Workshop on QCD Thermalization

(In place of a) Summary

Vienna: 10 - 12 August 2005

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PHENOMENOLOGY

Probes of thermalization

- Particle p_T spectra
- Hadron yields
  - Rafelski, Cleymans
- Collective flow
  - Ma, Hirano, Csernai, Borghini, Lacey, Grassi
- Heavy quarks (D, J/Ψ, etc.)
  - Nagle, Thews
- Jets, photons, and other hard probes
  - Cole, Odyniec

A few "obvious" remarks

- Matter created in a heavy ion collision cannot be *truly* thermal. Perfect thermalization requires either gravity or a static, confining box.
- If a QGP is formed, J/Ψ regeneration must occur, the question is how much. Any set of kinetic mechanisms will bring the number of J/Ψ closer to equilibrium.
- Deviations of data from predictions can be a sign of real physics (such as incomplete equilibration) or of the inadequacy of model assumptions.

3-D Hydrodynamics

- 3-D relativistic hydro codes with sophisticated freeze-out modeling are becoming state of the art.
- Microscopic treatment of hadronic phase unavoidable.
- Need to understand range of admissible initial conditions, EOS, dependence on details of freeze-out treatment.
  - E.g.: How does v_4/v_2^2 depend on α_4/α_2 of initial shape?
- Hydro codes must be applied to systematic studies of AA phenomenology: flow, hadron spectra, imbedded hard probes (photons, jets, charm).
- How far can we go without QGP viscosity? Borghini's study suggests that *Kn* > 0 effects are still sizable at RHIC.
  - Prediction and test: v_2 still grows at LHC !

(MICROSCOPIC)

TRANSPORT THEORY

Parton transport

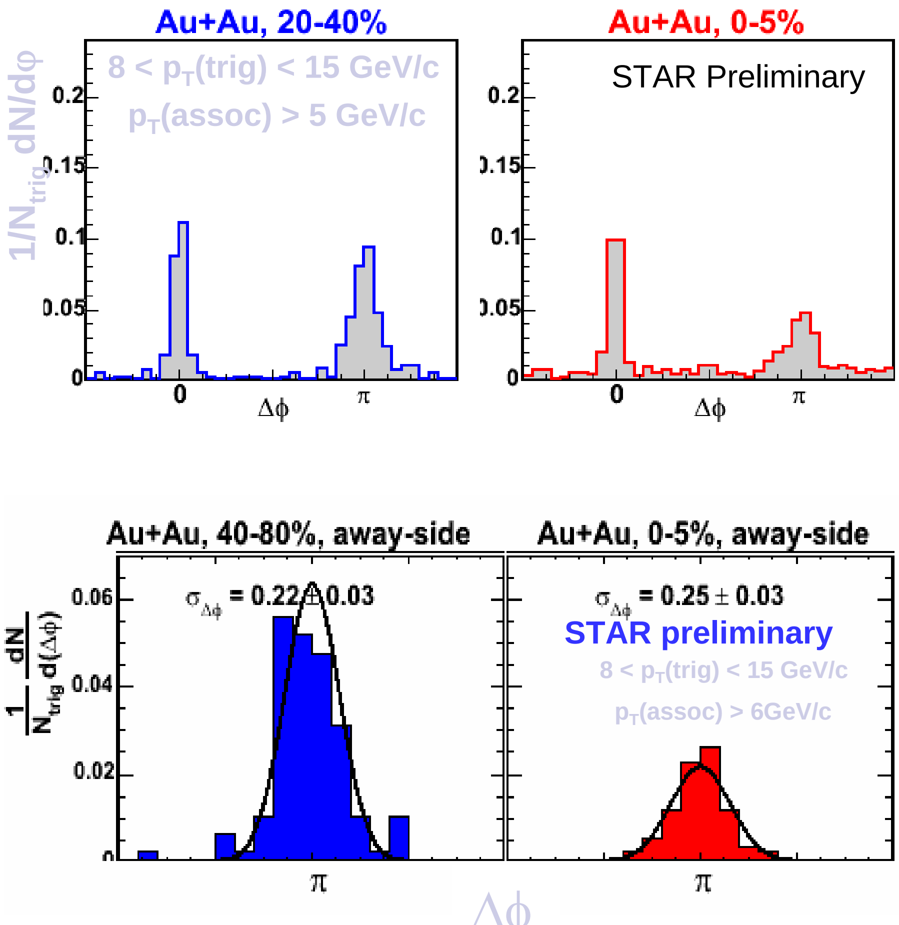
- Parton cascade with *gg* $\leftrightarrow$ *ggg* and detailed balance equilibrates remarkably rapidly (Xu, Xu).
  - More efficient than σ_{tr} would naively suggest.
  - Do calculation in weak coupling limit to check whether it agrees with the "bottom-up" scenario. If not, why not ?

