Signals of QGP instabilities and plasma isotropization

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Plasma anisotropies and signatures of instabilities

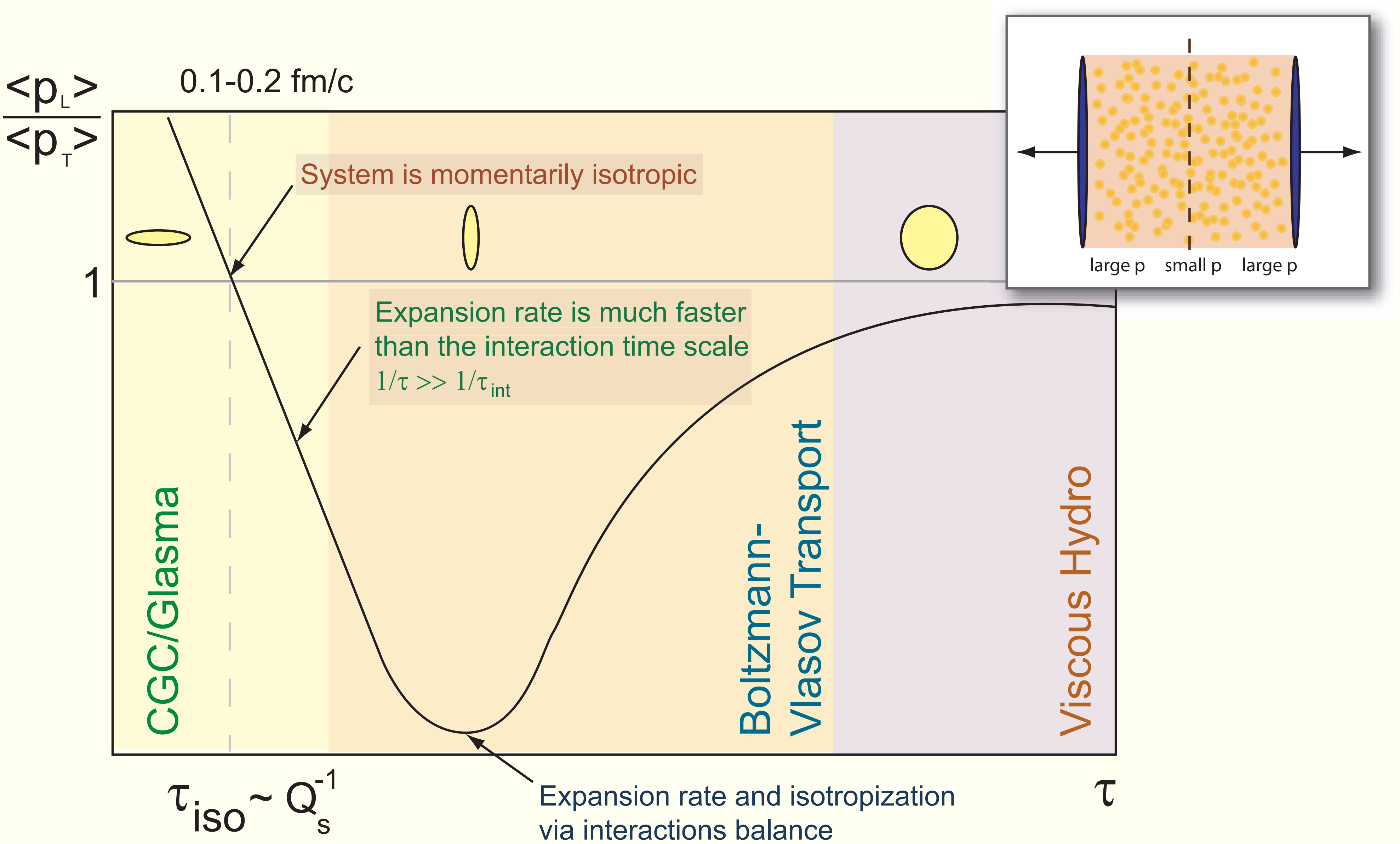
- The fact that ideal hydro seems to describe v_2 so well seems to imply early isotropization (and possibly thermalization).
- But this observable seems to be dependent on the late-time evolution of the plasma (eg, viscous hadronic phase), final-state interactions, etc.
- It would be nice to have other observables which could further constrain the physics at early times (ideally not dependent on fully 3d viscous hydro simulations + hadronic cascade + . . .).
- The catch-22 of thermalization:

If complete thermalization is achieved (and maintained) then subsequent emissions are independent of the initial condition and how precisely thermalization was achieved. So . . .

Signatures of non-equilibrium QGP evolution (cntd)

- We therefore have to concentrate observables which are sensitive to early times in the collision, $\tau \lesssim 1$ fm/c. Four natural candidates are: event-by-event fluctuations, jet broadening, dilepton emission, and photon emission.
- High-energy jets can act as “test particles” probing the properties of the medium at early times.
- Photons and dileptons give us clean electromagnetic signals which can hopefully be used to map out the early stages of plasma evolution.
- Can we determine from these observables when/if the system becomes locally isotropic in momentum space or, beyond that, thermal?
- Is there an alternative explanation for the seemingly small viscosity of the matter generated at RHIC which does not invoke strong-coupling AdS/CFT $\leftrightarrow$ QCD analogies?

Momentum Space Anisotropy Time Dependence

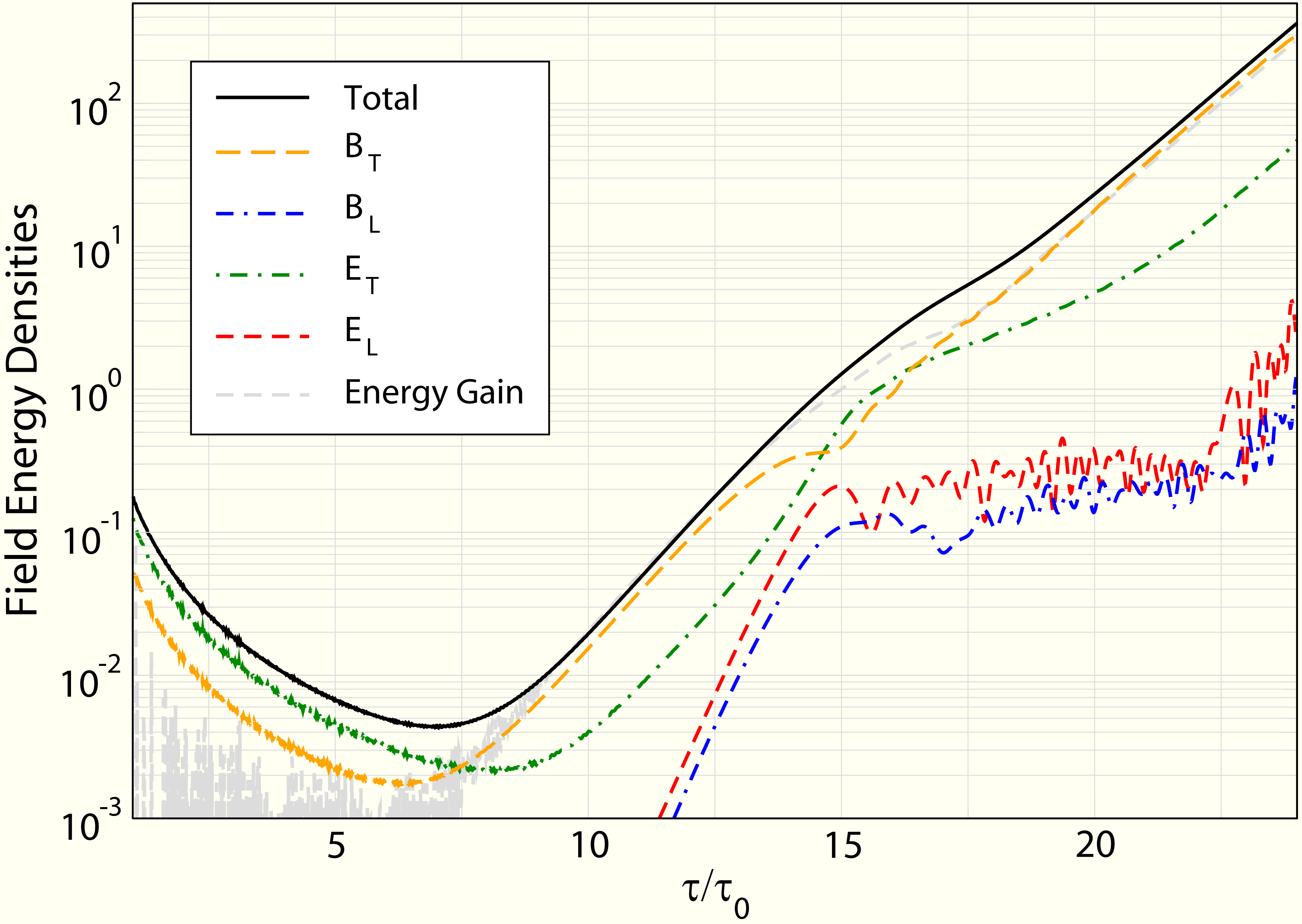


System is momentarily isotropic

Expansion rate is much faster than the interaction time scale $1/\tau >> 1/\tau_{int}$

