Measuring QGP thermalization time with dileptons

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KITP - Nonequilibrium Dynamics in Particle Physics and Cosmology
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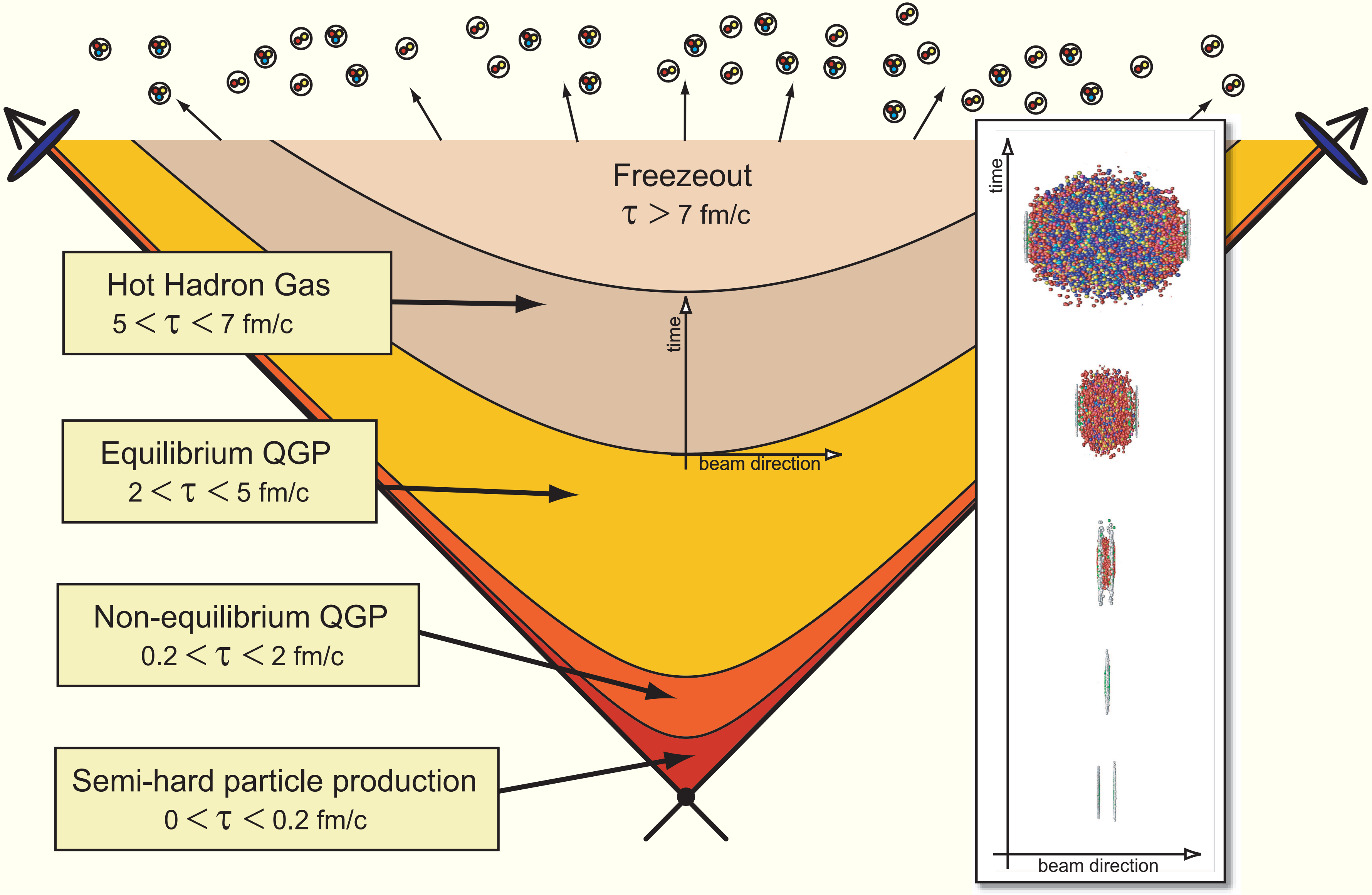
Heavy-ion collision timescales and “epochs” @ RHIC



Freezeout
$\tau > 7$ fm/c

Hot Hadron Gas
$5 < \tau < 7$ fm/c

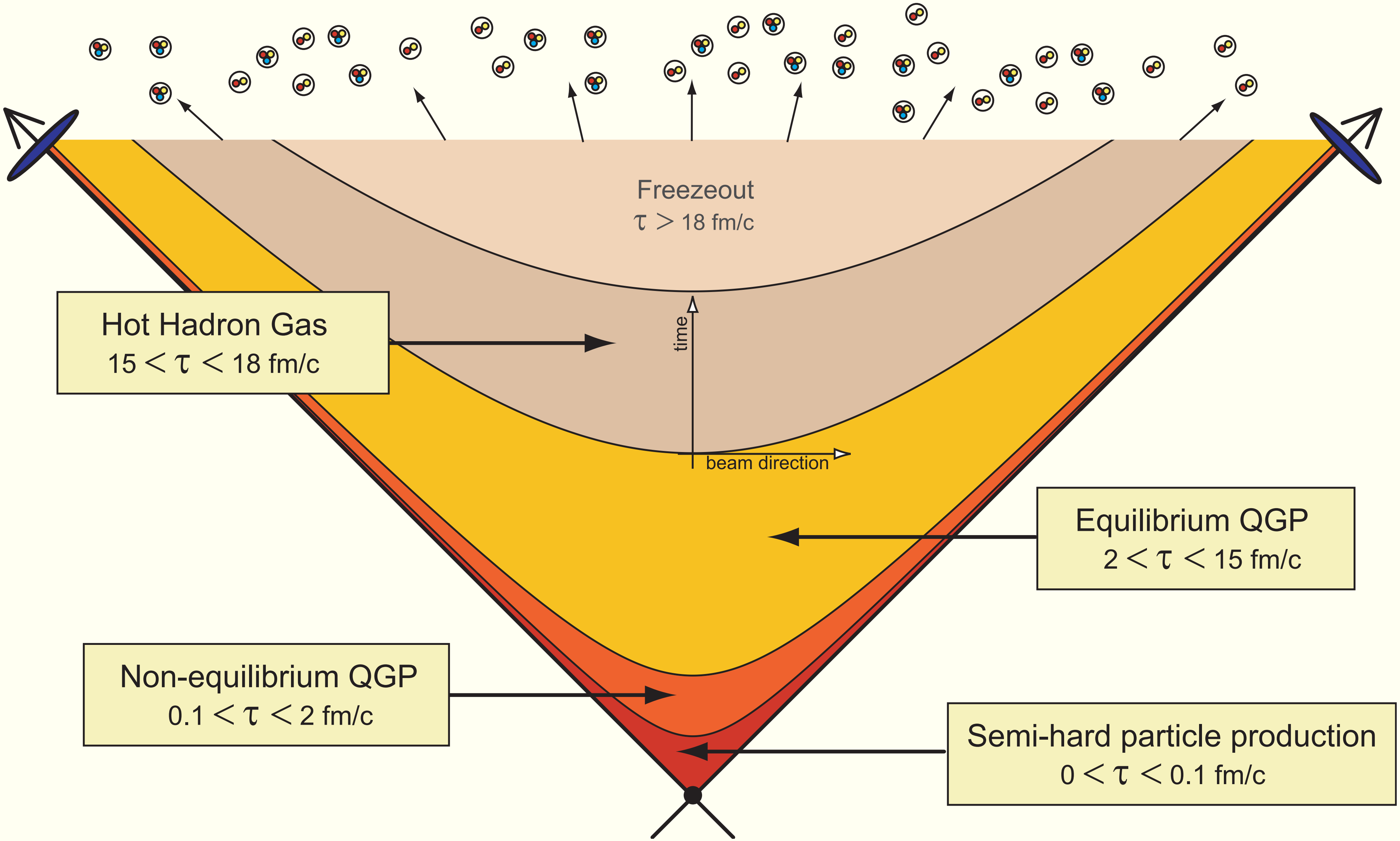
Equilibrium QGP
$2 < \tau < 5$ fm/c

Non-equilibrium QGP
$0.2 < \tau < 2$ fm/c

Semi-hard particle production
$0 < \tau < 0.2$ fm/c

*1 fm/c $\simeq 3 \times 10^{-24}$ seconds

Heavy-ion collision timescales and “epochs” @ LHC



Hot Hadron Gas
$15 < \tau < 18$ fm/c

Equilibrium QGP
$2 < \tau < 15$ fm/c

Non-equilibrium QGP
$0.1 < \tau < 2$ fm/c

Semi-hard particle production
$0 < \tau < 0.1$ fm/c

*1 fm/c $\simeq 3 \times 10^{-24}$ 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/thermalization of the QGP.

