Measuring QGP isotropization/thermalization time using high-energy E&M observables

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Nonequilibrium Dynamics in Particle Physics and Cosmology

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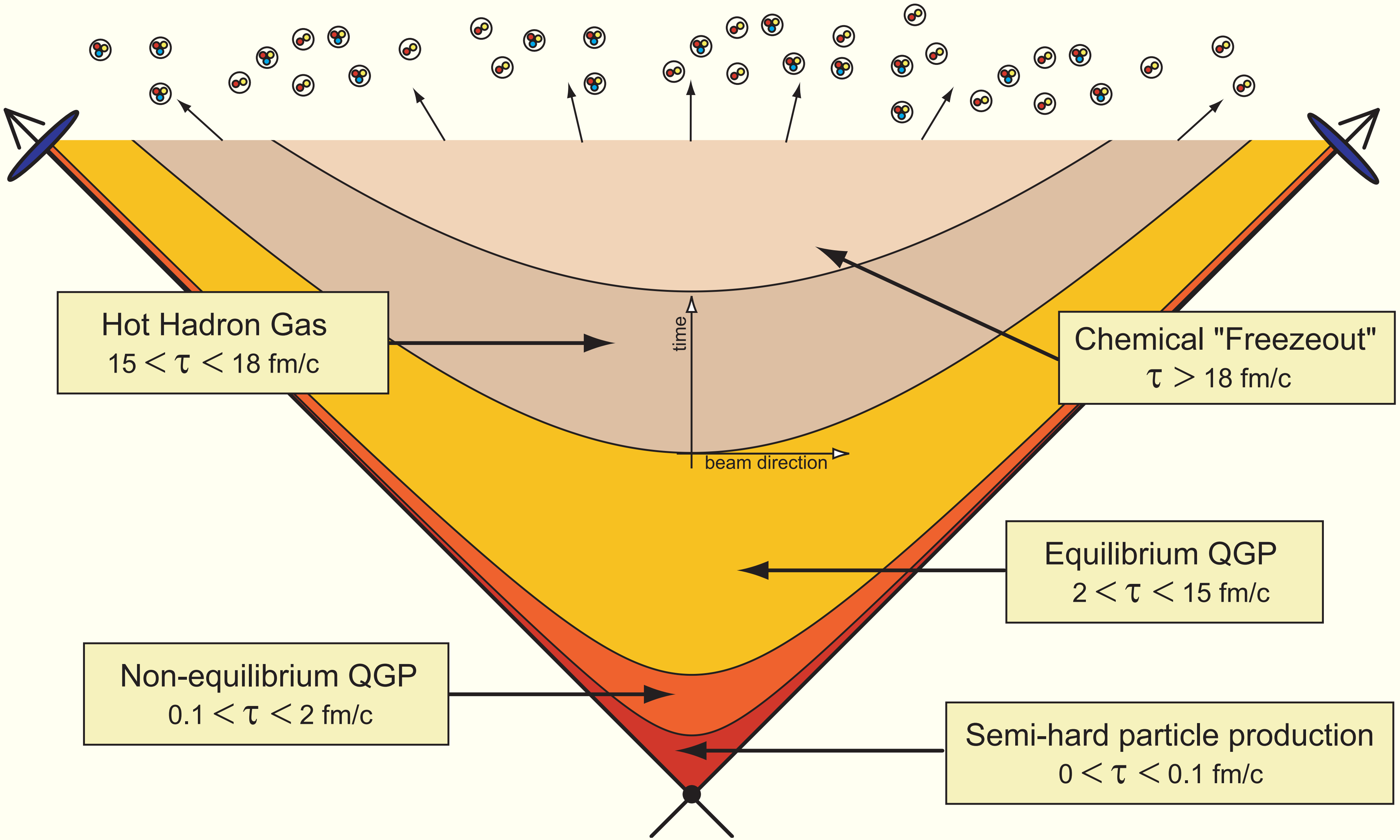
Heavy-ion collision timescales and “epochs” @ LHC



*1 fm/c $\simeq 3 \times 10^{-23}$ seconds

Determining plasma initial conditions

- The fact that hydrodynamic modeling of RHIC collisions seems to describe the elliptic flow, v_2, for $p_T < 2$ GeV has been taken as evidence for early isotropization (and possibly thermalization) of the QGP.

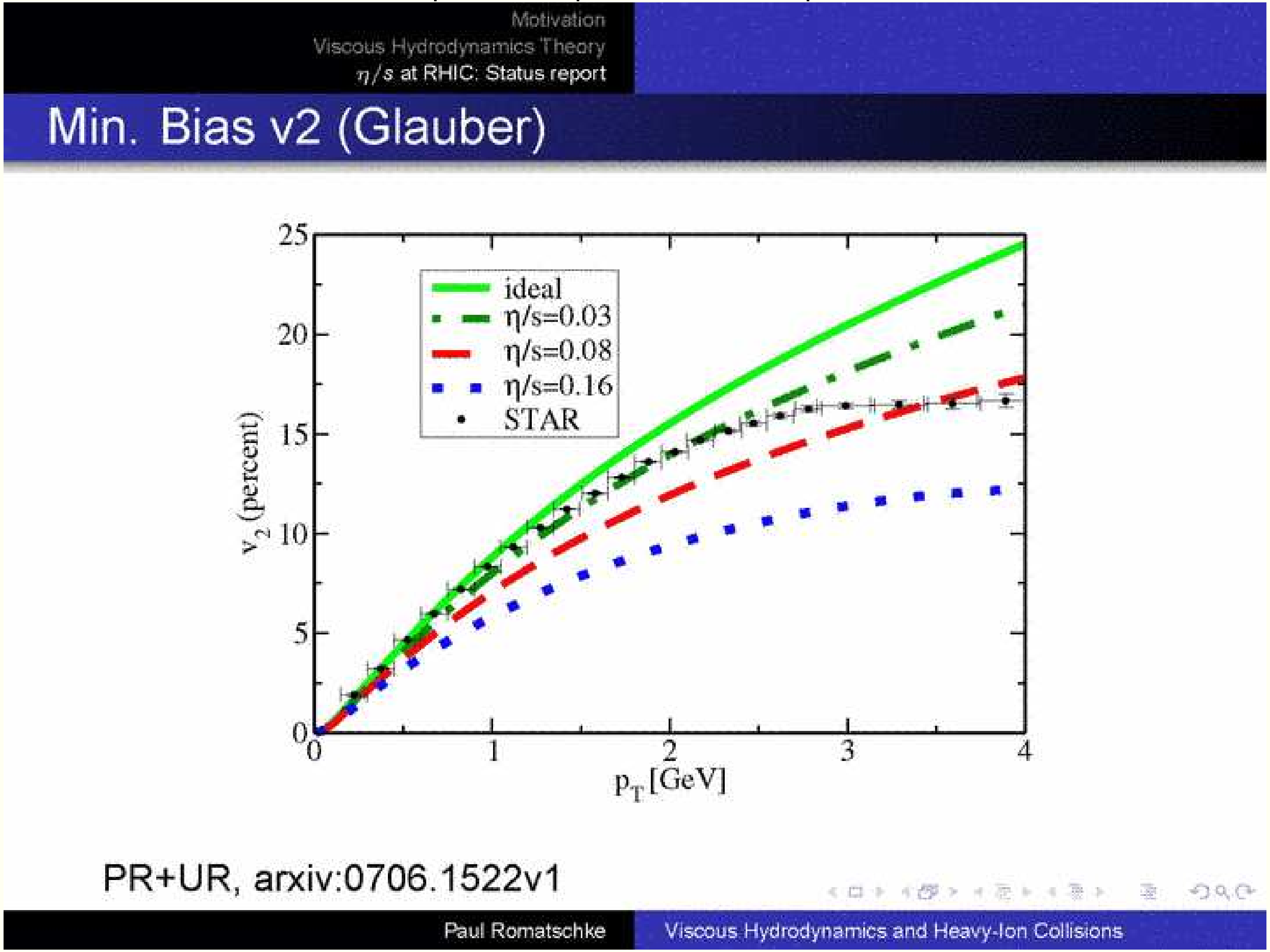
- Hydro results for v_2 depend on **initial conditions** but also details of the late-time modeling of the plasma lifetime: hadronization prescription (Cooper-Frye?), viscous hadronic phase, nuclear resonance “feed- downs”, radial flow, etc.

