From full stopping to transparency in a holographic model of heavy ion collisions

Michał P. Heller m.p.heller@uva.nl

University of Amsterdam, The Netherlands

&

National Centre for Nuclear Research, Poland (on leave)

based on

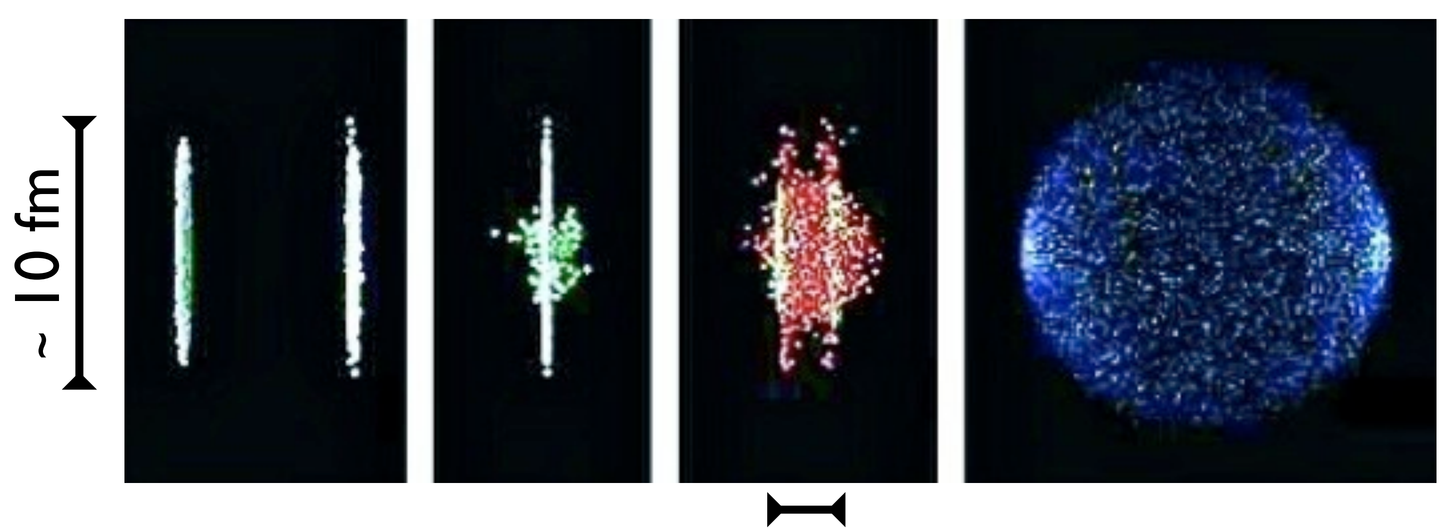
1305.4919 [hep-th] J. Casalderrey-Solana, MPH, D. Mateos, W. van der Schee

Fast "Thermalization" at RHIC and LHC

Heinz [nucl-th/0407067]

There are overwhelming evidences that relativistic heavy ion collision programs at RHIC and LHC created strongly coupled quark-gluon plasma (sQGP)

Successful description of experimental data is based on hydrodynamic simulations of an almost perfect fluid of $\eta/s = \mathrm{O}\left(1/4\pi\right)$ starting on very early (< 1 fm)



described by hydrodynamics after < 1 fm

"Thermalization" at strong coupling

Recent progress in numerical relativity in AdS opened a possibility to study equilibration processes in holographic (strongly coupled) gauge theories

0812.2053 [hep-th], 0906.4426 [hep-th], 1011.3562 [hep-th] P. Chesler & L. Yaffe

1103.3452 [hep-th], 1203.0755 [hep-th] MPH, R. A. Janik, P. Witaszczyk

1202.0981 [hep-th], 1304.5172 [hep-th] MPH, D. Mateos, W. van der Schee + others

...

The key lesson from these developments is that "thermalization" at strong coupling proceeds over a time scale set by the inverse of the "final" temperature

holography: $t_{equil} \times T_{final} \Big|_{\lambda=\infty} = \mathcal{O}(1)$ (LHC estimate: $0.25\,\mathrm{fm} \times 500\,\mathrm{MeV} = 0.63$)

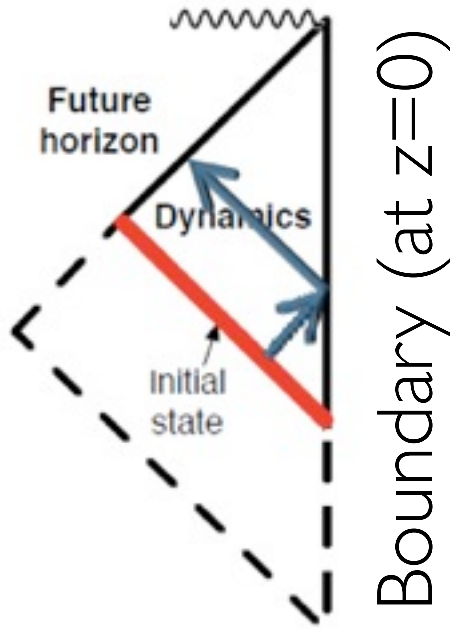
From this perspective, fast applicability of hydrodynamics at RHIC and LHC might not be so surprising given that the coupling there is not parametrically small