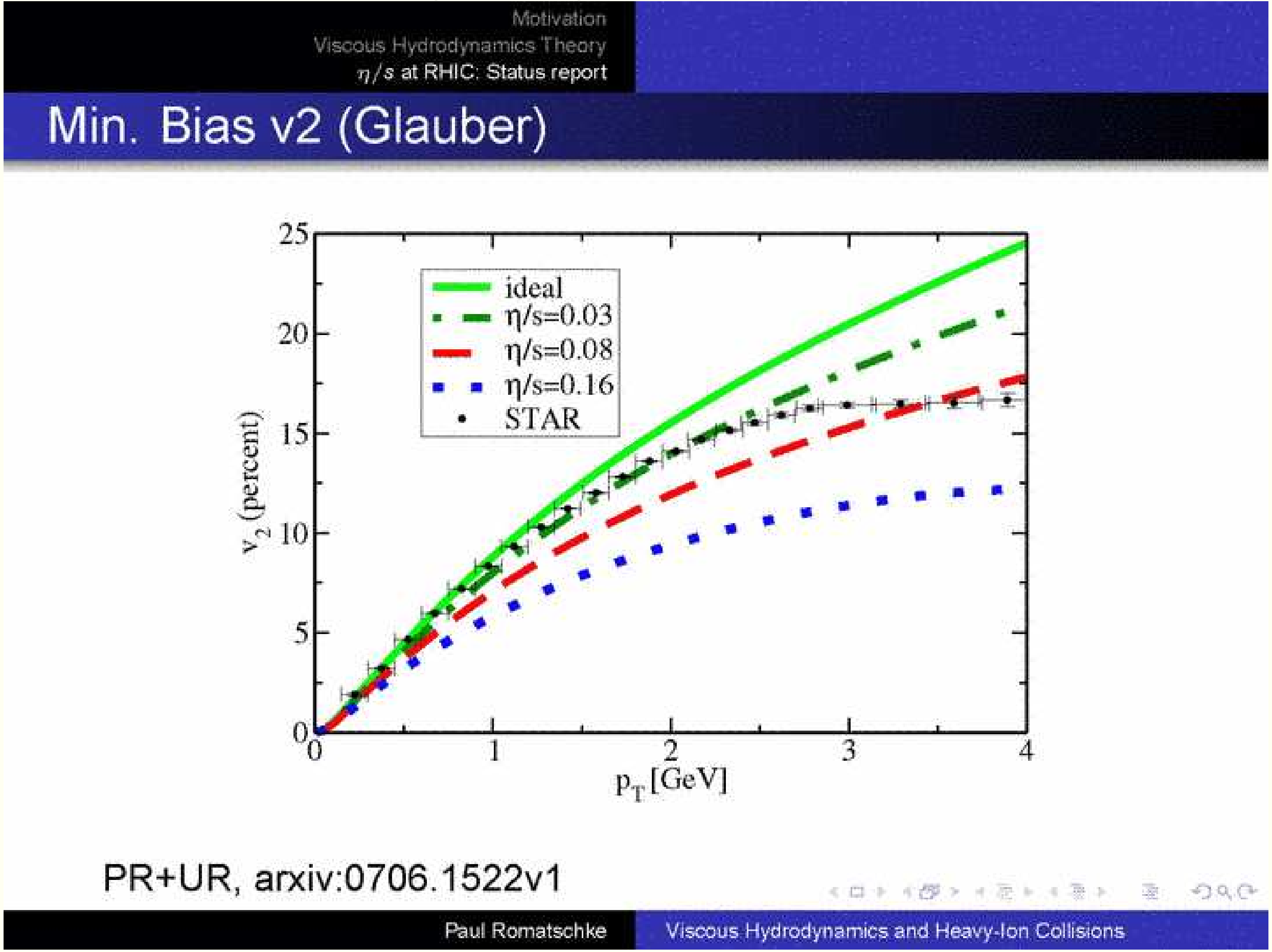
- Early ideal hydro fits indicate $\tau_{\rm iso} = 0.6$ fm/c (Kolb et al); however, recent results (Romatschke et al) seem to indicate that larger $\tau_{\rm iso} \sim 2$ fm/c are also consistent with low-p_T elliptic flow.

- Hydro results depend on **initial conditions** and 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 + $\ldots$).

Hydro Results 1

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



Motivation
Viscous Hydrodynamics Theory
η/s at RHIC: Status report

Min. Bias v2 (Glauber)

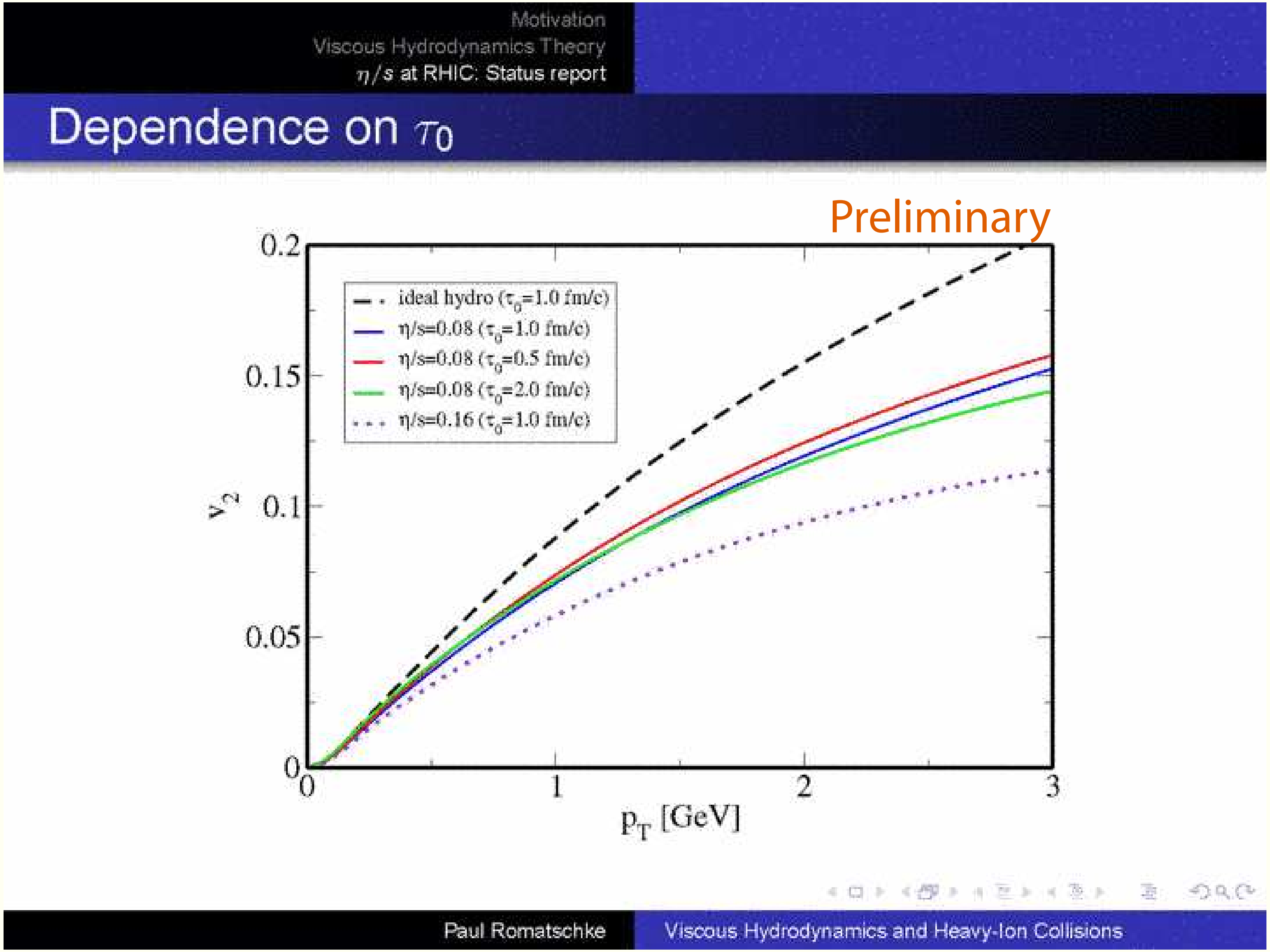
PR+UR, arxiv:0706.1522v1

Paul Romatschke

Viscous Hydrodynamics and Heavy-Ion Collisions

Hydro Results 2

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



Motivation
Viscous Hydrodynamics Theory
η/s at RHIC: Status report

Dependence on τ_0

Preliminary

Paul Romatschke
Viscous Hydrodynamics and Heavy-Ion Collisions

What does theory have to say?

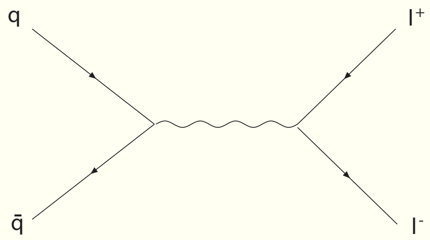
- The weak-coupling QCD “bottom-up” thermalization scenario predicted $\tau_{\text{therm}} = \alpha_s^{-13/5} Q_s^{-1}$. [Baier, Mueller, Son, Schiff]
- Assuming $\alpha_s = 0.3$ at RHIC energies this implies $\tau_{\text{therm}} = 2 - 3$ fm/c and at LHC energies that $\tau_{\text{therm}} = 1 - 2$ fm/c.
- Nonabelian chromo-Weibel plasma instabilities will accelerate thermalization but it is currently unknown by precisely how much. [Mrowczynski, Strickland, Romatschke, Arnold, Lenaghan, Moore, Rebhan, Yaffe, Venugopalan, Dumitru, Nara, Bödeker, Rummukainen, Fukushima, Gelis, McLerran, Berges, Sexty, Scheffler, . . .]
- AdS/CFT → time should scale inversely with the temperature of the extra-dimensional black hole so it should be $\tau_{\text{therm}} \lesssim \#1$ fm/c. Question of formation of the black hole itself from anisotropic initial state is very much unsolved. AdS/QCD? Initial Conditions?

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.
- Dilepton spectra contain more information 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 anisotropy (beam) axis.