- It would be better to have observables which were primarily sensitive to the first 1-2 fm/c (and not dependent on fully 3d viscous hydro simulations + . . .).

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 . . .

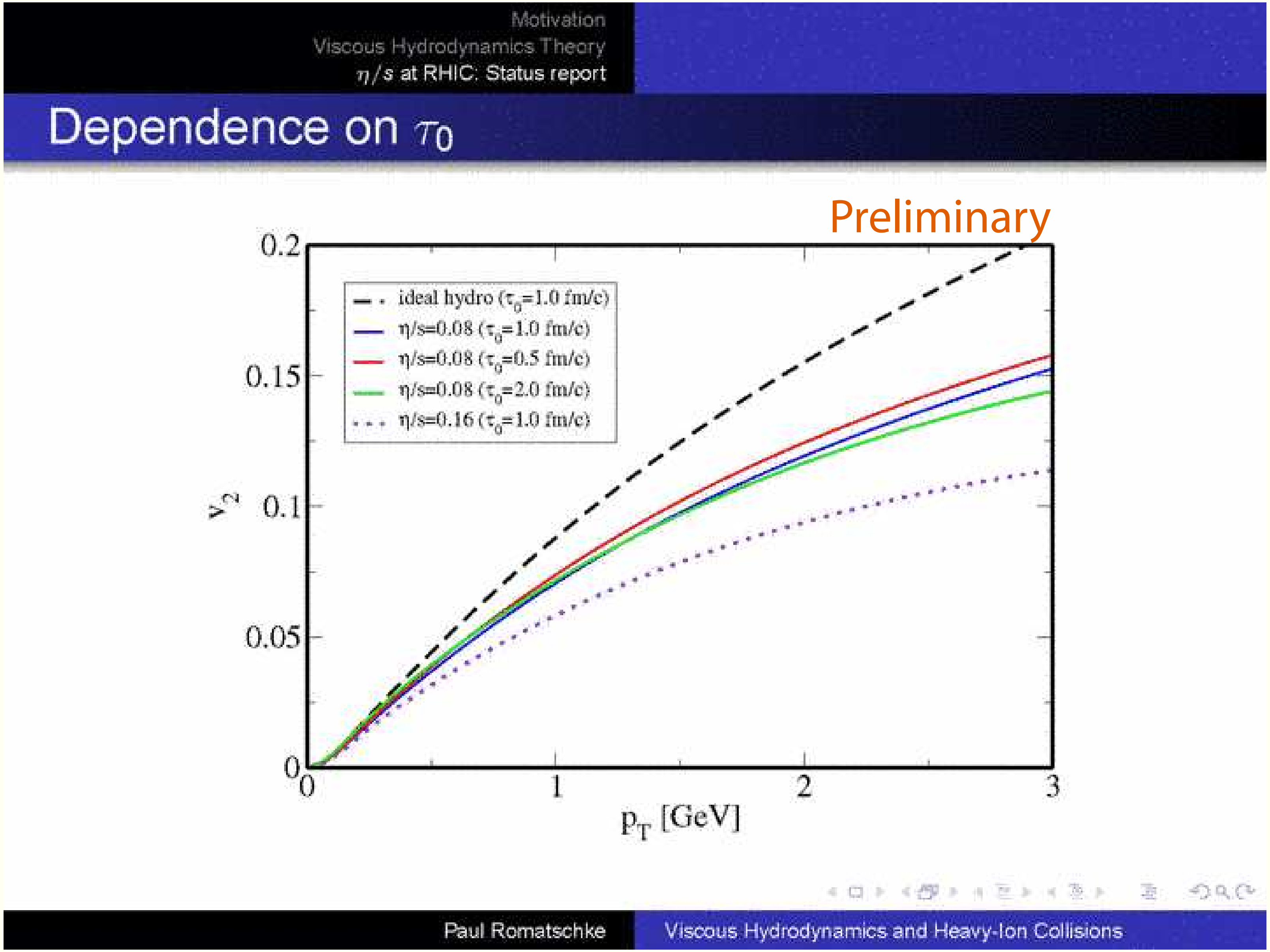
Hydro Results 1

http://online.itp.ucsb.edu/online/partcosmo08/romatschke/oh/60.html



Hydro Results 2

http://online.itp.ucsb.edu/online/partcosmo08/romatschke/oh/60.html



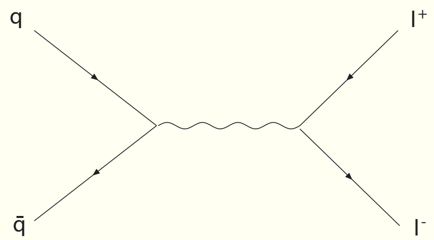
- Electromagnetic Observables -

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); rates folded over model evolution are forthcoming.
- Dileptons offer a better opportunity since one can study production as a function of invariant pair mass (photon virtuality) and transverse momentum. In addition, leading order Drell-Yan has support only at $p_T = 0$ so you have to go to NLO at finite p_T.