- Connection between shear viscosity and charm energy loss / flow (Teaney). Collisional Langevin equation for charm quark:

$$\frac{dp}{dt} = \eta_D p + \xi(t) \quad \text{with} \quad \eta_D = \frac{T}{MD}, \left\langle \xi_i(t)\xi_k(t') \right\rangle = \frac{2T^2}{3D}\delta_{ik}\delta(t-t')$$

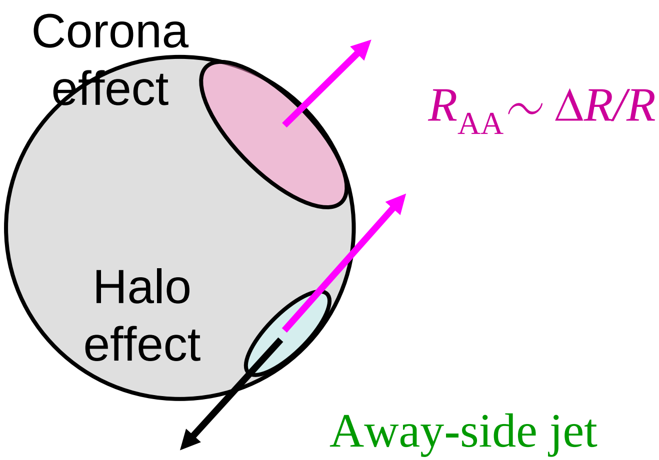
$$\text{pQCD:} \quad D \approx \frac{6}{8\pi\alpha_s^2 T} \approx 6\frac{\eta}{sT} \xrightarrow[\text{Data}]{\text{PHENIX}} D = \frac{3\cdots 6}{2\pi T} \Leftrightarrow \frac{\eta}{s} = \frac{1\cdots 2}{4\pi}$$