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

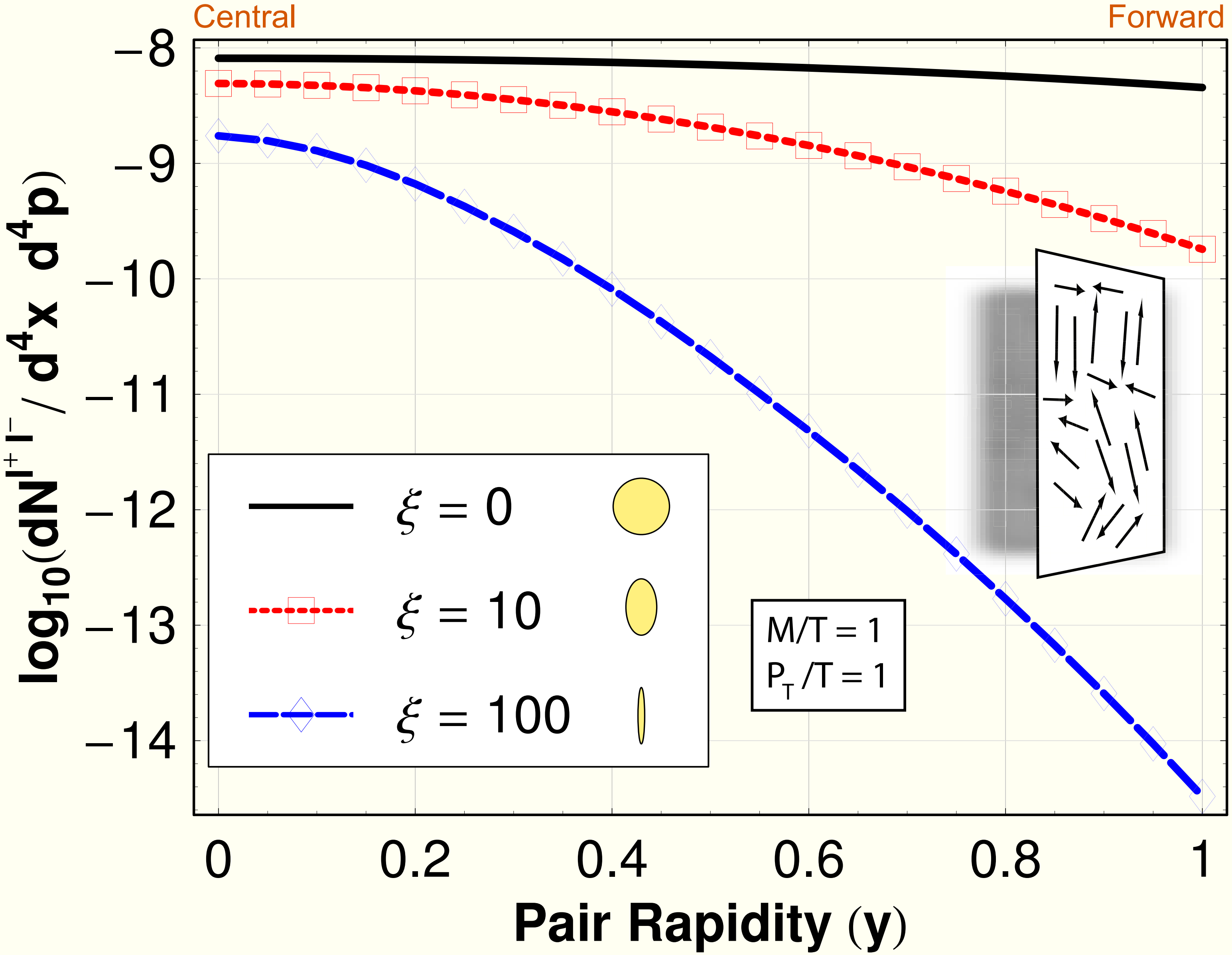
$$f^{q,\bar{q}}(\mathbf{p},\mathbf{x}) = f^{q,\bar{q}}_{\rm iso}\left(p_T^2 + (1+\xi)p_L^2\right)$$

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

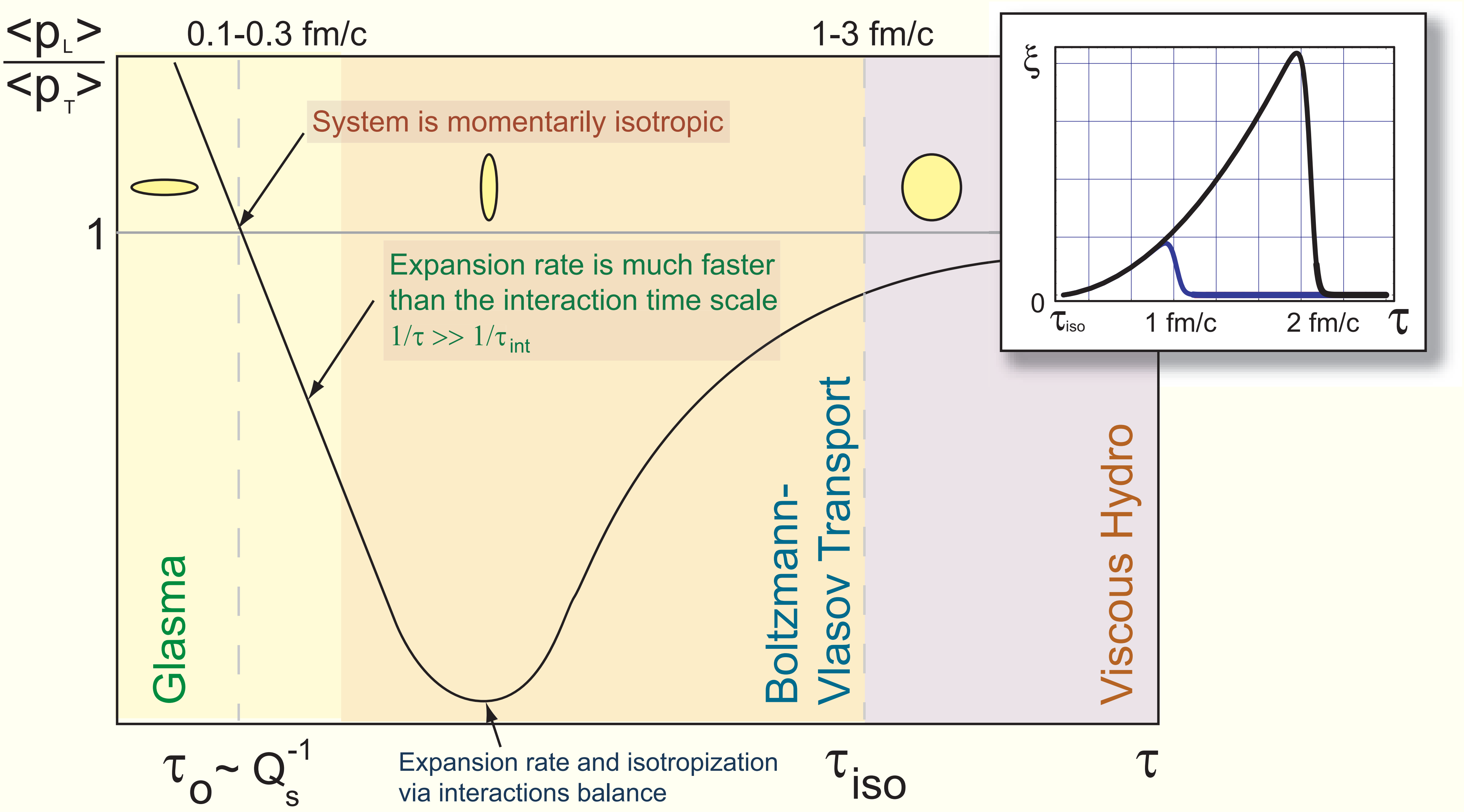
$$\frac{\langle p_T^2\rangle}{2\langle p_L^2\rangle} \sim 1+\xi$$