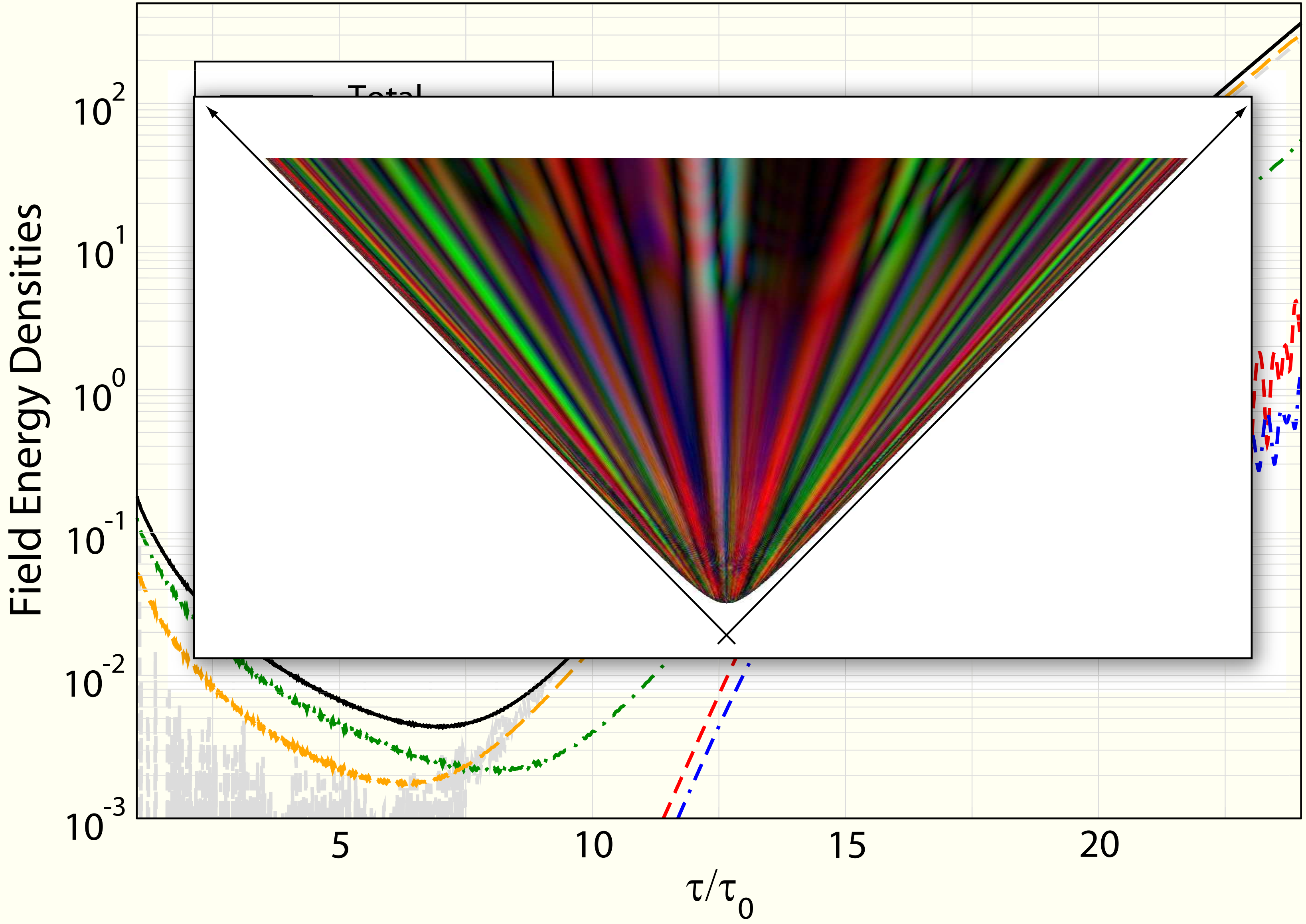
Expansion rate and isotropization via interactions balance

Expansion dynamically generates large chromo fields



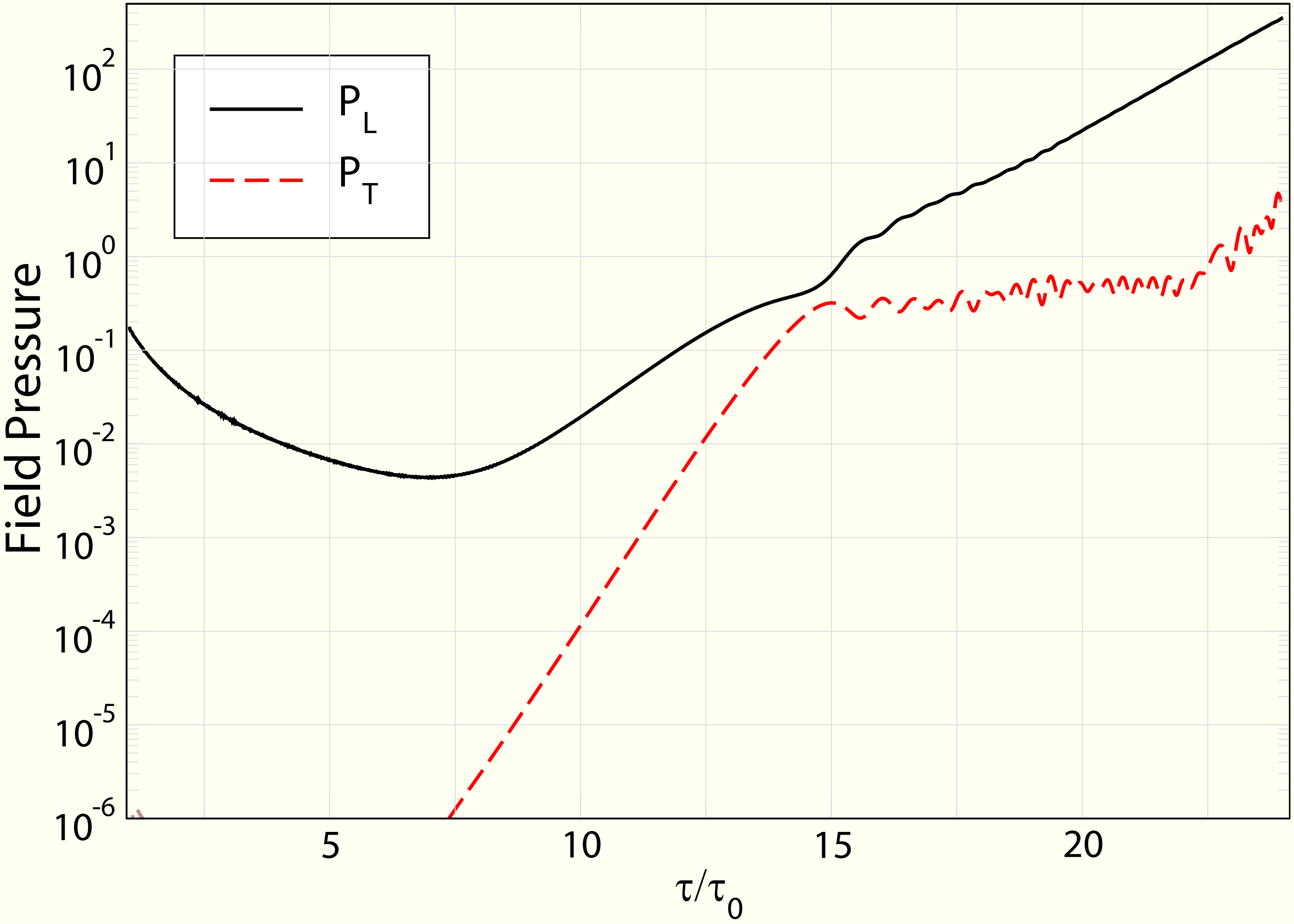
Non-abelian Hard-Expanding-Loops, A. Rebhan, MS, and M. Attems, forthcoming

Expansion dynamically generates correlated fields



Non-abelian Hard-Expanding-Loops, A. Rebhan, MS, and M. Attems, forthcoming

Resulting chromo-fields generate longitudinal pressure

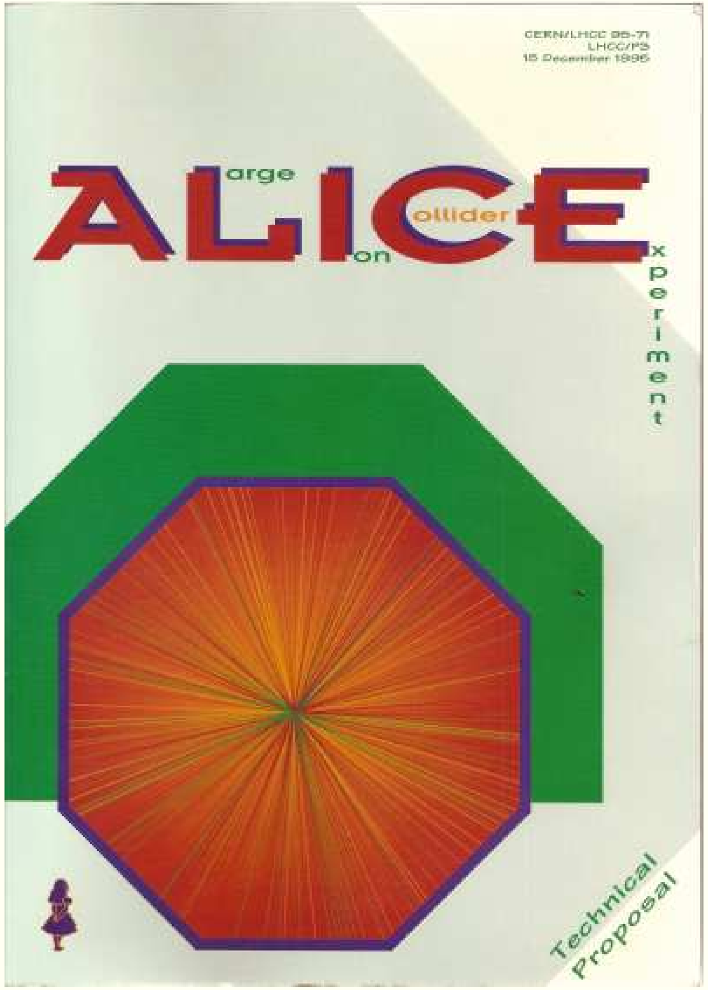


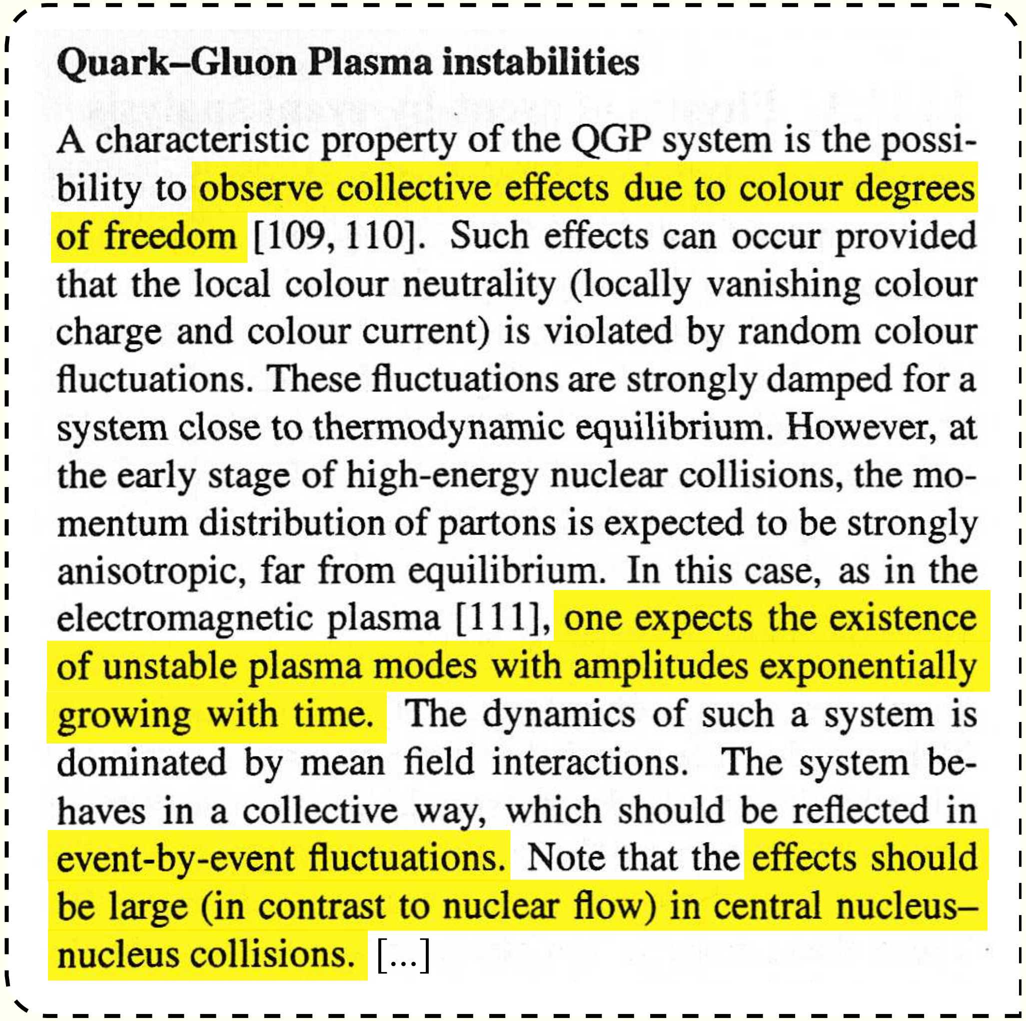
Non-abelian Hard-Expanding-Loops, A. Rebhan, MS, and M. Attems, forthcoming

- Event-by-Event Fluctuations -

Event-by-Event Fluctuations

The original proposal for possible signatures of plasma instabilities was large event-by-event azimuthal fluctuations.