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

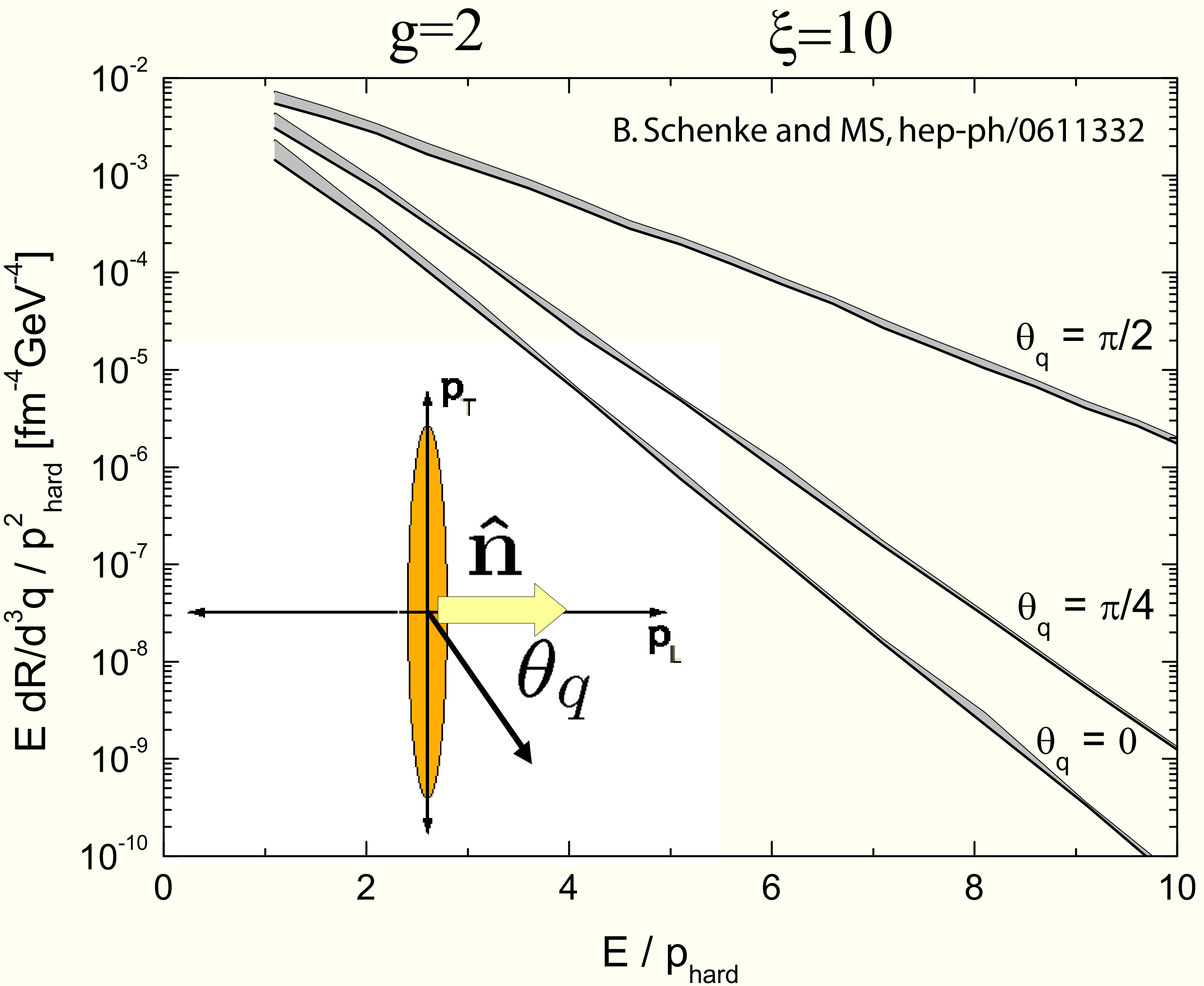
$$f^{q,\bar{q}}(\mathbf{p},\mathbf{x}) = f^{q,\bar{q}}_{\rm iso}\left(p_T^2 + (1+\xi)p_L^2\right)$$

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

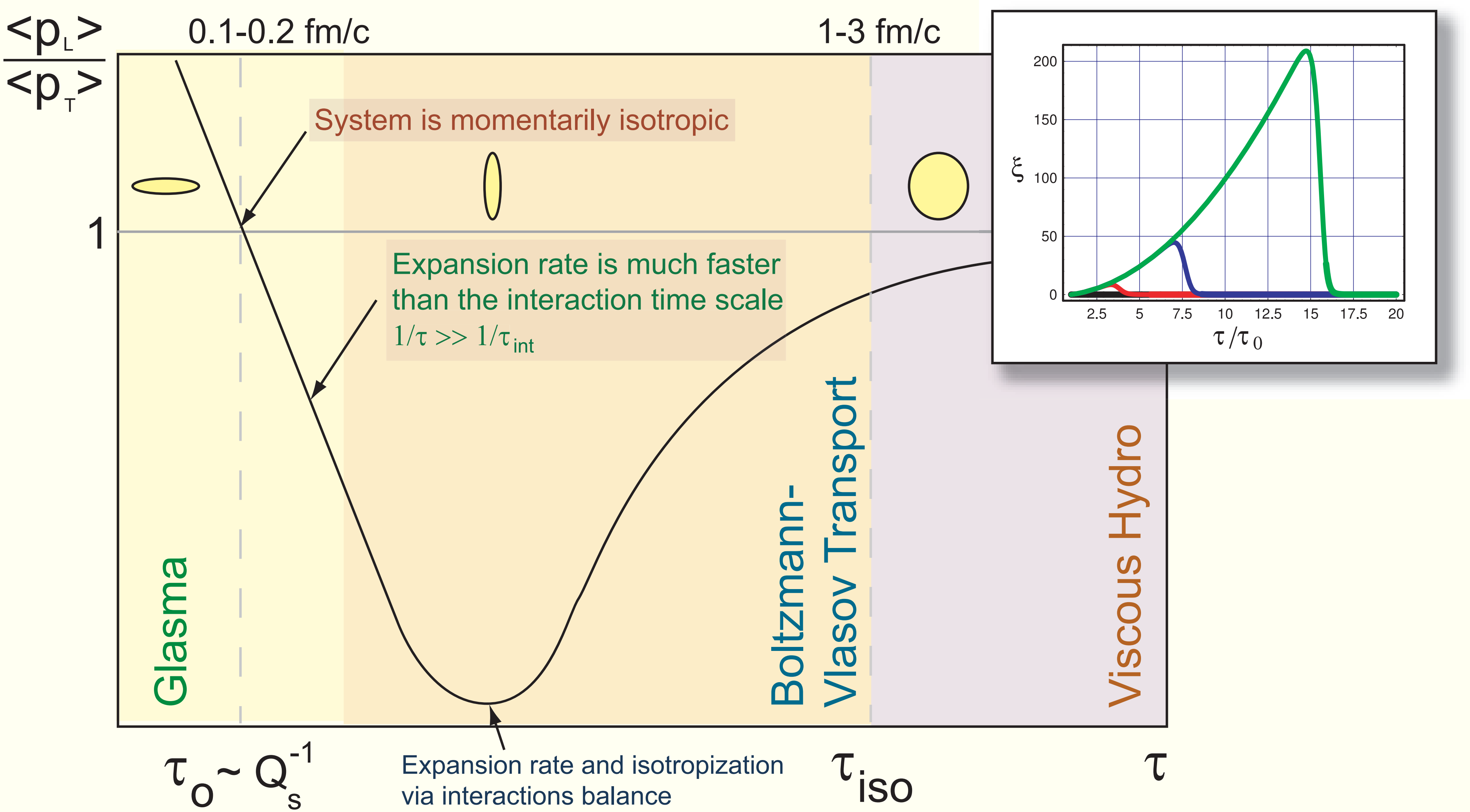
$$\frac{\langle p_T^2 \rangle}{2\langle p_L^2 \rangle} \sim 1 + \xi$$