M. Martinez and MS, arXiv:0709.3576, PRL (in press).

Dilepton rate depends on degree of QGP anisotropy



Momentum Space Anisotropy Time Dependence

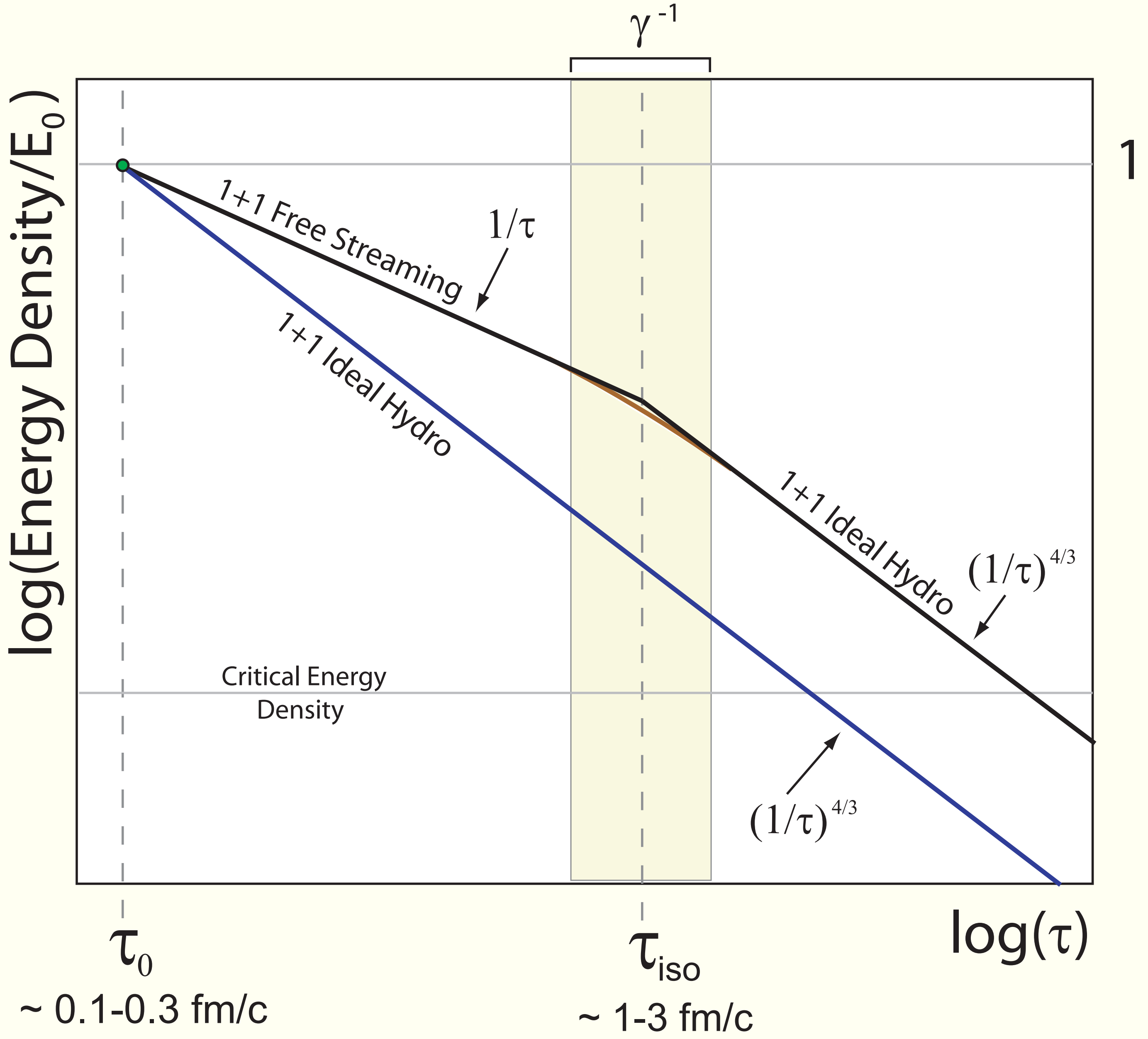


System is momentarily isotropic

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

Expansion rate and isotropization via interactions balance

Phenomenological model parameters



Model: Break evolution into two pieces

1) $\tau \lesssim \tau_{\rm iso}$ - 1d free streaming

$$\langle p_T^2 \rangle \sim 2Q_s^2 \qquad \langle p_L^2 \rangle \sim 1/\tau^2$$

$$\xi(\tau) = \frac{1}{2}\langle p_T^2\rangle/\langle p_L^2\rangle - 1$$

$$\Downarrow$$

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

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

$$\text{“}T\text{”}(\tau) = T_0 \sim \langle p_T \rangle$$

In the limit $\tau_{\rm iso} \to \infty$ the system undergoes indefinite longitudinal free streaming.

2) $\tau \gtrsim \tau_{\rm iso}$ - 1d ideal hydro

$$\langle p_T^2 \rangle = 2\langle p_L^2 \rangle$$

$$\xi(\tau) = \frac{1}{2}\langle p_T^2\rangle/\langle p_L^2\rangle - 1$$

$$\Downarrow$$

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

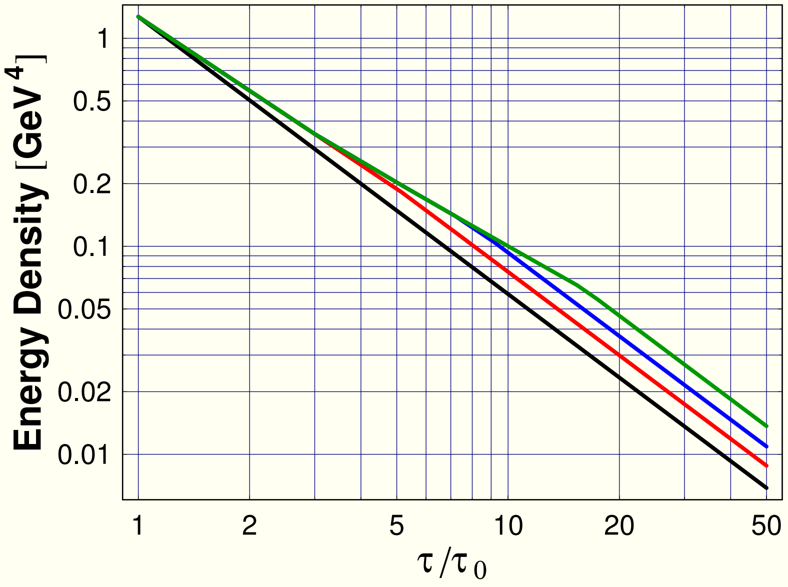
$$\mathcal{E}(\tau) = \mathcal{E}_0 \left(\frac{\tau_0}{\tau}\right)^{4/3}$$

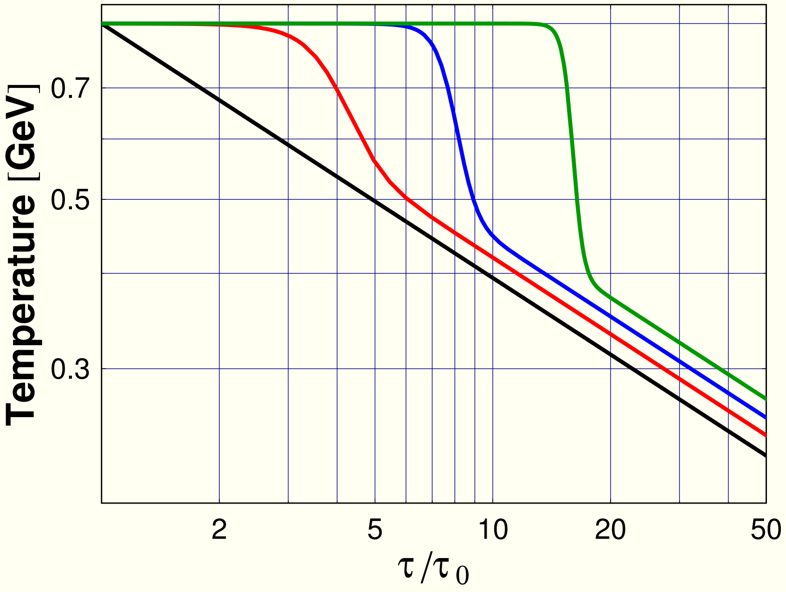
$$T(\tau) = T_0 \left(\frac{\tau_0}{\tau}\right)^{1/3}$$

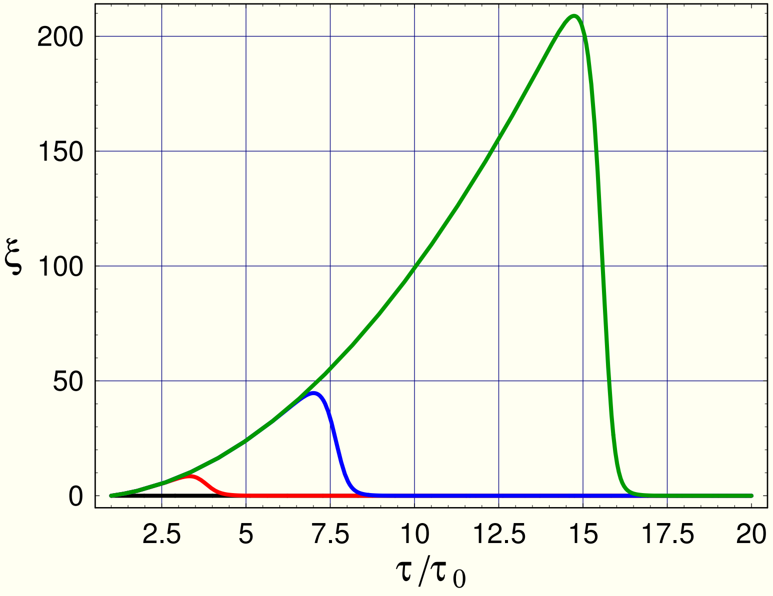
In the limit $\tau_{\rm iso} \to \tau_0$ the system begins ideal 1d hydrodynamic flow “instantly”.

M. Martinez and MS, arXiv:0709.3576, PRL (in press).

Space-time evolution incorporating anisotropies (LHC)