A typical holographic thermalization process

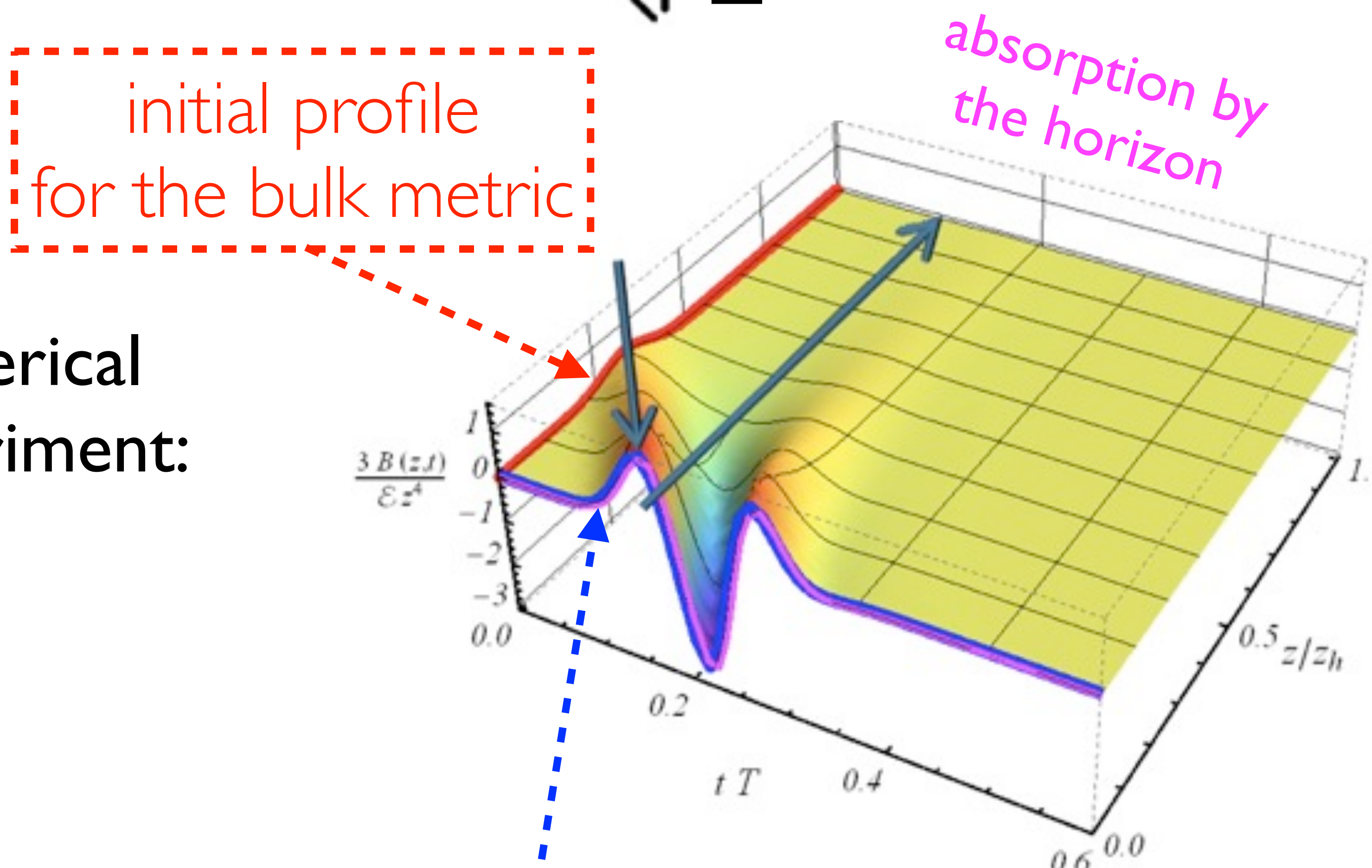
1202.0981 [hep-th]

MPH, D. Mateos, W. van der Schee, D. Trancanelli

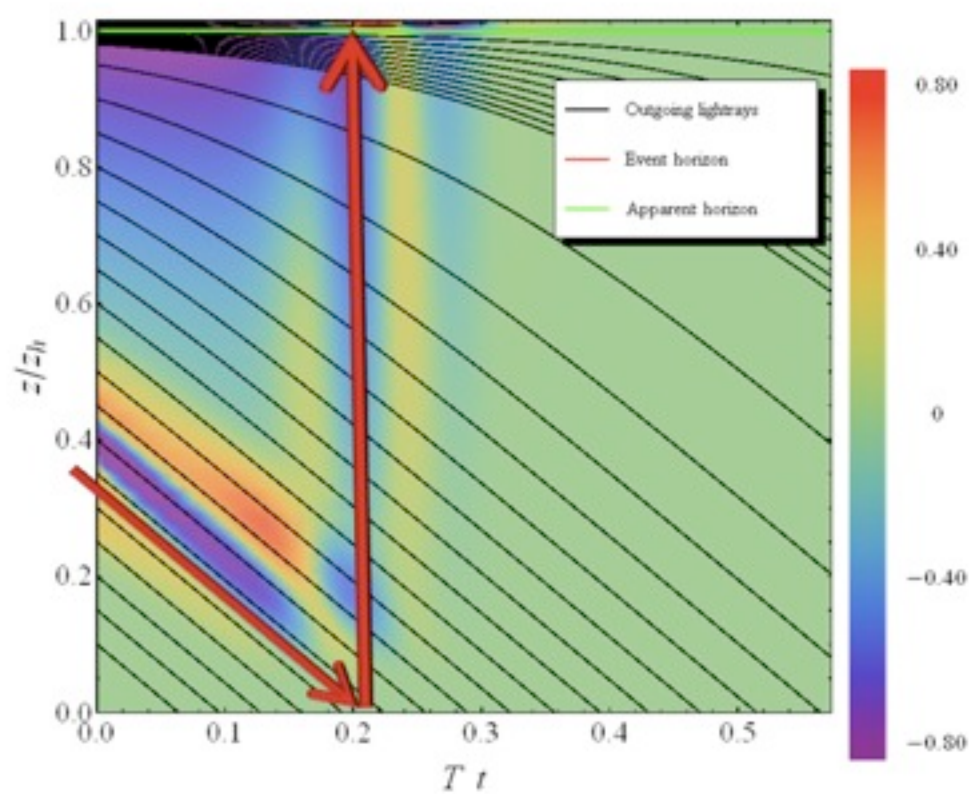
Theory:



Numerical experiment:

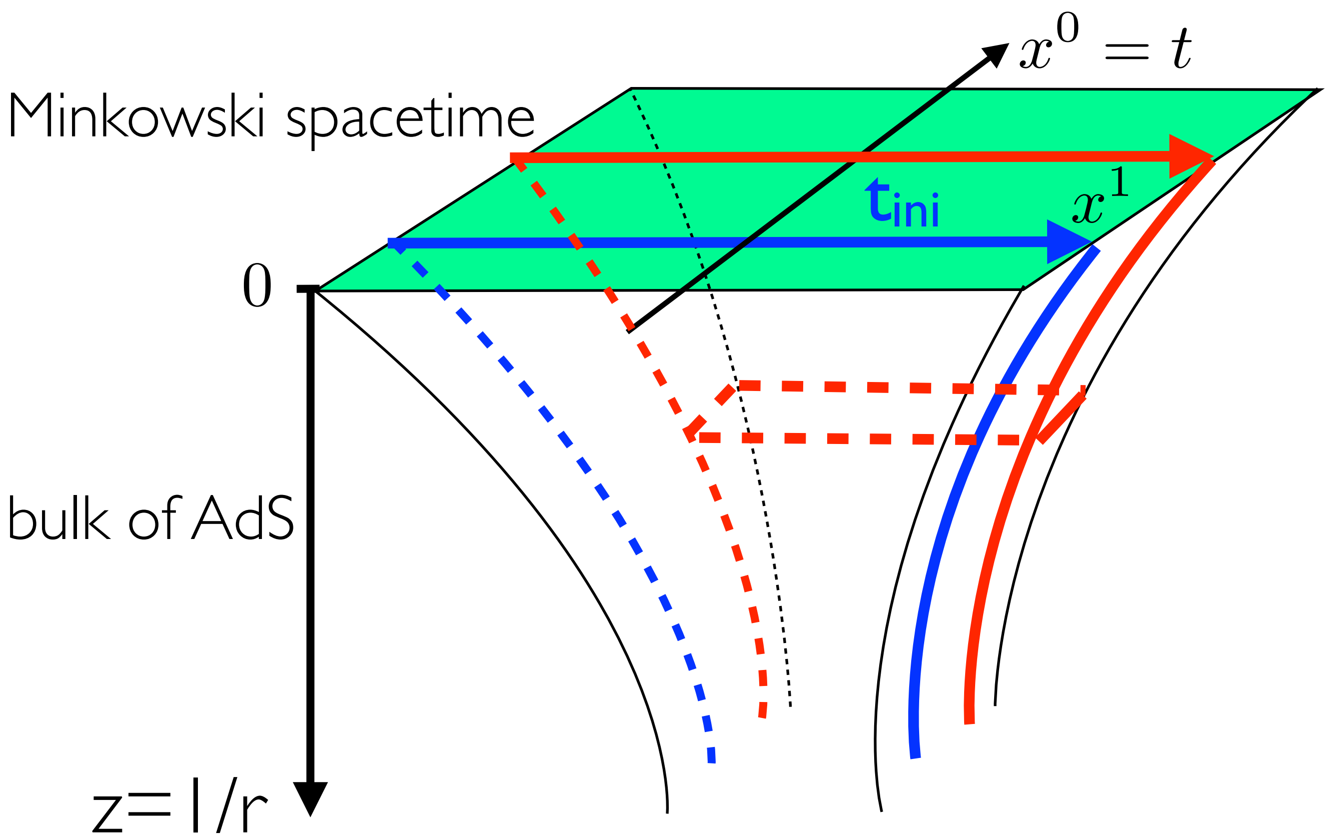


Curvature (BH subtracted)



$$\langle T_{\mu\nu}\rangle = \mathrm{diag}\left\{\epsilon,\ \frac{1}{3}\epsilon - \frac{2}{3}\boxed{\Delta P(t)},\ \frac{1}{3}\epsilon + \frac{1}{3}\Delta P(t),\ \frac{1}{3}\epsilon + \frac{1}{3}\Delta P(t)\right\}$$

The main problem



HUGE FREEDOM OF CHOICE

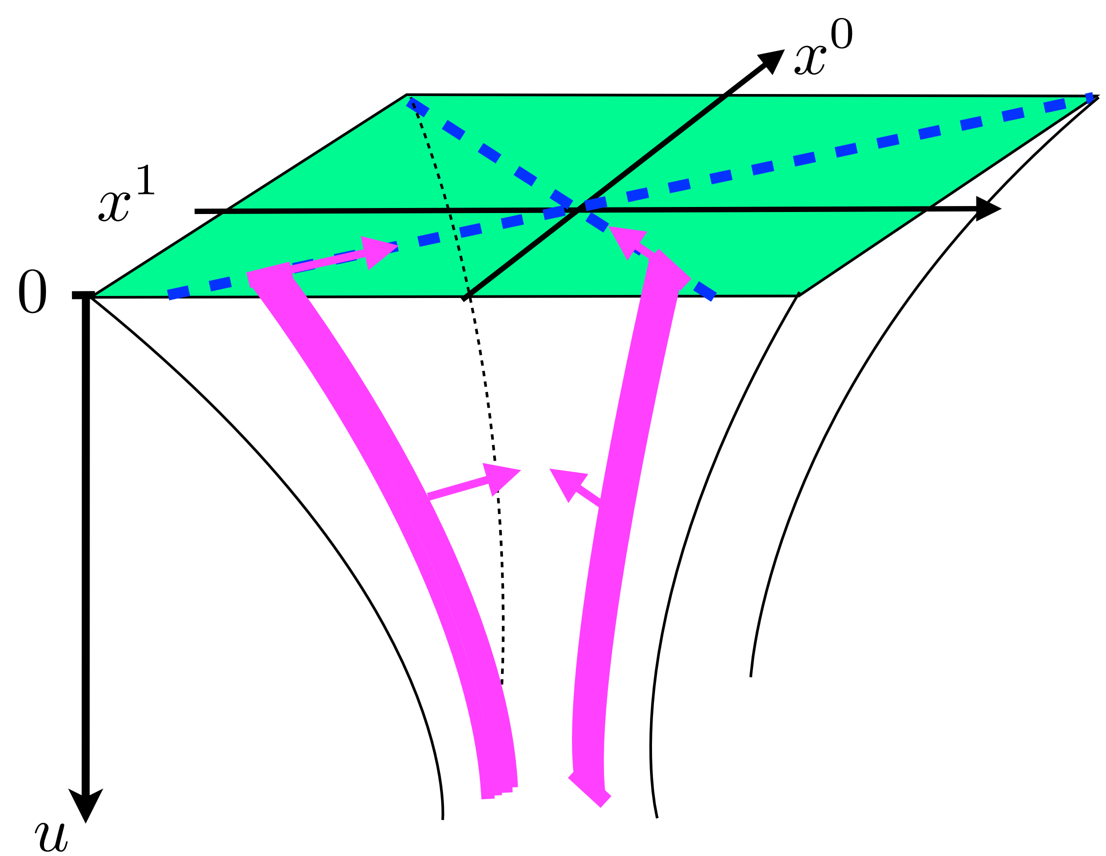
Which far from equilibrium initial condition is the closest to the experiment?

