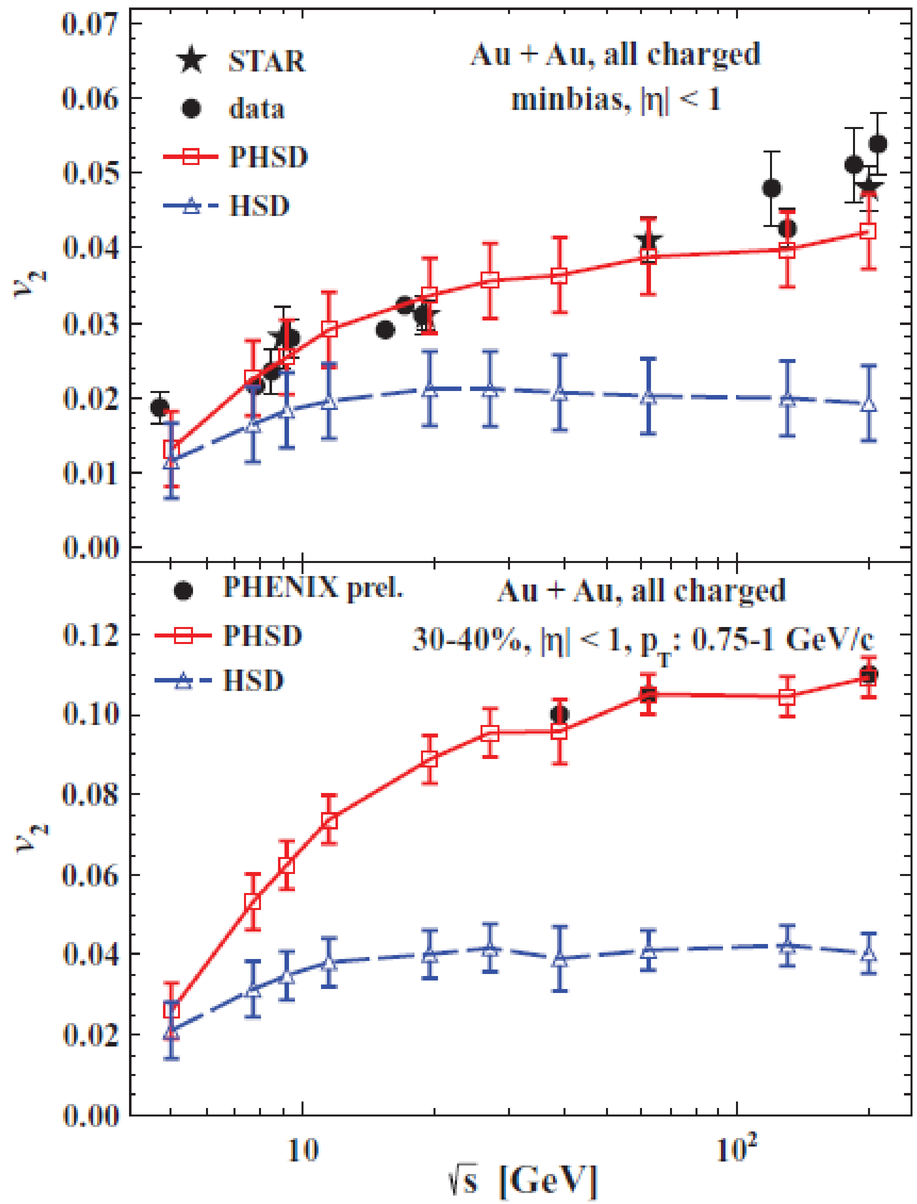
Time evolution of v_n for Au + Au collisions at $s^{1/2}$ = 200 GeV with impact parameter b = 8 fm.

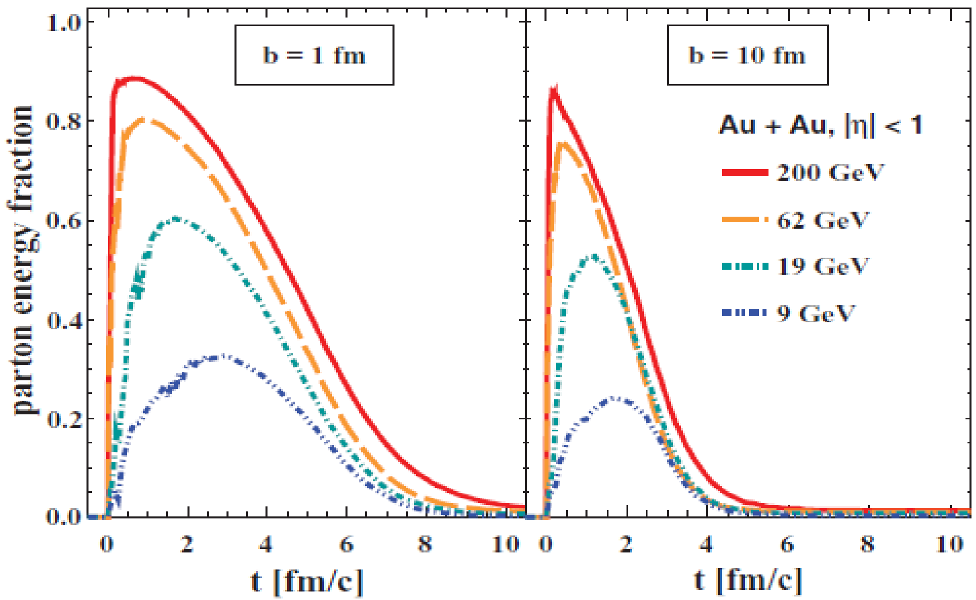


- Flow coefficients reach their asymptotic values by the time of 6–8 fm/c after the beginning of the collision