M. Guerrero and MS, arXiv:0709.3576.

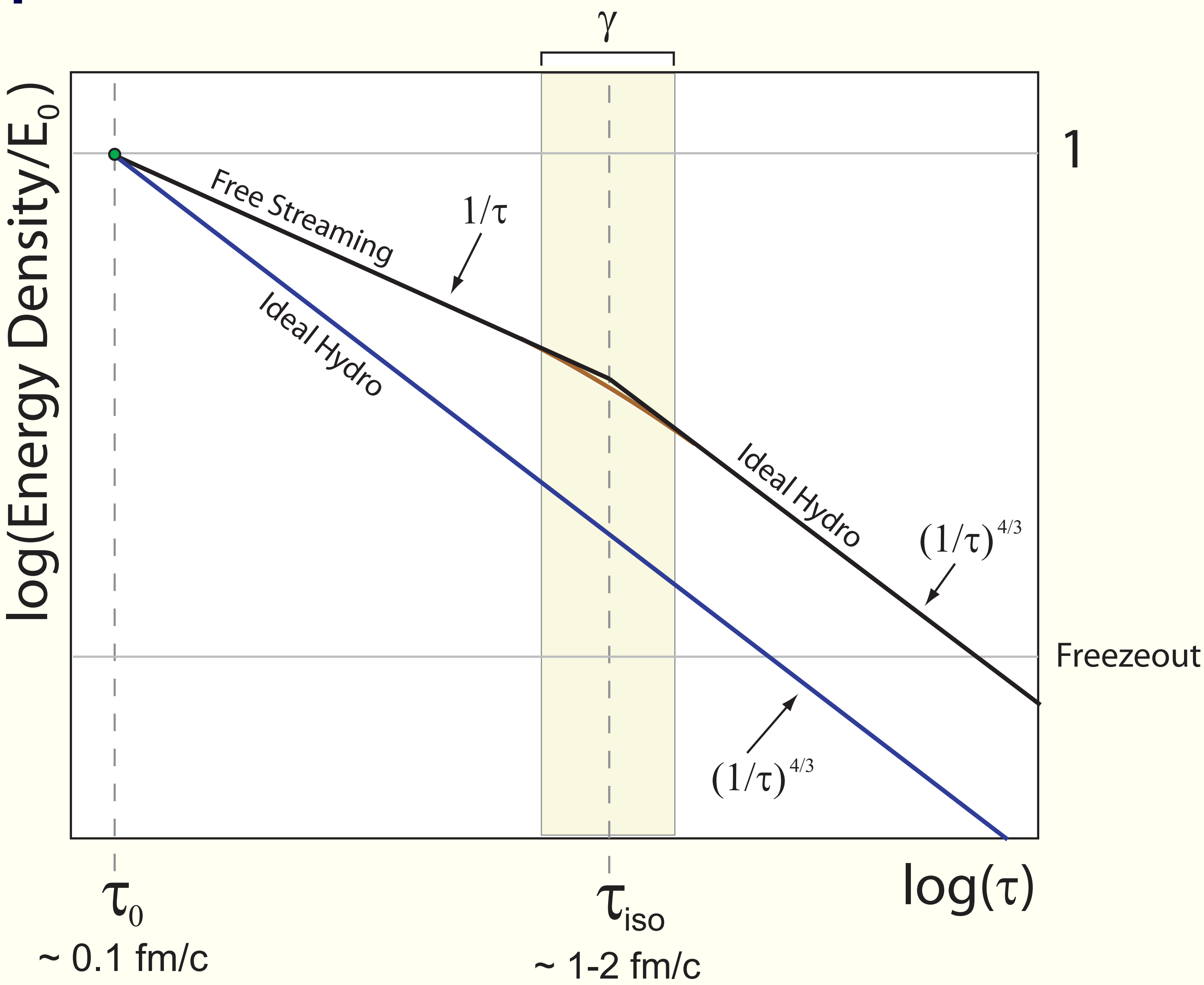
Rate variation with ξ



Momentum Space Anisotropy Time Dependence



Model parameters



Dileptons from an Anisotropic Plasma

For a free streaming plasma

$$\xi(\tau) = \left(\frac{\tau}{\tau_0}\right)^2 - 1$$

$$\lim_{\tau \gg \tau_0} \mathcal{E}(\tau) \rightarrow \mathcal{E}_0 \left(\frac{\tau_0}{\tau}\right)$$

$$\text{“}T\text{”}(\tau) = T_0$$

For an isotropic plasma

$$\xi(\tau) = 0$$

$$\mathcal{E}(\tau) = \mathcal{E}_0 \left(\frac{\tau_0}{\tau}\right)^{4/3}$$

$$T(\tau) = T_0 \left(\frac{\tau_0}{\tau}\right)^{1/3}$$

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

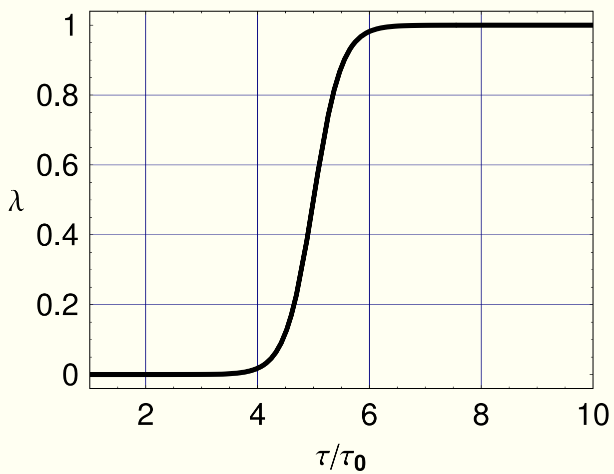
$$\lambda(\tau, \tau_{\rm hydro}, \gamma) = \frac{1}{2}\tanh\left(\gamma(a - a_{\rm hydro})\right) \qquad a \equiv \tau/\tau_0$$

$$\xi(\tau) = a^{2(1-\lambda)} - 1$$

$$\mathcal{E}(\tau) = \mathcal{E}_{\rm FS}\, f\left(a_{\rm hydro}^2 - 1\right)^{\lambda} \left(\frac{a_{\rm hydro}}{a}\right)^{\lambda/3}$$

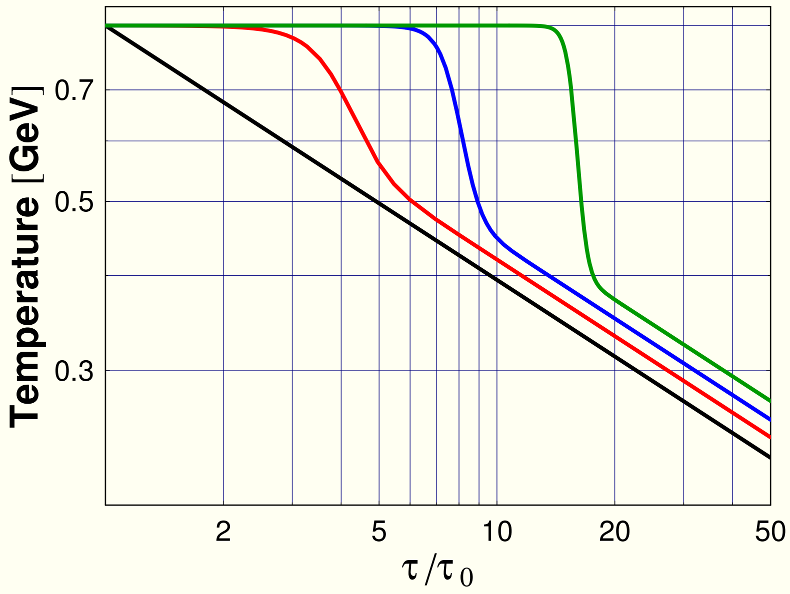
$$T(\tau) = T_0\, f\left(a_{\rm hydro}^2 - 1\right)^{\lambda/4} \left(\frac{a_{\rm hydro}}{a}\right)^{\lambda/3}$$