Towards a holographic „heavy ion collision"

Operational view:

collide holographically two lumps of matter moving at relativistic speeds

unfortunately necessarily deconfined, i.e. with $\langle T^{\mu\nu} \rangle = \mathcal{O}(N_c^2)$



State of the art as of July 2013: colliding gravitational shock wave solutions

Gravitational shock wave solutions

Janik & Peschanski **[hep-th/0512162]** Chesler & Yaffe **1011.3562 [hep-th]**

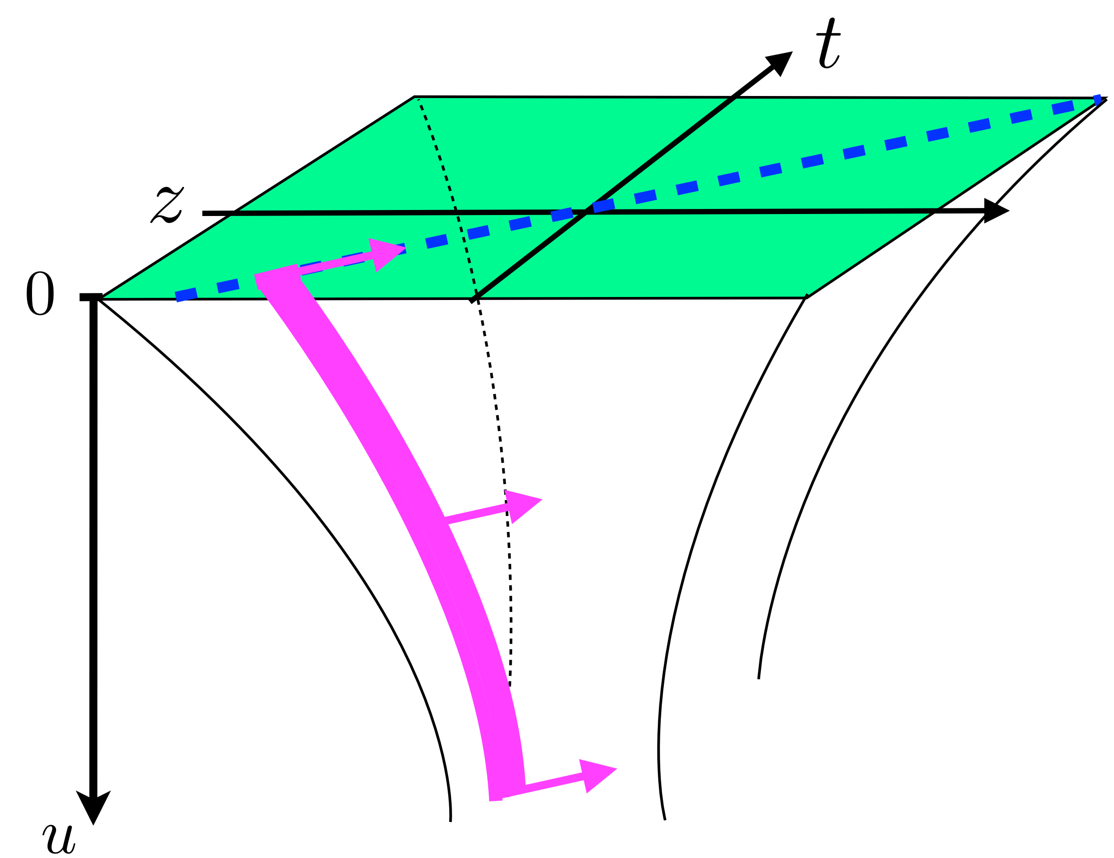
dual stress tensor:

$$T^{tt} = T^{zz} = +T^{tz} = \frac{N_c^2}{2\pi^2} h(t-z)$$

shock wave disturbance
moving with the speed of light

$$ds^2 = \frac{1}{u^2}(du^2 + \eta_{\mu\nu}dx^\mu dx^\nu) + u^2 h(x_-)dx_-^2$$

Poincare patch
vacuum AdS



Solution of Einstein's equations with the negative CC
for <u>any</u> longitudinal profile $h(x_-)$

We will specialize to $h(t \pm z) = \mathcal{E}_0 \exp\left[-(t \pm z)^2/2\sigma^2\right]$. But we're in a CFT, so the only qty that matters is

