Off-shell dynamical approach for relativistic heavy-ion collisions

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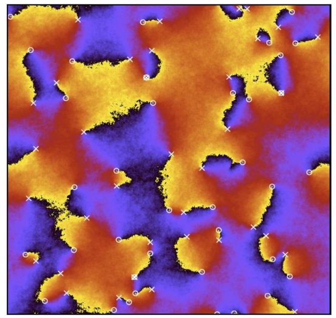
Relaxation, Turbulence, and Non-Equilibrium Dynamics of Matter Fields
• RETUNE 2012

Heidelberg · Germany · 21 – 24 June 2012



The 2nd International Symposium on Non-equilibrium Dynamics (NeD-2012) and
the 3d Network I3-HP3 Workshop on Theory of Ultra-Relativistic heavy-Ion Collisions (TURIC-2012)
will be held together from June 25 to 30, 2012, in Hersonissos, Crete, Greece

NeD topics:

- dynamical description of strongly interacting systems
- Kadanoff-Baym equations and solutions
- transport models for strongly interacting systems
- description of phase transitions
- viscous hydrodynamics

TURIC topics:

- properties of the quark-gluon plasma before hadronization and the phase transition towards the hadronic world
- transport properties of hard probes in the quark gluon plasma and their traces in final hadronic spectra
- microscopic study of initial thermalization

The venue and accommodation of participants will be at the 'Creta Maris Beach Resort' in Hersonissos, Crete

Organizers:

Elena Bratkovskaya (ITP & FIAS, Frankfurt U.)
Joerg Aichelin (SUBATECH, Nantes)
Marcus Bleicher (ITP & FIAS, Frankfurt U.)

HIC for FAIR
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HadronPhysics I3
Study of Strongly Interacting Matter

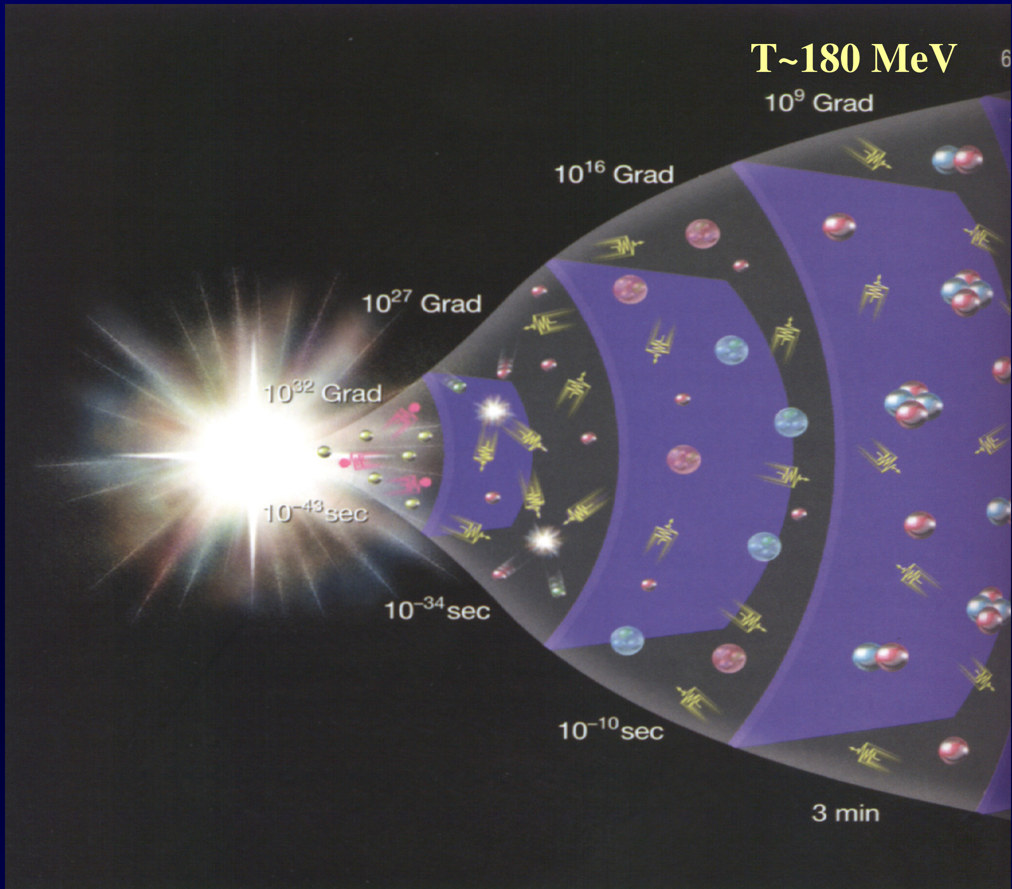
Home-page: http://fias.uni-frankfurt.de/crete2012/

Contact: crete2012@fias.uni-frankfurt.de





From Big Bang to Formation of the Universe



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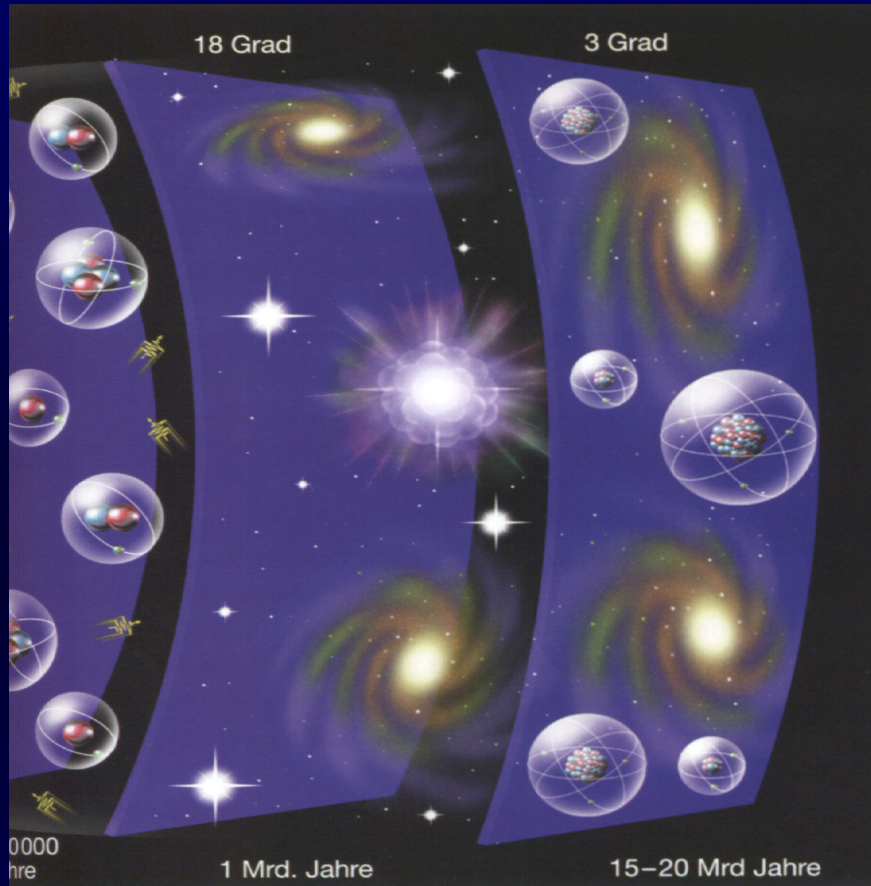


time →

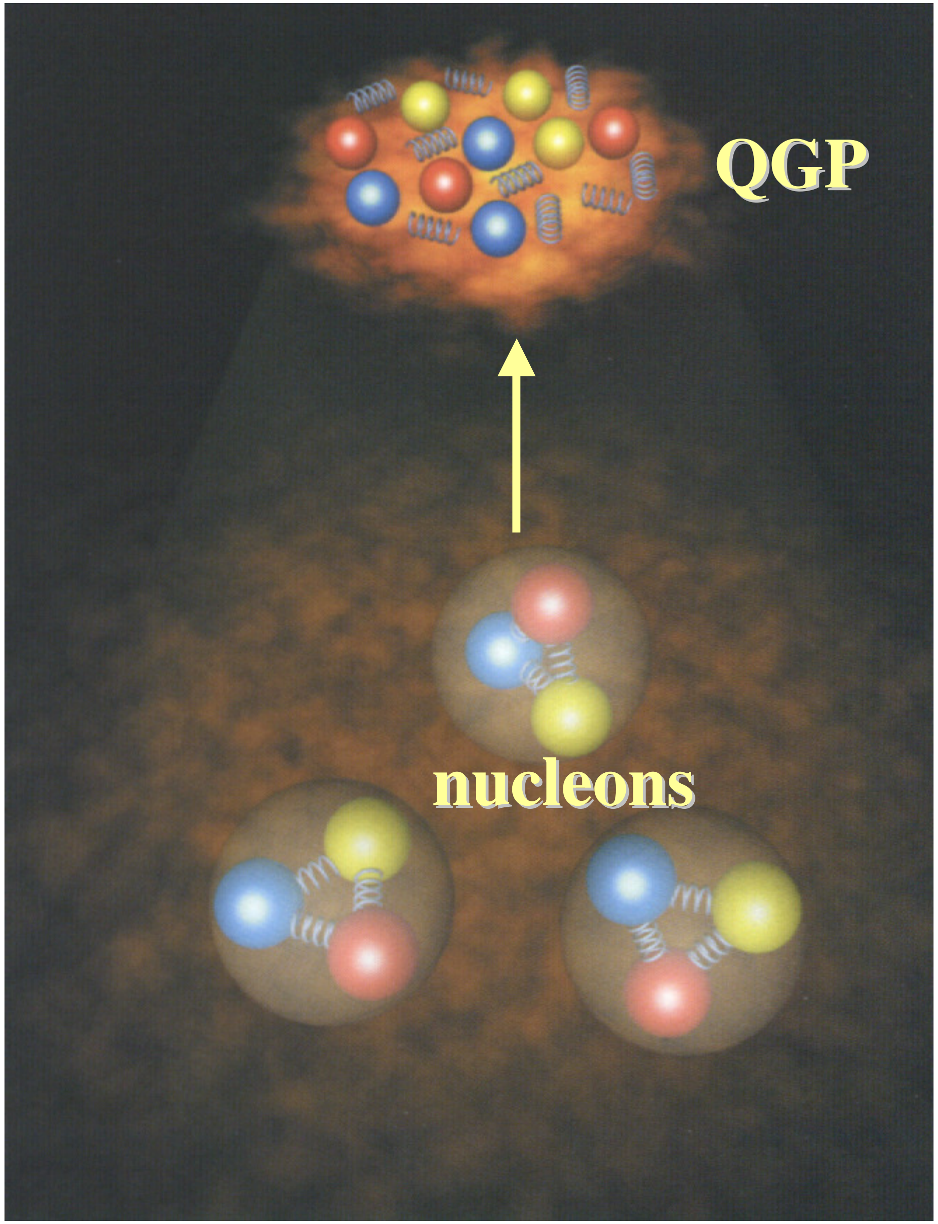
time	10^{-3}sec	3 min	300000 years	15 Mrd years
	quarks gluons photons	nucleons deuterons α–particles	atoms	our Universe

← **Can we go back in time ?**

... back in time

‚Re-create‘ the Big Bang conditions:
matter at high temperature and pressure
such that
nucleons/mesons decouple to quarks and gluons --
Quark-Gluon-Plasma

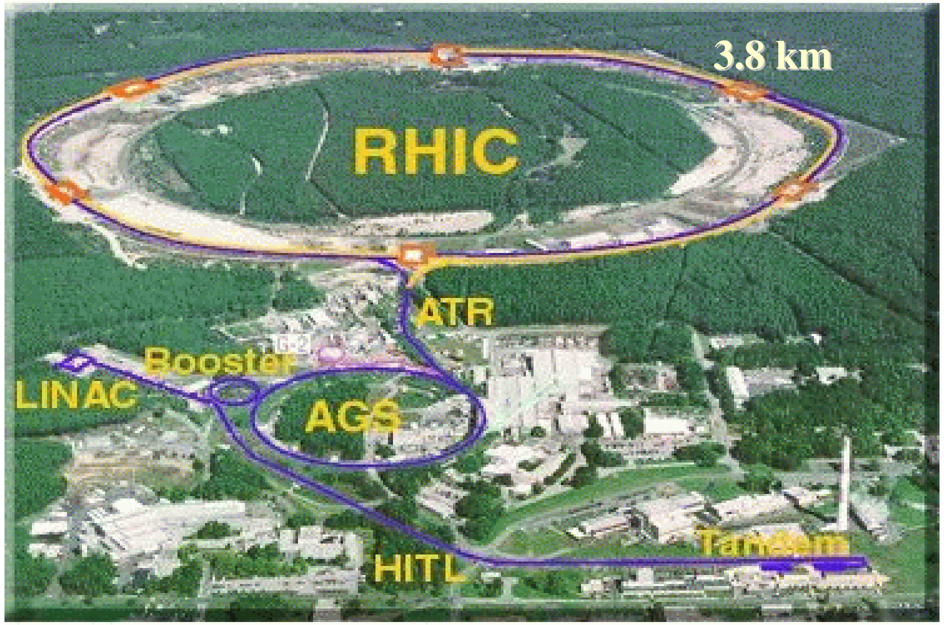
‚Little Bangs‘ in the Laboratory :
Heavy-ion collisions at ultrarelativistic energies