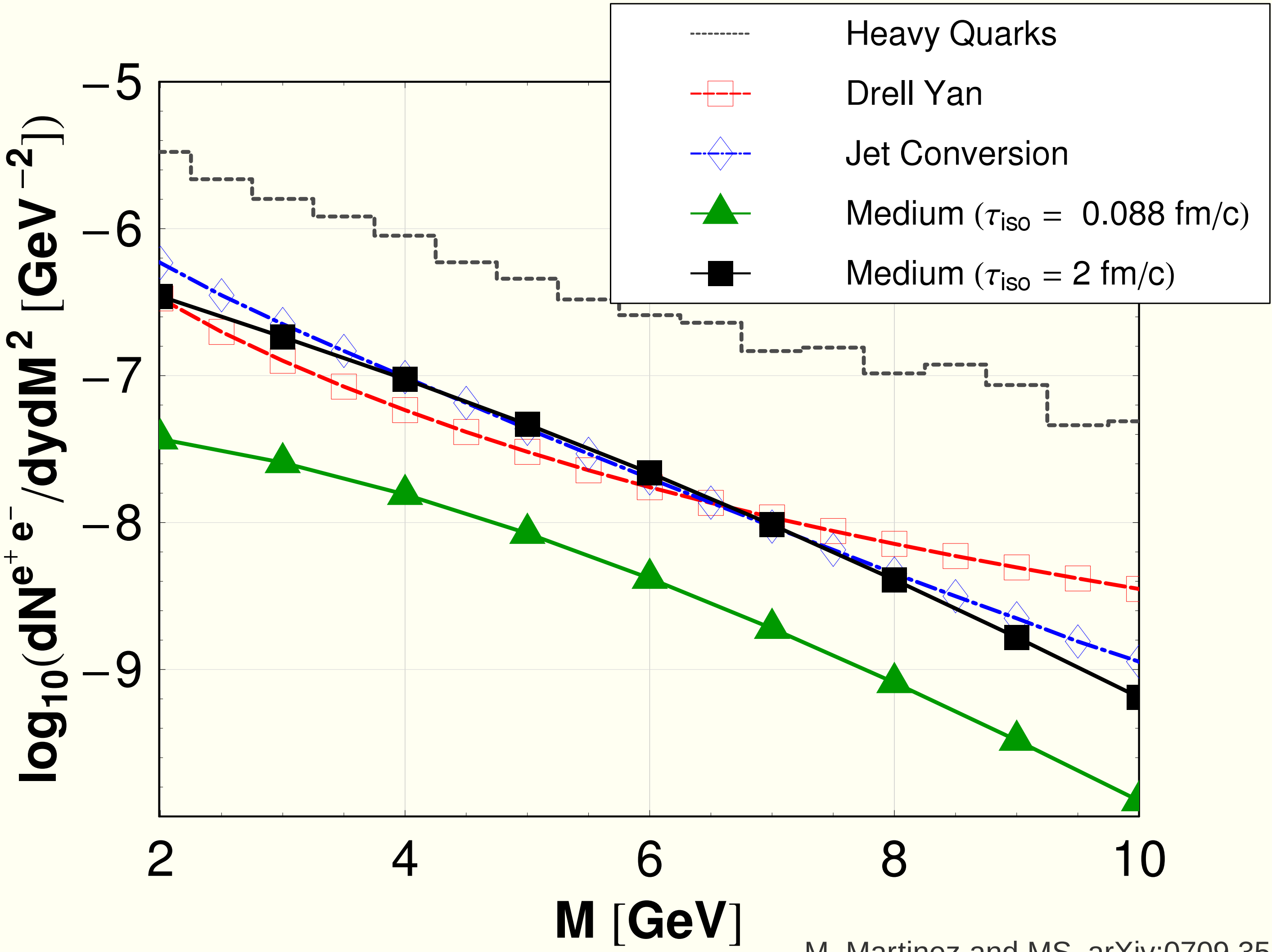




- $\gamma = 2 \quad \Rightarrow$ “width” of 0.4 fm/c.
- $\tau_{\rm iso} \to \tau_0$: “instant” isotropization/thermalization.
- $\tau_{\rm iso} \to \infty$: never isotropizes; 1d free-streaming.

LHC Predictions - Dileptons vs M with backgrounds

$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $\gamma = 2$, $T_c = 160$ MeV
Cuts: $p_T > 8$ GeV

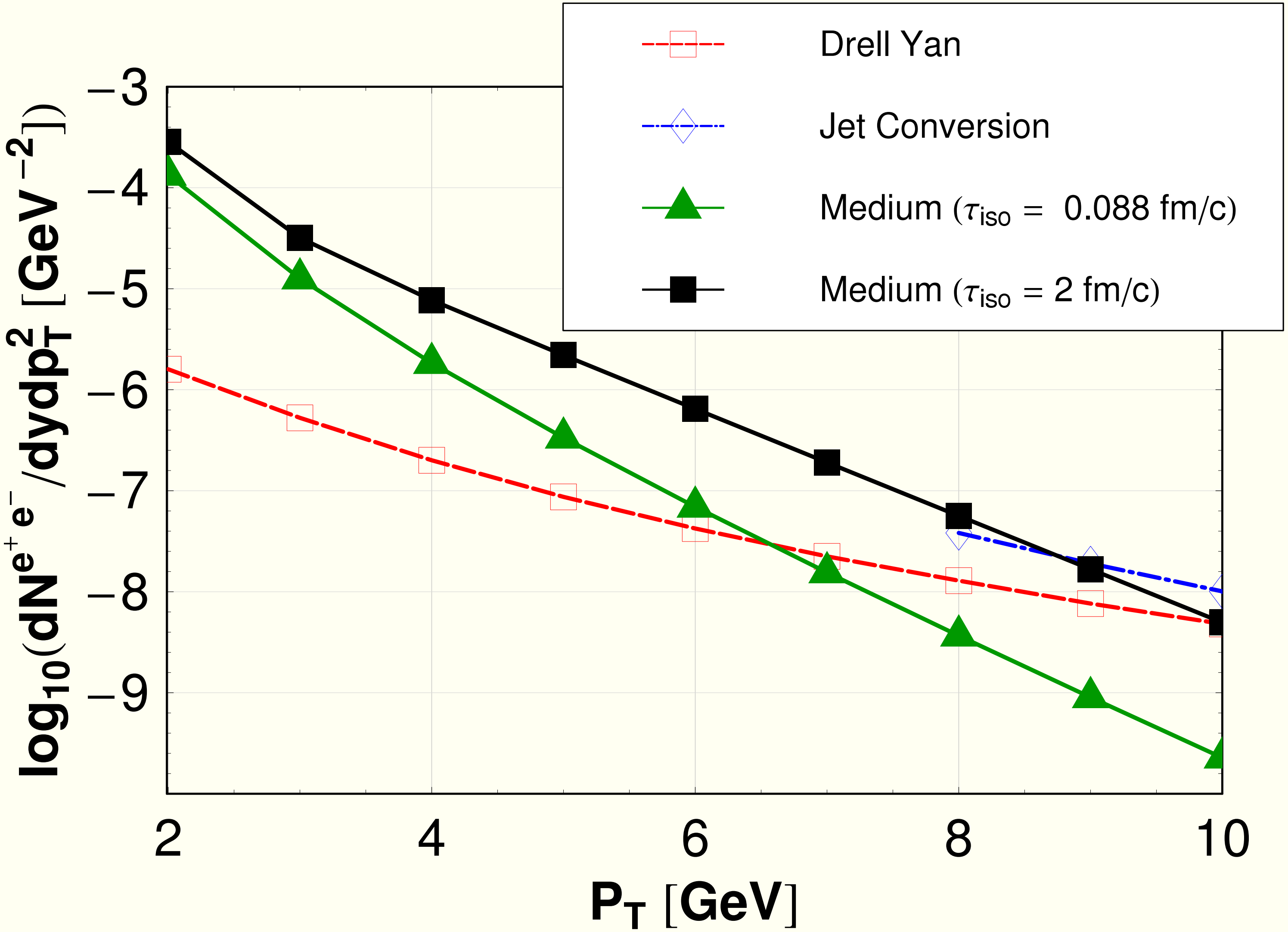


M. Martinez and MS, arXiv:0709.3576, PRL (in press).

LHC Predictions - Dileptons vs P_T with backgrounds

$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $\gamma = 2$, $T_c = 160$ MeV