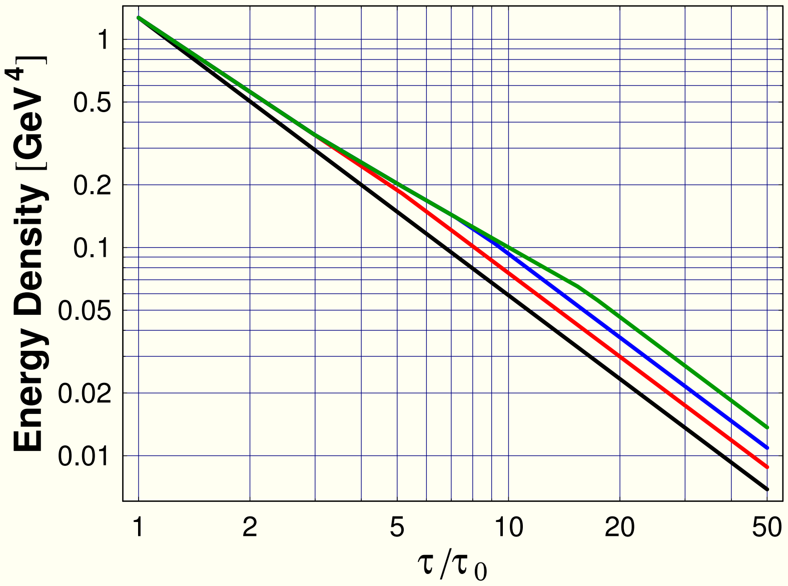
$\tau_{\rm hydro}/\tau_0 = 5, \gamma = 2$

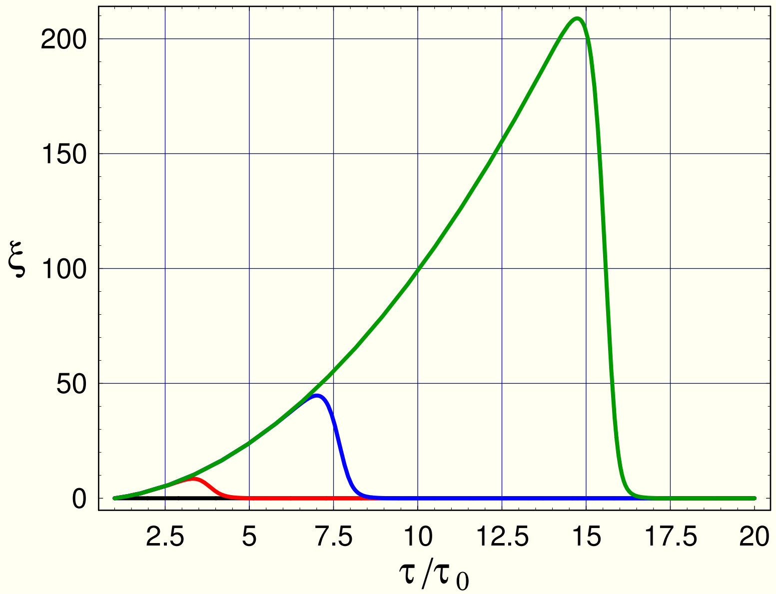


M. Guerrero and MS, arXiv:0709.2576

Space-time evolution incorporating anisotropies (LHC)





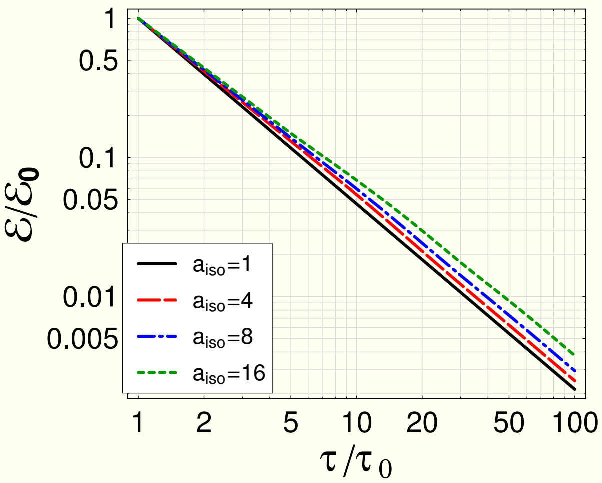


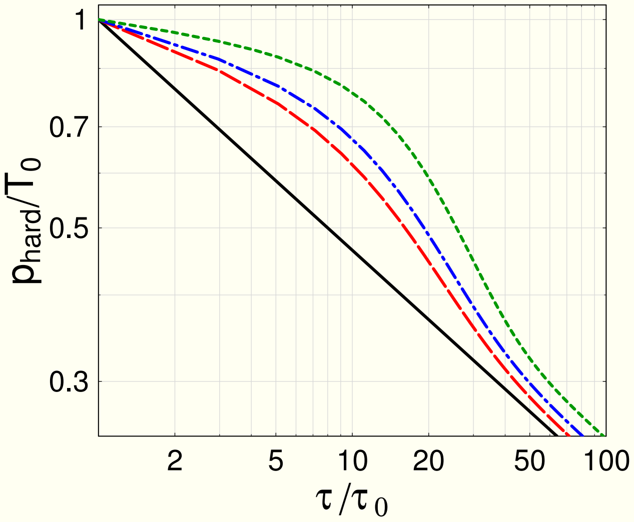
- $\tau_{\mathrm{hydro}}/\tau_0 \rightarrow 1$: instant isotropization/thermalization.
- $\tau_{\mathrm{hydro}}/\tau_0 \rightarrow \infty$: never isotropizes or thermalizes; free-streaming.

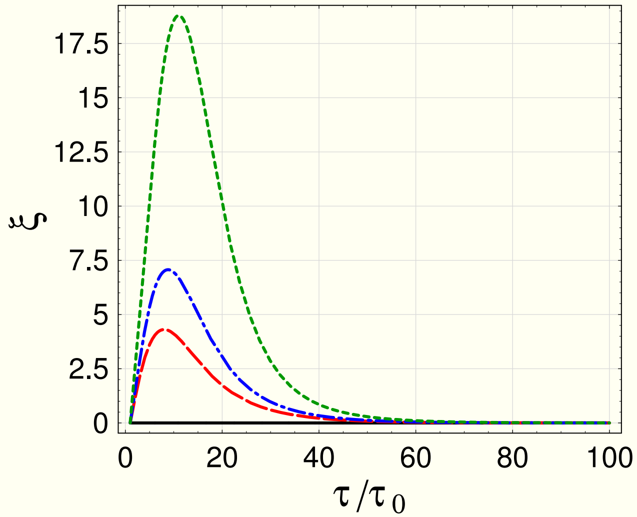
M. Guerrero and MS, arXiv:0709.3576.

Model - Smaller Gamma

Can take larger transition widths, say $\gamma = 0.05$.