Heavy-ion accelerators

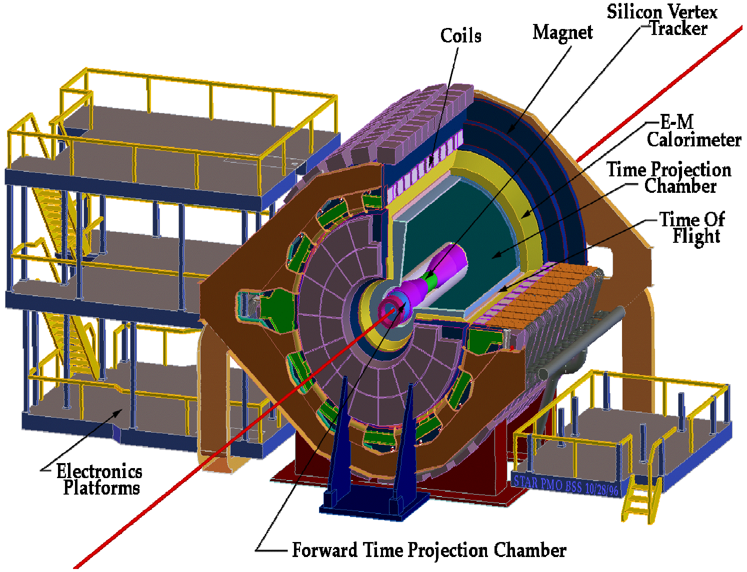
- **Super-Proton-Synchrotron – SPS - (CERN):** Pb+Pb at 160 A GeV

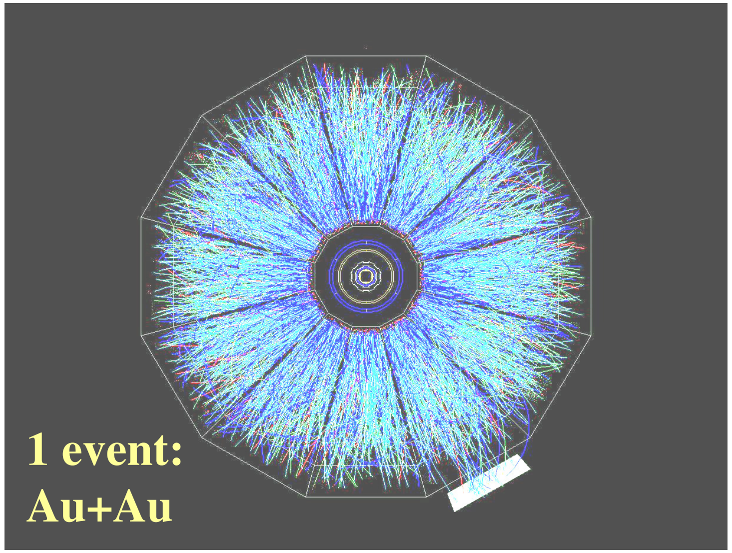
- **Relativistic-Heavy-Ion-Collider - RHIC - (Brookhaven):** Au+Au at 21.3 A TeV



- **Large Hadron Collider – LHC - (CERN):** Pb+Pb at 574 A TeV
- **Future facilities: FAIR (GSI), NICA (Dubna)**

STAR detector at RHIC



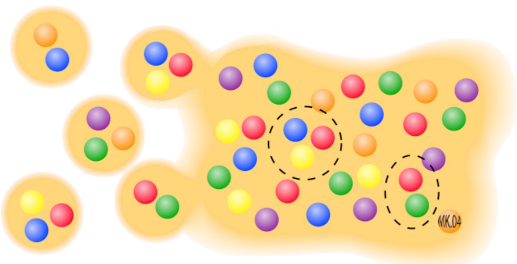


The QGP in Lattice QCD

Quantum Chromo Dynamics :

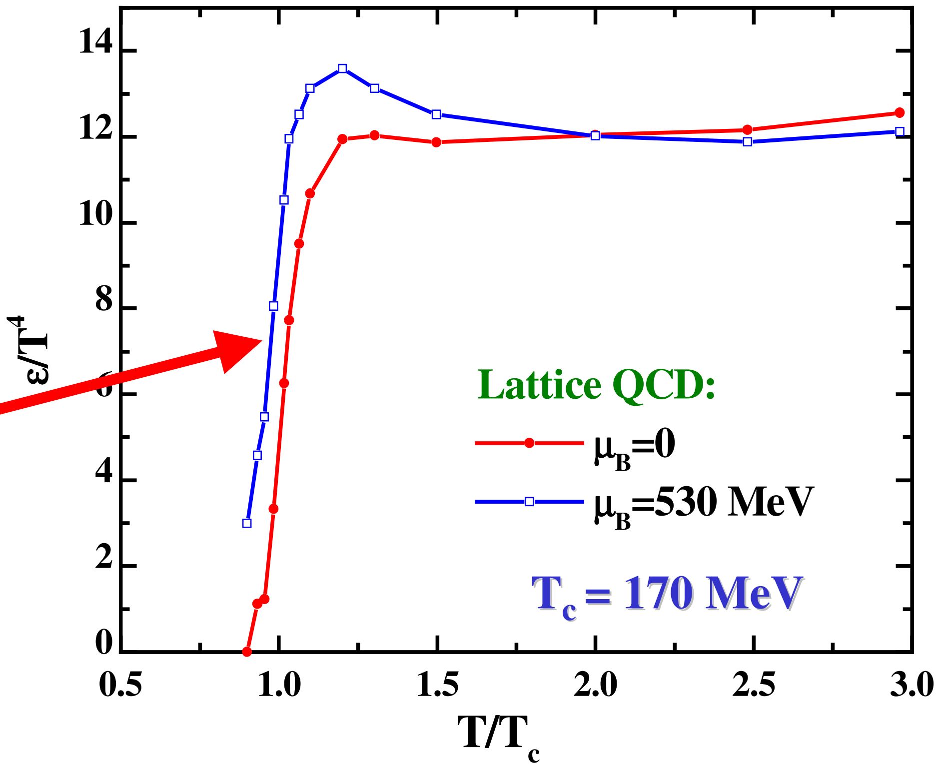
predicts strong increase of the energy density ε at critical temperature T_C ~170 MeV

⇒ Possible phase transition from hadronic to partonic matter (quarks, gluons) at critical energy density ε_C ~0.5 GeV/fm^3



Lattice QCD:

energy density versus temperature

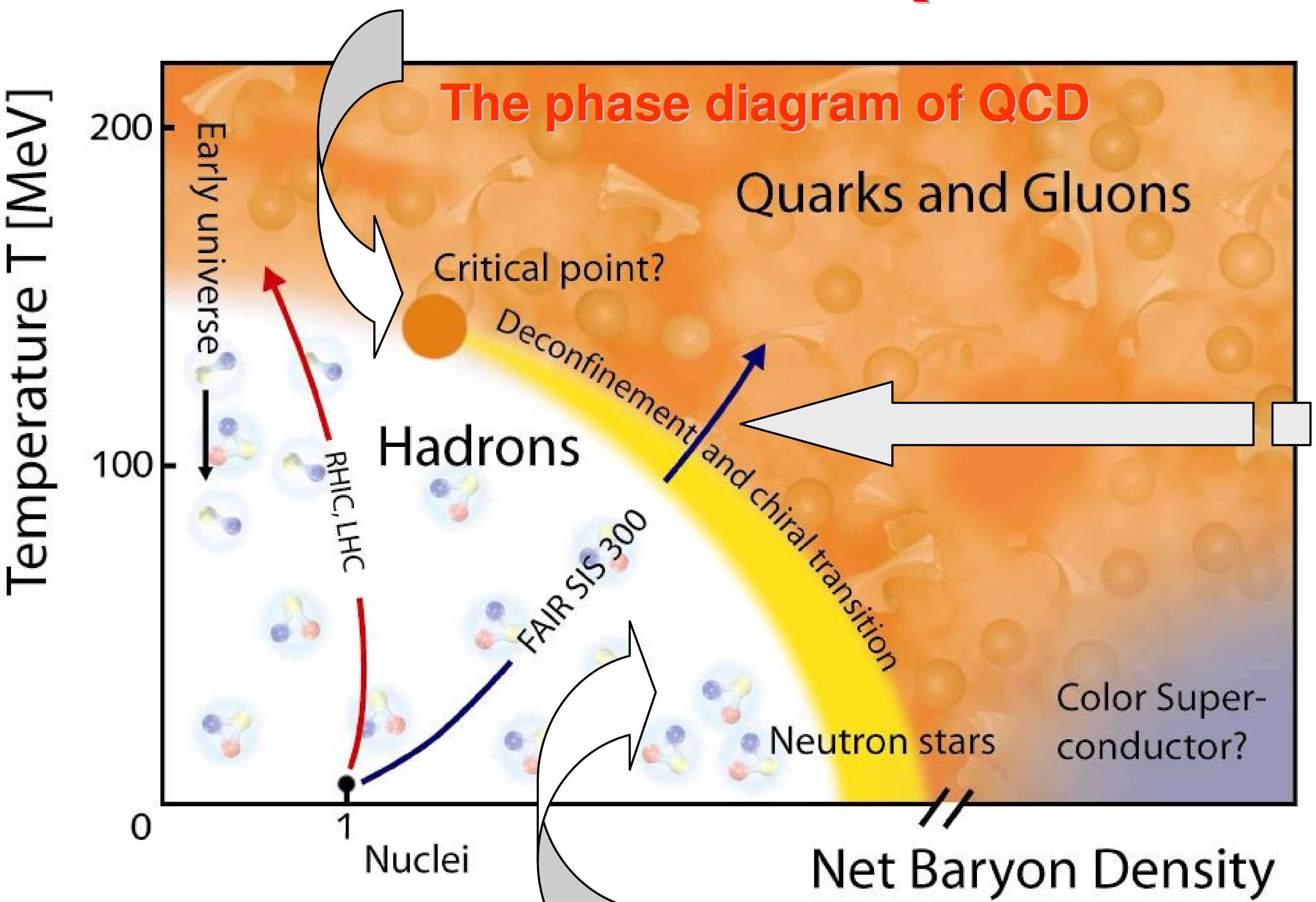


Z. Fodor et al., PLB 568 (2003) 73

Critical conditions - ε_C ~0.5 GeV/fm^3 , T_C ~170 MeV - can be reached in heavy-ion experiments at bombarding energies > 5 GeV/A

The holy grail:

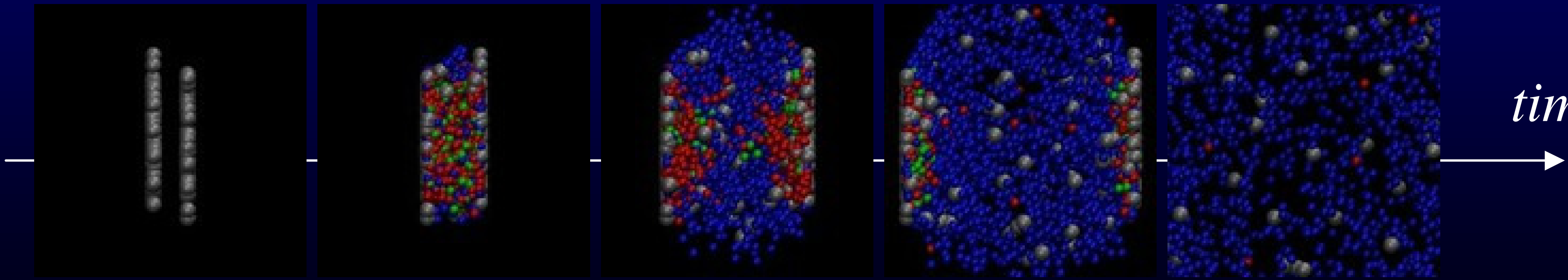
- Search for the critical point



- 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
- Study of the partonic medium beyond the phase boundary