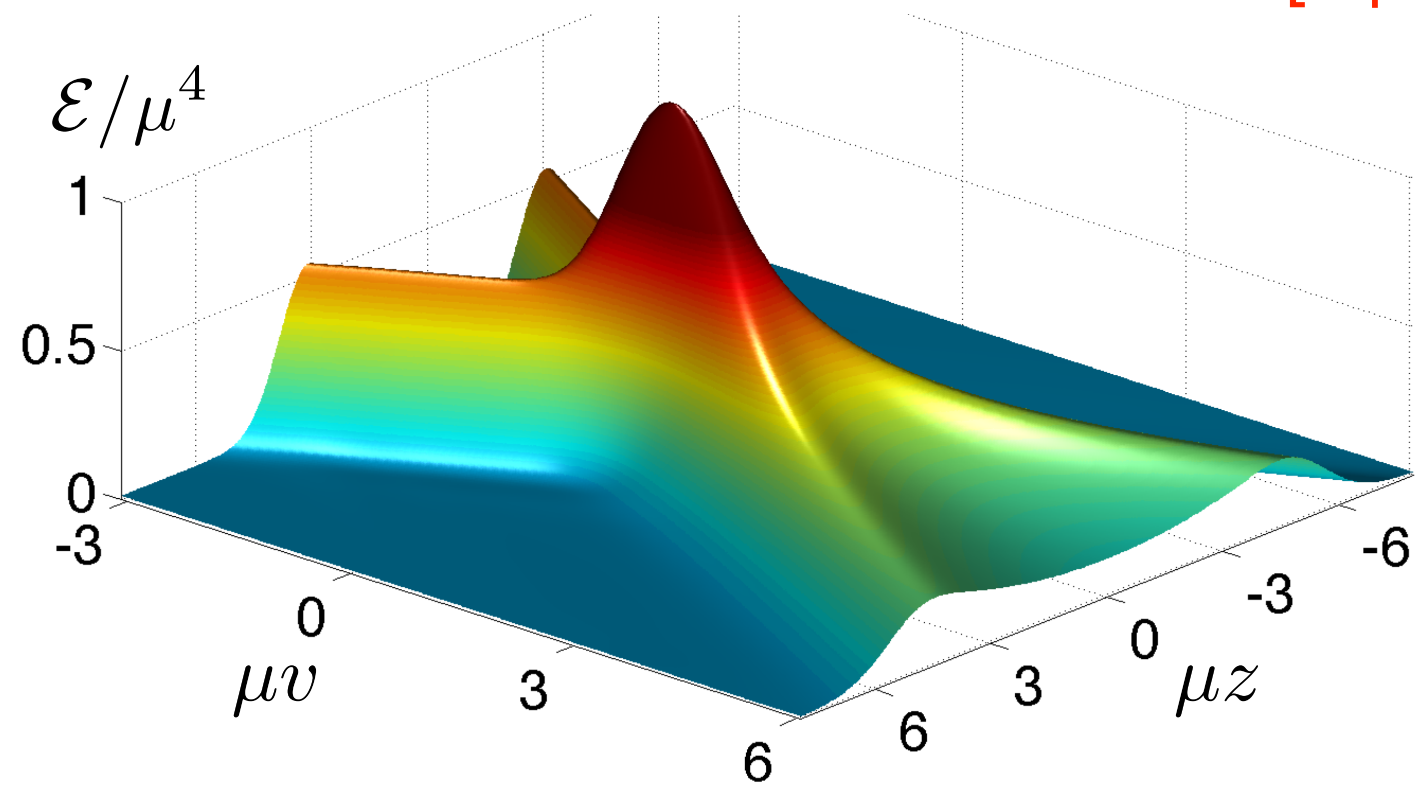
$$e = \mathcal{E}_0^{1/4}\sigma \quad \text{(in real HIC } e \sim \gamma^{-1/2}\text{)}$$

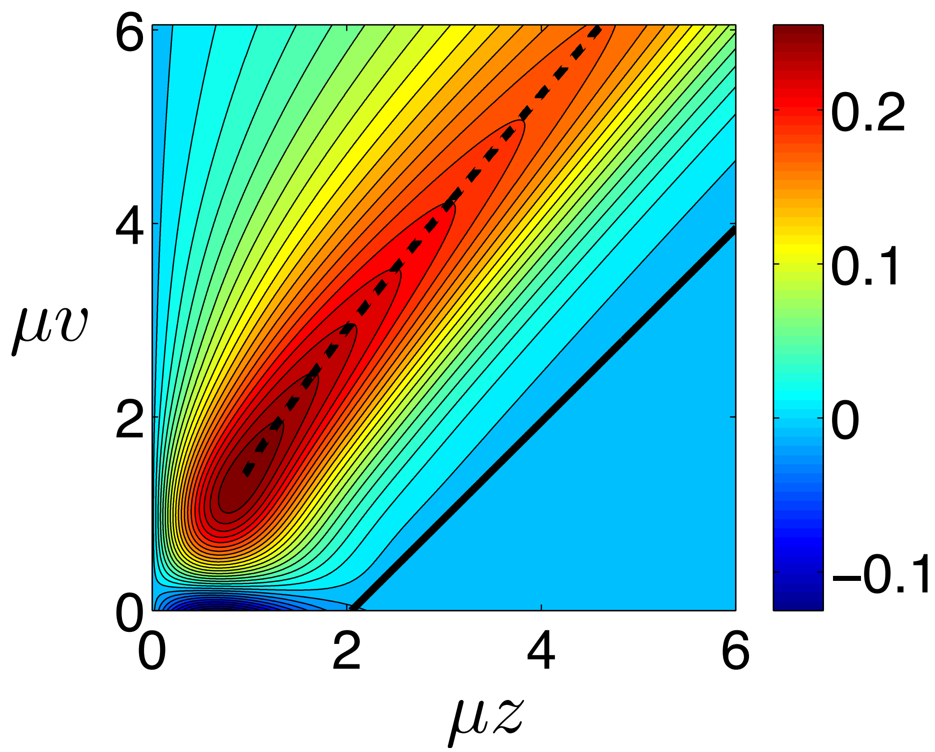
Colliding shocks at $e_{CY} \simeq 0.64$