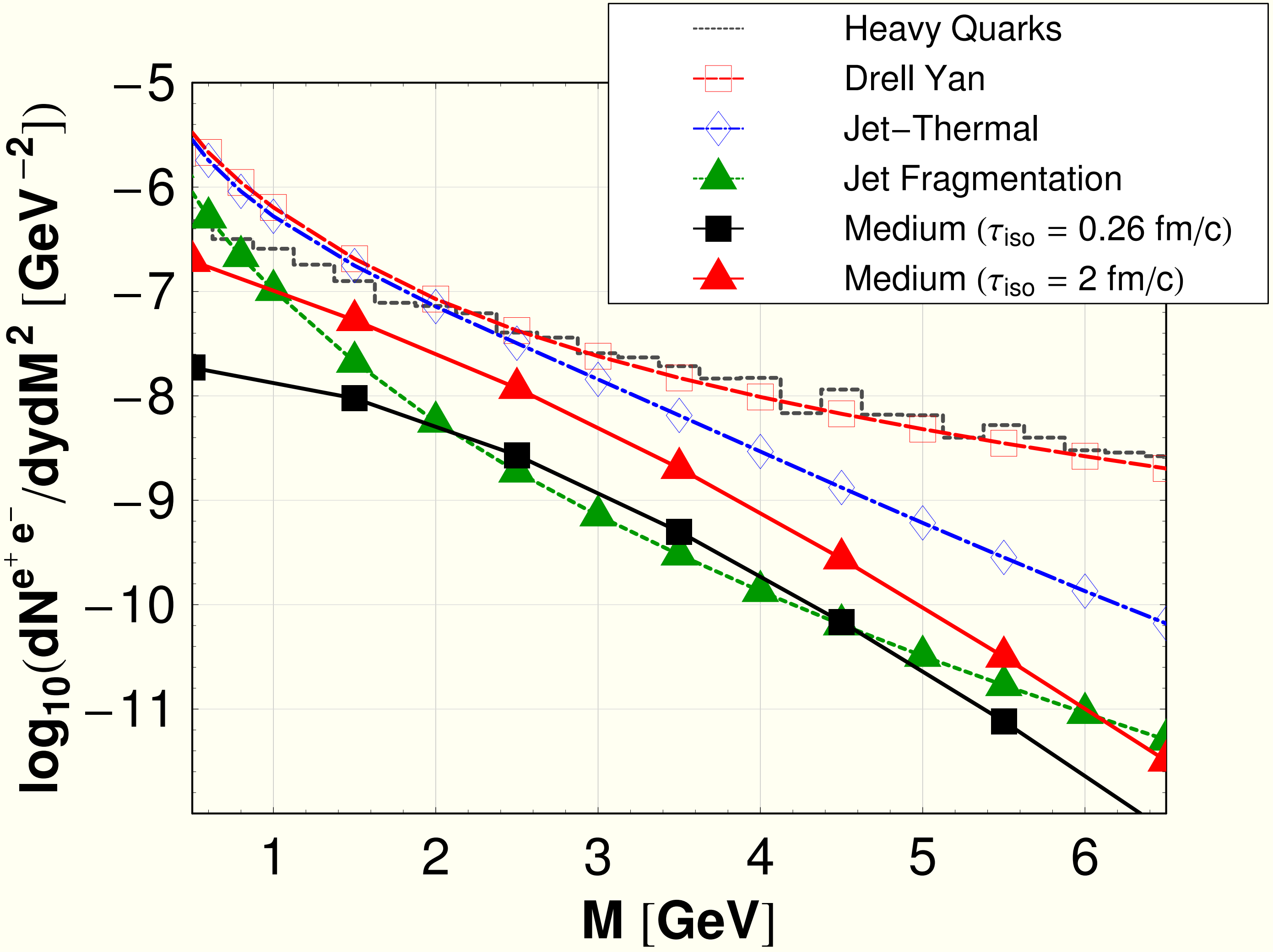
Cuts: $0.5 < M < 1$ GeV



M. Martinez and MS, arXiv:0709.3576, PRL (in press).

RHIC Predictions - Dileptons vs M with backgrounds

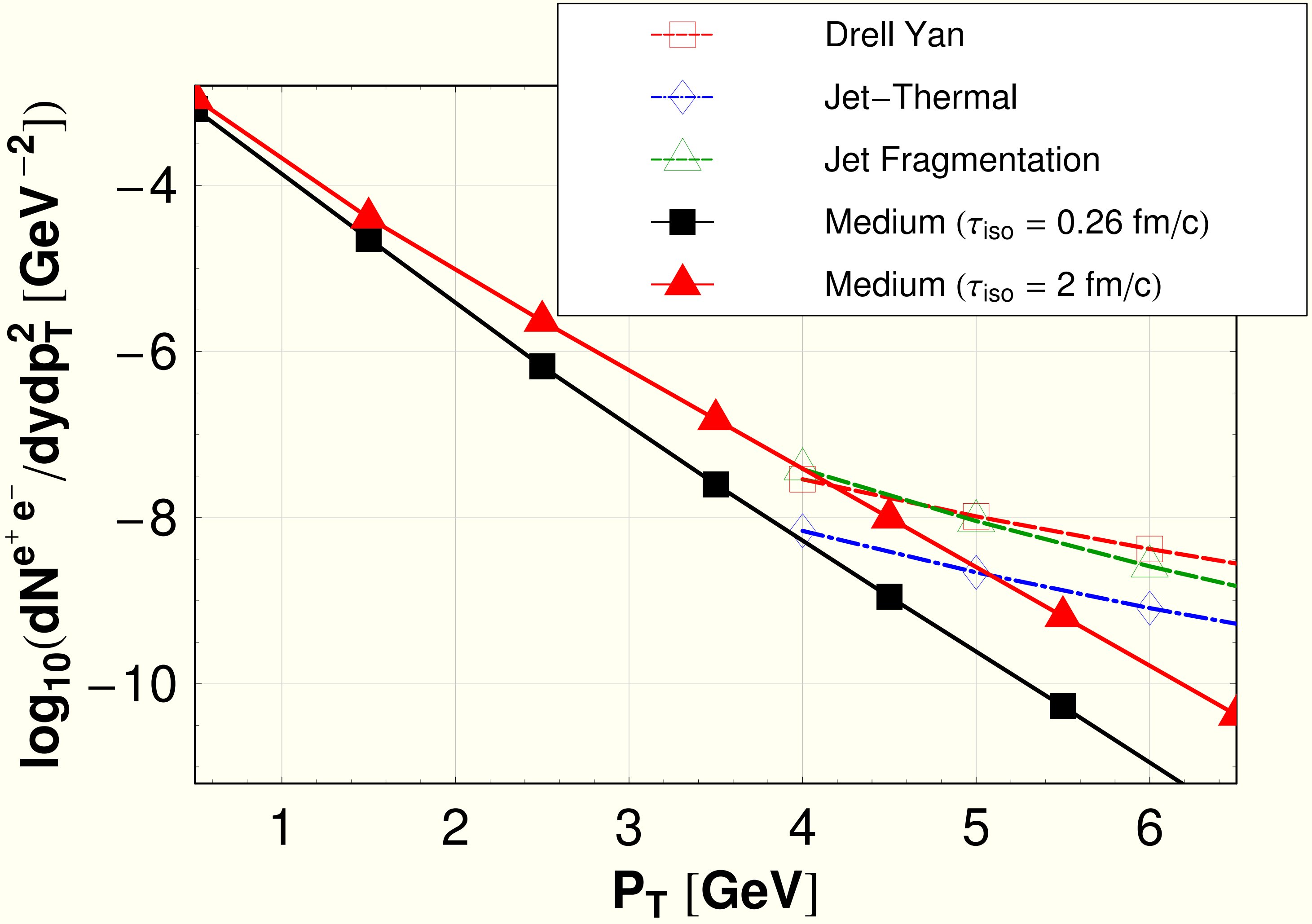
$T_0 = 370$ MeV, $\tau_0 = 0.26$ fm/c, $\gamma = 2$, $T_c = 160$ MeV
Cuts: $p_T > 4$ GeV



M. Martinez and MS, forthcoming.

RHIC Predictions - Dileptons vs P_T with backgrounds

$T_0 = 370$ MeV, $\tau_0 = 0.26$ fm/c, $\gamma = 2$, $T_c = 160$ MeV
Cuts: $0.5 < M < 1$ GeV



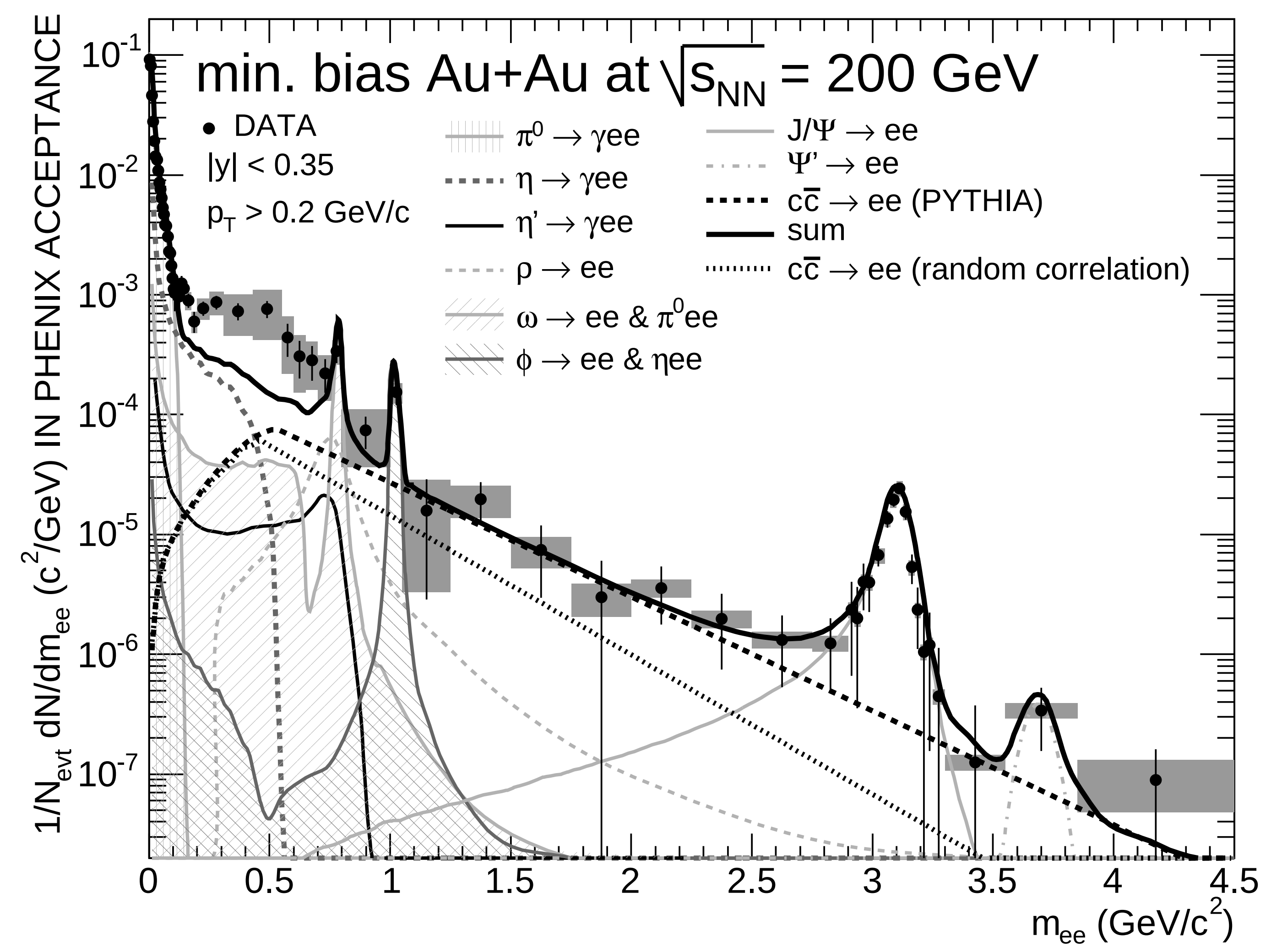
M. Martinez and MS, forthcoming.

Conclusions

- We need more observables which are sensitive to the initial 1-2 fm/c of the plasma lifetime. Dileptons seem to be promising.
- 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 . . .
- Our dilepton results show a window from $p_T \sim$ 2 - 6 GeV where it may be 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 -