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 011902

Elliptic flow v_2 vs. collision energy for Au+Au

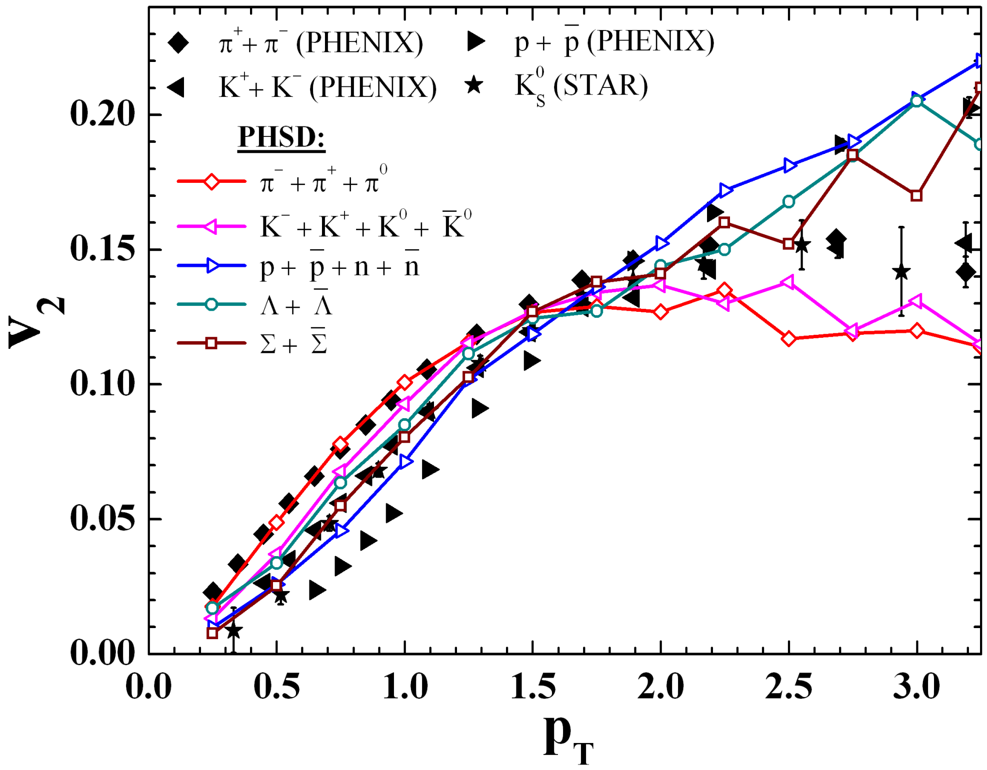


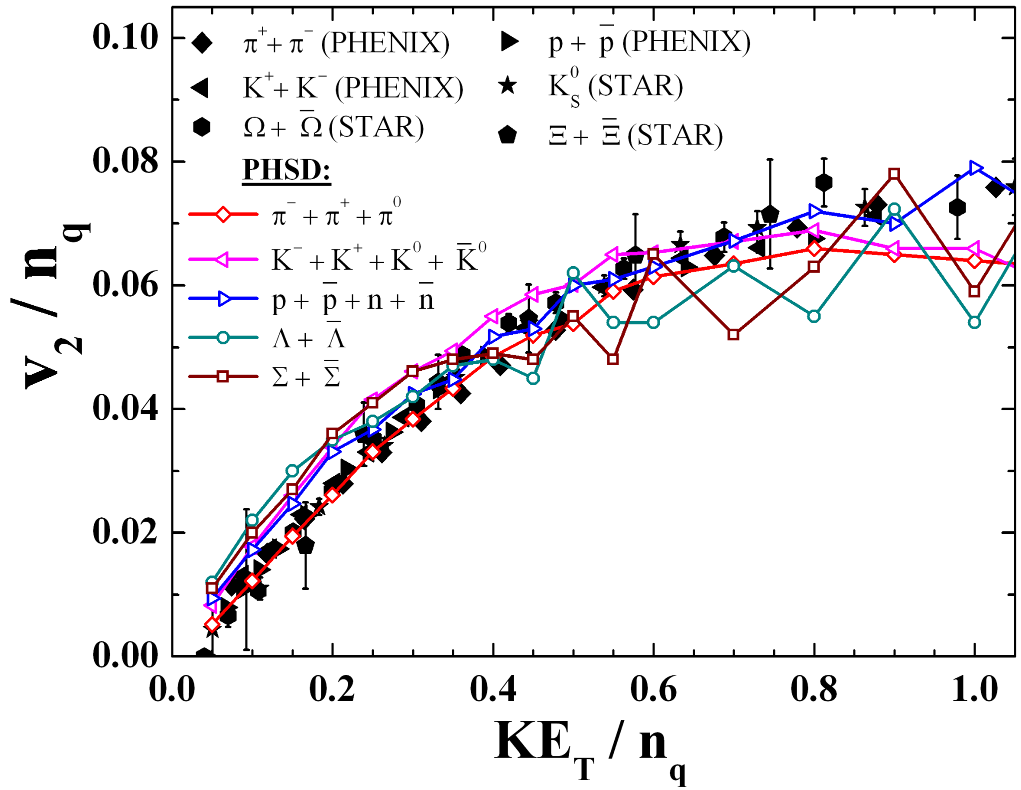


- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys. Rev. C 85 (2012) 011902