‚Little Bangs‘ in the Laboratory



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

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

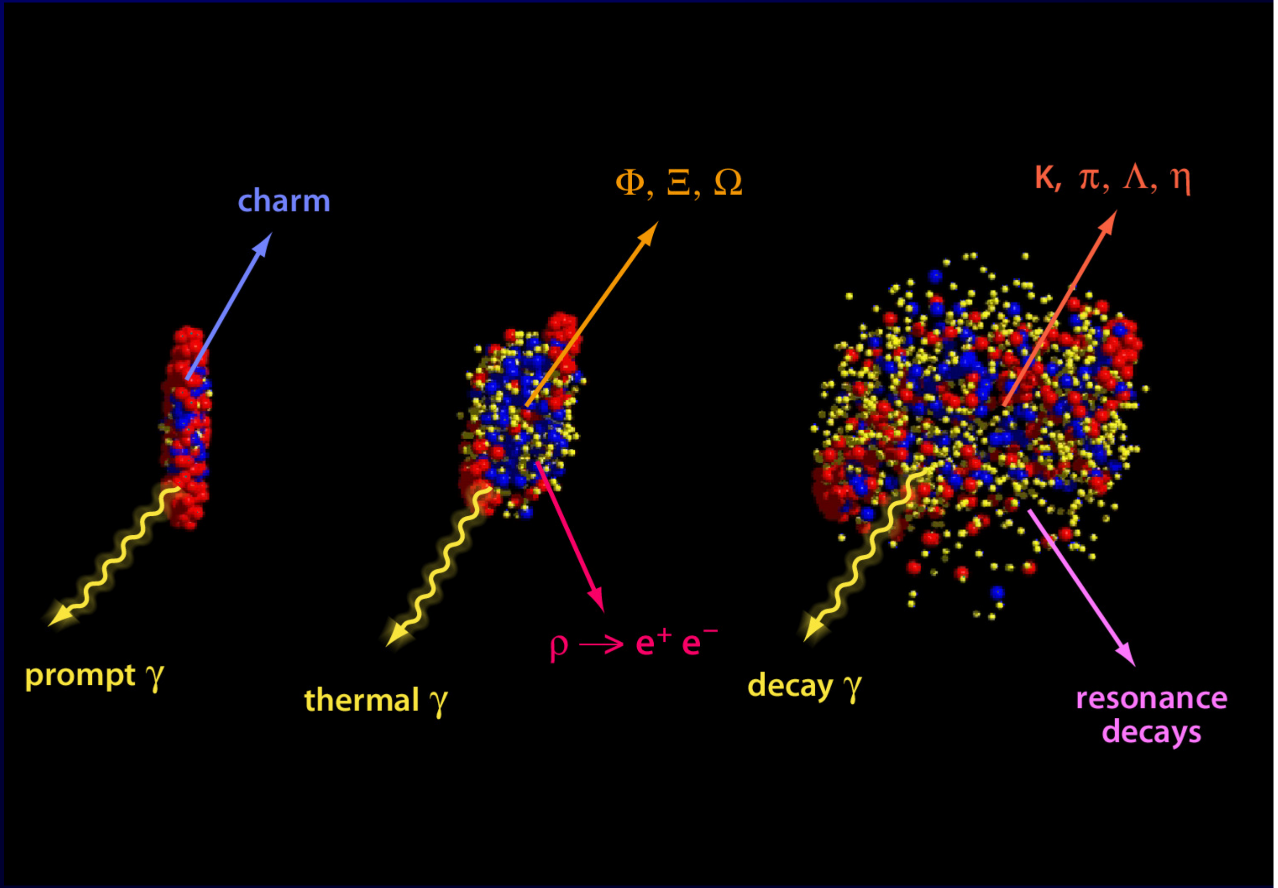
Signals of the phase transition:

- 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 - off-shell Kadanoff-Baym equations for the Green-functions $S^{<}_{h}(x,p)$ in phase-space representation. Actual solutions: Monte Carlo simulations with a large number of test-particles

[+: full dynamics | -: very complicated]

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

Dynamics of heavy-ion collisions –> complicated many-body problem!

Appropriate way to solve the many-body problem including all quantum mechanical features →

Kadanoff-Baym equations for Green functions $S^<$ (from 1962)

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

$\hat{S}_{0x}^{-1}$ denotes the (negative) Klein-Gordon differential operator e.g. for bosons $\hat{S}_{0x}^{-1} = -(\partial_x^\mu \partial_\mu^x + M_0^2)$

"$\odot$" implies an integration over the intermediate spacetime coordinates from $-\infty$ to ∞.

Greens functions S / self-energies Σ :

retarded (ret), advanced (adv) (anti-)causal (a,c)

$$i\,S_{xy}^{c} \;=\; i\,S_{xy}^{++} \;=\; <T^c\{\Phi(x)\,\Phi^\dagger(y)\}>, \qquad i\,S_{xy}^{<} \;=\; i\,S_{xy}^{+-} \;=\; \eta <\{\Phi^\dagger(y)\,\Phi(x)\}>,$$

$$i\,S_{xy}^{>} \;=\; i\,S_{xy}^{-+} \;=\; <\{\Phi(x)\,\Phi^\dagger(y)\}>, \qquad i\,S_{xy}^{a} \;=\; i\,S_{xy}^{--} \;=\; <T^a\{\Phi(x)\,\Phi^\dagger(y)\}>.$$

$$S_{xy}^{ret} \;=\; S_{xy}^{c} - S_{xy}^{<} \;=\; S_{xy}^{>} - S_{xy}^{a}, \qquad S_{xy}^{adv} \;=\; S_{xy}^{c} - S_{xy}^{>} \;=\; S_{xy}^{<} - S_{xy}^{a}$$

$\eta = +1$ for bosons and η = -1 for fermions.
T^c (T^a) represent the (anti-)time-ordering operators.

- **do Wigner transformation** $\quad F_{XP} \;=\; \int d^4(x-y)\; e^{iP_\mu(x^\mu - y^\mu)}\; F_{xy}$
- **consider only contribution up to first order in the gradients**
  = a standard approximation of kinetic theory which is justified if the gradients in the mean spacial coordinate *X* are small

‚On-shell' transport models

Basic concept of the ‚on-shell' transport models (VUU, BUU, QMD etc.):

1) **Transport equations = first order gradient expansion of the Wigner transformed Kadanoff-Baym equations**
2) **quasiparticle approximation: $A(x,p) = 2\pi\,\delta(p^2 - M^2)$**

- **for each particle species *i* (*i* = *N*, *R*, *Y*, π, ρ, K, …) the phase-space density f_i follows the transport equations**

$$\left(\frac{\partial}{\partial t} + \left(\nabla_{\vec{p}} U\right)\nabla_{\vec{r}} - \left(\nabla_{\vec{r}} U\right)\nabla_{\vec{p}}\right) f_i(\vec{r},\vec{p},t) = I_{coll}(f_1, f_2, \ldots, f_M)$$

  - **with collision terms I_{coll} describing elastic and inelastic hadronic reactions:**

    baryon-baryon, meson-baryon, meson-meson, formation and decay of baryonic and mesonic resonances, string formation and decay (for inclusive particle production:

    BB –> X , mB –>X, X =many particles)

  - **with propagation of particles in self-generated mean-field potential $U(p,\rho) \sim Re(\Sigma^{ret})/2p_0$**

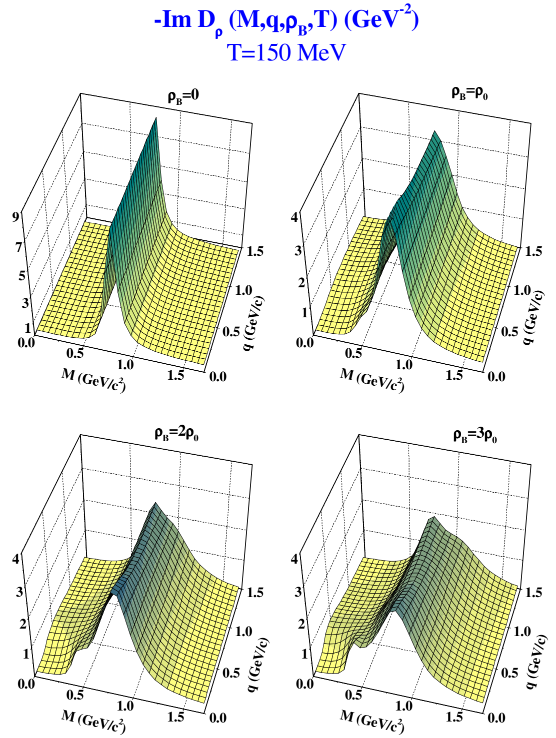
- **Numerical realization – solution of classical equations of motion + Monte-Carlo simulations for test-particle interactions**

Study of in-medium effects within transport approaches

- **Semi-classical on-shell transport models** work very well in describing interactions of point-like particles and **narrow resonances !**

- **In-medium models -** chiral perturbation theory, chiral SU(3) model, coupled-channel G-matrix approach, chiral coupled-channel effective field theory etc. predict **changes of the particle properties** in the hot and dense medium, e.g. strong **broadening of the spectral functions**

R. Rapp: ρ meson spectral function



■ **Problem : How to treat short-lived (broad) resonances in semi-classical transport models?**

Semi-classical approaches: on-shell transport models based on quasi-particle approximation $A(X,P) = 2\pi\,\delta(P^2-M^2)$

● **Accounting for in-medium effects with medium-dependent spectral functions requires off-shell transport models bejong quasi-particle approximation !**

➔ **back to Kadanoff-Baym equations**

From Kadanoff-Baym equations to 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:

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 $A_{XP} = 2\,\pi\,\delta(p^2\text{-}M^2)$

➔ ‚on-shell' transport models (VUU, BUU, QMD, IQMD, UrQMD etc.)

Greens function $S^<$ characterizes the **number of particles** (N) and their properties (A – spectral function): $iS^<_{XP}=A_{XP}N_{XP}$

The imaginary part of the retarded propagator is given by normalized **spectral function:**

$$A_{XP} = i \left[S^{ret}_{XP} - S^{adv}_{XP} \right] = -2\, Im\, S^{ret}_{XP} \,, \qquad \int \frac{dP_0^2}{4\pi} A_{XP} = 1$$

For bosons in first order in gradient expansion:

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

Γ_{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

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 off-shell equations of motion:

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

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

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

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

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

The baseline concepts of HSD

HSD – Hadron-String-Dynamics transport approach:

- for each particle species *i* (*i* = *N*, *R*, *Y*, π, ρ, K, …) the phase-space density f_i follows the generalized transport equations

  with collision terms I_{coll} describing:

  - elastic and inelastic hadronic reactions:

    baryon-baryon, meson-baryon, meson-meson

  - formation and decay of

    baryonic and mesonic resonances

  and strings - excited color singlet states *(qq - q)* or *(q – qbar)* -

  (for inclusive particle production: BB –> X , mB –>X, X =many particles)

BB <–> B´B´, BB <–> B´B´m

mB <–> m´B´, mB <–> B´

Baryons:

B=(p, n, Δ(1232),

N(1440), N(1535), ...)

Mesons:

m=(π, η, ρ, ω, φ, ...)