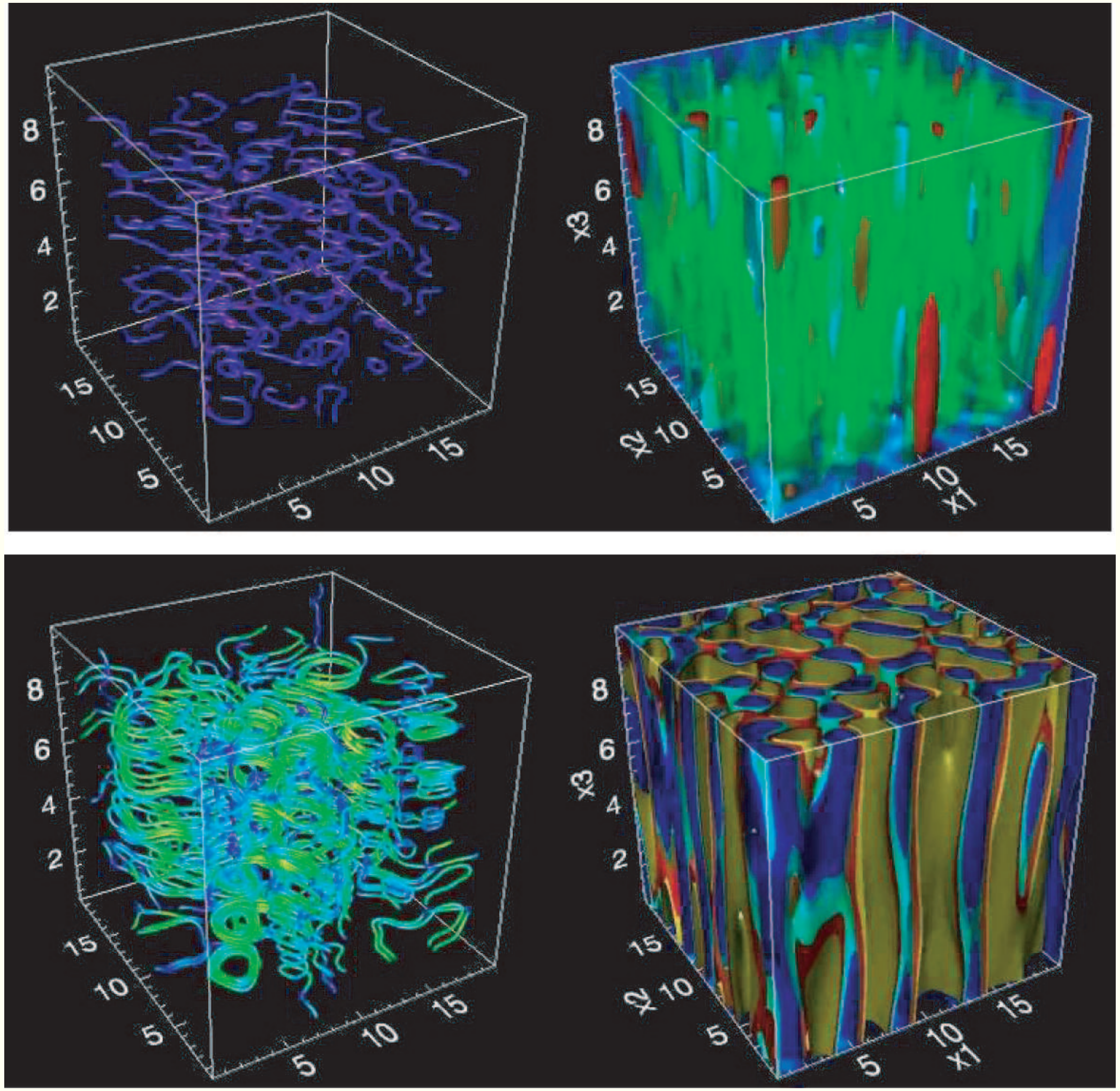


Quark–Gluon Plasma instabilities

A characteristic property of the QGP system is the possibility to observe collective effects due to colour degrees of freedom [109, 110]. Such effects can occur provided that the local colour neutrality (locally vanishing colour charge and colour current) is violated by random colour fluctuations. These fluctuations are strongly damped for a system close to thermodynamic equilibrium. However, at the early stage of high-energy nuclear collisions, the momentum distribution of partons is expected to be strongly anisotropic, far from equilibrium. In this case, as in the electromagnetic plasma [111], one expects the existence of unstable plasma modes with amplitudes exponentially growing with time. The dynamics of such a system is dominated by mean field interactions. The system behaves in a collective way, which should be reflected in event-by-event fluctuations. Note that the effects should be large (in contrast to nuclear flow) in central nucleus–nucleus collisions. [...]

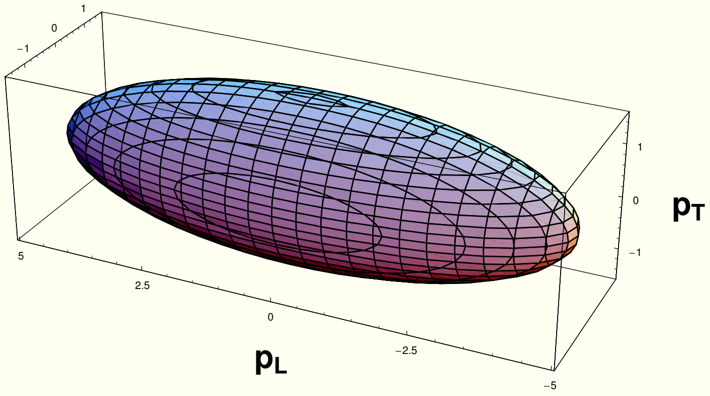
St. Mrowczynski and M. Gazdzicki, Alice Technical Proposal, CERN/LHCC/95-71 LHCC/P3, 194 (1995).

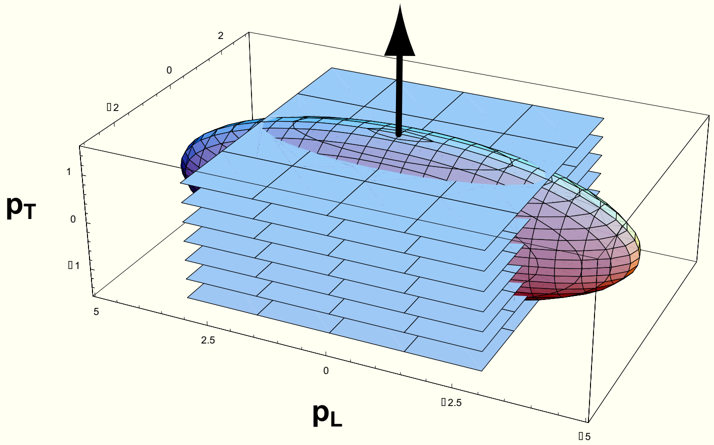
Particle correlations due to instabilities

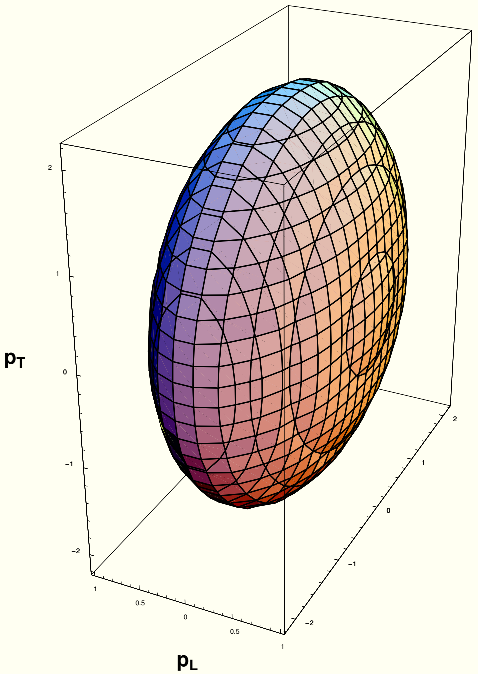


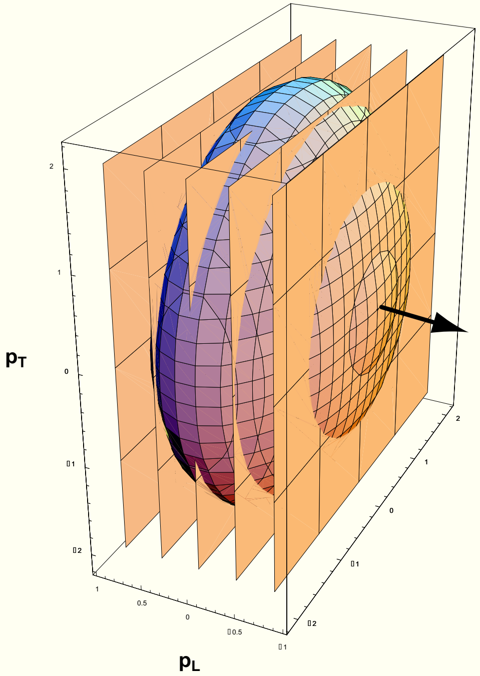
“Generation of Magnetic Fields in Cosmological Shocks”, Medvedev, et al, Journal of the Korean Astr. Soc. 37 (5), 533 (2004).

Sausage vs Pancake









Perhaps there’s a comprimise?

Azimuthal Fluctuations?

- This flow fluctuation would appear also in central collisions. Event-by-event direction of the correlation in ϕ would be random.
- Bad news: there are currently no quantitative estimates of the size of azimuthal fluctuations due to non-abelian plasma instabilities. Detailed analytical and numerical studies are required.
- It’s not clear that correlated “abelianized” field configurations would be obtained in a heavy-ion collision. 3d simulations of non-abelian theories indicate a transition to a *turbulent regime* at late times.
- At RHIC, STAR and PHOBOS results seem to indicate that v2 fluctuations are consistent with initial state ellipticity fluctuations.[†]
- However, both the STAR and PHOBOS results have a dependence on the assumed hydro equation of state indicating that this observable may be sensitive to more than just the initial condition.