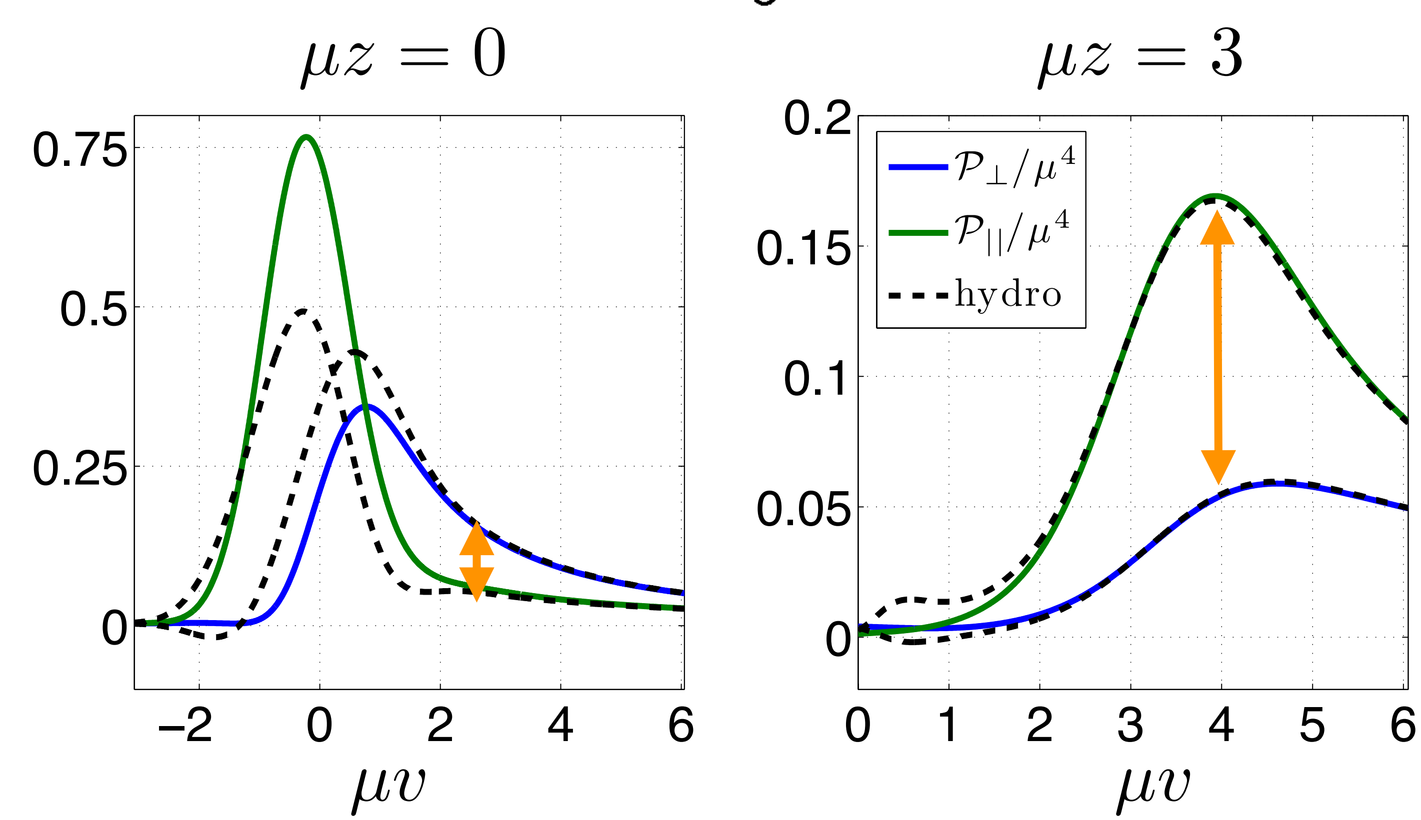
Chesler & Yaffe **1011.3562 [hep-th]**

$e_{CY} \simeq 0.64$ is roughly the value corresponding to Pb nuclei boosted to RHIC energies

$\mu \sim$ total energy*
$\mathcal{E} \sim T^{00}$







significant stopping:
15% slow-down of T^{00} maxima

large anisotropy at hydrodynamization!

is it the full story?

Dynamical crossover

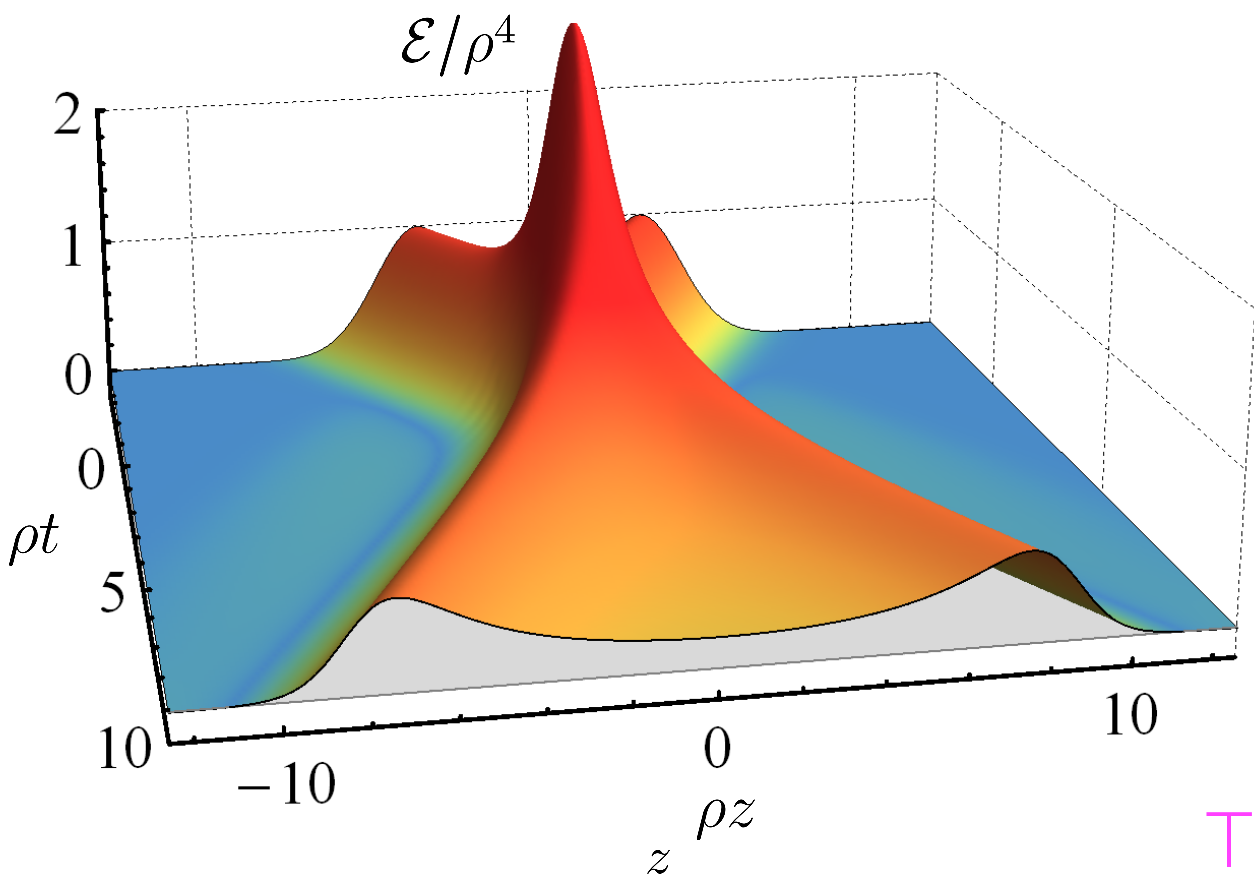
1305.4919 [hep-th] Casalderrey-Solana, MPH, Mateos, van der Schee