Away-side jets



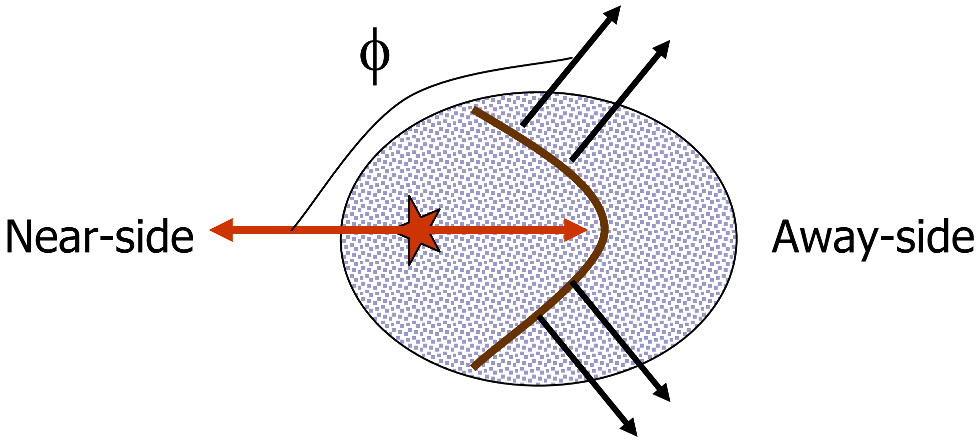
STAR result: di-jet suppression

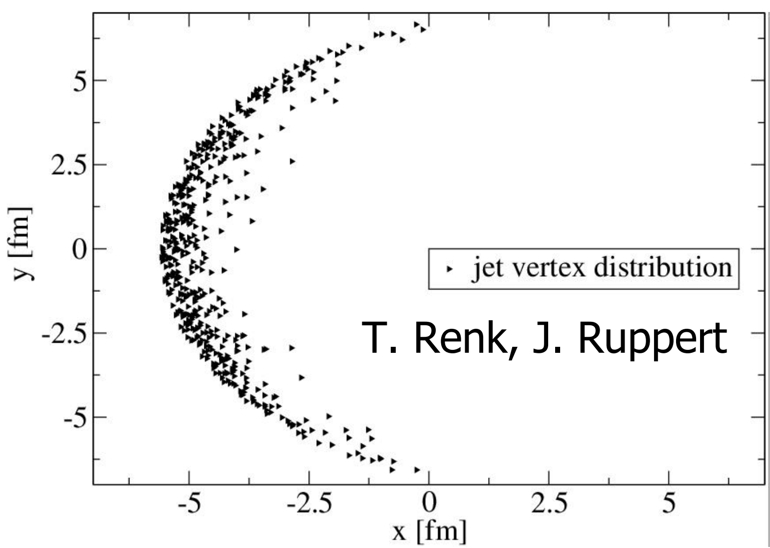
$$R_{AA} \approx I_{AA} \approx 0.23$$

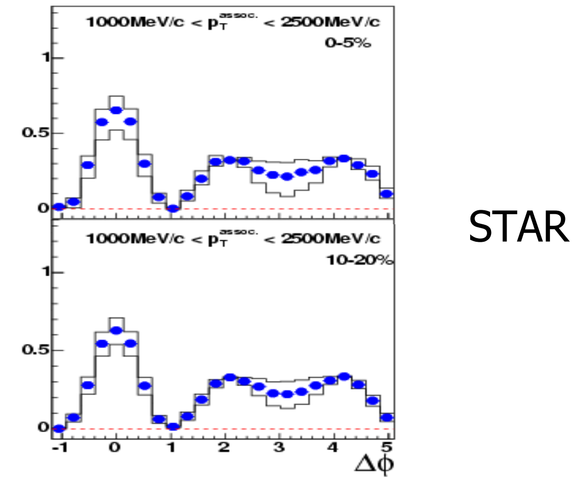


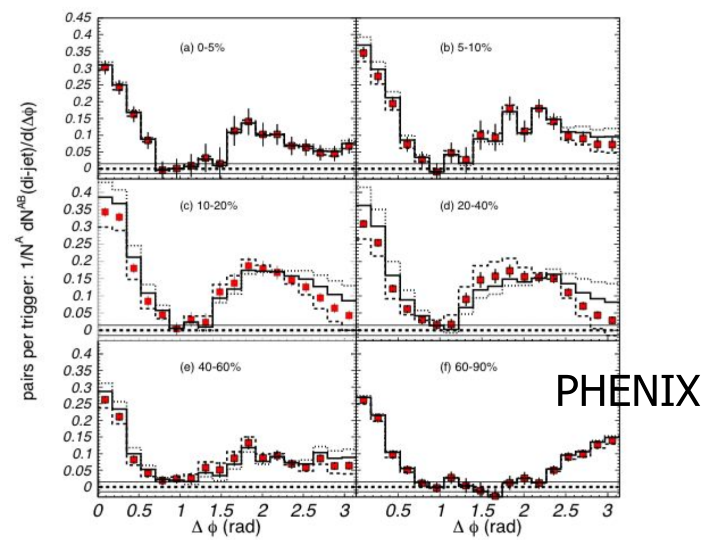
$$I_{AA} = R_{AA}^{\text{dijet}} / R_{AA} \sim \Delta R / R$$

Jet correlations of secondaries







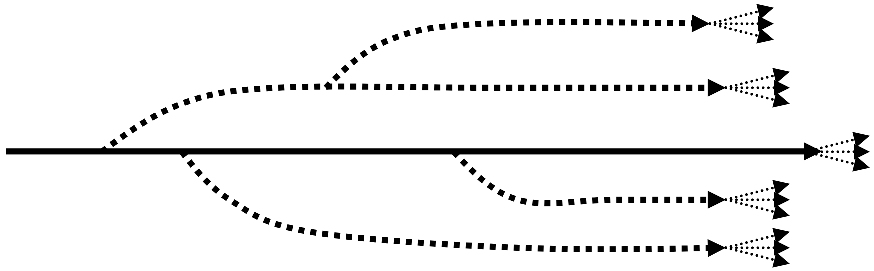


Collective motion or heat ?

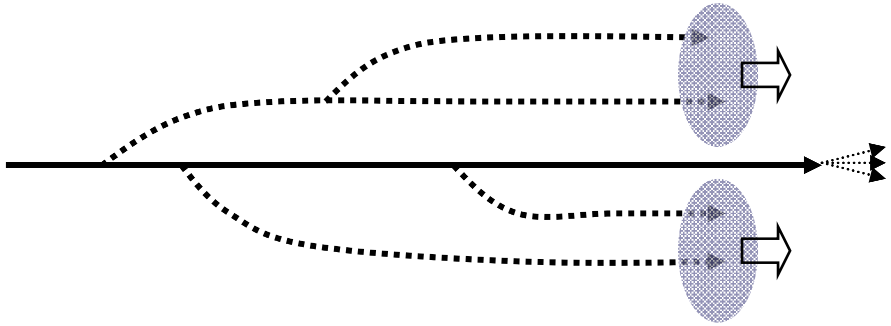
- What happens to the radiated energy?
- Extreme alternatives:
  - The radiation propagates (nearly) frictionless as quasiparticle modes, which may fragment further and eventually hadronize outside the dense medium.
  - The radiation gets absorbed in the medium and heats it locally. The radiated energy and momentum is shared with the absorbing medium.
- General case: $f_{\text{mach}} + f_{\text{heat}} = 1$.