[†] STAR, nucl-ex/0612021; PHOBOS, [nucl-ex] 0707.4424v1

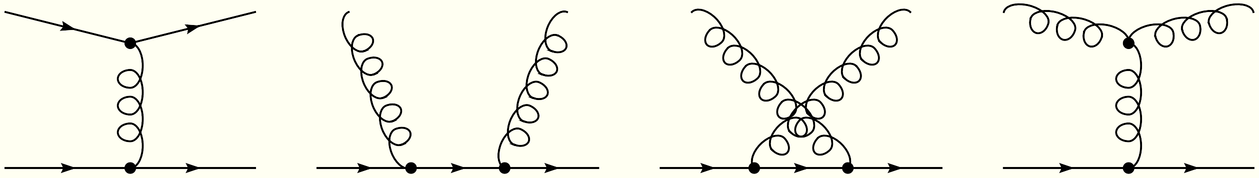
- Jet Energy Loss/Broadening -

Anisotropic heavy quark collisional energy loss

- What is the effect of anisotropic quark/gluon distribution functions on heavy quark energy loss?
- We can split the problem into hard ($p \sim p_{\rm hard}$) and soft ($p \sim g p_{\rm hard}$) contributions.
- The soft contribution is given by the expression

$$-\left(\frac{{\rm d}W}{{\rm d}t}\right)_{\rm soft} = g^2\, C_F \, {\rm Im} \int \frac{d^3\mathbf{q}}{(2\pi)^3} \, (\mathbf{q}\cdot\mathbf{v})\, v^i \left[\Delta^{ij}(Q) - \Delta_0^{ij}(Q)\right] v^j \; ,$$

- The hard contribution is given by evaluating these diagrams

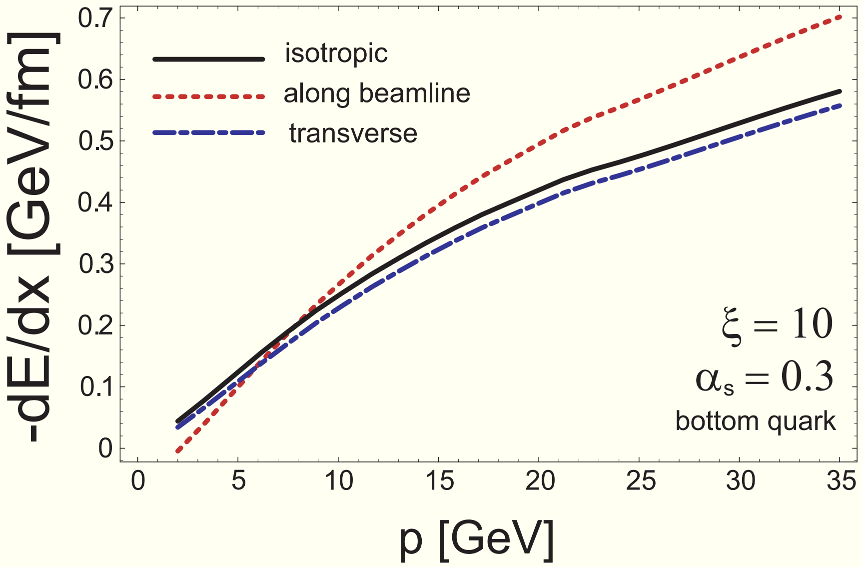


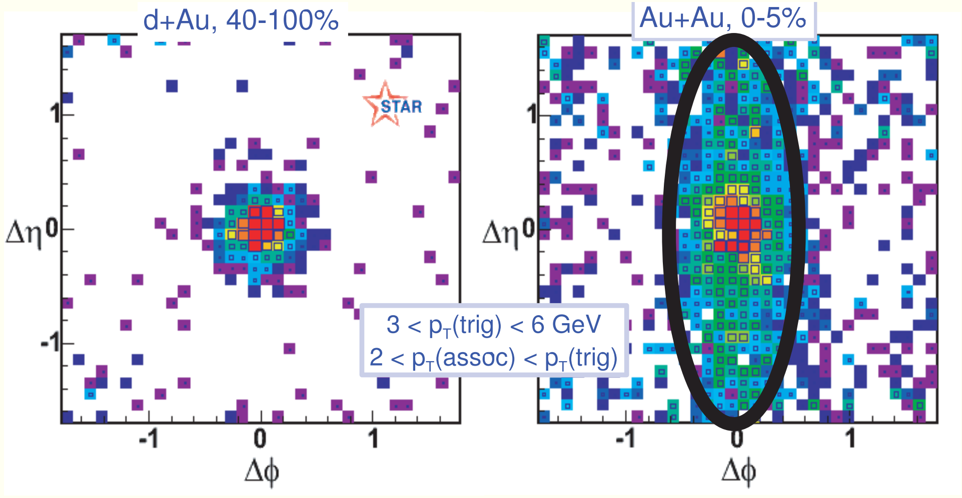
Michael Strickland

P. Romatschke and MS, hep-ph/0408275

Collisional Energy Loss Results

In an anisotropic plasma the collisional energy loss depends on the direction of propagation of the jet.





$$\frac{d}{dt}\langle p\rangle = -p\,\eta_D(p) \qquad \frac{d}{dt}\langle(\Delta p_{||})^2\rangle = \kappa_{||}(p)$$

$$\frac{d}{dt}\langle(\Delta p_\perp)^2\rangle = \kappa_\perp(p) \qquad \frac{d}{dt}\langle(\Delta p_z)^2\rangle = \kappa_z(p),$$

[left] P. Romatschke and MS, hep-ph/0408275; P. Romatschke, hep-ph/0607327; [right] Experiment nucl-ex/0509030, nucl-ex/0503022.

Including radiative energy loss

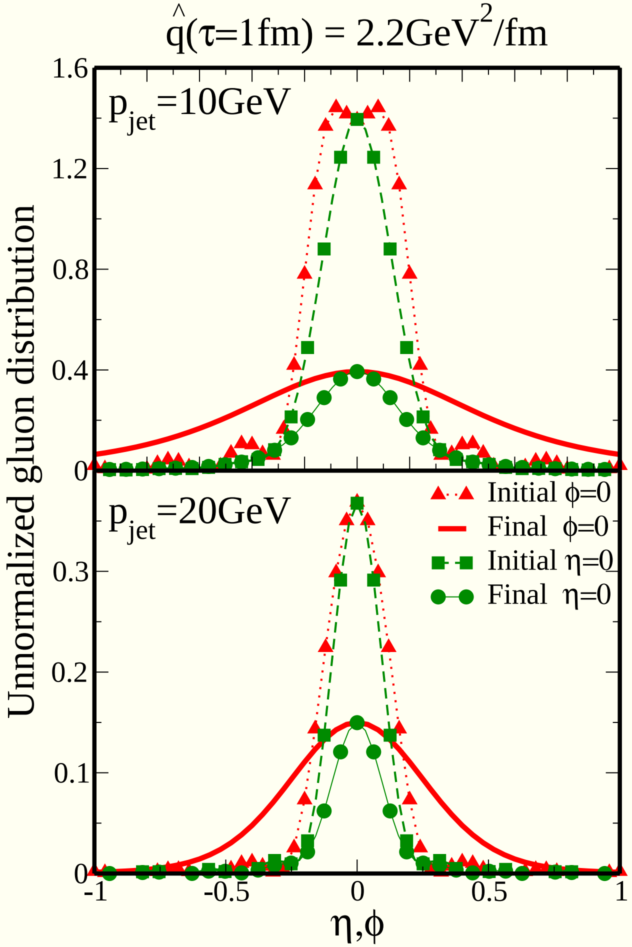
Majumder, Müller, and Bass (hep-ph/0611135) assume a background of large-amplitude transverse chromo-magnetic fields and then can calculate the energy loss of a heavy quark traversing this medium to NLO.

$$\left[\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla_r - \nabla_p D(\mathbf{p},t)\nabla_p\right]\bar{f} = C[\bar{f}]$$

with

$$D_{ij} = \int_{-\infty}^{t} dt' \left\langle F_i(\bar{r}(t'),t')F_j(\bar{r}(t),t)\right\rangle$$

$\mathbf{F} = gQ^a(\mathbf{E}^a + \mathbf{v}\times\mathbf{B}^a)$ is the color Lorentz force generated by the turbulent color fields, and $C[f]$ denotes the collision term.



3D Colored-Particle-in-Cell Simulations (CPIC)

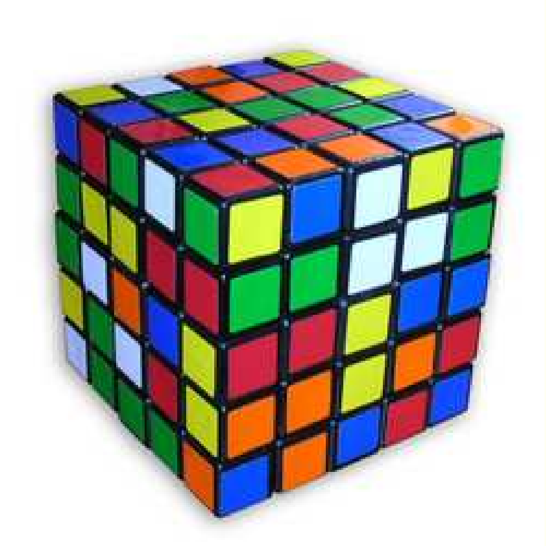
Can also simulate particle-field systems in real-time using 3D Colored-Particle-in-Cell (CPIC) codes. Includes large-angle deflection of particles by their self-generated fields.