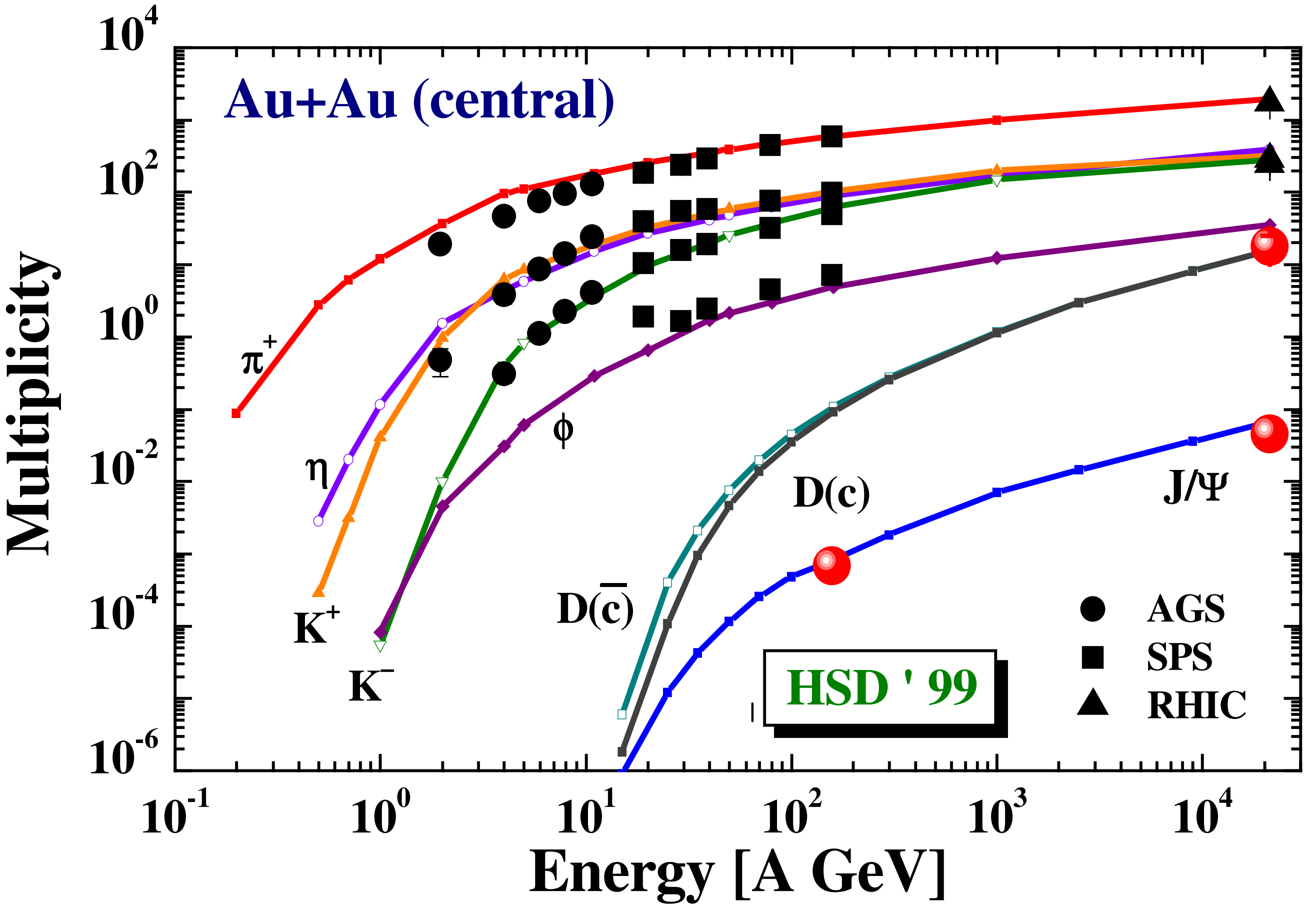
- implementation of detailed balance on the level of 1<–>2 and 2<–>2 reactions (+ 2<–>n multi-particle reactions in HSD !)

- off-shell dynamics for short-lived states

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

HSD – a microscopic model for heavy-ion reactions

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

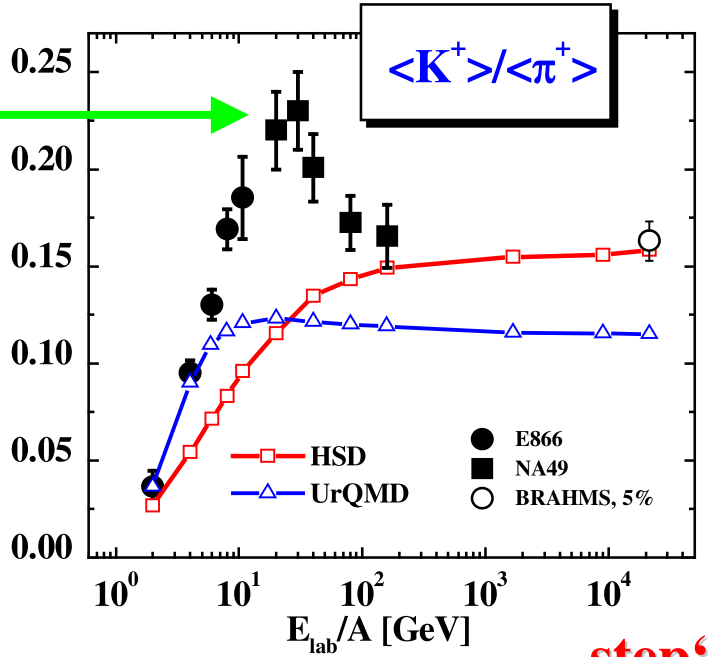


HSD predictions from 1999; data from the new millenium

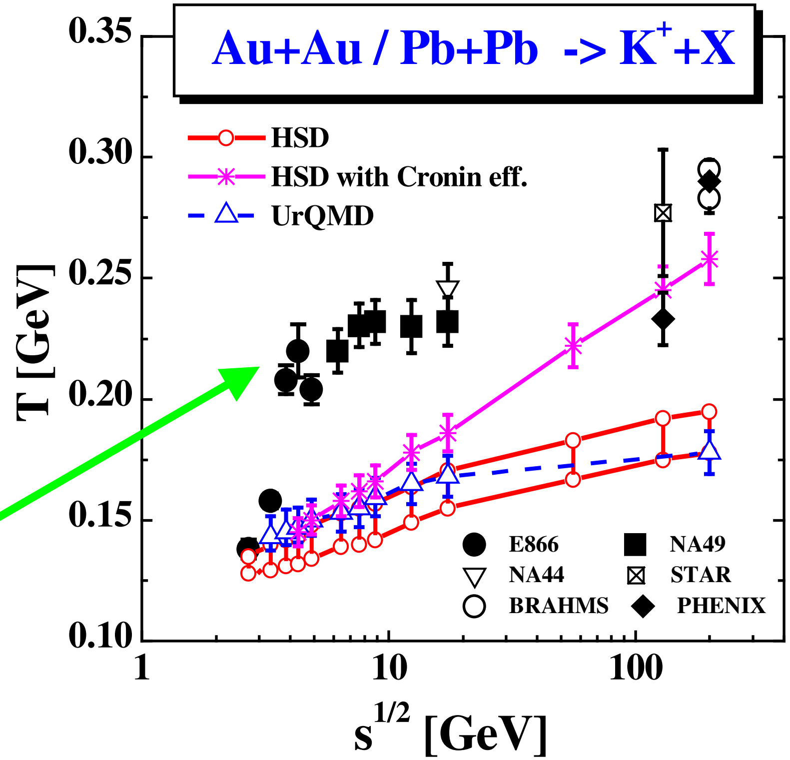
Hadron-string transport models (HSD, UrQMD) versus observables

Strangeness signals of QGP

‚horn‘ in K^+/π^+



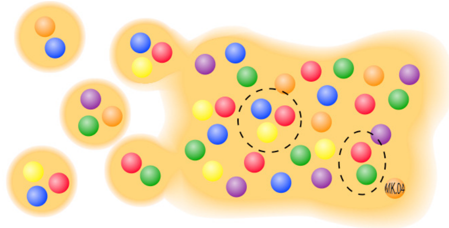
‚step‘ in slope T



Exp. data are not reproduced in terms of the hadron-string picture
=> evidence for nonhadronic 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:

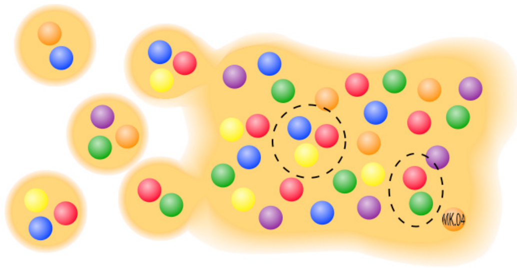
- QGP phase: hydro with QGP EoS
- hadronic freeze-out: after burner - hadron-string transport model

➔ 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)

The Dynamical QuasiParticle Model (DQPM)

Basic idea: **Interacting quasiparticles**

- **massive quarks and gluons** (g, q, q_{bar}) **with spectral functions :**

$$\rho(\omega) = \frac{\gamma}{E}\left(\frac{1}{(\omega - E)^2 + \gamma^2} - \frac{1}{(\omega + E)^2 + \gamma^2}\right)$$

$$E^2 = p^2 + M^2 - \gamma^2$$

A. Peshier, PRD 70 (2004) 034016

■ **quarks**

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

width: $$\gamma_q(T) = \frac{N_c^2 - 1}{2N_c}\frac{g^2 T}{4\pi} \ln\frac{c}{g^2}$$

■ **gluons:**

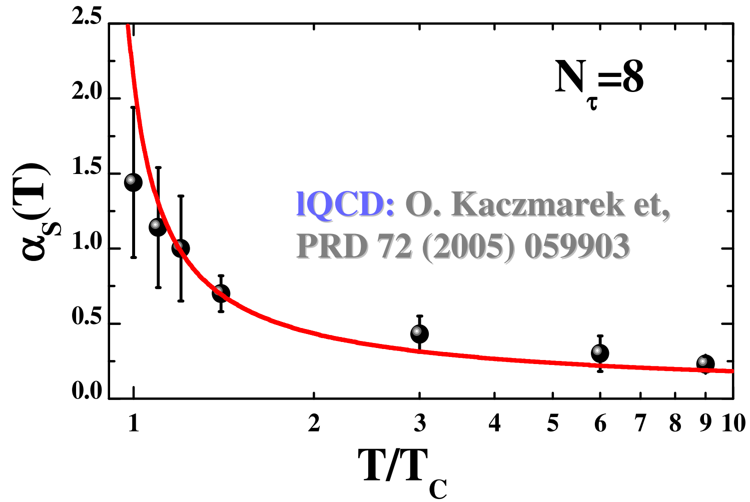
$$M^2(T) = \frac{g^2}{6}\left(\left(N_c + \frac{1}{2}N_f\right)T^2 + \frac{N_c}{2}\sum_q \frac{\mu_q^2}{\pi^2}\right)$$

$$\gamma_g(T) = N_c \frac{g^2 T}{4\pi} \ln\frac{c}{g^2}$$

$N_c = 3$, $N_f = 3$

running coupling: $\alpha_S(T) = g^2(T)/(4\pi)$

$$g^2(T/T_c) = \frac{48\pi^2}{(11N_c - 2N_f)\ln(\lambda^2(T/T_c - T_s/T_c)^2}$$



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

with 3 parameters: T_s/T_c=0.46; c=28.8; λ=2.42

➔ **quasiparticle properties** (mass, width)

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

DQPM thermodynamics (N_f=3) and lQCD

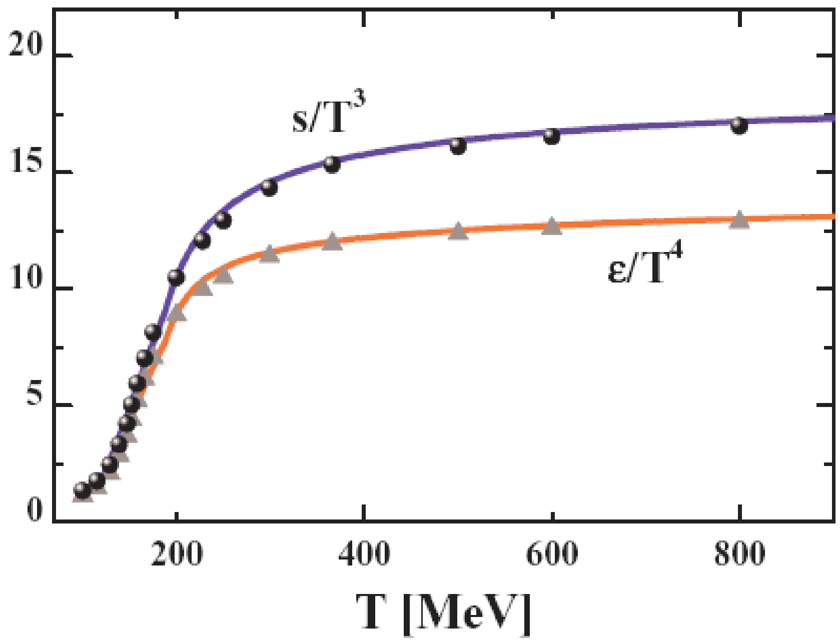
entropy $s = \frac{\partial P}{dT}$ → **pressure P**

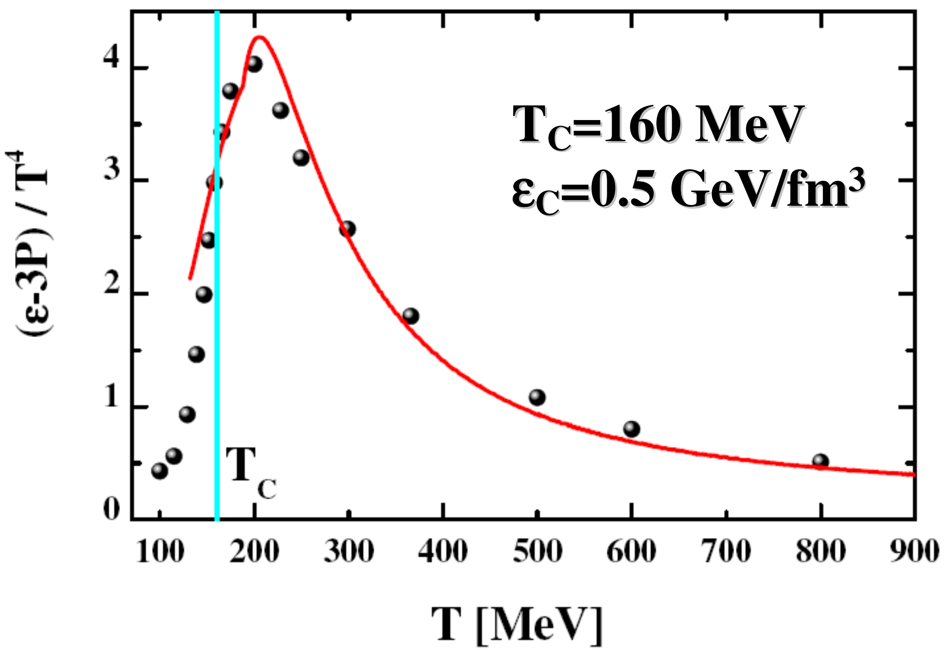
energy density: $\epsilon = Ts - P$

interaction measure:

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

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



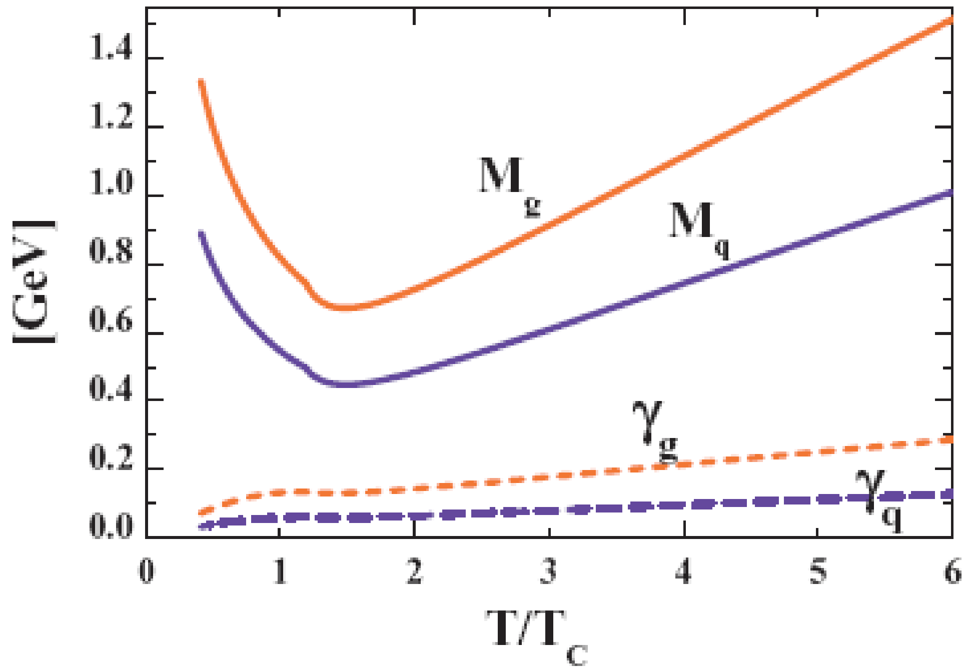


DQPM gives a good description of lQCD results !

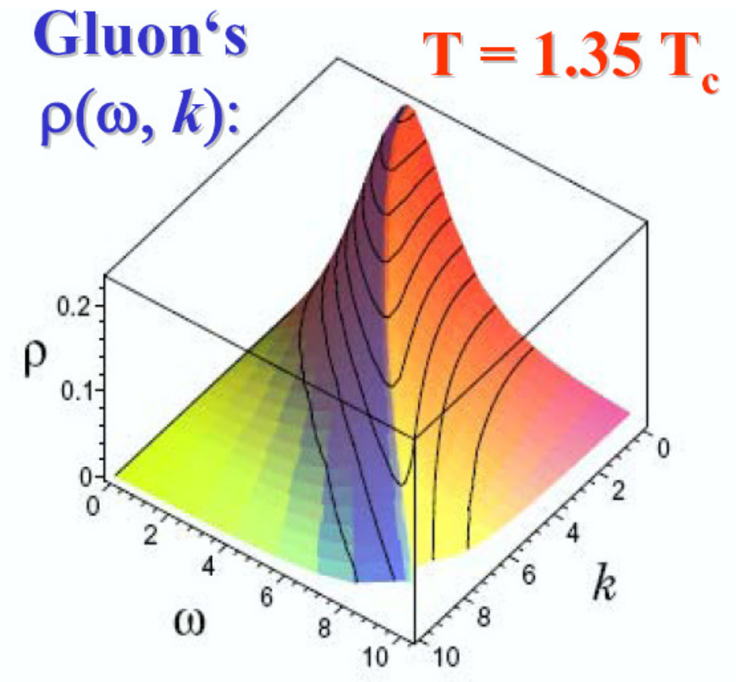
The Dynamical QuasiParticle Model (DQPM)

➔ **Quasiparticle properties:**

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



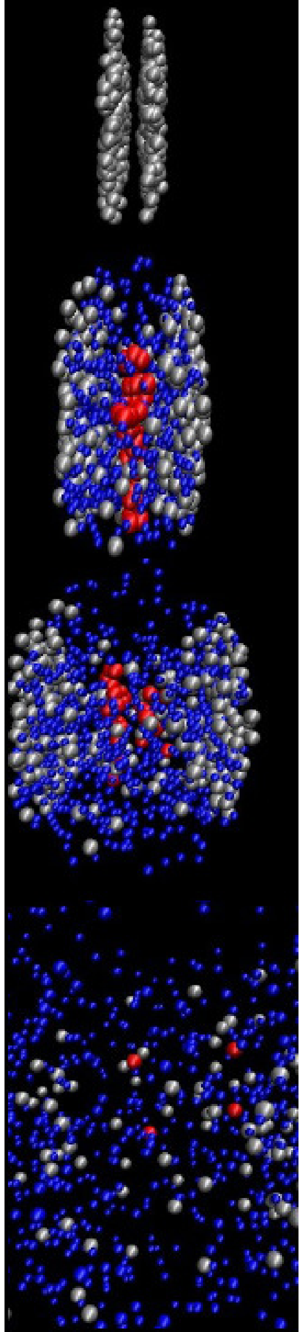
➔ **Broad spectral function :**



- **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)

PHSD - basic concept



Initial A+A collisions – HSD: string formation and decay to pre-hadrons

Fragmentation of pre-hadrons into quarks: using the quark spectral functions from the Dynamical QuasiParticle Model (DQPM) - approximation to QCD

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

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

- ❑ elastic and inelastic parton-parton interactions:
  using the effective cross sections from the DQPM
  - ✓ q + qbar (flavor neutral) <=> gluon (colored)
  - ✓ gluon + gluon <=> gluon (possible due to large spectral width)
  - ✓ q + qbar (color neutral) <=> hadron resonances
- ❑ self-generated mean-field potential for quarks and gluons

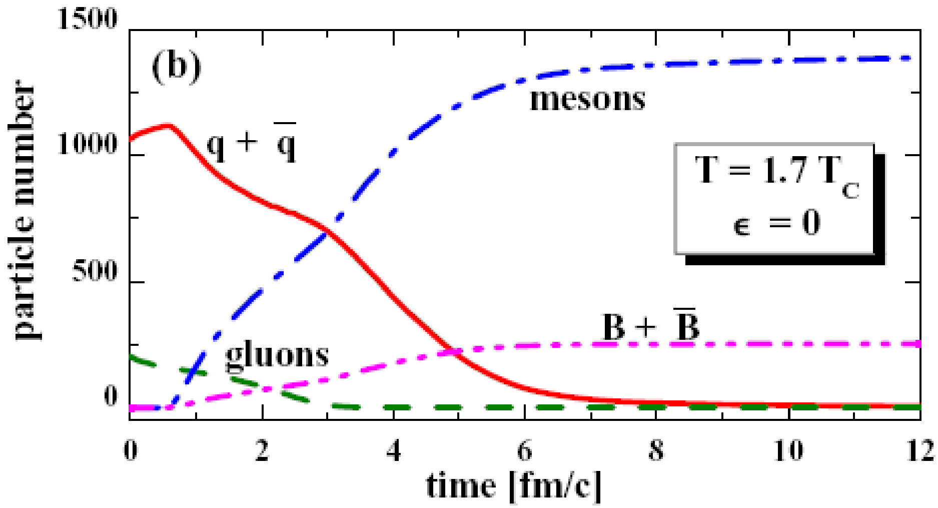
Hadronization: based on DQPM - massive, off-shell quarks and gluons with broad spectral functions hadronize to off-shell mesons and baryons:
gluons → q + qbar; q + qbar → meson (or string);
q + q +q → baryon (or string) (strings act as ‚doorway states' for hadrons)

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

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

PHSD: hadronization of a partonic fireball

E.g. time evolution of the partonic fireball at initial temperature 1.7 T_c at μ_q=0



Consequences:

➢Hadronization: q+q_{bar} or 3q or 3q_{bar} fuse to color neutral hadrons (or strings) which subsequently decay into hadrons in a microcanonical fashion, i.e. obeying all conservation laws (i.e. 4-momentum conservation, flavor current conservation) in each event!

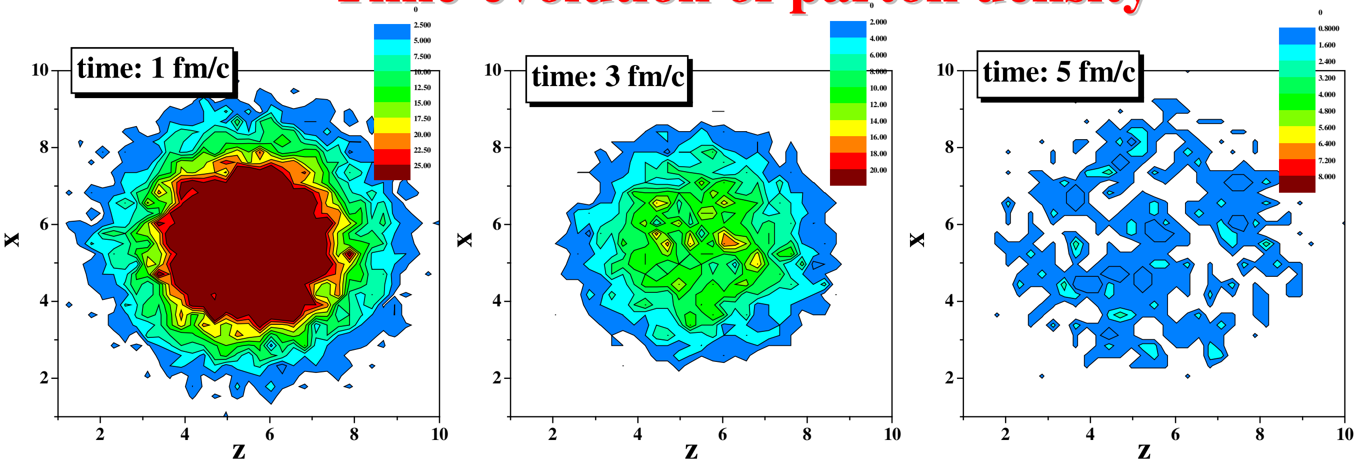
➢ Hadronization yields an increase in total entropy S (i.e. more hadrons in the final state than initial partons) and not a decrease as in the simple recombination models!