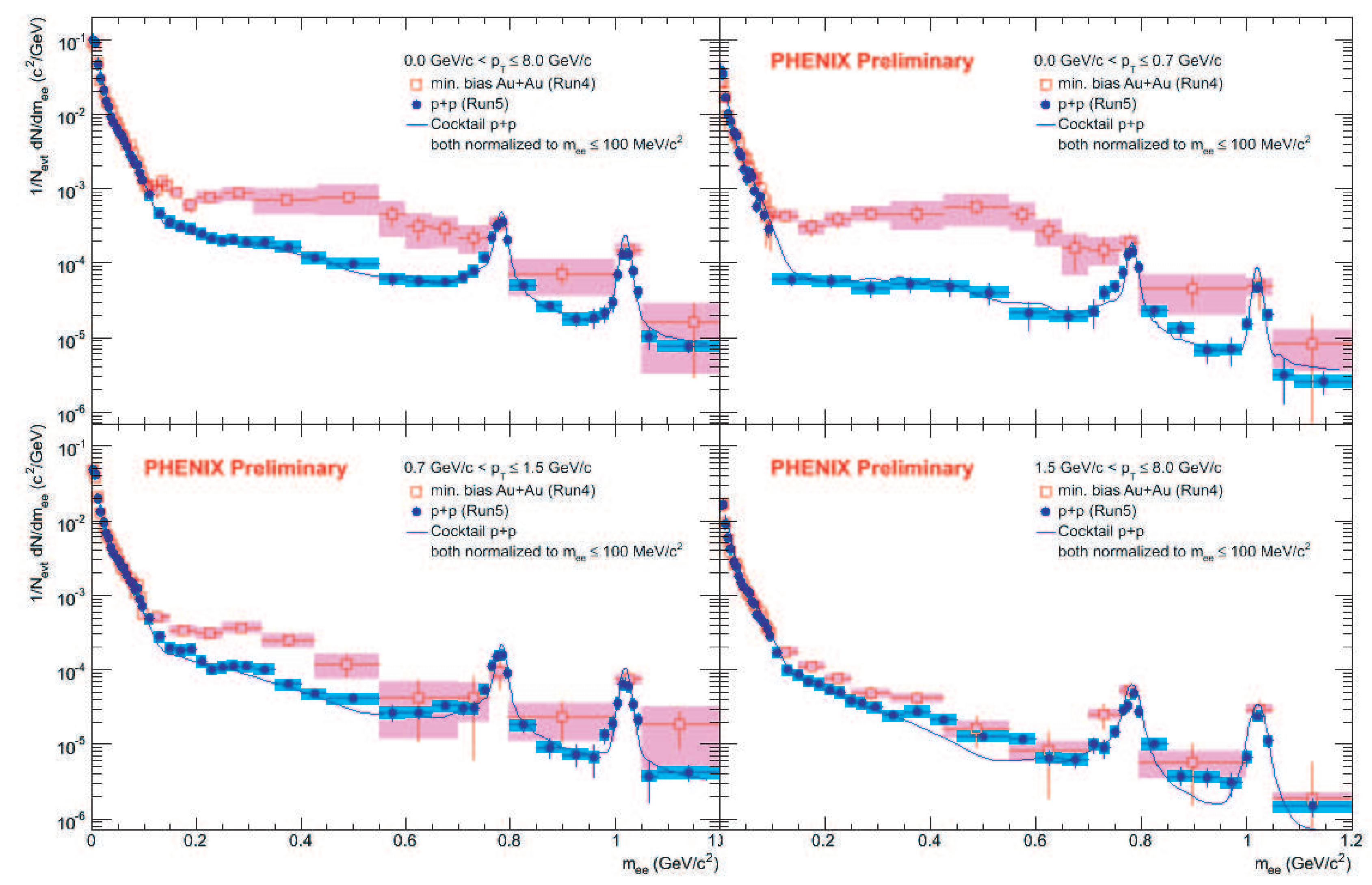
Latest RHIC Experimental Results



Enhancement seen at low invariant masses.

PHENIX collaboration, arXiv: 0706.3034.

Latest RHIC Experimental Results

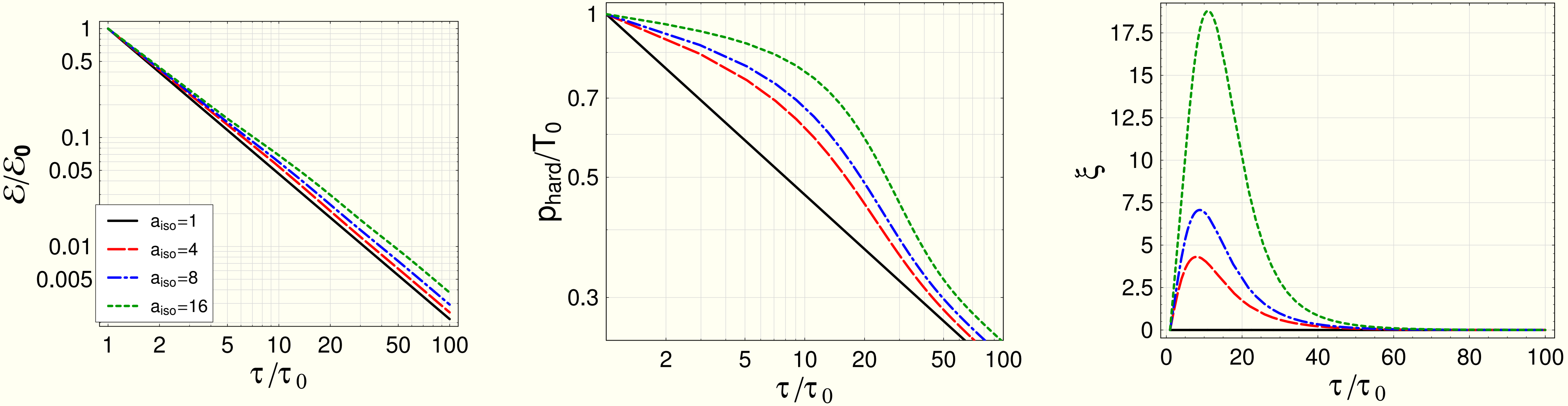


Enhancement concentrated at low transverse momentum, $p_T < 1$ GeV.

Alberica Toia, PHENIX collaboration, arXiv:0706.3034, arXiv:0802.0050.