Include back-reaction by solving collisional QCD transport equations without linearization

$$p^\mu[\partial_\mu - g q^a F^a_{\mu\nu}\partial^\nu_p - g f_{abc} A^b_\mu q^c \partial_{q^a}] f(x,p,q) = C[f]$$

Coupled to the Yang-Mills equation for the soft gluon fields

$$D_\mu F^{\mu\nu} = J^\nu = g \int \frac{d^3p}{(2\pi)^3} dq\, q\, v^\nu f(t,\boldsymbol{x},\boldsymbol{p},q)$$

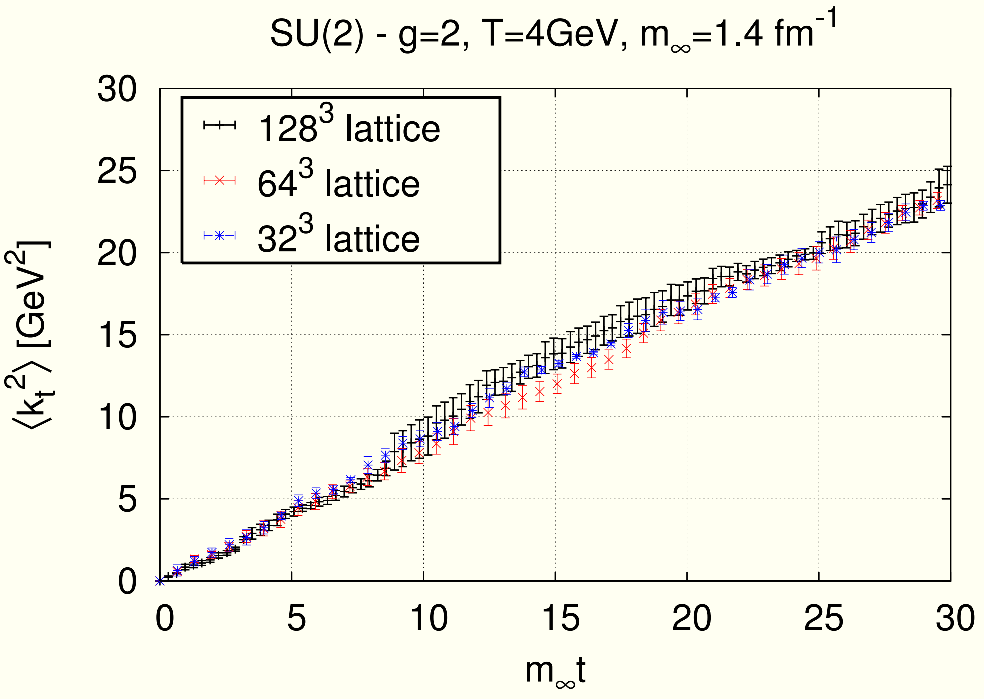


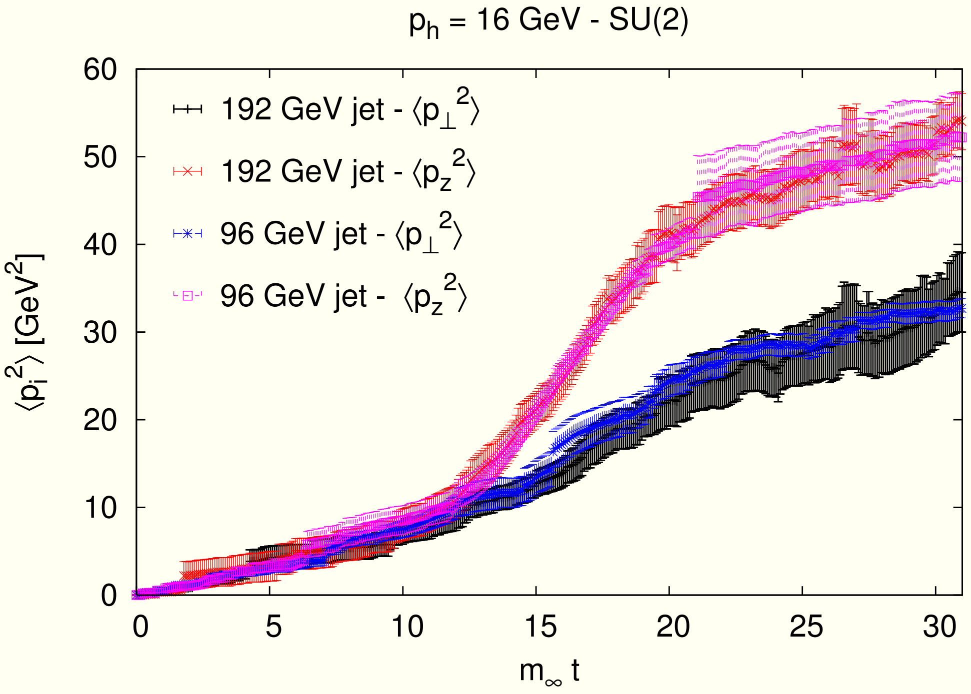
A. Dumitru, Y. Nara, and MS, hep-ph/0604149; A. Dumitru, Y. Nara, B. Schenke, and MS, forthcoming.

Using CPIC to study jet broadening via instabilities

Can use CPIC code to simulate parton transport through self-consistently generated color-field backgrounds!

Jets are modelled as additional high-energy “test particles”. Using this code we can perform real-time measurements of jet (statistical) properties.





A. Dumitru, Y. Nara, B. Schenke, and MS, forthcoming.

“The Ridge” – Open questions

- Need data on η-broadening of the away-side jet.
- If this is a medium effect then the ridge should appear there as well.
- Detailed analysis of near-side jet average path length is necessary.
- Surface bias implies relatively short path length in which to generate the effect.

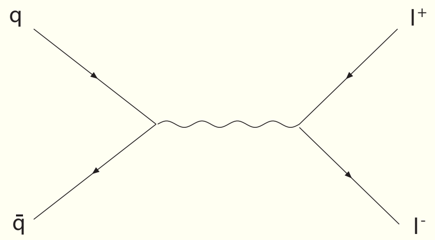
- Electromagnetic Observables -

E&M Probes to determine plasma isotropization time

- Can we experimentally determine when/if the plasma becomes locally isotropic in momentum-space?
- Need observables which provide complementary ways of probing early-time dynamics.
- Ideal candidates for this are E&M observables, eg photon and dilepton emission.
- Dependence of photon rate on anisotropy has been evaluated to LO (Schenke and MS, hep-ph/0611332); however, photons are notoriously difficult for experimentalists to measure due to large backgrounds.
- Dileptons offer a better opportunity since one can study production as a function of invariant pair mass (photon virtuality) and transverse momentum.

Dileptons from an Anisotropic Plasma

- The dilepton rate d^4R/d^4p depends on plasma anisotropy and the angle of the dilepton pair with respect to the beam axis.



- To leading order it can be obtained using anisotropic momentum space distributions of the form

$$f^{q,\bar{q}}(\mathbf{p},\mathbf{x}) = f^{q,\bar{q}}_{\rm iso}\left(p_T^2 + (1+\xi)p_L^2\right)$$

- $\xi = 0$ gives isotropic plasma and $\xi = 10$ corresponds to a squish by a factor of approximately three along the longitudinal momentum direction.

$$\frac{\langle p_T^2 \rangle}{\langle p_L^2 \rangle} \sim 1 + \xi$$

M. Guerrero and MS, forthcoming.

Dileptons from an Anisotropic Plasma

For a free streaming plasma

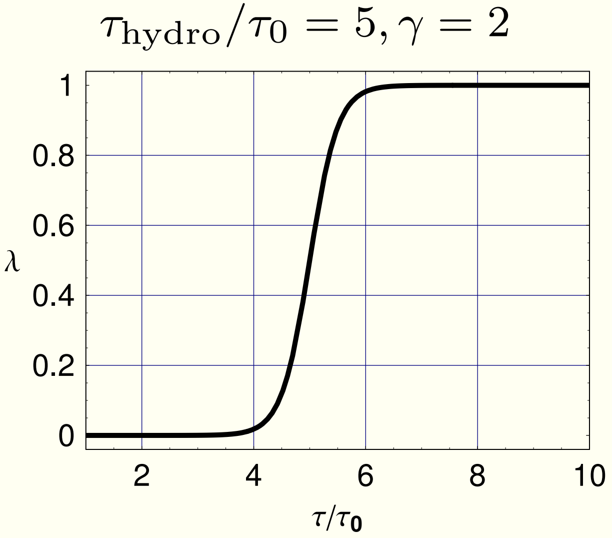
$$\begin{aligned} \xi(\tau) &= \left(\frac{\tau}{\tau_0}\right)^2 - 1 \\ \lim_{\tau \gg \tau_0} \mathcal{E}(\tau) &\to \mathcal{E}_0 \left(\frac{\tau_0}{\tau}\right) \\ \text{``}T\text{''}(\tau) &= T_0 \end{aligned}$$

For an isotropic plasma

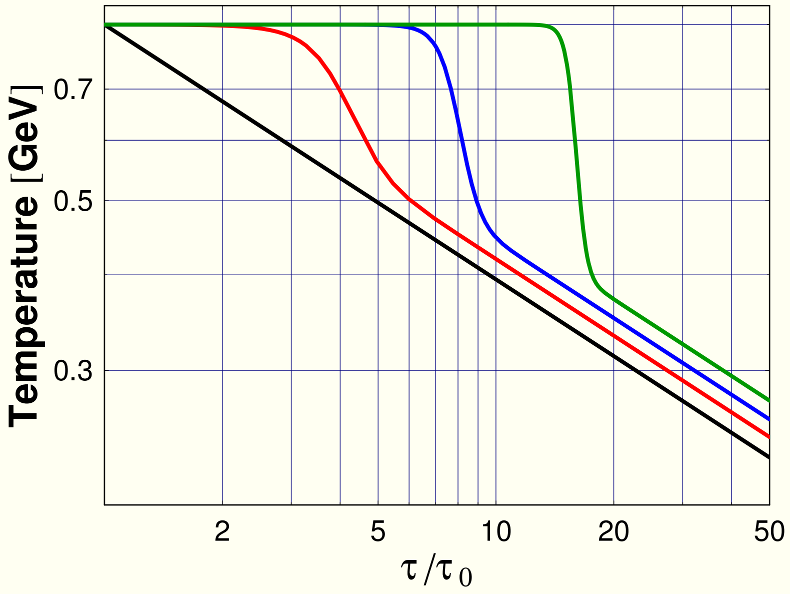
$$\begin{aligned} \xi(\tau) &= 0 \\ \mathcal{E}(\tau) &= \mathcal{E}_0 \left(\frac{\tau_0}{\tau}\right)^{4/3} \\ T(\tau) &= T_0 \left(\frac{\tau_0}{\tau}\right)^{1/3} \end{aligned}$$

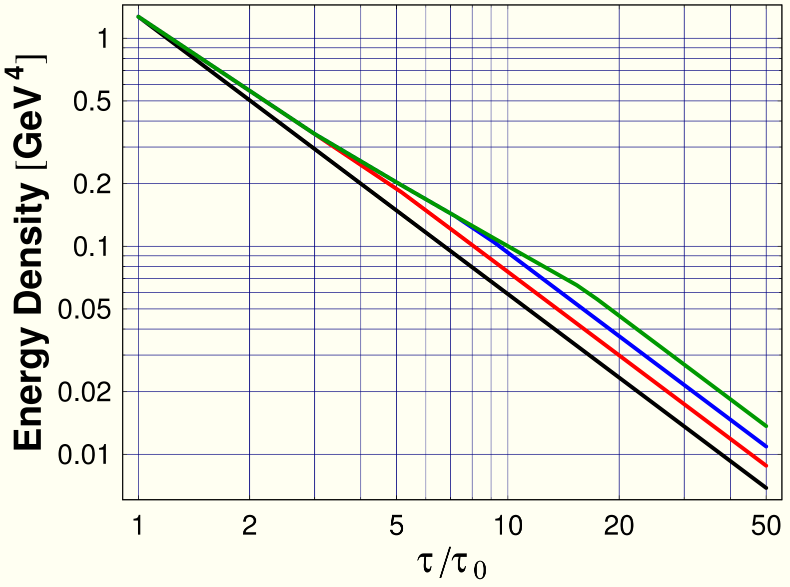
Can construct models which interpolate between free streaming and isotropic hydrodynamic expansion, eg:

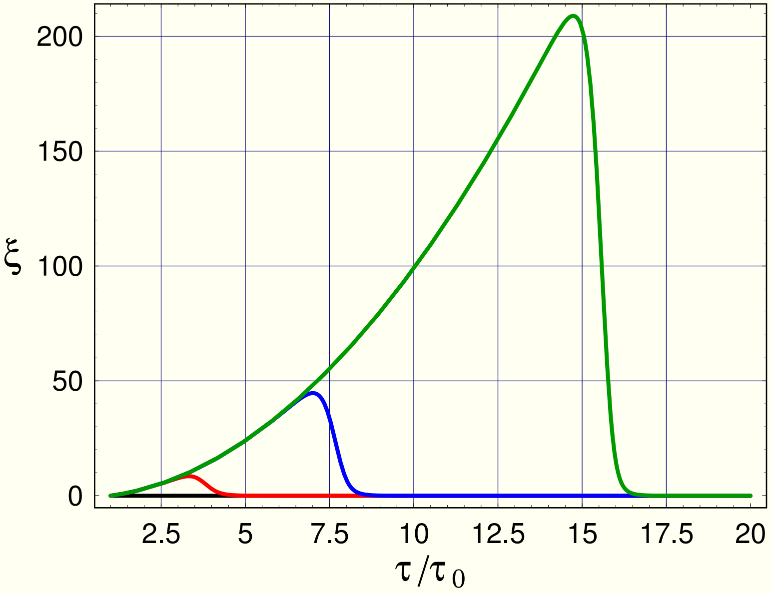
$$\begin{aligned} \lambda(\tau, \tau_{\rm hydro}, \gamma) &= \frac{1}{2}\tanh\left(\gamma(a - a_{\rm hydro})\right) \qquad a \equiv \tau/\tau_0 \\ \xi(\tau) &= a^{2(1-\lambda)} - 1 \\ \mathcal{E}(\tau) &= \mathcal{E}_{\rm FS}\, f\left(a_{\rm hydro}^2 - 1\right)^{\lambda} \left(\frac{a_{\rm hydro}}{a}\right)^{\lambda/3} \\ T(\tau) &= T_0\, f\left(a_{\rm hydro}^2 - 1\right)^{\lambda/4} \left(\frac{a_{\rm hydro}}{a}\right)^{\lambda/3} \end{aligned}$$



Space-time evolution incorporating anisotropies (LHC)







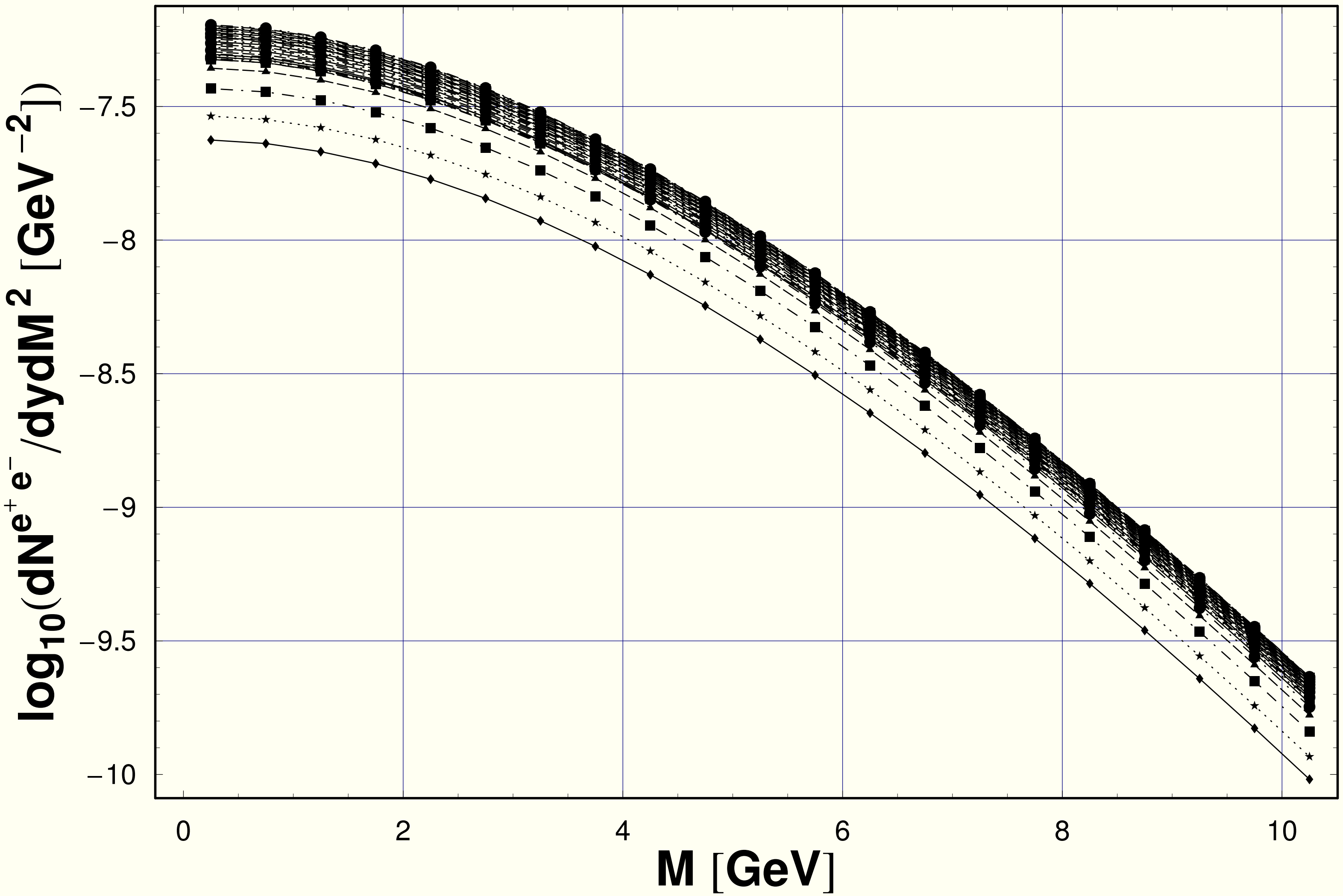
- $\tau_{\rm hydro}/\tau_0 \to 1$: instant isotropization/thermalization.
- $\tau_{\rm hydro}/\tau_0 \to \infty$: never isotropizes or thermalizes; free-streaming.

M. Guerrero and MS, forthcoming.

Results - Dileptons vs M

$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $T_c = 160$ MeV, $\tau_0 \le \tau_{\rm hydro} \le 1$ fm/c

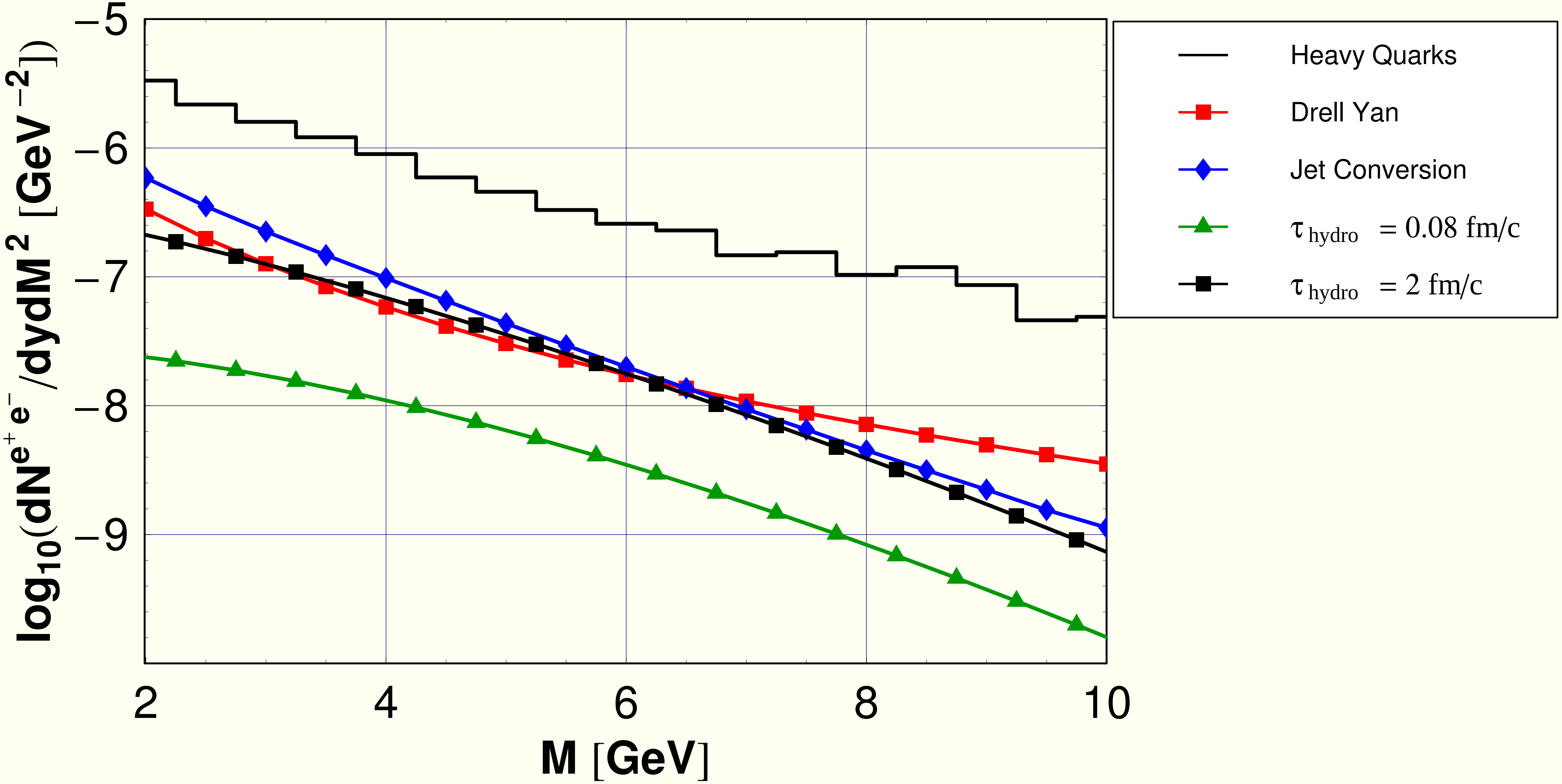
Cuts: $p_T > 8$ GeV



M. Guerrero and MS, forthcoming.

Results - Dileptons vs M with backgrounds

$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $T_c = 160$ MeV
Cuts: $p_T > 8$ GeV