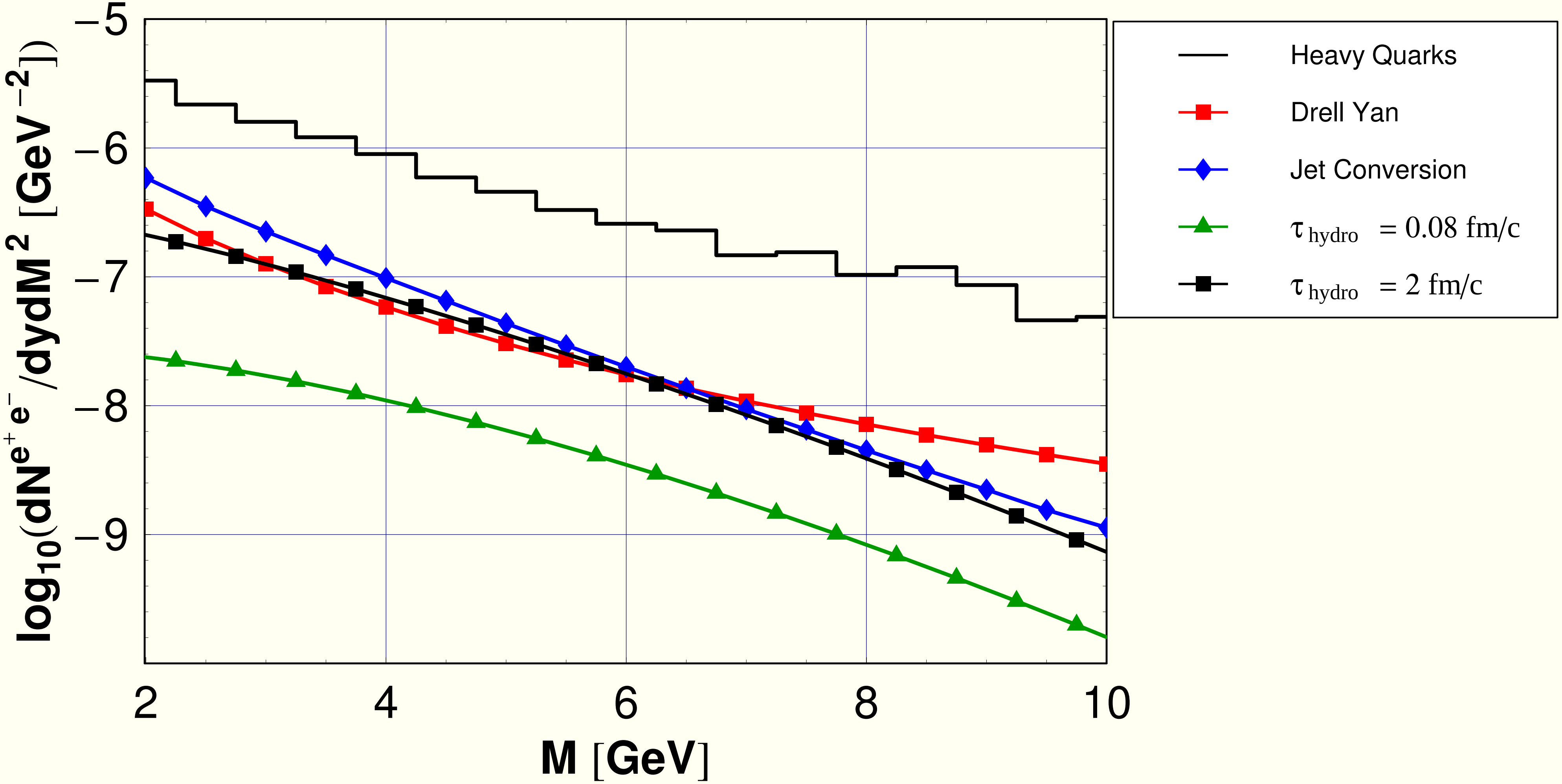






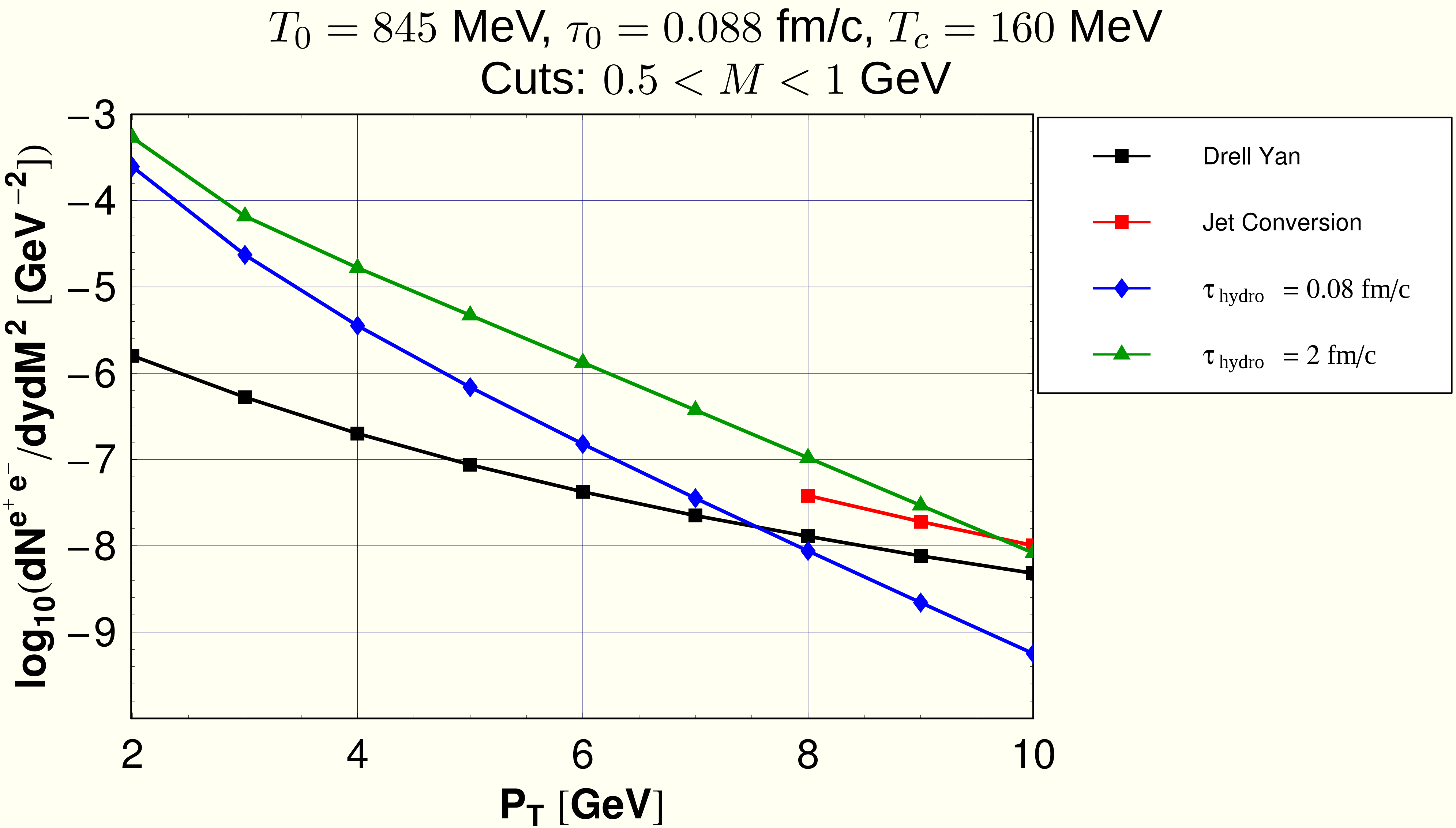
Results - Dileptons vs M with backgrounds