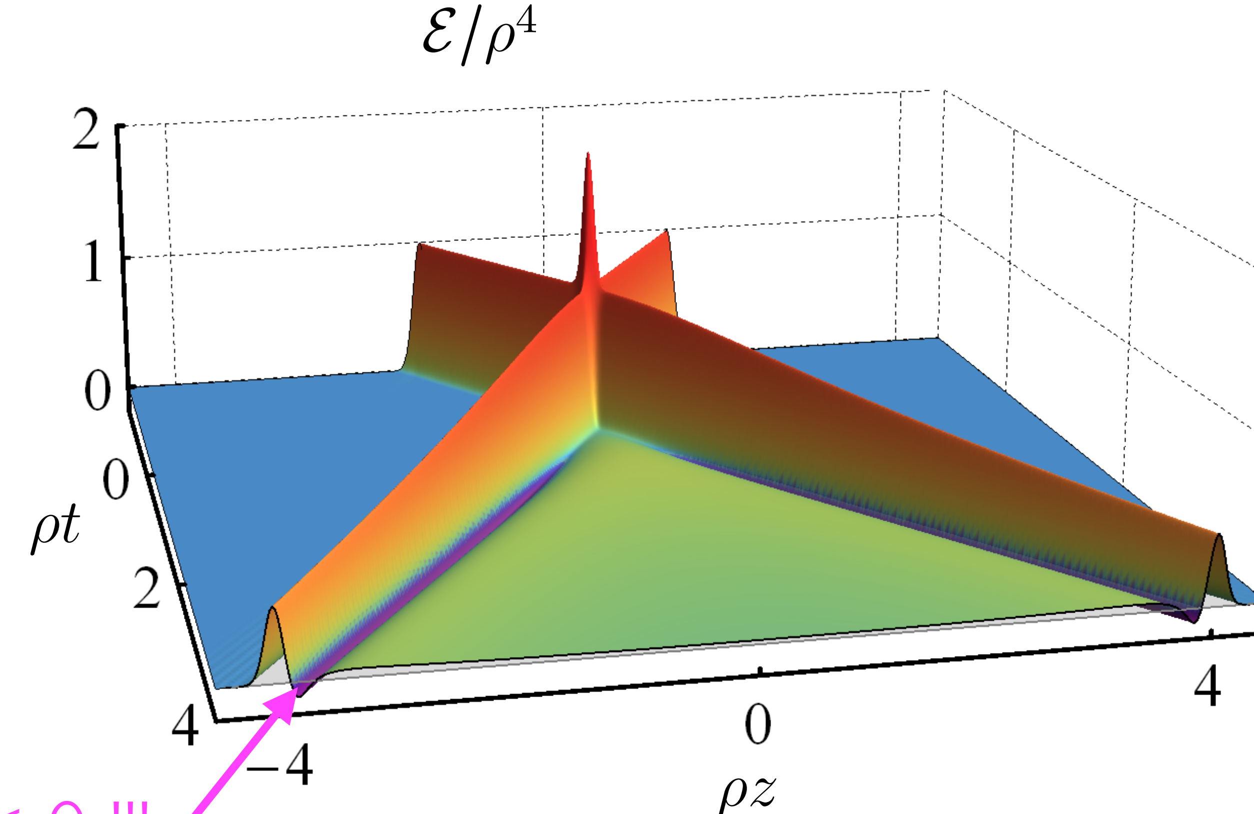
$$e_{left} = 2\, e_{CY}$$

„low energy''

$$e_{right} = \frac{1}{8}\, e_{CY}$$

„high energy''





$T^{00} < 0$!!!

again, significant stopping:
12% slow-down of T^{00} maxima ($v \approx 0.88$)

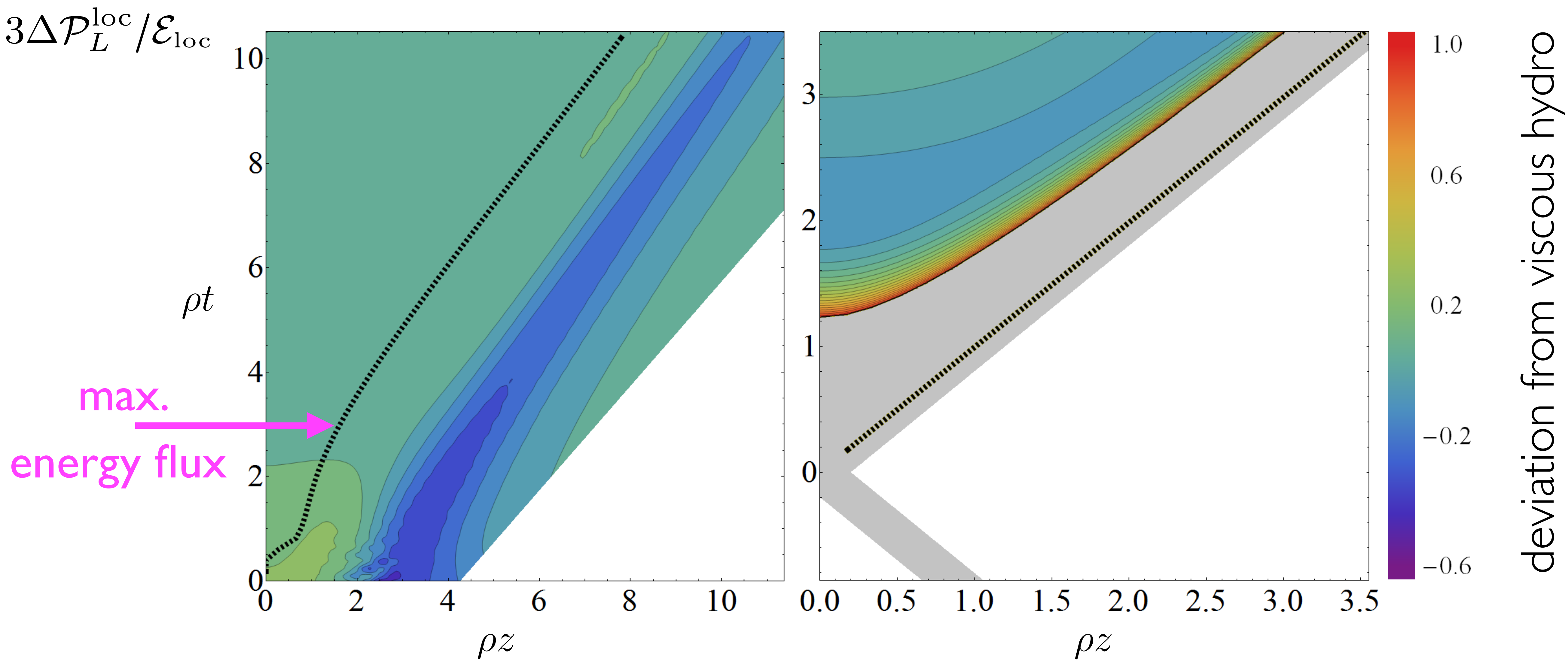
no stopping:
T^{00} maxima move with $v \approx 1$