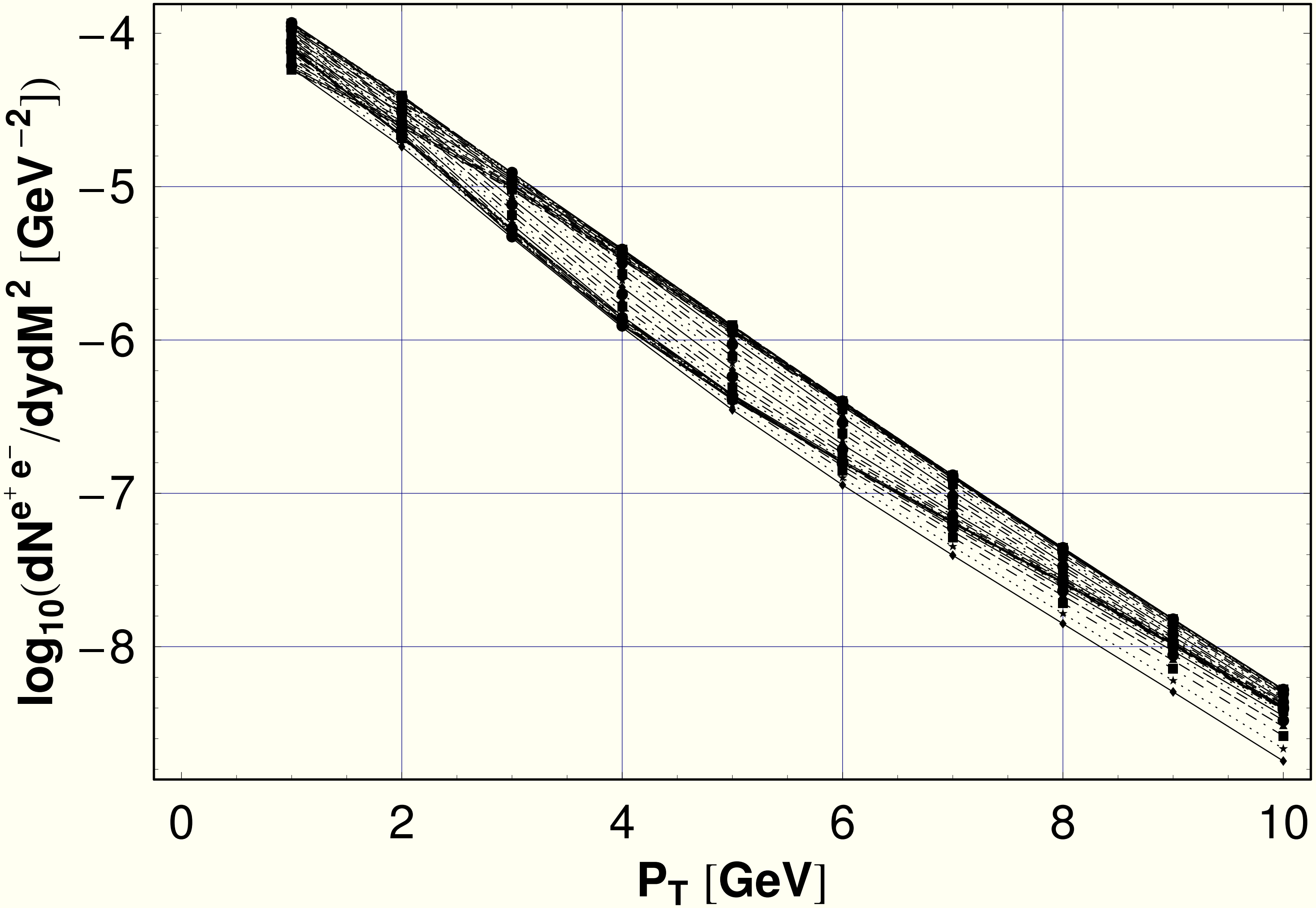


M. Guerrero and MS, forthcoming.

Results - Dileptons vs P_T

$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $T_c = 160$ MeV, $\tau_0 \le \tau_{\rm hydro} \le 2$ fm/c

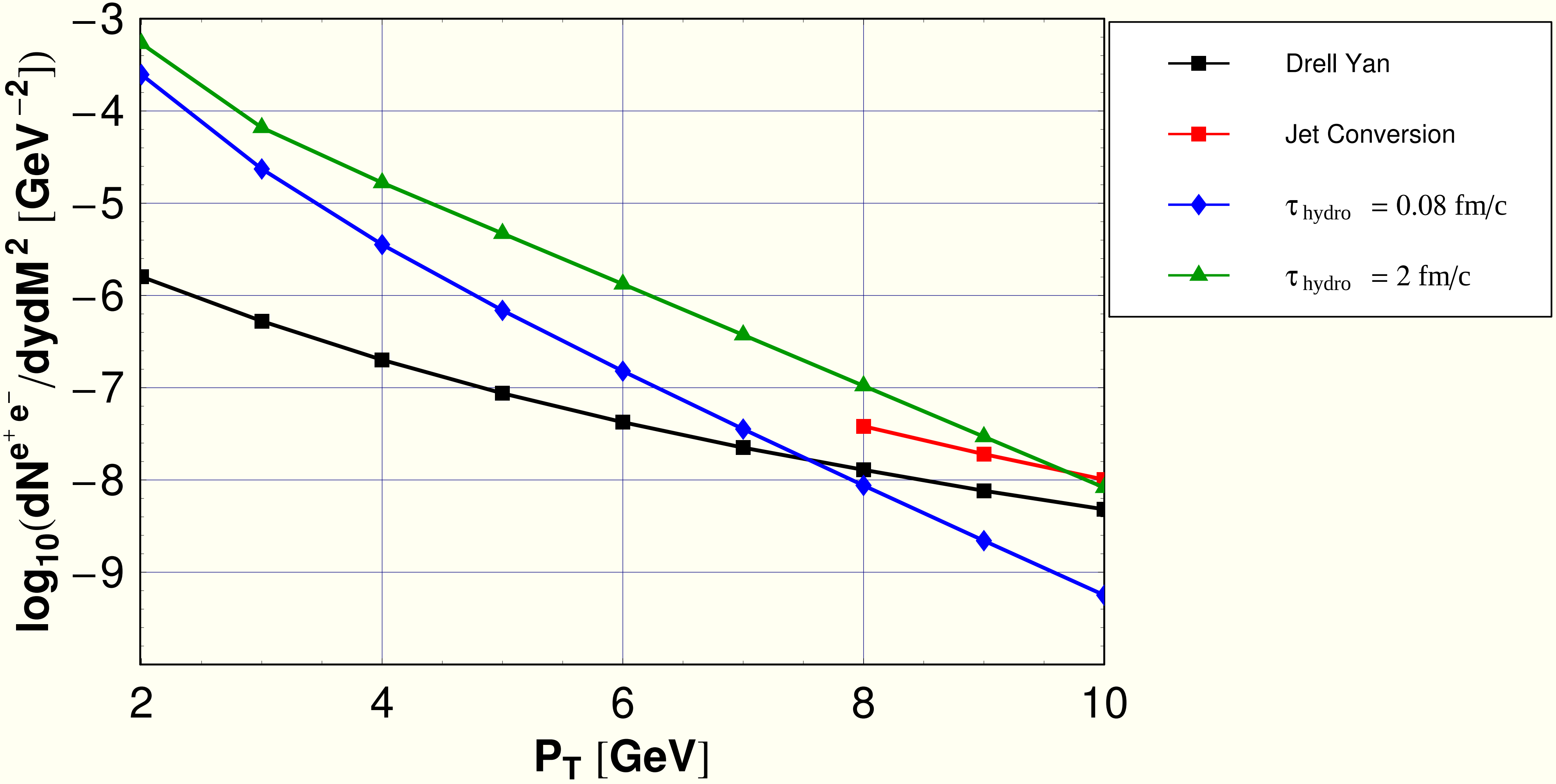
Cuts: $M > 2$ GeV



M. Guerrero and MS, forthcoming.

Results - Dileptons vs P_T with backgrounds

$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $T_c = 160$ MeV
Cuts: $0.5 < M < 1$ GeV



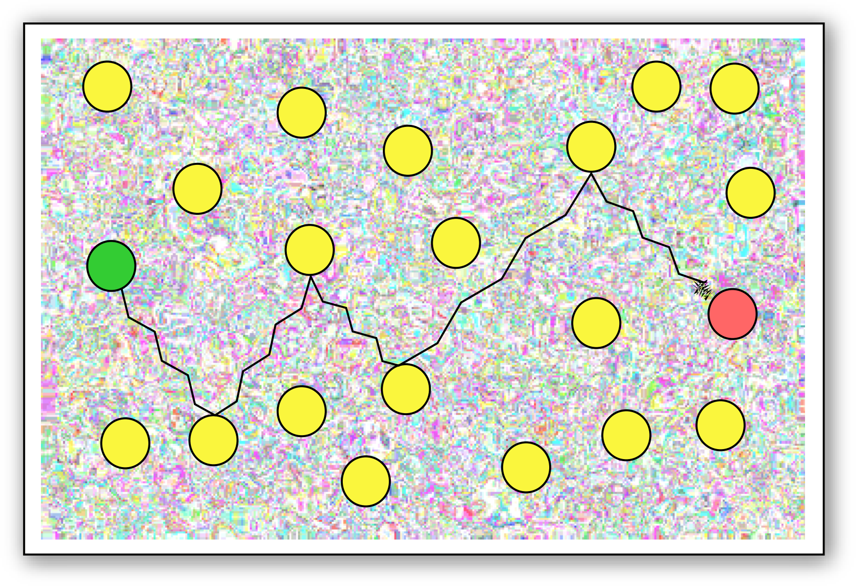
M. Guerrero and MS, forthcoming.

- Anomalous Viscosity -

Possibility of Anomalous Viscosity

- These large amplitude color fields can be thought of as a highly-populated ensemble of low-momentum or "soft" particles.
- In the presence of such large fields one must revisit basic calculations such as the calculation of the viscosity.*
- In a weakly-coupled isotropic + high-temperature thermal system the viscosity is related to the collisional mean free path of the partons[†]

$$\begin{aligned} \eta \sim \lambda_{\rm f} T^4 \quad &\sim \quad \frac{T^3}{g^4 \log(1/g)} \\ \lambda_{\rm hard} \quad &\sim \quad \frac{1}{g^4 T} \\ \lambda_{\rm soft} \quad &\sim \quad \frac{1}{g^2 T} \end{aligned}$$



[†] Arnold, Moore, Yaffe, hep-ph/0010177.