Extreme scenarios

(A)



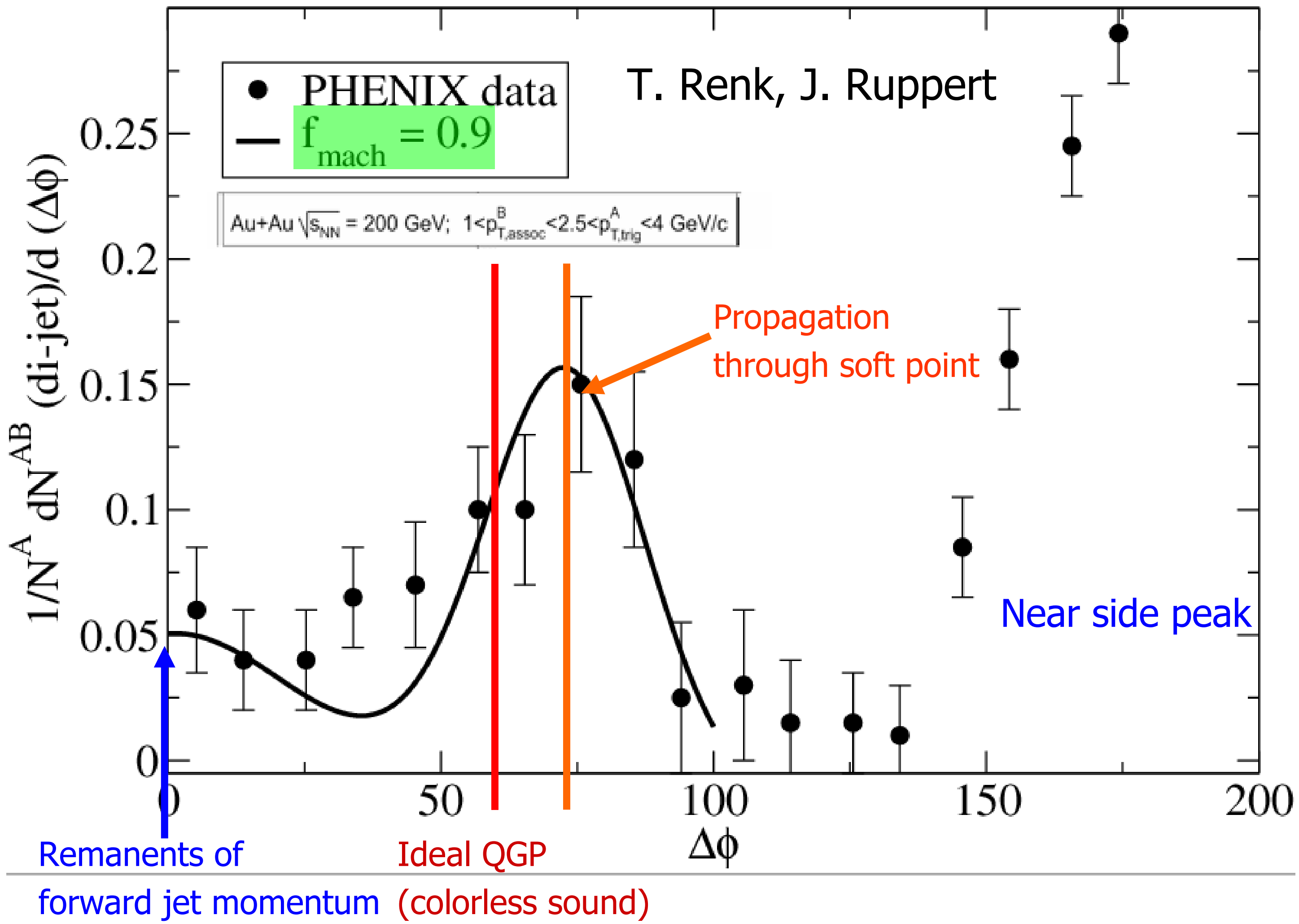
(B)



Mach cones in an evolving medium

- Fireball evolution model describing hadronic m_t spectra, HBT, photon emission and R_{AA} (T. Renk, Phys. Rev. C 70 (2004) 021903)
- Space-time position dependent jet energy deposition
- Fraction f_{mach} of energy deposition into collective mode ("sound")
- Local speed of sound c_s (and fireball thermodynamics) from lattice EOS
- Propagation of sound waves through evolving medium (incl. flow)
- Freeze-out using Cooper-Frye formula
- Monte-Carlo sampling using trigger conditions and acceptance cuts