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



M. Guerrero and MS, arXiv:0709.3576.

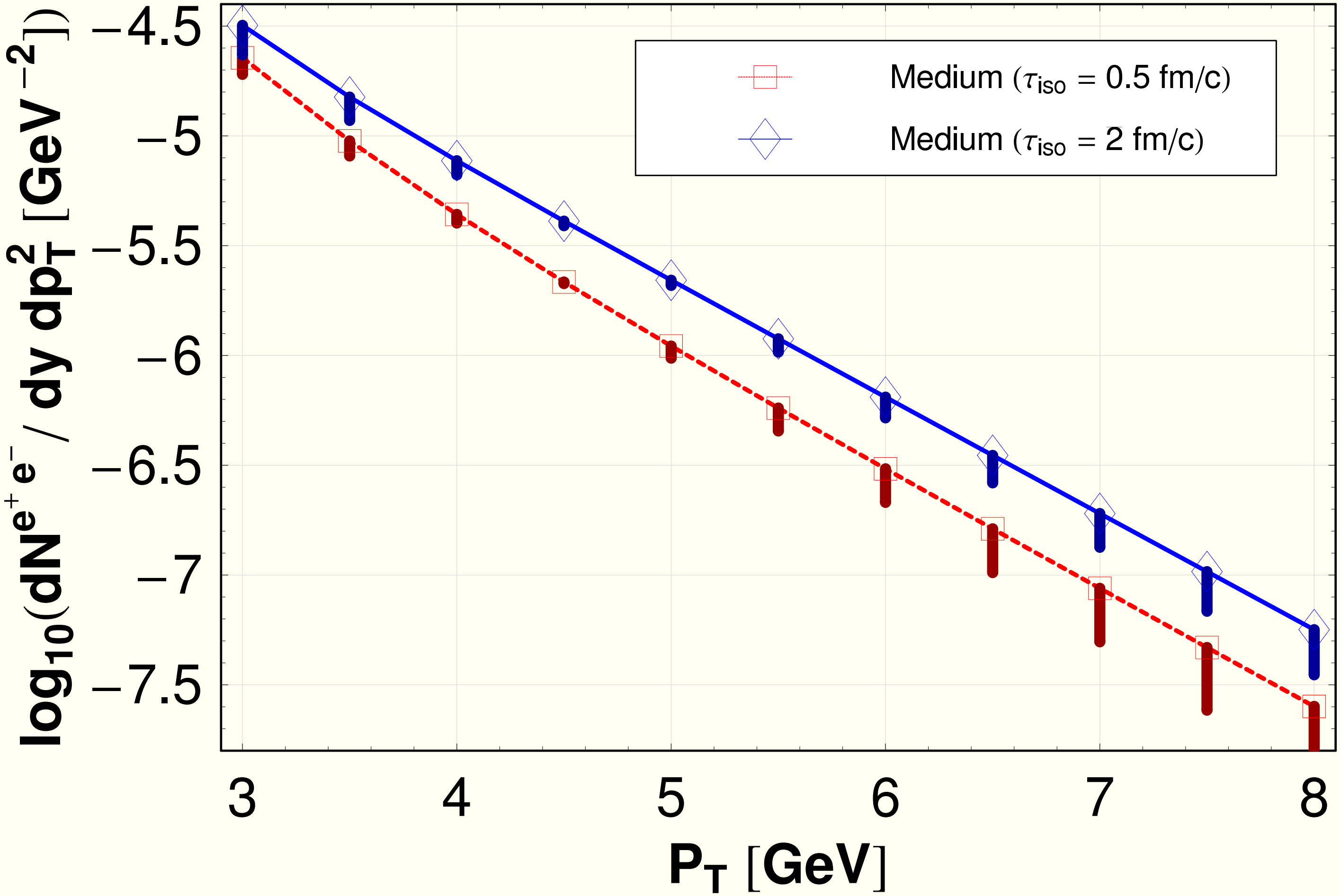
Results - Dileptons vs P_T with backgrounds



M. Guerrero and MS, arXiv:0709.3576.

Results - Model variation

$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $T_c = 160$ MeV
Cuts: $0.5 < M < 1$ GeV
Model Variation: $0.05 < \gamma < 10$



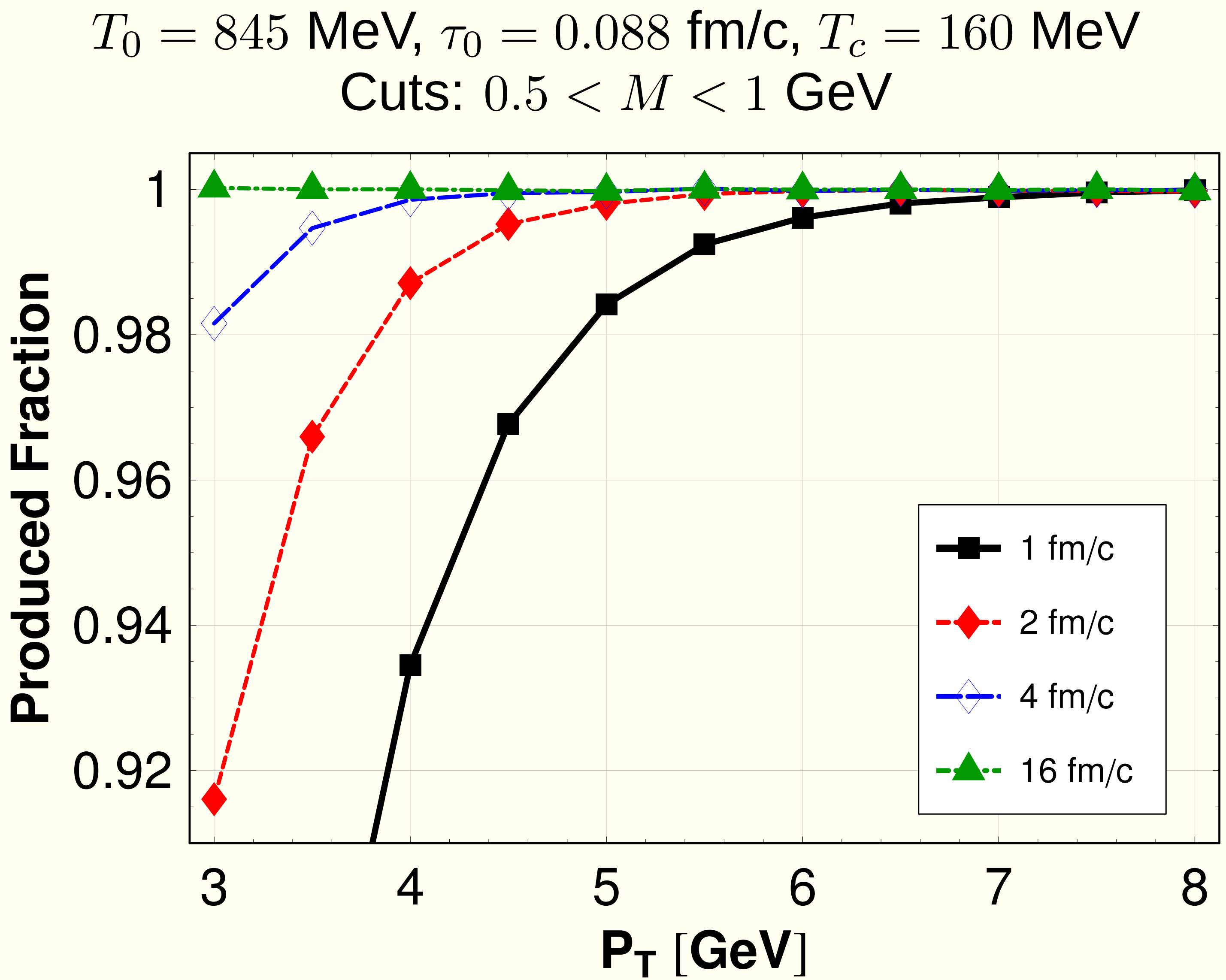
M. Guerrero and MS, arXiv:0709.3576

Conclusions

- We need more observables which are sensitive to the initial 1-2 fm/c of the plasma lifetime.
- 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 . . .
- 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.
- TODO: Calculation of NLO rate underway; inclusion of possible chemical non-equilibrium (effect will remain but overall rates will be modified); modification of jet-medium production due to early-time anisotropies; . . .