Scaling properties: quark number scaling

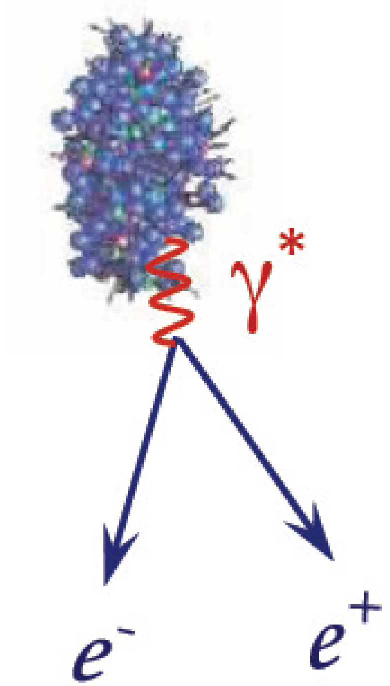


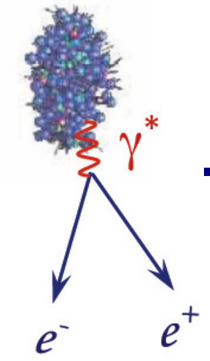


- **The mass splitting at low p_T is approximately reproduced as well as the meson-baryon splitting for $p_T > 2$ GeV/c !**
- **The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data at RHIC.**

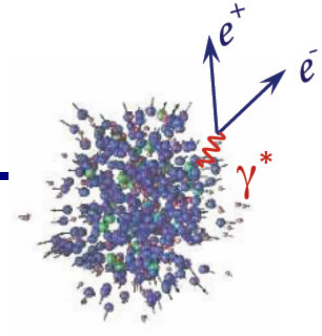
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

Dileptons





Electromagnetic probes: dileptons and photons



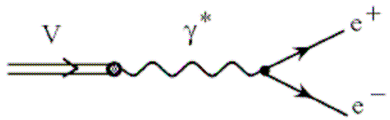
➢ **Dileptons are emitted from different stages of the reaction and not much effected by final-state interactions**

Dilepton sources:

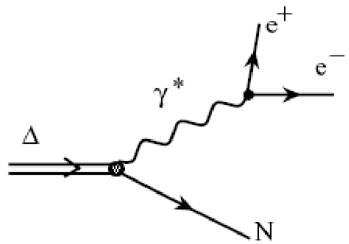
- **from the QGP via partonic (q,qbar, g) interactions:**