➢Off-shell parton transport roughly leads a hydrodynamic evolution of the partonic system

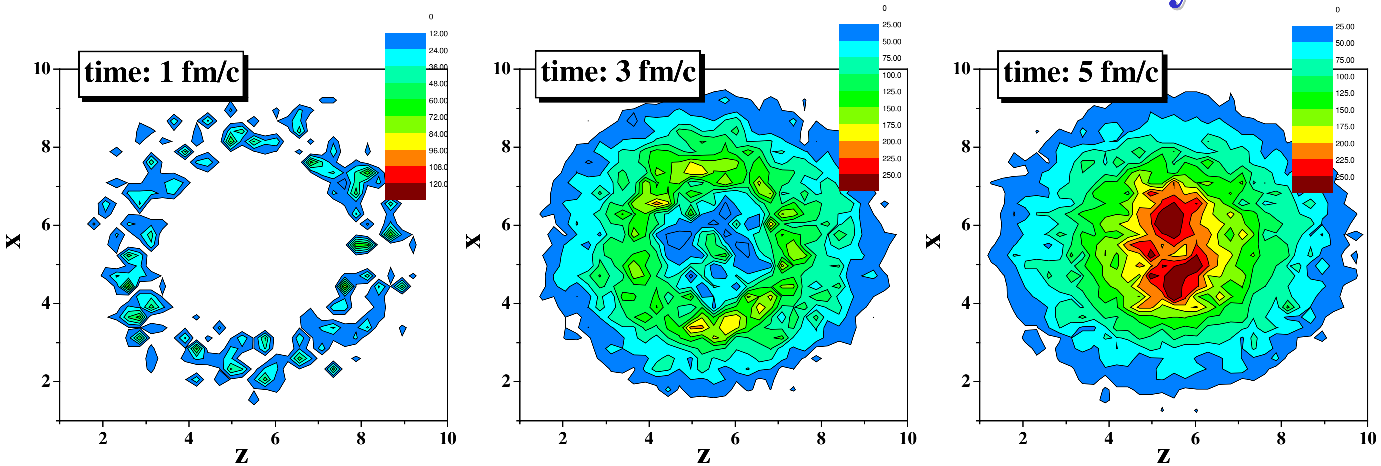
W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

PHSD: Expanding fireball

Time-evolution of parton density



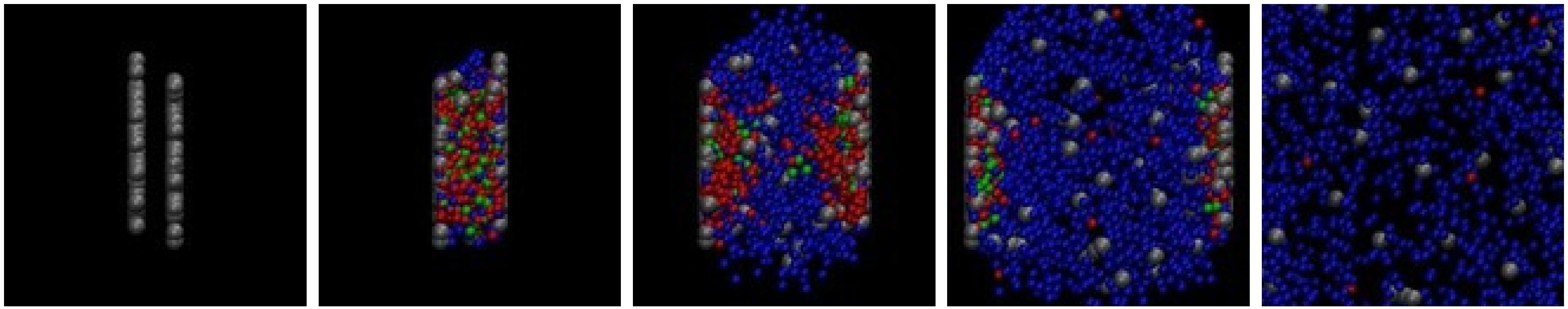
Time-evolution of hadron density



Expanding grid: $\Delta z(t) = \Delta z_0(1+a\ t)$!

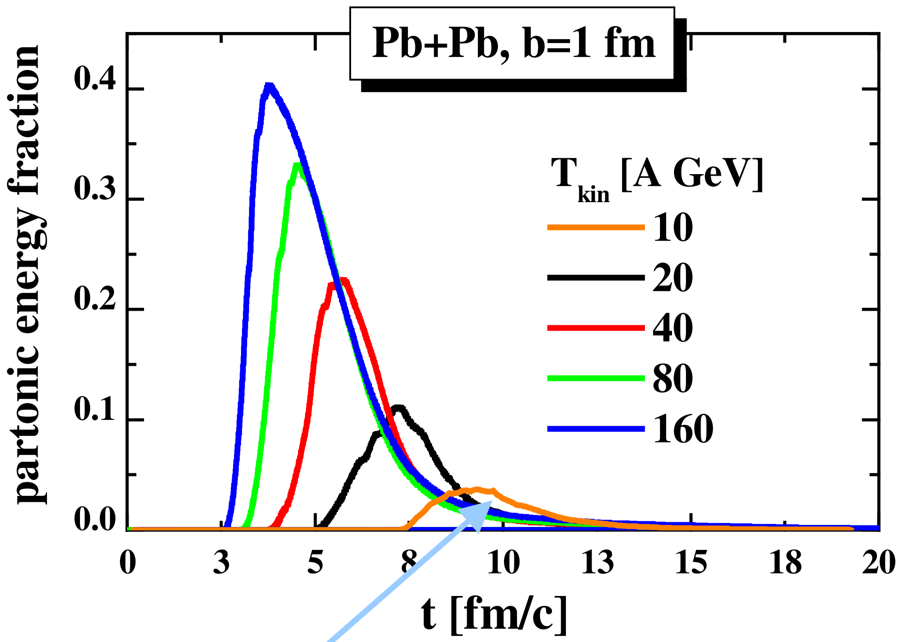
PHSD: spacial phase ‚co-existence' of partons and hadrons, but NO interactions between hadrons and partons (since it is a cross-over)

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

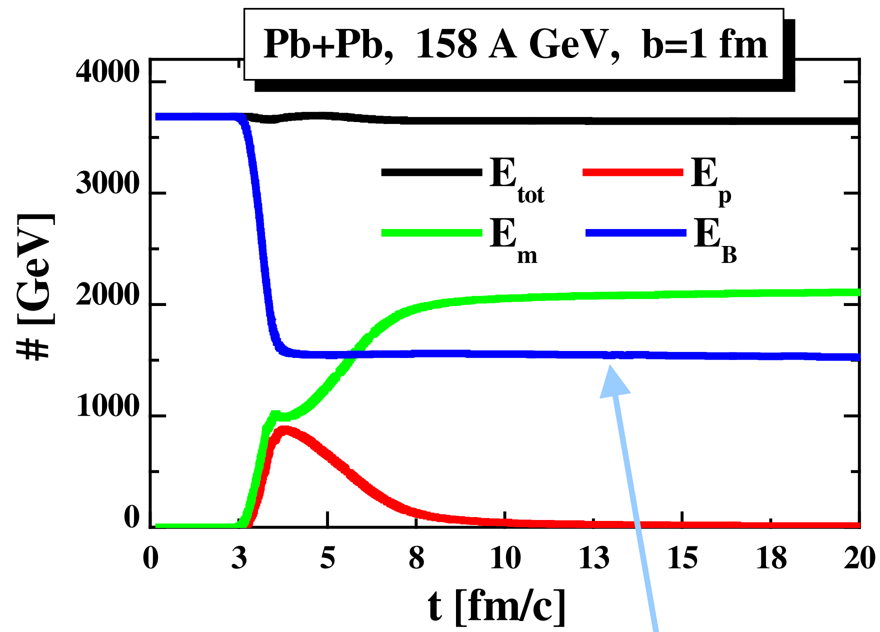


Application to nucleus-nucleus collisions

partonic energy fraction vs energy



energy balance



- Dramatic decrease of partonic phase with decreasing energy

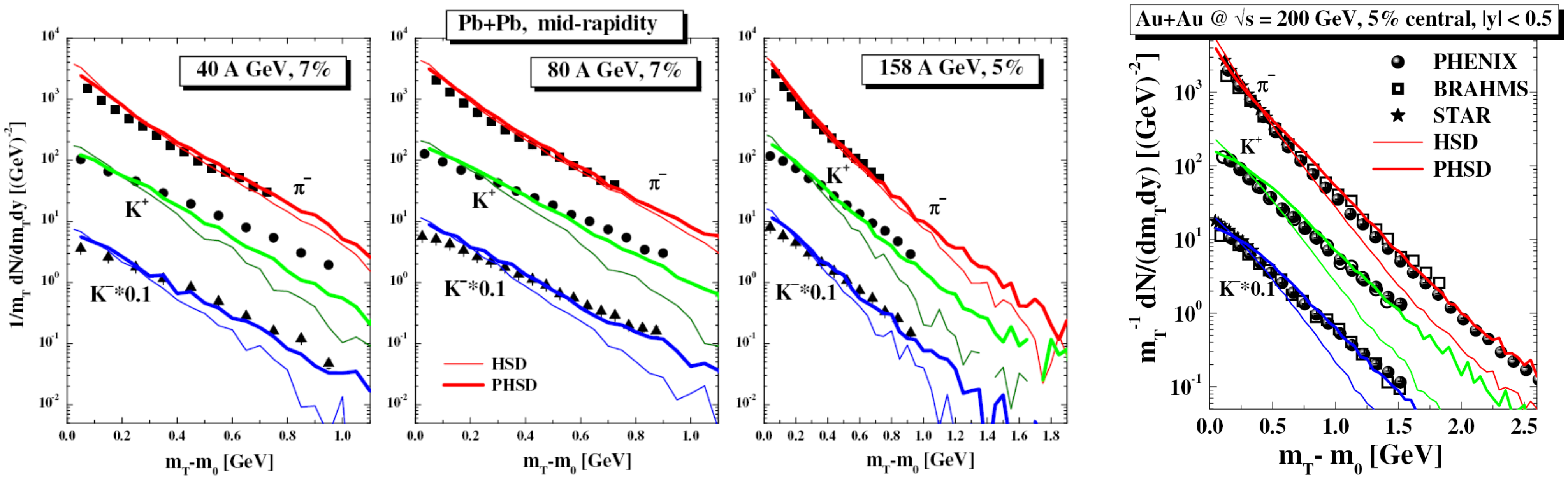
- Pb+Pb, 160 A GeV: only about 40% of the converted energy goes to partons; the rest is contained in the large hadronic corona and leading partons!

Cassing & Bratkovskaya, NPA 831 (2009) 215

PHSD: Transverse mass spectra

Central Pb + Pb at SPS energies

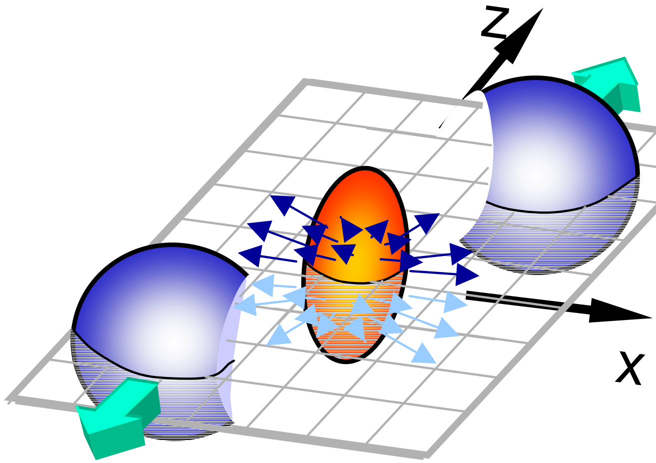
Central Au+Au at RHIC



- 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

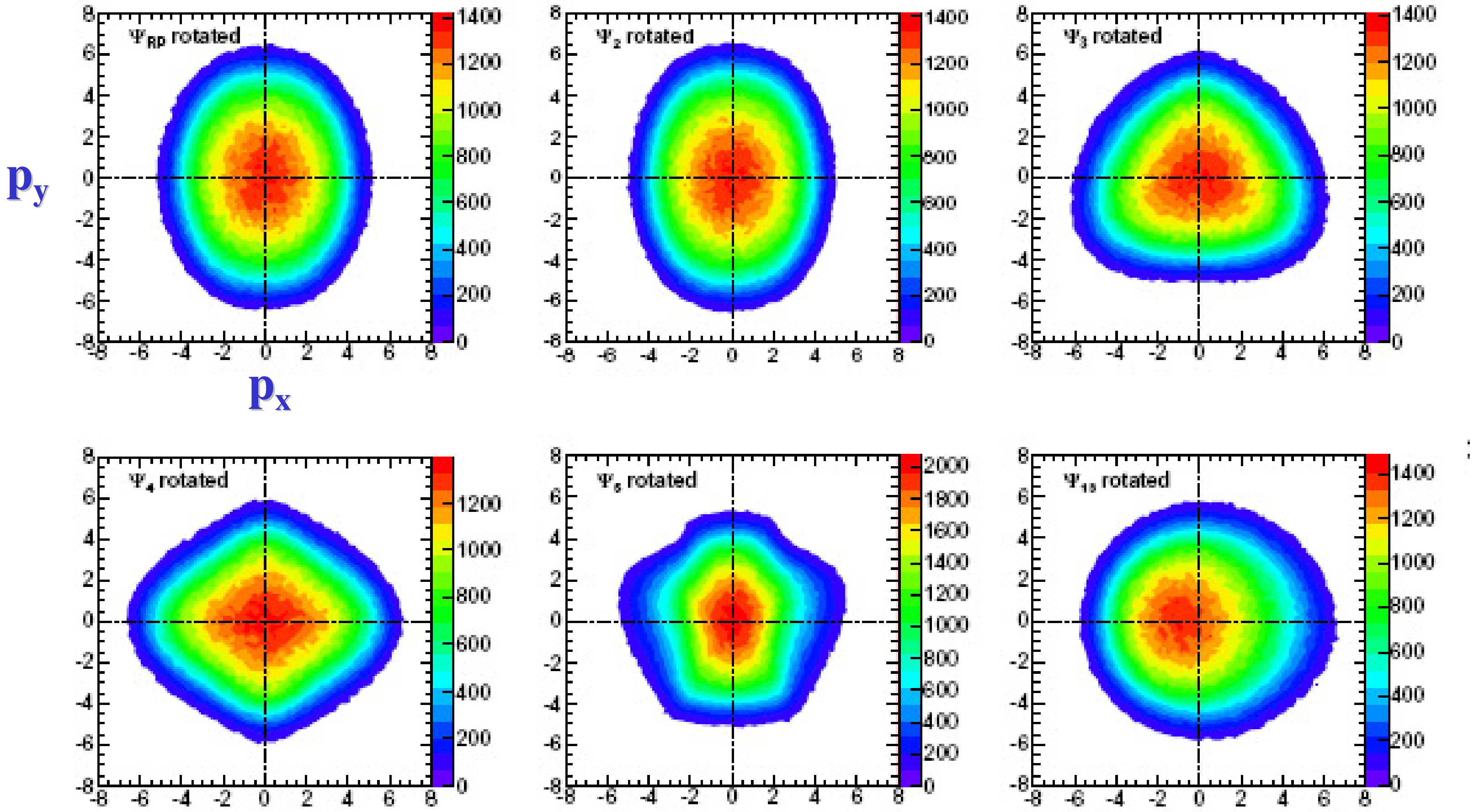
W. Cassing & E. Bratkovskaya, NPA 831 (2009) 215
E. Bratkovskaya, W. Cassing, V. Konchakovski, O. Linnyk, NPA856 (2011) 162