Model - Smaller Gamma

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

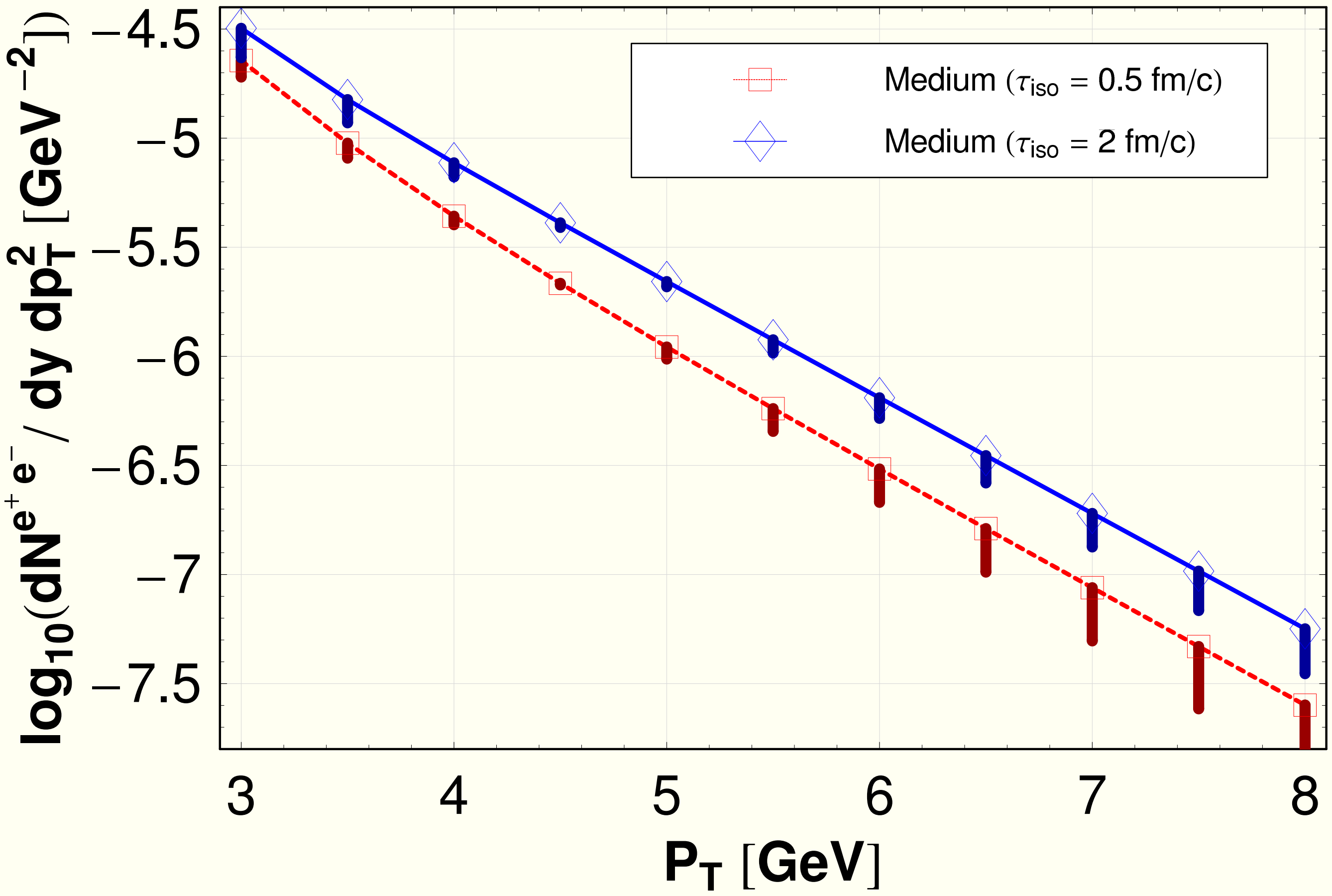


LHC Results - Model variation

$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $T_c = 160$ MeV

Cuts: $0.5 < M < 1$ GeV

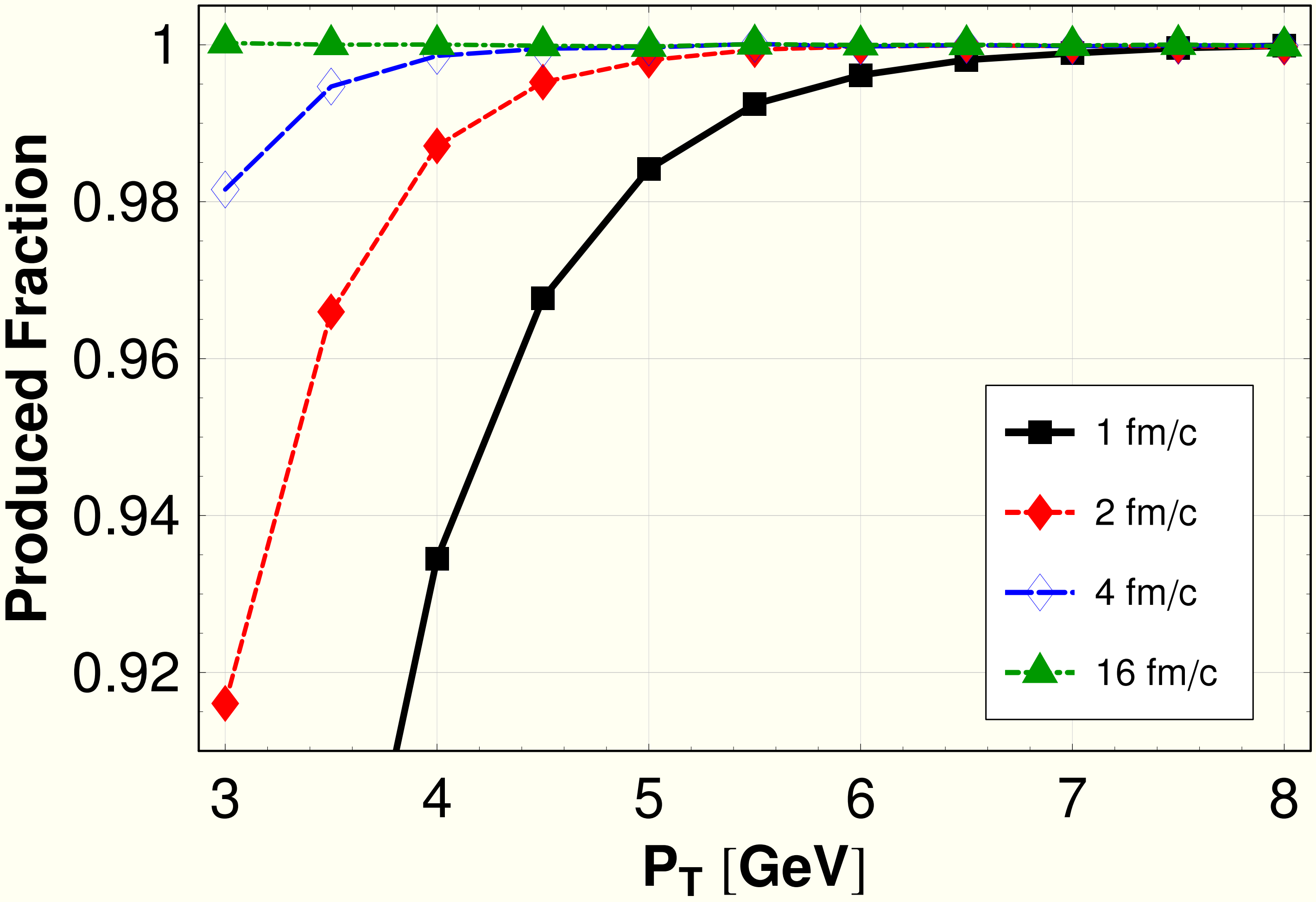
Model Variation: $0.05 < \gamma < 10$



M. Martinez and MS, arXiv:0709.3576, PRL (in press).

LHC Results - Time scales

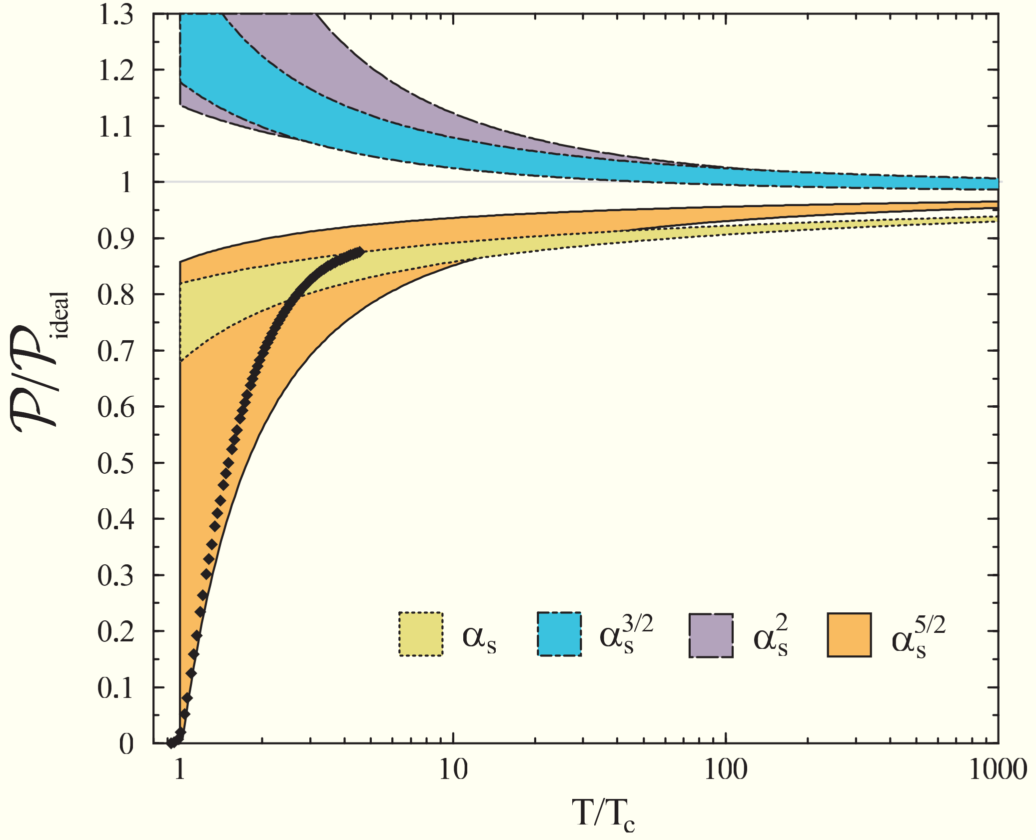
$T_0 = 845$ MeV, $\tau_0 = 0.088$ fm/c, $T_c = 160$ MeV
Cuts: $0.5 < M < 1$ GeV



M. Martinez and MS, arXiv:0709.3576, PRL (in press).

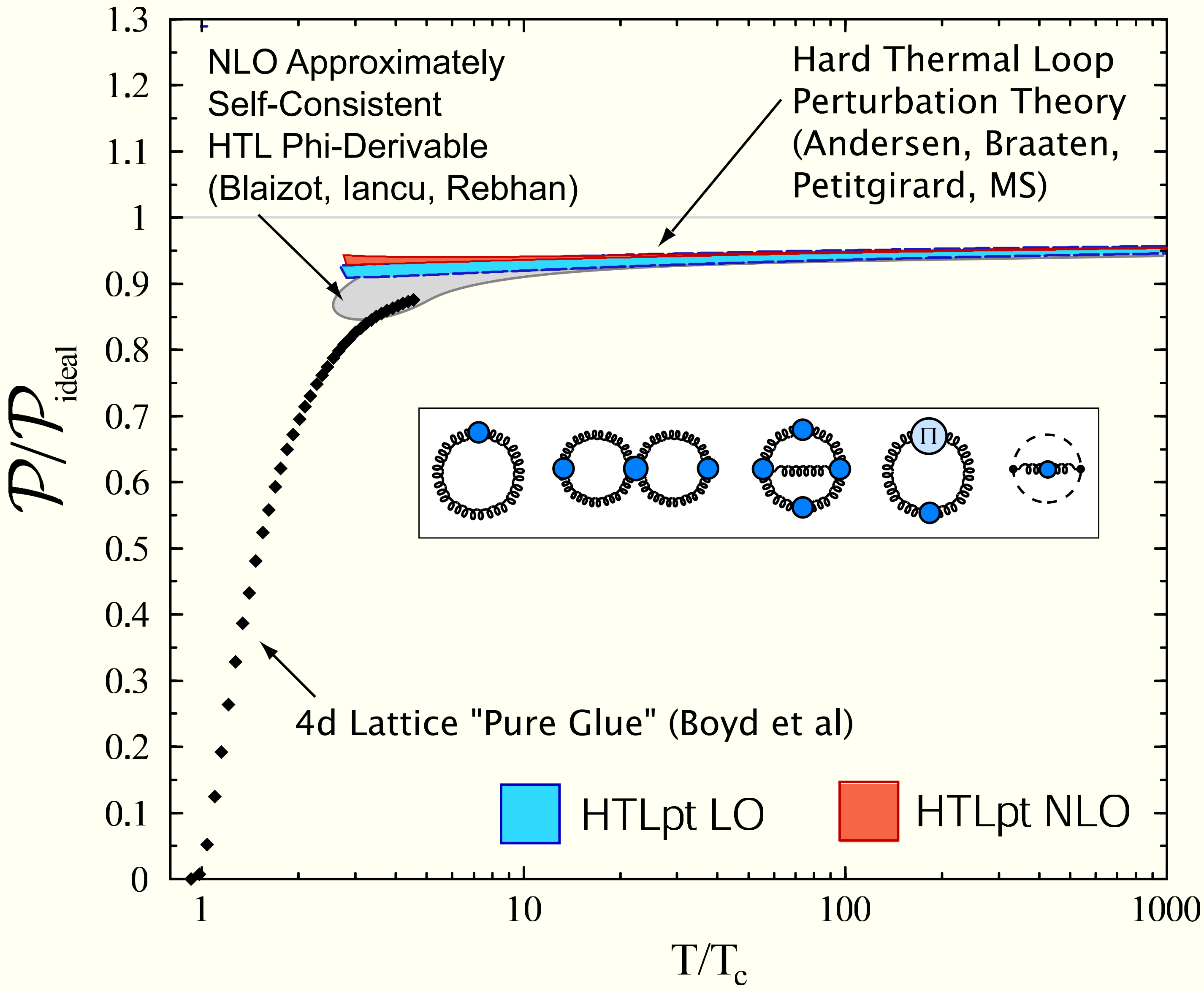
Cause for despair

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