- **from hadronic sources:**

• **direct decay of vector mesons (ρ,ω,ϕ,J/Ψ,Ψ‘)**

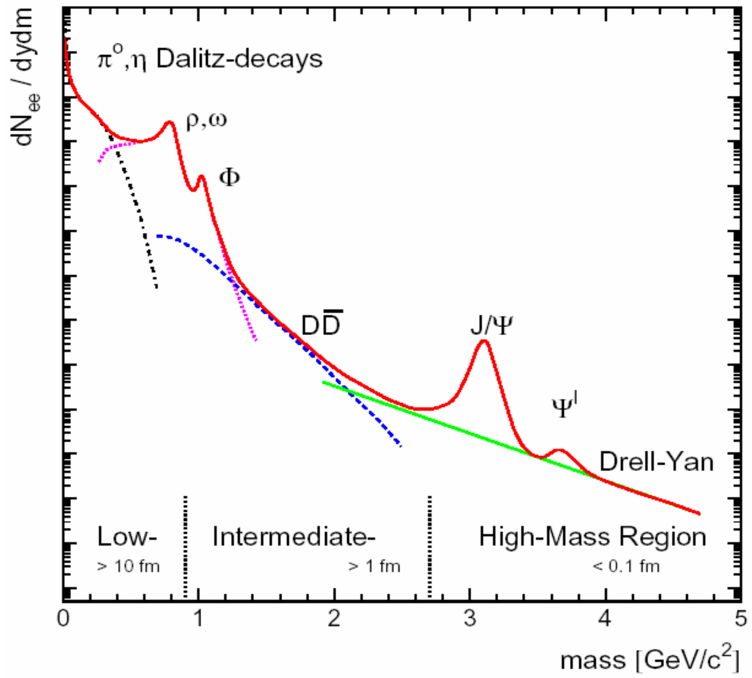


• **Dalitz decay of mesons and baryons (π^0,η, Δ,…)**



• **correlated D+Dbar pairs**

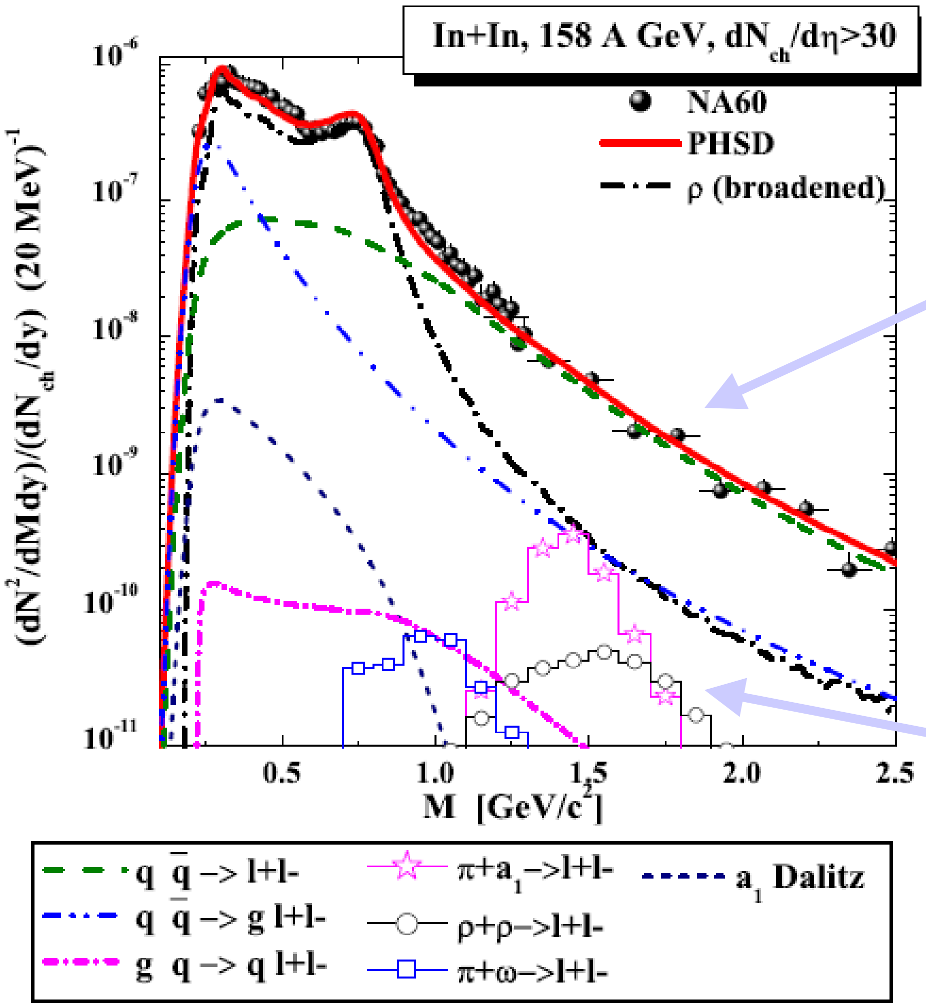
• **radiation from multi-meson reactions (π+π, π+ρ, π+ω, ρ+ρ , π+a_1) - ‚4π‘**



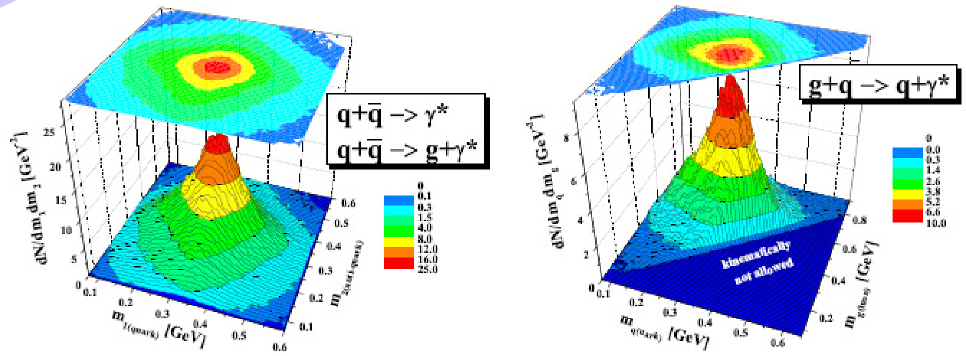
➔ **Dileptons are an ideal probe to study the properties of the hot and dense medium**