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



Final angular distributions of hadrons

10k Au+Au collision events at b = 8 fm at 21 TeV rotated to different event planes:

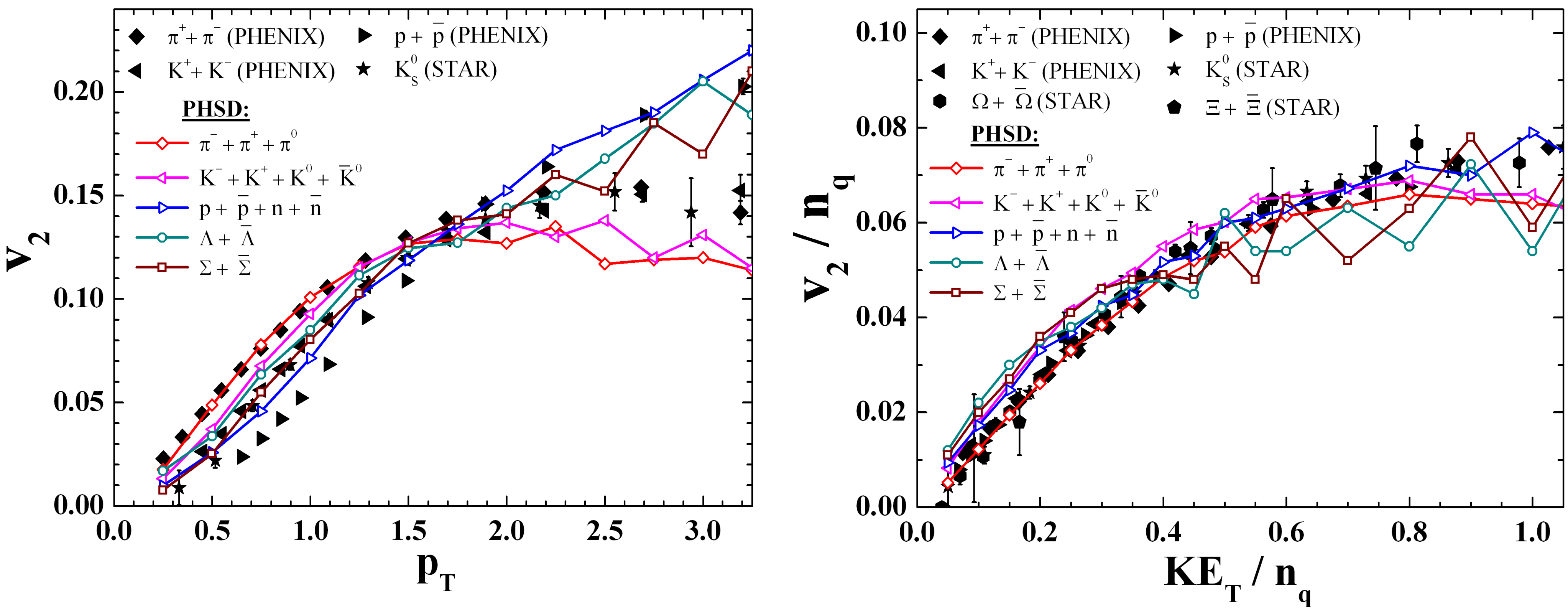


$$E\frac{d^3N}{d^3p} = \frac{d^2N}{2\pi p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n(p_T)\cos(n(\psi-\Psi_n))\right)$$

show higher order harmonics v_n

S. A. Voloshin, arXiv:1111.7241

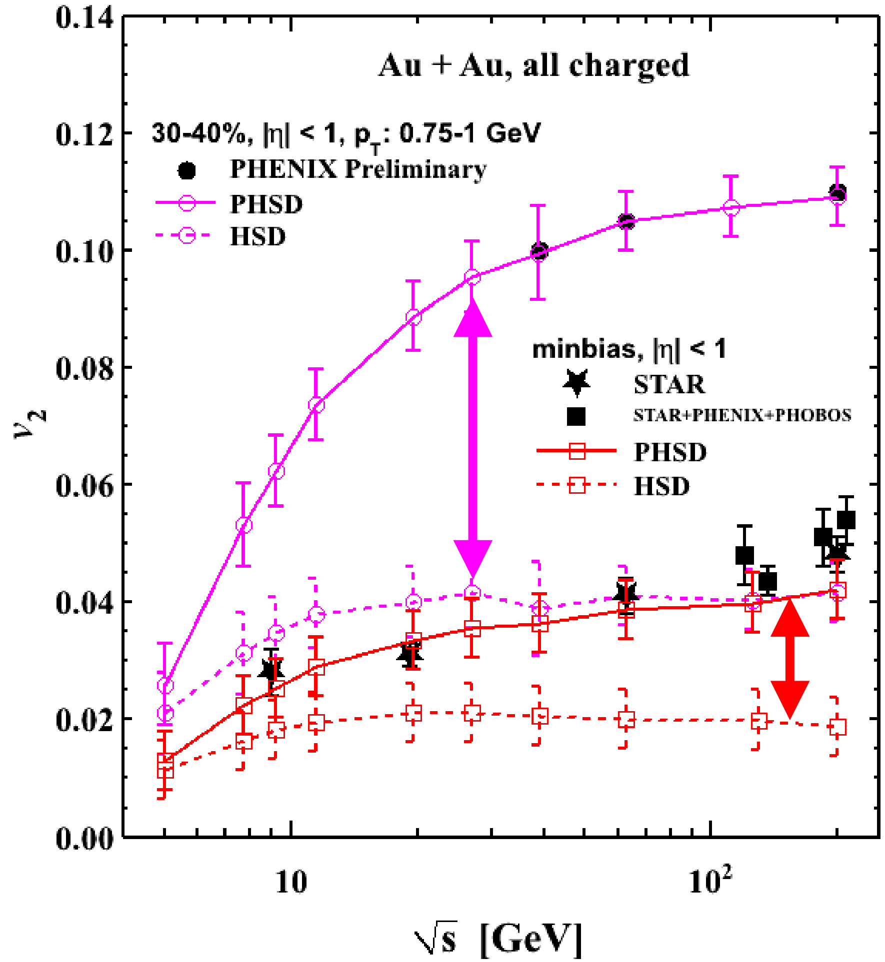
Elliptic flow scaling at RHIC

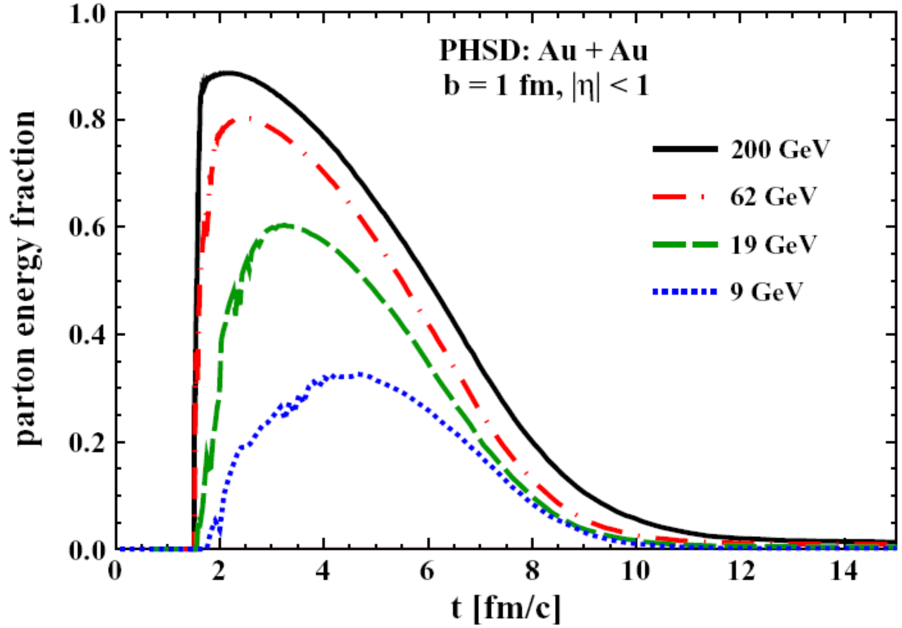


- The mass splitting at low p_T is approximately reproduced as well as the meson-baryon splitting for $p_T > 2$ GeV/c !
- The scaling of v_2 with the number of constituent quarks n_q is roughly in line with the data .

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

Elliptic flow v_2 vs. collision energy for Au+Au

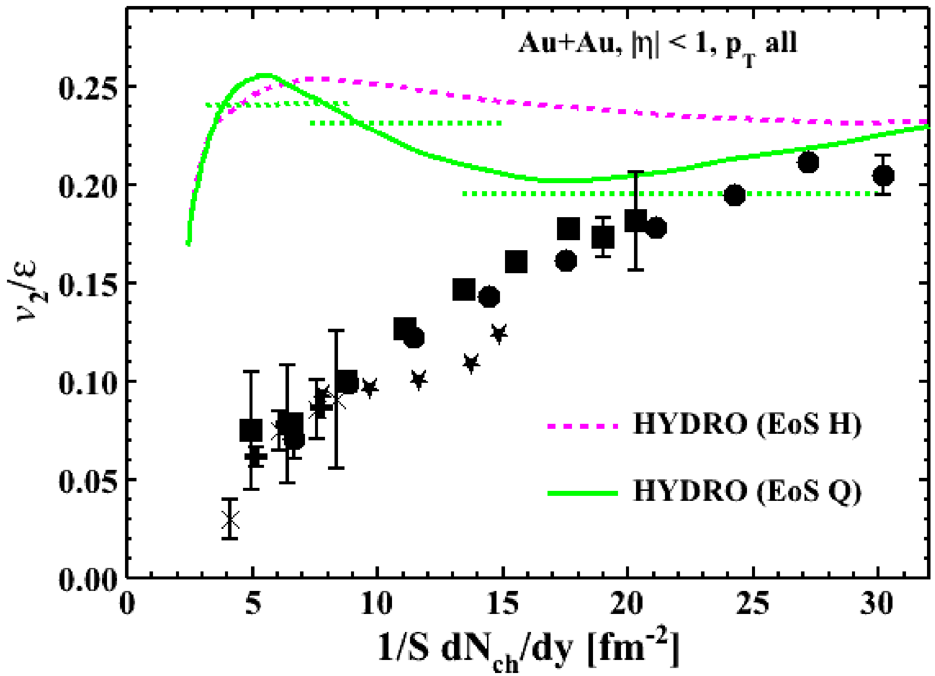


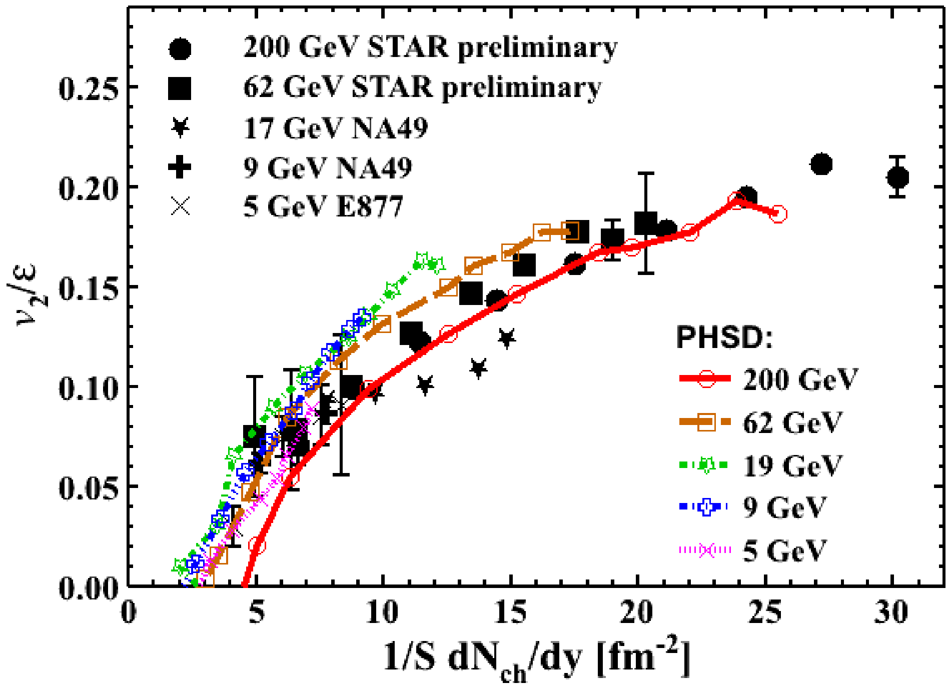


- v_2 in PHSD is larger than in HSD due to the repulsive scalar mean-field potential $U_s(\rho)$ for partons
- v_2 grows with bombarding energy due to the increase of the parton fraction