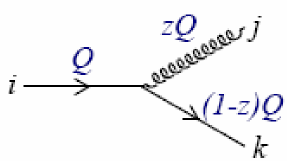
Comparison with data

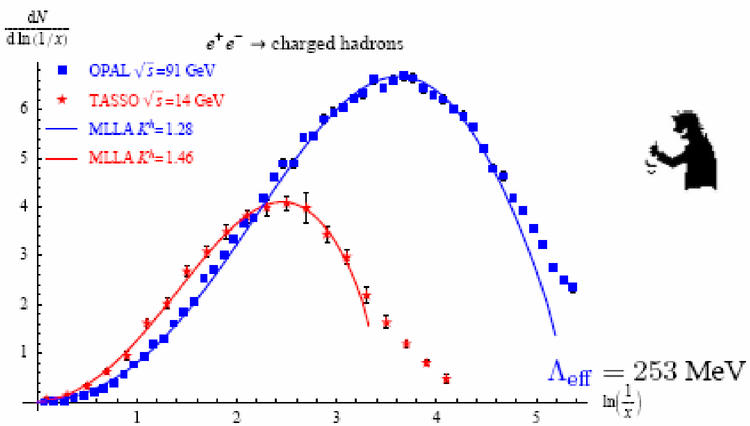


Medium modified MLLA

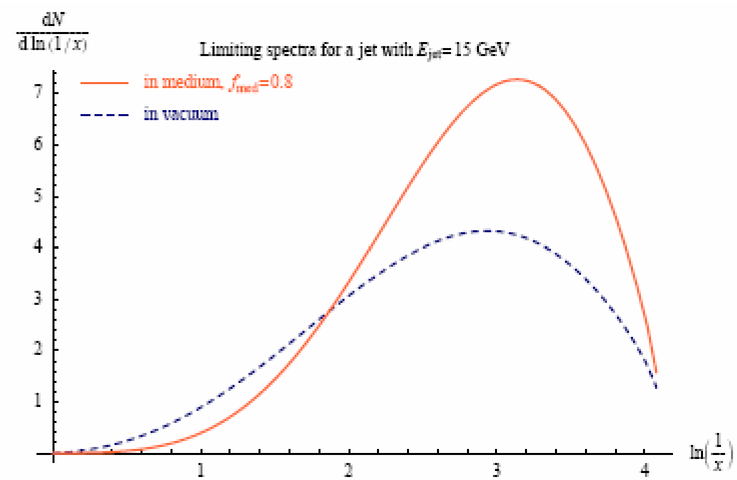
Borghini & Wiedemann

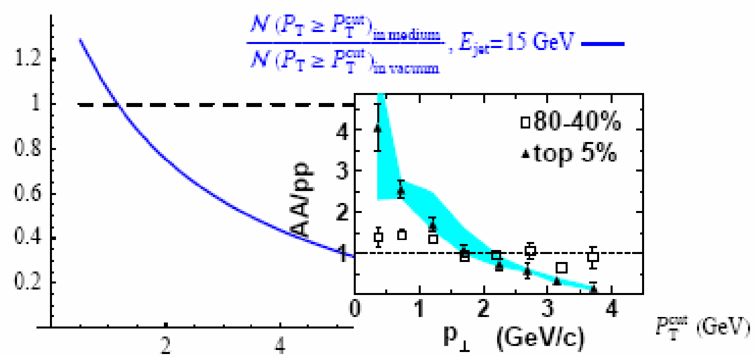
$$Z_i[Q,\Theta;u(k)] = e^{-w_i(Q,\Theta)}\,u(Q) + \sum_j \int^{\Theta} \frac{d\Theta'}{\Theta'} \int_0^1 dz\, e^{w_i(Q,\Theta')-w_i(Q,\Theta)} \frac{\alpha_s(k_\perp)}{2\pi} \times P_{ji}(z)\, Z_j[zQ,\Theta';u]\, Z_k[(1-z)Q,\Theta';u]$$





$$\bar{D}^h(x,\tau,\Lambda_{\rm eff}) = K^h\,\bar{D}^{\rm lim}(x,\tau,\Lambda_{\rm eff})$$