Dileptons at SPS: NA60

Acceptance corrected NA60 data



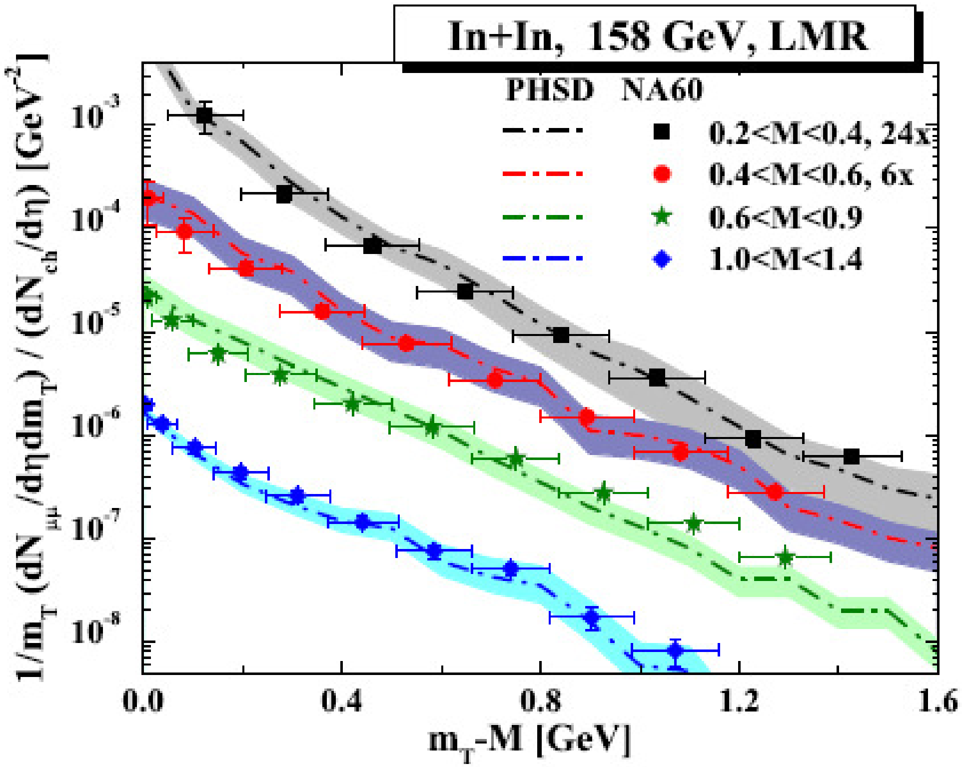
- Mass region above 1 GeV is dominated by partonic radiation !



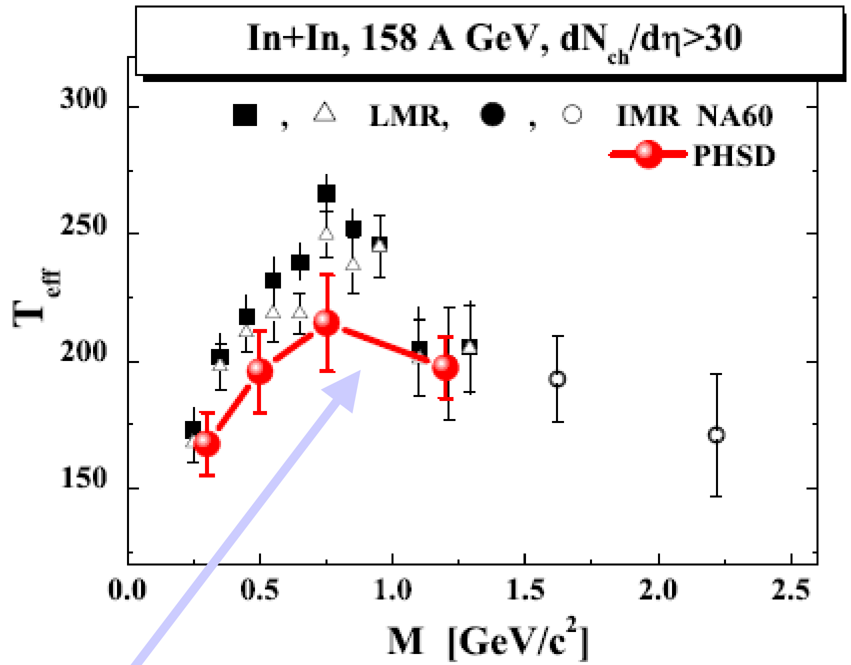
- Contributions of "4π" channels (radiation from multi-meson reactions) are small