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys.Rev. C85 (2012) 044922

v_2/ε vs. centrality at different collision energies

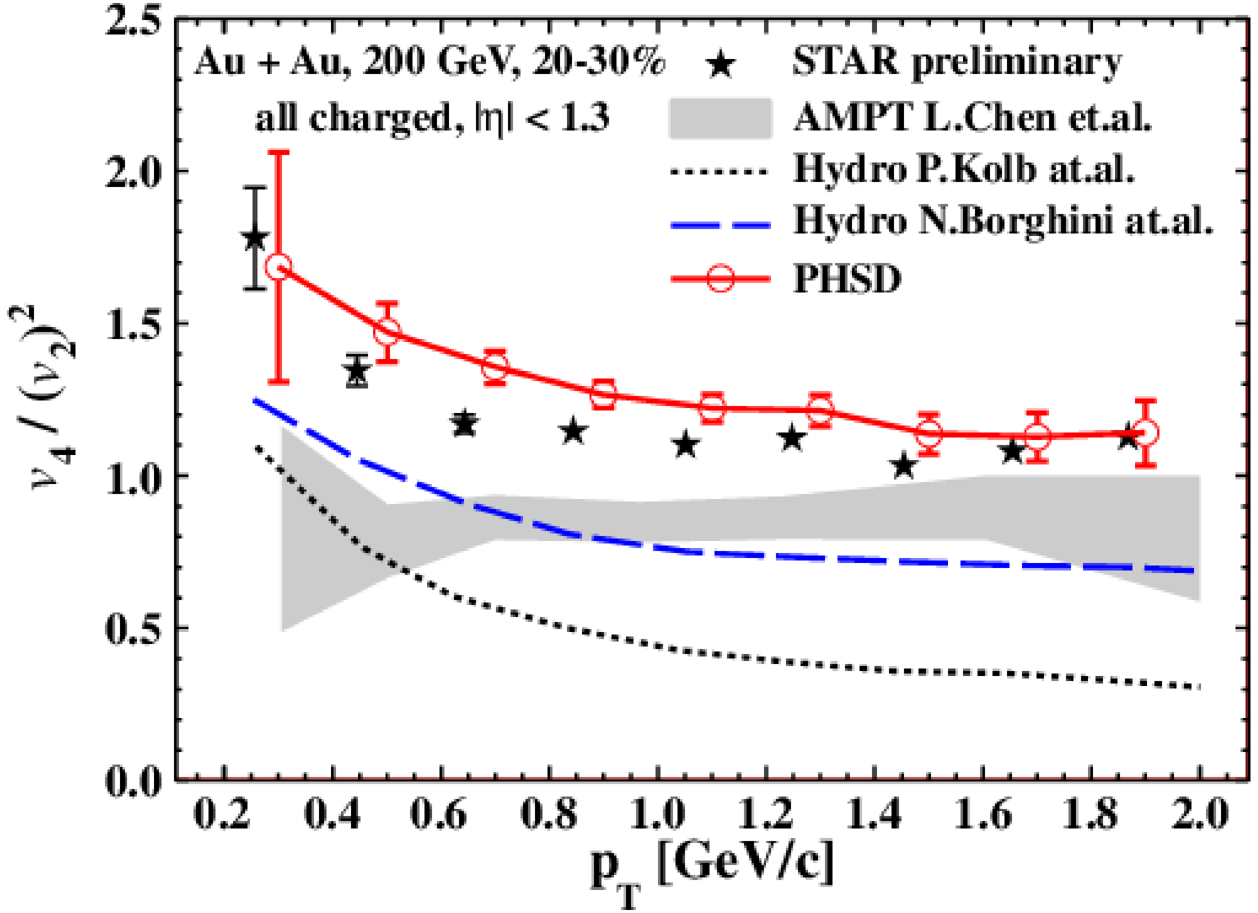




- **PHSD: v_2/ε vs. centrality follows an approximate scaling with energy in line with experimental data**

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys.Rev. C85 (2012) 044922

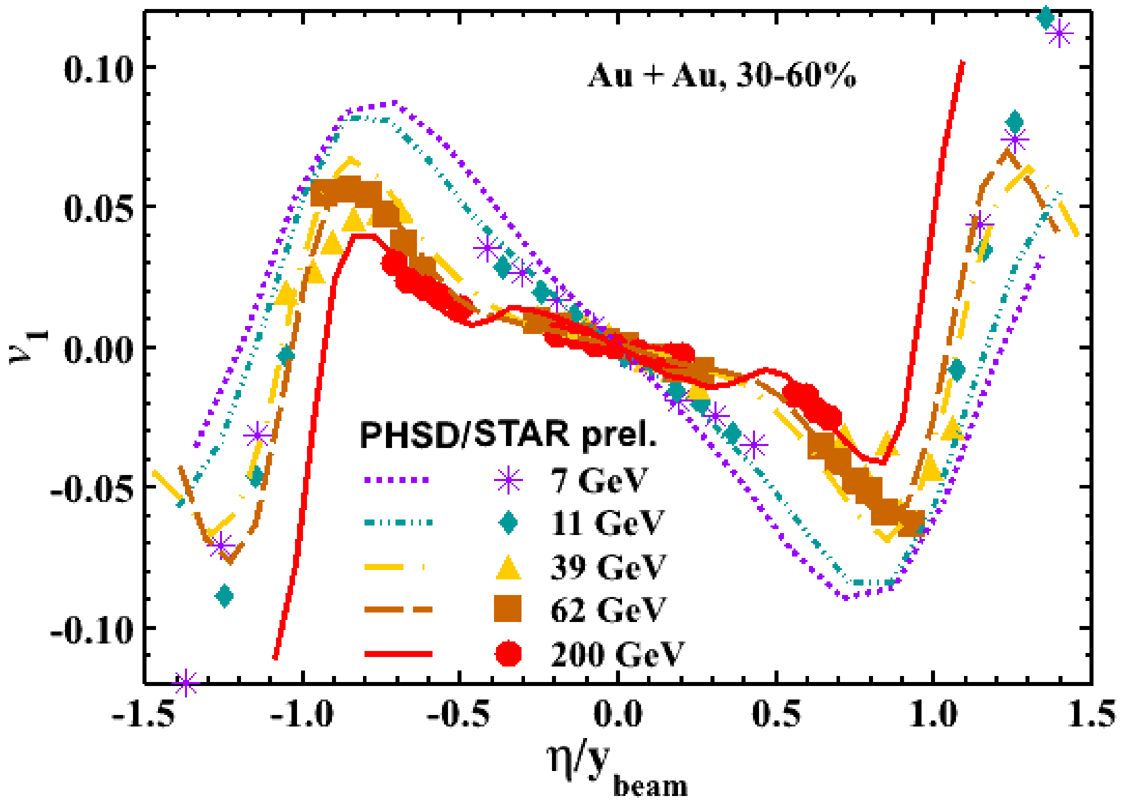
Ratio $v_4/(v_2)^2$ vs. p_T



- The ratio $v_4/(v_2)^2$ from PHSD grows at low p_T - in line with exp. data

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys.Rev. C85 (2012) 044922

v_1 vs. pseudo-rapidity at different collision energies

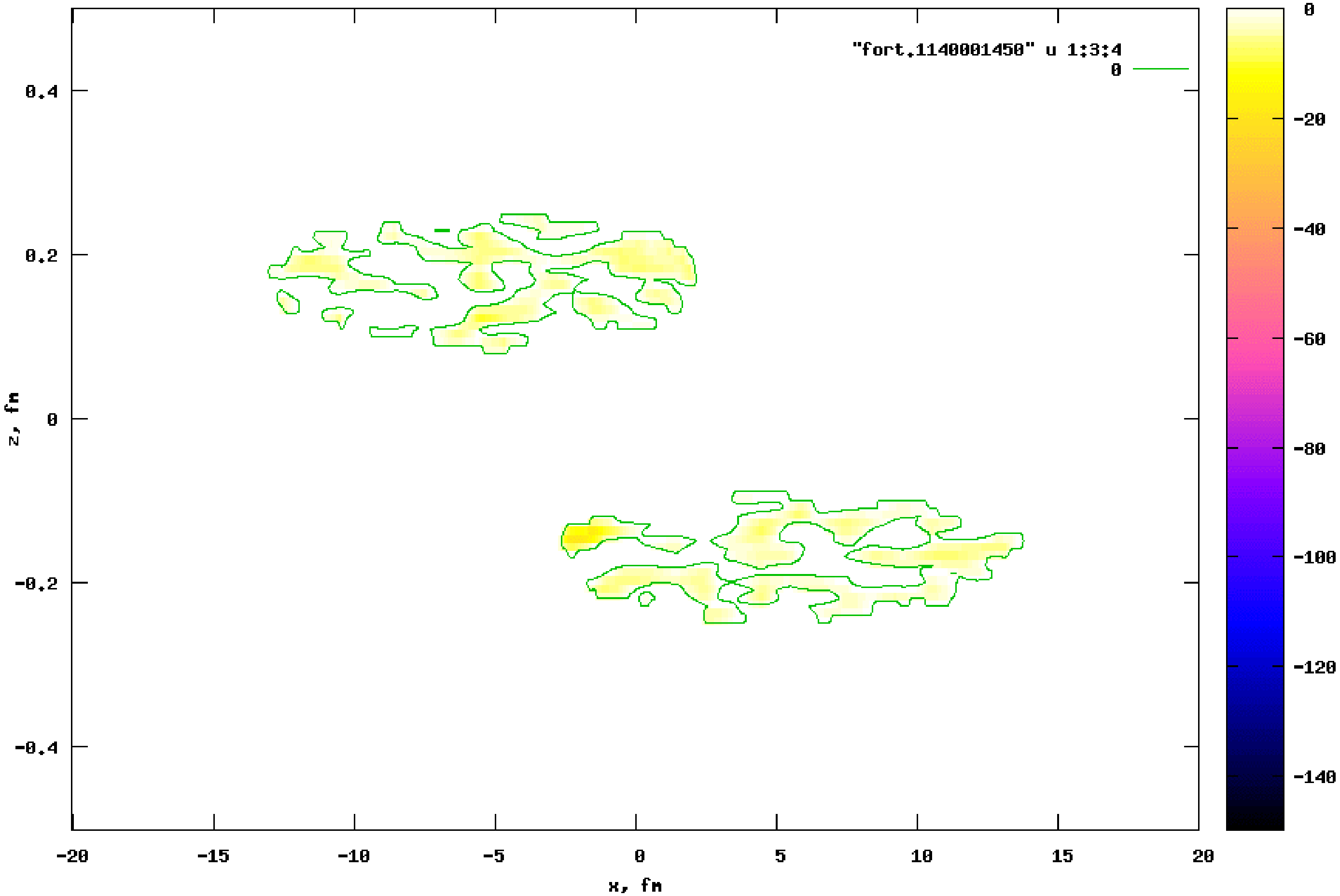


- **PHSD: v_1 vs. pseudo-rapidity follows an approximate scaling for high invariant energies $s^{1/2}$=39, 62, 200 GeV - in line with experimental data – whereas at low energies the scaling is violated!**

V. Konchakovski, E. Bratkovskaya, W. Cassing, V. Toneev, V. Voronyuk, Phys.Rev. C85 (2012) 044922

‚Turbulence' in heavy-ion collisions

- **Au+Au @ $s^{1/2}$=200 GeV :** **rotating charge density**



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)
  jet suppression
  …

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

⇒ formation of the sQGP established!

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