- Backup Slides -

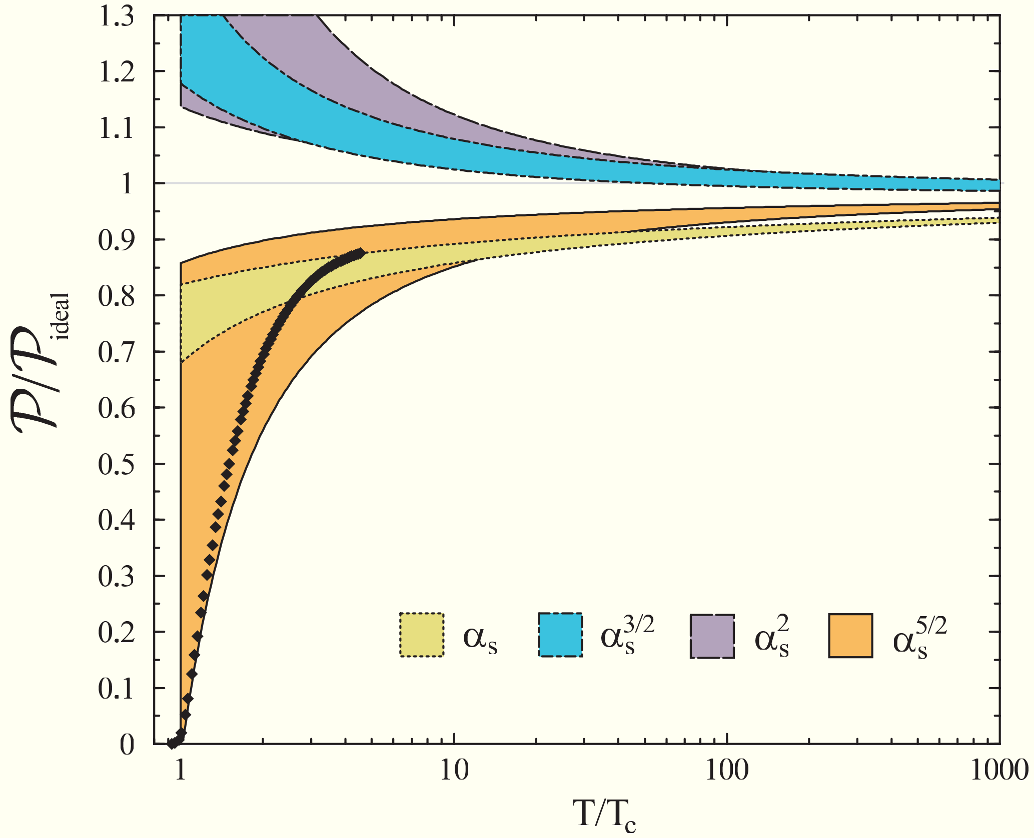
Results - Time scales



M. Guerrero and MS, arXiv:0709.3576.

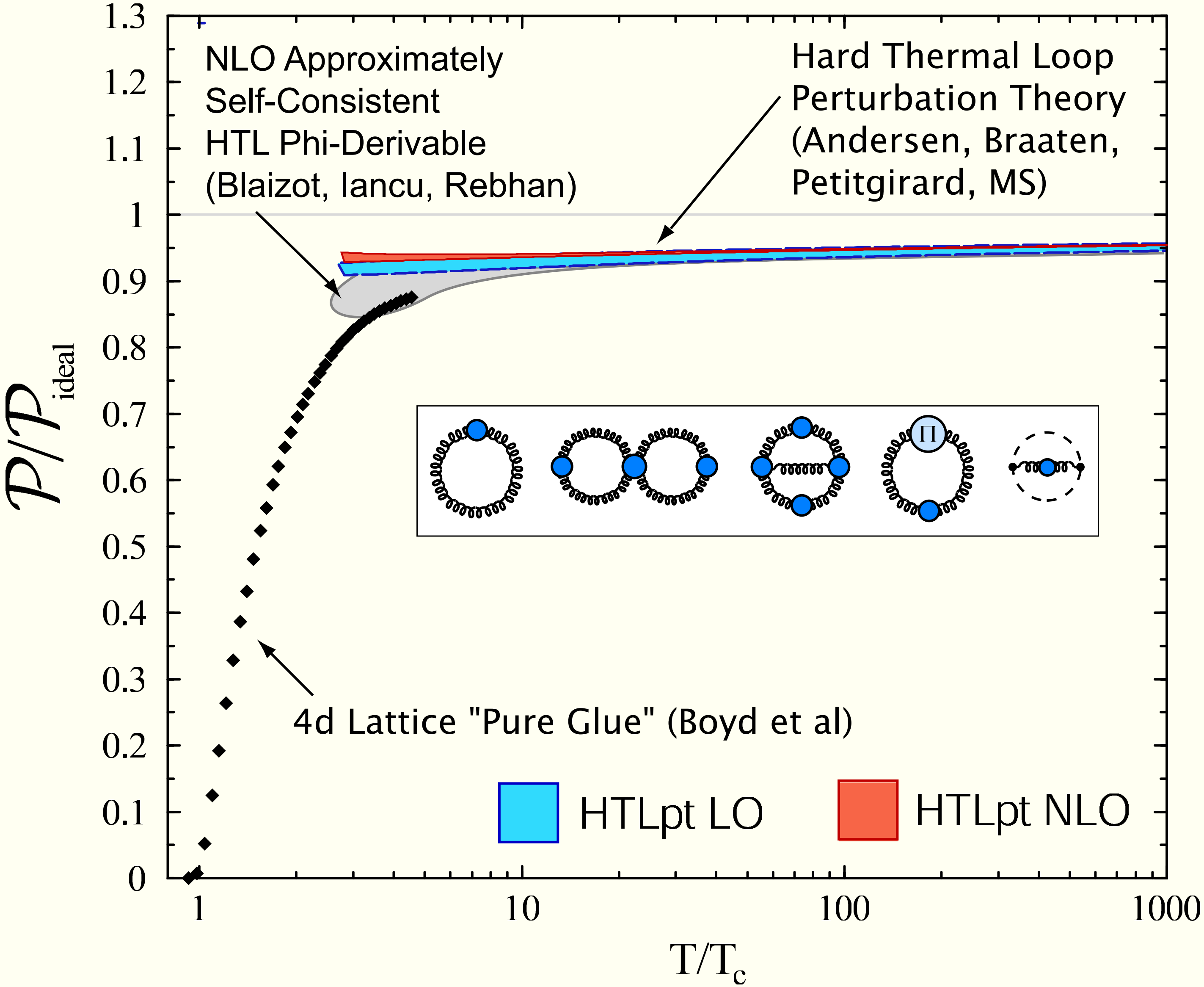
Cause for despair

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



What about strong-coupling AdS/CFT?

Strong-coupling calculations in $\mathcal{N} = 4$ SUSY theories show that the high-energy photon rate is insensitive to whether you take the weak or strong coupling limits. [Caron-Huot, Kovtun, Moore, Starinets, Yaffe, arXiv:hep- th/0607237]

Jan-e Alam 2007 J. Phys. G: Nucl. Part. Phys. 34 S865-S868