O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

NA60: m_T spectra



- Inverse slope parameter T_{eff} for dilepton spectra vs NA60 data

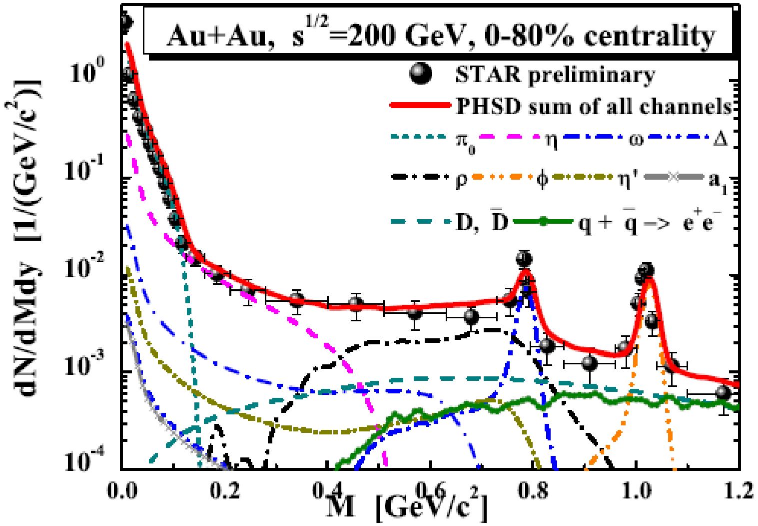


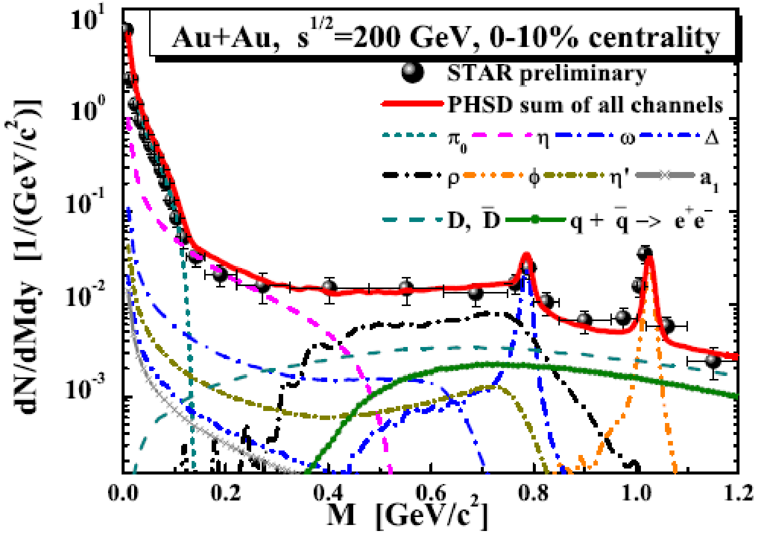
Conjecture:

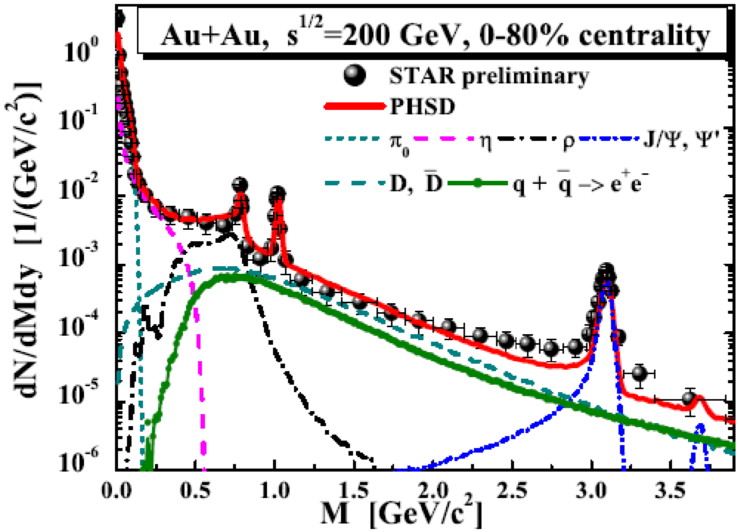
- spectrum from sQGP is softer than from hadronic phase since quark-antiquark annihilation occurs dominantly before the collective radial flow has developed (cf. NA60)

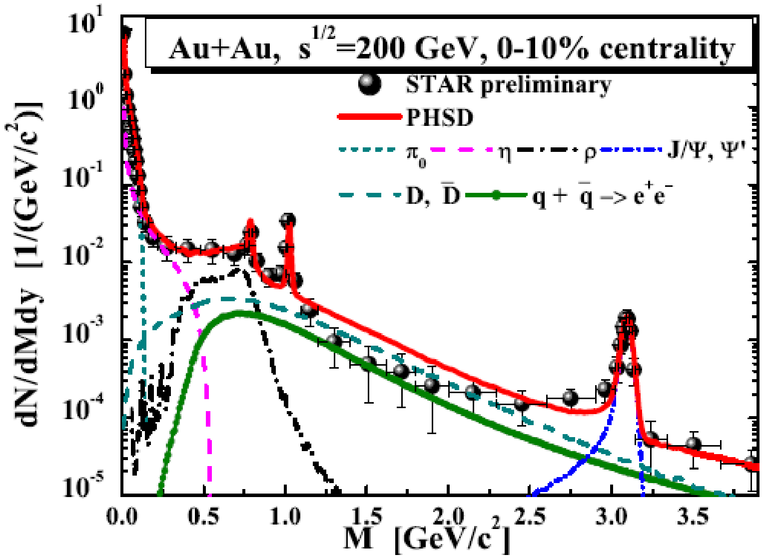
O. Linnyk, E.B., V. Ozvenchuk, W. Cassing and C.-M. Ko, PRC 84 (2011) 054917