MECHANISMS OF

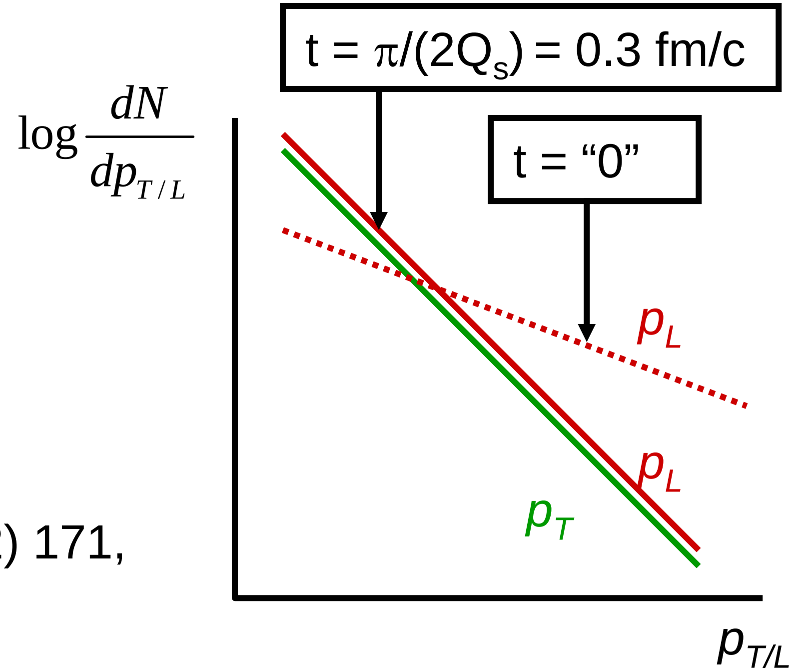
THERMALIZATION

Thermalization

- Matters of principle
  - Kovchegov
- Thermalization in (resummed) perturbation theory
  - Mueller, Borsanyi, Arrizabalaga
- Plasma instabilities
  - Moore, Manuel, Nara, Strickland , Romatschke
- Quarks
  - Lappi
- Prethermalization
  - Berges, Kharzeev

Modified BUS

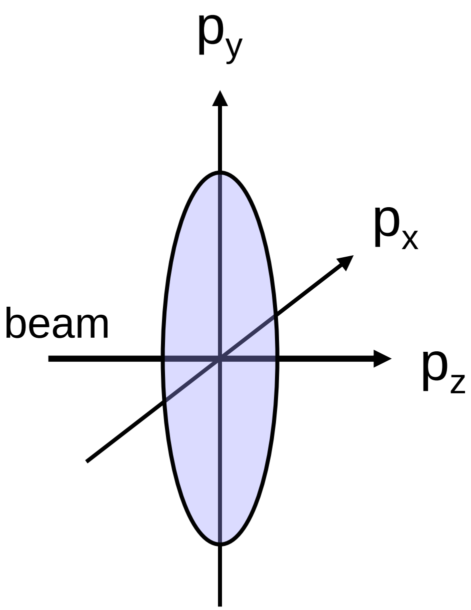
- New scaling solution does not change the parametric dependence of long time tail (depletion of hard partons): $\tau_{th} \sim \alpha_s^{-13/5} Q_s^{-1}$ [~ 6 Q_s^{-1} ~ 1 fm/c for α_s = 0.5 !]
- But what is the initial time?



Biro et al., PLB 283 (1992) 171, PRC 48 (1993) 1275

Color instabilities

Unstable modes occur generally due to the anisotropy of the momentum distribution:



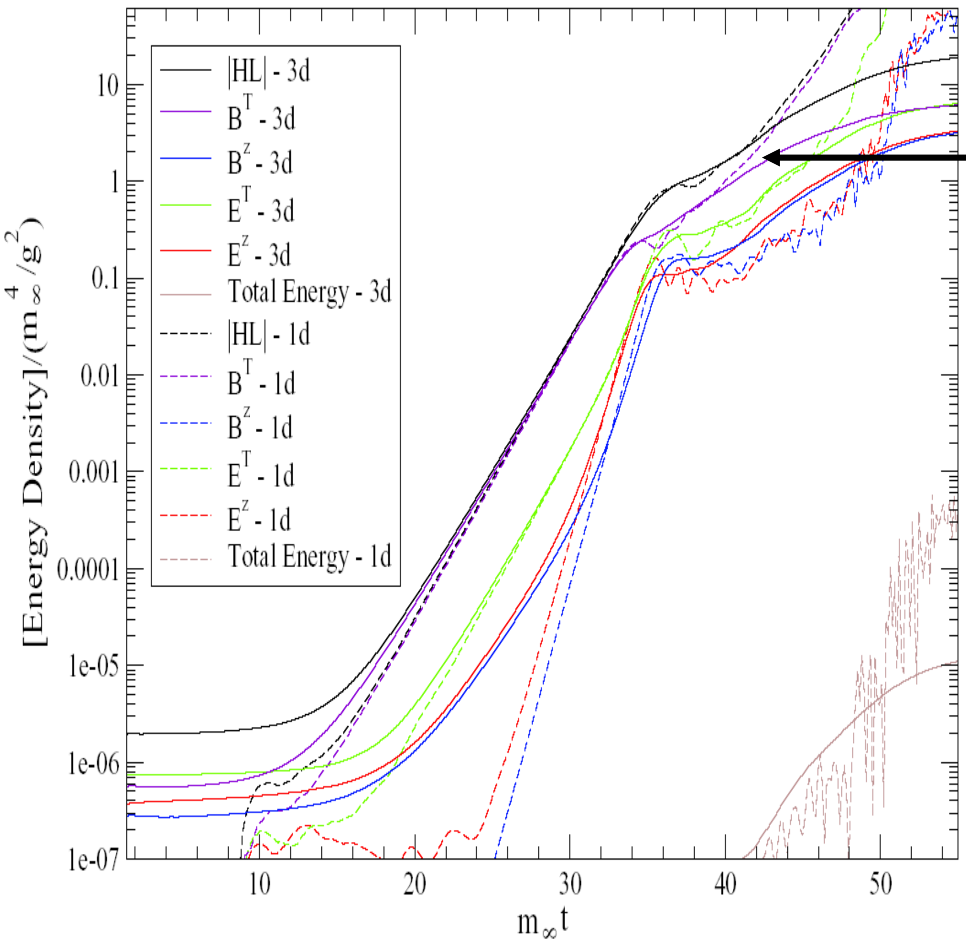
$$\left\langle (\Delta p_x)^2 \right\rangle = \left\langle (\Delta p_y)^2 \right\rangle = Q_s^2 \gg \left\langle (\Delta p_z)^2 \right\rangle \quad \text{for} \quad \tau \gg \frac{1}{Q_s}$$