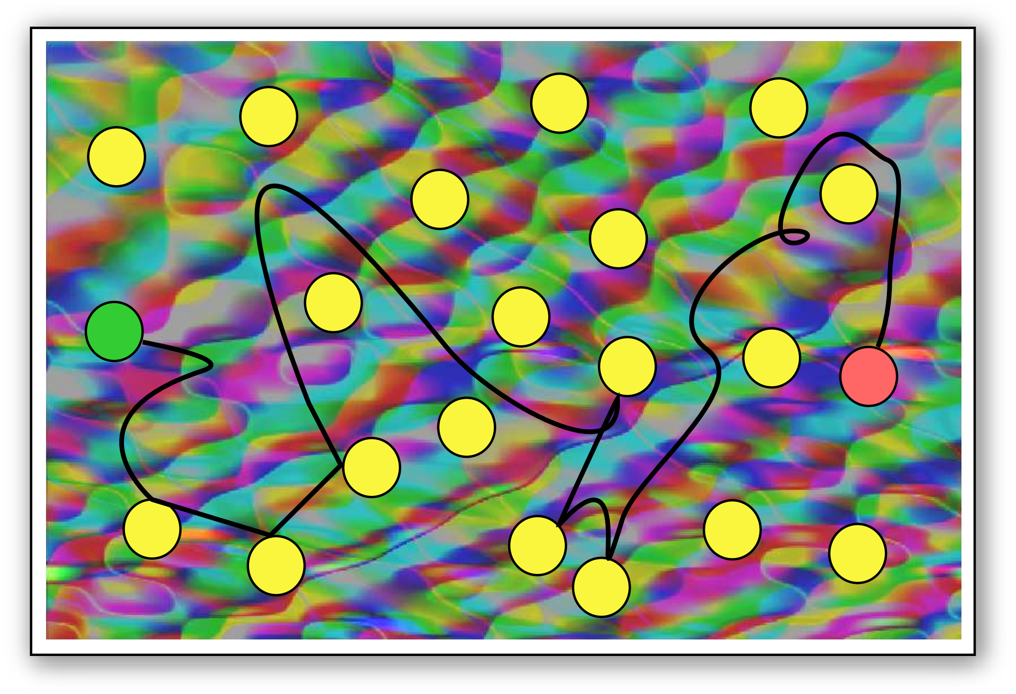
* Asakawa, Müller, and Bass, hep-ph/0608270

Anomalous Viscosity (cntd)

- Asakawa, Müller, and Bass have recently (hep-ph/0608270) performed a computation of the viscosity due to large-amplitude turbulent field configurations.
- Therein they compute the mean free path of a particle propagating in such a background and find

$$\lambda_{\rm f}^{(\rm A)} \sim \frac{\bar{p}^2}{g^2 Q^2 \langle \mathcal{E}^2 + \mathcal{B}^2 \rangle r_{\rm m}}$$

$$\frac{\eta_{\rm A}}{s} = \frac{1}{g^{3/2}} \left(\frac{(N_c^2 - 1) T \tau}{10 b_0 N_c} \right)^{1/2}$$



$\eta_{\rm A}/s$ is not bound from below by the AdS-CFT bound.

Asakawa, Müller, and Bass, hep-ph/0608270

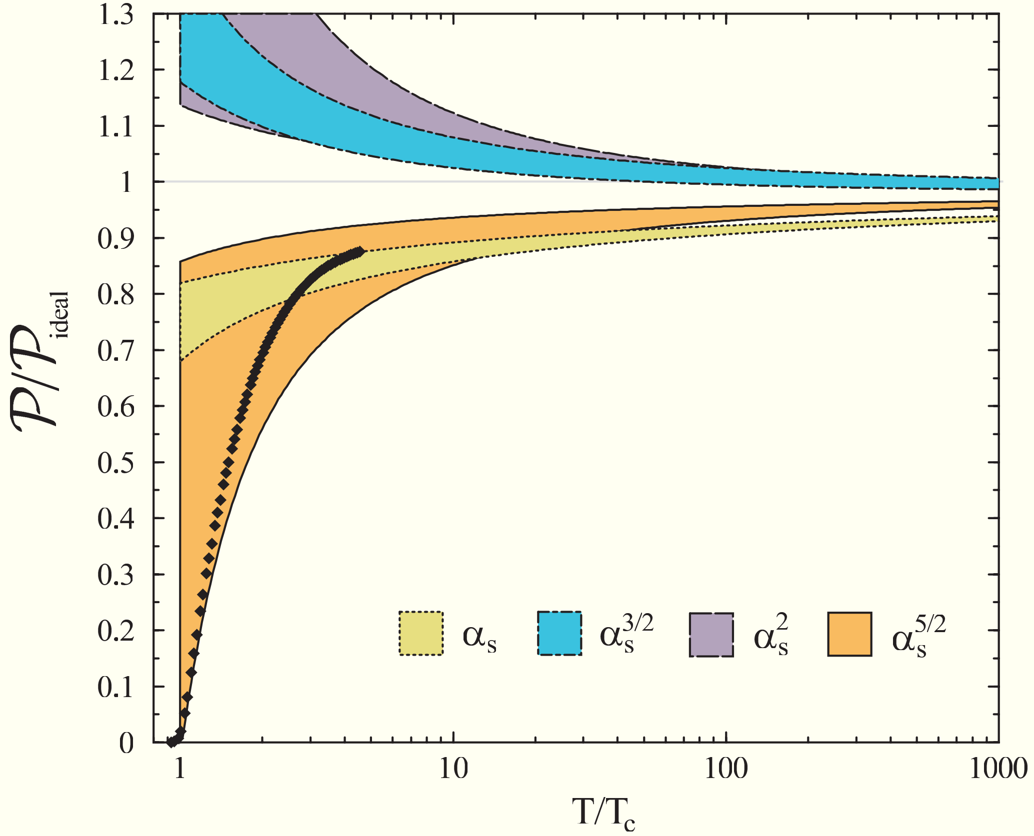
Conclusions

- Anisotropic plasmas are qualitatively different than isotropic ones.
- Unstables modes result in spontaneous generation of large amplitude soft background fields.
- These non-equilibrium fields can modify fundamental properties of a quark-gluon plasma such as viscosity, 3d jet diffusion, plasma thermalization time, etc.
- We now have simple models which allow us to calculate the effect of anisotropies on experimental observables, eg jet and E&M signatures. More to come . . .
- There is continuous advancement in the numerical techniques which can be used for simulating non-equilibrium gauge dynamics.
- At LHC energies, our dilepton results show a window from $p_T \sim$ 3 - 7 GeV where is it possible to determine much-needed information about the initial 1 fm/c of the QGP's lifetime.

- Backup Slides -

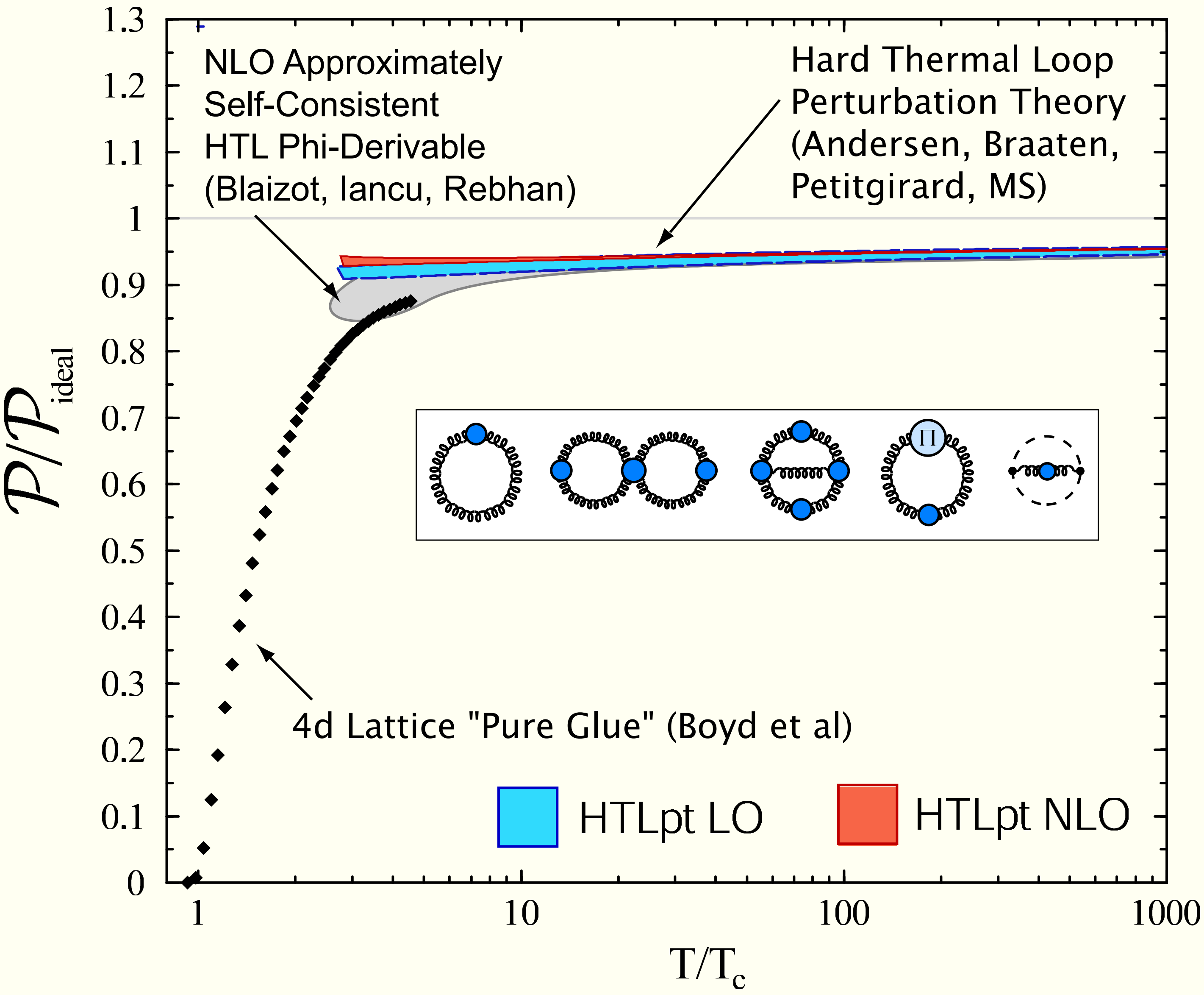
Cause for despair

Naive application of resummed finite-temperature perturbation theory to thermodynamics fails to converge at any reasonable temperature so should we abandon it?



$$
\begin{aligned}
\mathcal{P}_{\rm QCD}/\mathcal{P}_{\rm ideal} = 1 &- \frac{15}{4}\frac{\alpha_s}{\pi} + 30\left(\frac{\alpha_s}{\pi}\right)^{3/2} \\
&+ \frac{135}{2}\left(\log\frac{\alpha_s}{\pi} - \frac{11}{36}\log\frac{\mu}{2\pi T} + 3.51\right)\left(\frac{\alpha_s}{\pi}\right)^2 \\
&+ \frac{495}{2}\left(\log\frac{\mu}{2\pi T} - 3.23\right)\left(\frac{\alpha_s}{\pi}\right)^{5/2} \\
&+ \mathcal{O}(\alpha_s^3\log\alpha_s)
\end{aligned}
$$

Cause for (limited) hope



NLO Approximately Self-Consistent HTL Phi-Derivable (Blaizot, Iancu, Rebhan)

Hard Thermal Loop Perturbation Theory (Andersen, Braaten, Petitgirard, MS)

4d Lattice "Pure Glue" (Boyd et al)

🟦 HTLpt LO 🟥 HTLpt NLO