STAR: mass spectra





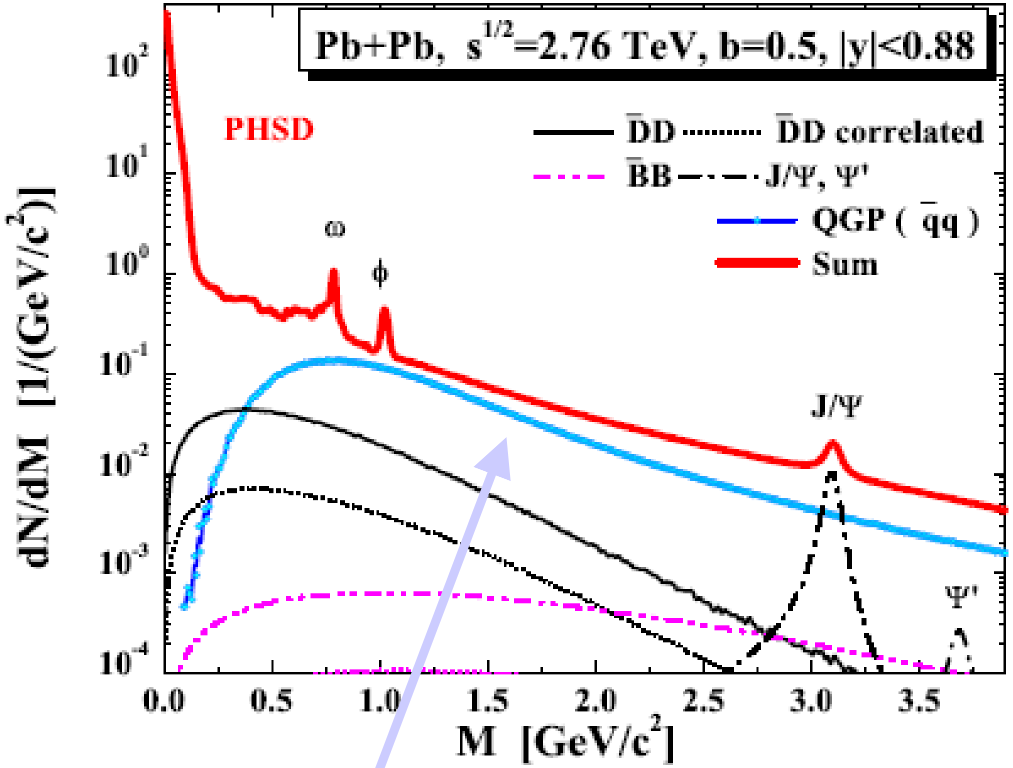


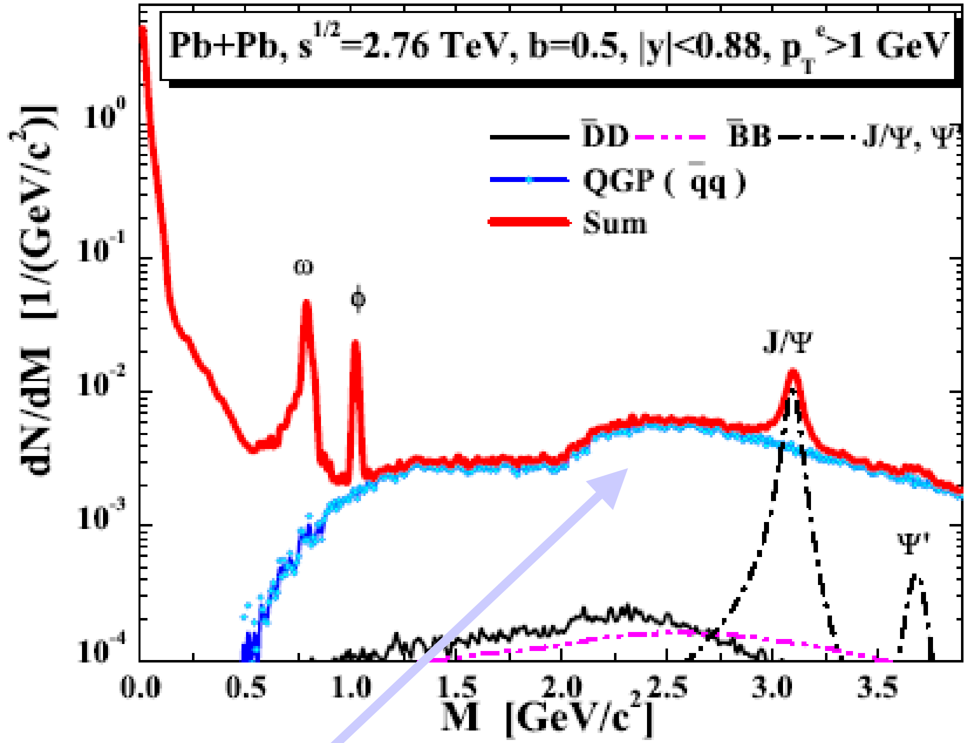


- The partonic channels dominate at M>1 GeV

O. Linnyk, W. Cassing, J. Manninen, E.B. and C.-M. Ko, PRC 85 (2012) 024910

LHC: mass spectra with exp. cuts

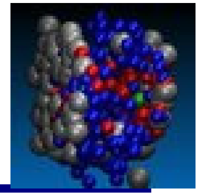




- QGP(qbar-q) dominates at M>1.2 GeV !
- p_T cut enhances the signal of QGP(qbar-q)

D-, B-mesons: from Pol-Bernard Gossiaux and Jörg Aichelin
J/Ψ, Ψ': from C.M. Ko and T. Song

O. Linnyk, W. Cassing, J. Manninen, E.B., P.B. Gossiaux, J. Aichelin, T. Song, C.-M. Ko, Phys.Rev. C87 (2013) 014905; arXiv:1208.1279



Summary

- PHSD provides a consistent description of off-shell parton dynamics in line with the lattice QCD equation of state (from the BMW collaboration)

- PHSD versus experimental observables:
  - enhancement of meson m_T slopes (at top SPS and RHIC)
  - strange antibaryon enhancement (at SPS)
  - partonic emission of high mass dileptons at SPS and RHIC
  - enhancement of collective flow v_2 with increasing energy
  - quark number scaling of v_2 (at RHIC)
  - …

⇒ evidence for strong nonhadronic interactions in the early phase of relativistic heavy-ion reactions

⇒ formation of the sQGP!