Wavelength and growth rate of unstable modes can be calculated perturbatively:

$$k_z \sim gQ_s \,, \quad \gamma \sim gQ_s < k_z$$

Moore, Strickland, Dumitru, Manuel

Color instabilities (2)



Exponential growth moderates when

$B^2 > g^2 Q_s^4$, $g^2 T^4$.

Force = g **v** × **B** = d**p**/dt

$$\Delta p \sim p \quad \text{for} \quad t = t_{\text{iso}}$$

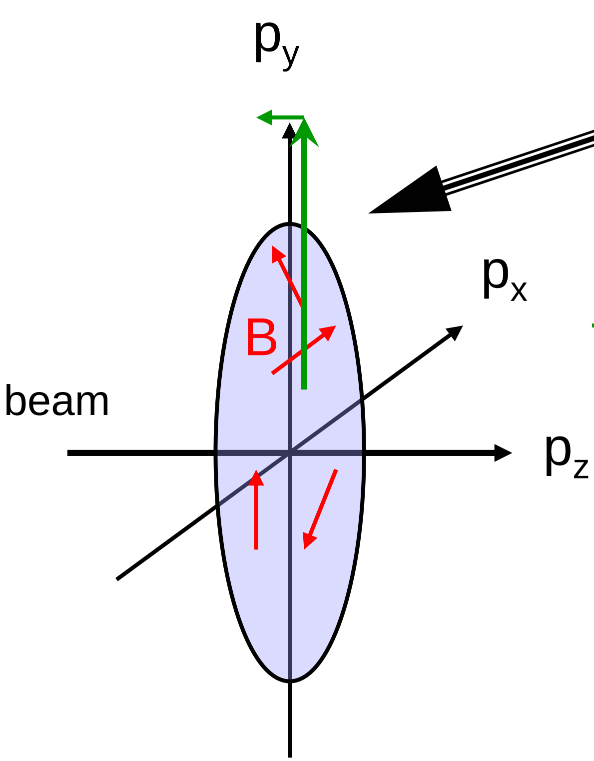
$$t_{\text{iso}}^{-1} \sim \frac{gB}{p} \sim g^2 Q_s,\, g^2 T$$

Note: $t_{iso}^{-1} \sim (dS/dt)/S \sim \lambda$

in classical gauge fields

Color instabilities (3)

1. Do longitudinal instabilities persist, if “hard” particles are replaced by “hard” classical color fields? Maybe not (Romatschke, but see: W. Pöschl & BM, CPC 125 (2000) 282, PRD 60 (99) 114505).



2. Are the cla

- v_2 flu
- $r_\eta >$ r

SU(2) weak coupling:

gA2 << kA

3. Fields v
counterac):

Effective ics
(CMHD) ((?)