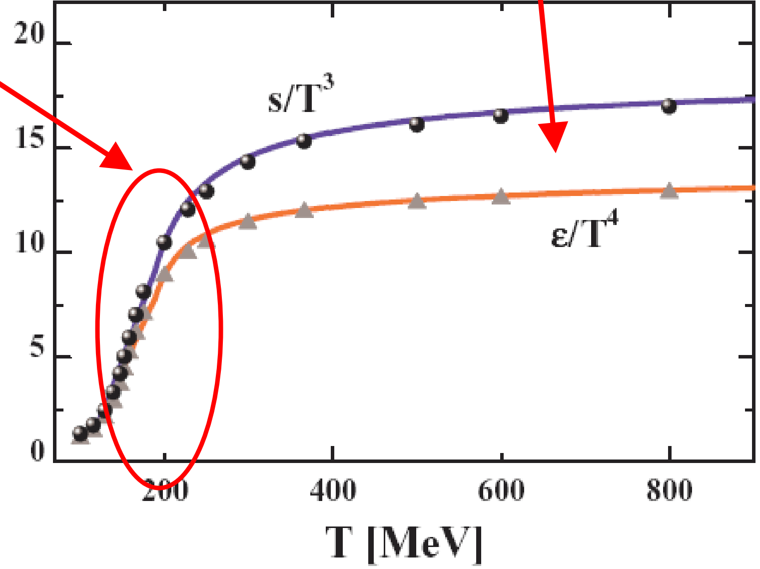
Outlook - Perspectives

What is the stage of matter close to T_c :

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

(V.D. Toneev et al.)

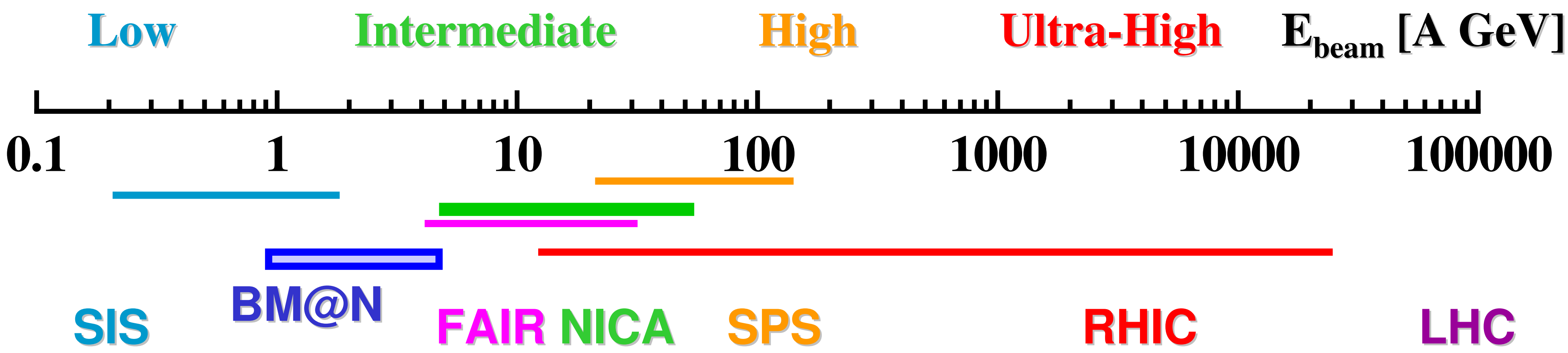
Lattice EQS for μ=0
➔ ‚crossover‘ , $T > T_c$



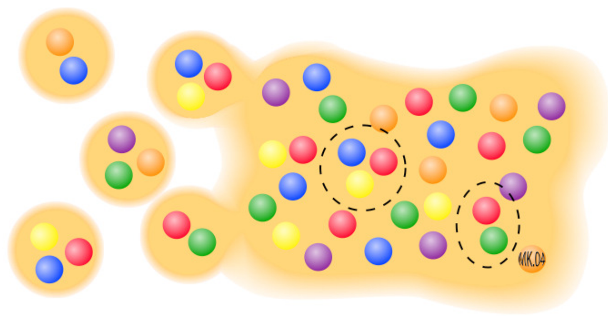
Open problems:

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

HIC experiments



Baryonic matter ‖ **Meson and baryon spectroscopy** **In-medium effects** **EoS**	**‚Mixed' phase:** **hadrons (baryons, mesons) + quarks and gluons** ‖ **In-medium effects** **Chiral symmetry restoration** **Phase transition to sQGP** **Critical point in the QCD phase diagram**	**QGP: quarks and gluons** ‖ **Properties of sQGP**



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