REAL TIME DYNAMICS OF COLLIDING GAUGE . . . PHYSICAL REVIEW D 60 114505

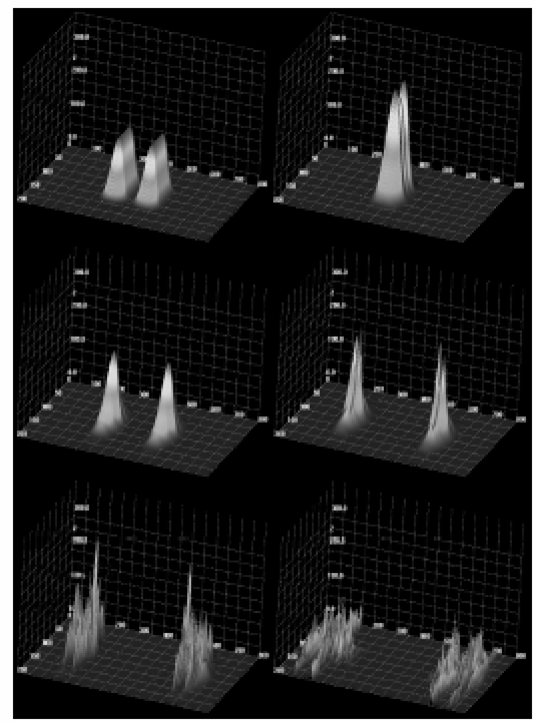


FIG. 8. The transverse color electric field energy density $w_\perp^{(E)}(t,x_1,x_2)$ is shown for six selected snapshots taken at the time steps [illegible], and [illegible]. The corresponding pictures are ordered from the upper left to the lower right.

THE STRUCTURE OF

THERMAL QCD MATTER

The QGP near T_c

- Perturbative analysis of QGP for $T \geq 2-3T_c$ has been achieved by loop expansion around HTL quasiparticles (Blaizot, Iancu, Rebhan; Andersen, Braaten, Strickland). What happens nearer to T_c ?
- Are there quasiparticles with $\Gamma < M$? If so, what are these quasiparticles? Is there short- or long-range order?
- Pair correlation function, e.g. $g(r) = \langle \psi^+(0)\psi(0)\psi^+(r)\psi(r)\rangle$ could show a small *peak* at r=0 for moderate coupling, because of attractive channels.

The SUSY connection

- A challenge to physicists:
  - What is the limit of perfection?
  - Strong coupling limit of N = 4 SYM (Starinets):

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + + \frac{135\,\zeta(3)}{8(2g^2 N_c)^{3/2}}\right)$$

  - Does limit apply to QCD ?
  - No long-range structure formation in SYM (no large mass scale compared with *T*).

QCD molecular dynamics?

$$\frac{dp_i^\mu}{d\tau} = gQ_i^a F^{a\mu\nu} \mathrm{v}_{i\nu} \quad \oplus \quad \frac{dQ_i^a}{d\tau} = g f_{abc} A^{a\mu} Q_i^c \mathrm{v}_{i\mu}$$

$$\partial_\mu F^{a\mu\nu} = j^{a\nu} \equiv \int d\tau \sum_i g Q_i^a \mathrm{v}_i^\nu \delta\left(x - \xi_i(\tau)\right)$$

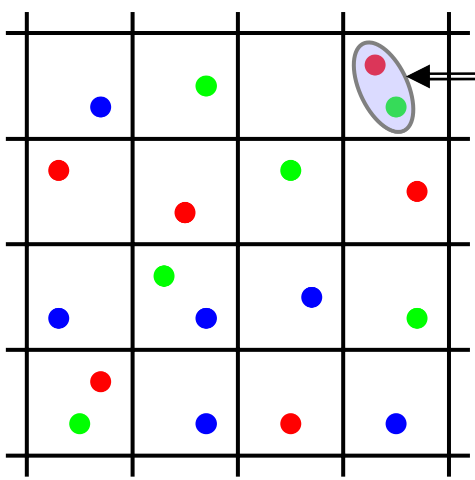
Wong

Heinz

Shuryak

Reproduces HTL pert. th. at weak coupling (Kelly, Liu, Lucchesi, Manuel)

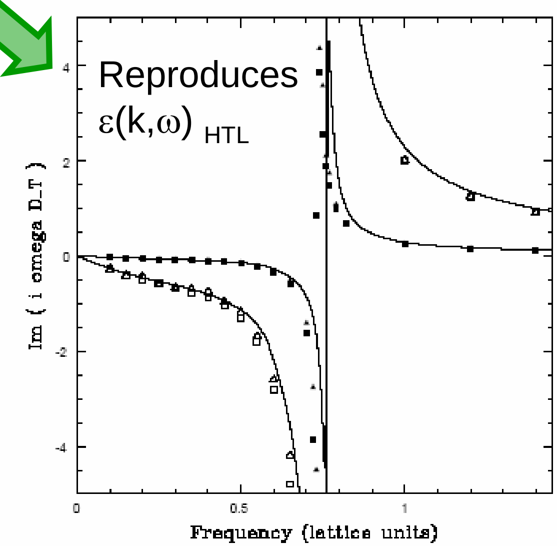
Lattice/particle formulation exists (Hu, BM, Moore - Dumitru, Nara)



Collisions of particles within the same cell could be easily added

“Well suited” for studies of equilibrium properties

(problems with transport)



Participants of QCD-TH @ Vienna