Dynamical crossover

1305.4919 [hep-th] Casalderrey-Solana, MPH, Mateos, van der Schee

$e_{left} = 2\, e_{CY}$ „low energy"

$e_{right} = \frac{1}{8}\, e_{CY}$ „high energy"



hydro kicks in soon after the outer parts of incoming shocks meet

more like the old Landau picture (at $\rho t = 0.58$ (max. $\mathcal{E}$) v < 0.1)

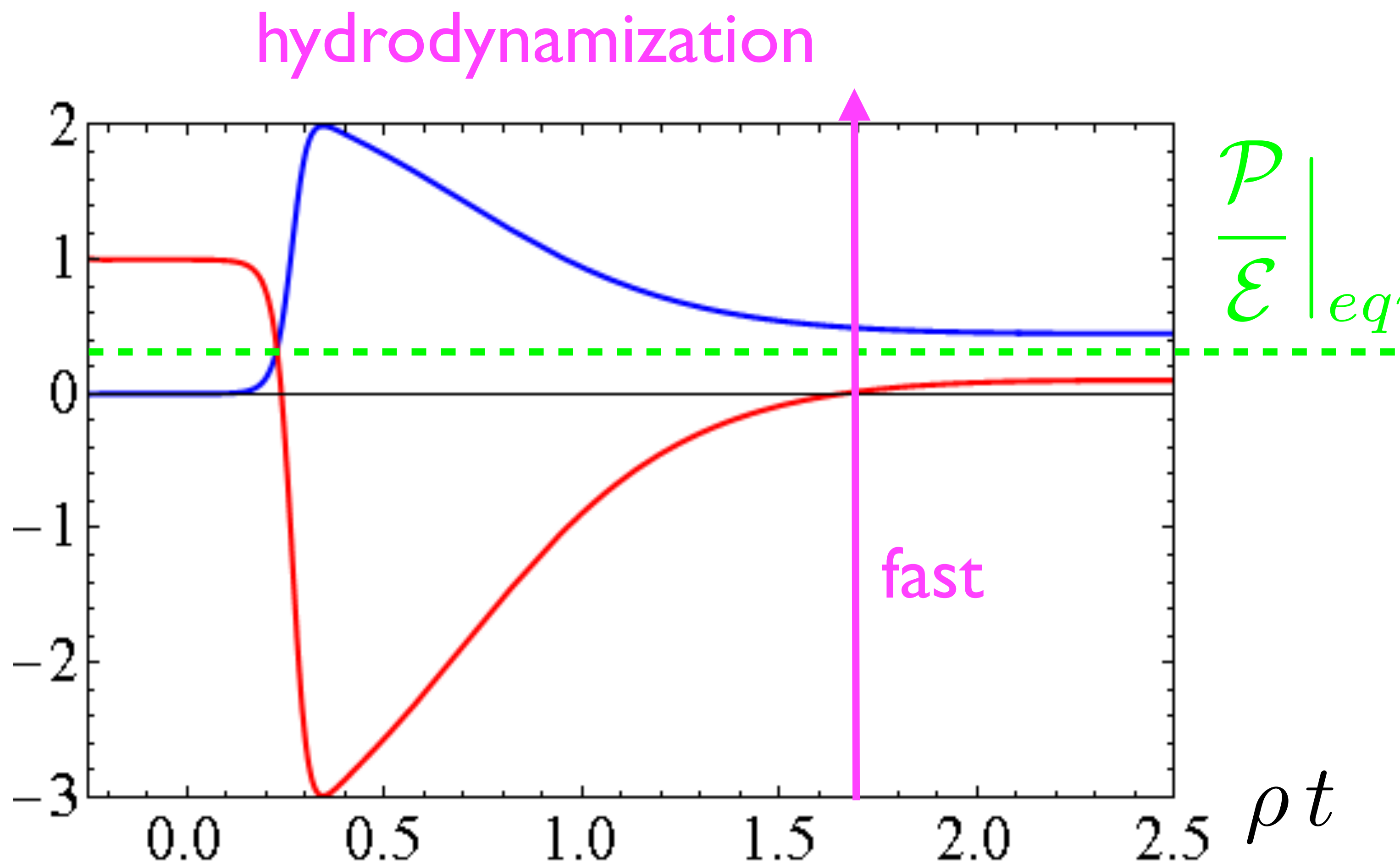
hydro applicable only at mid-rapidities and late enough!!!

<u>**more like what seems to be happening at RHIC and LHC**</u>

Plasma creation for thin shocks collision

1305.4919 [hep-th] Casalderrey-Solana, MPH, Mateos, van der Schee

$\frac{\mathcal{P}_L}{\mathcal{E}}$ & $\frac{\mathcal{P}_T}{\mathcal{E}}$



$$\left.\frac{\mathcal{P}}{\mathcal{E}}\right|_{equilibrium} = \frac{1}{3}$$

Assume boost-invariance: $\mathcal{P}_L = -\mathcal{E} - \tau\,\mathcal{E}'$ and $\mathcal{P}_T = \mathcal{E} + \frac{1}{2}\tau\,\mathcal{E}'$

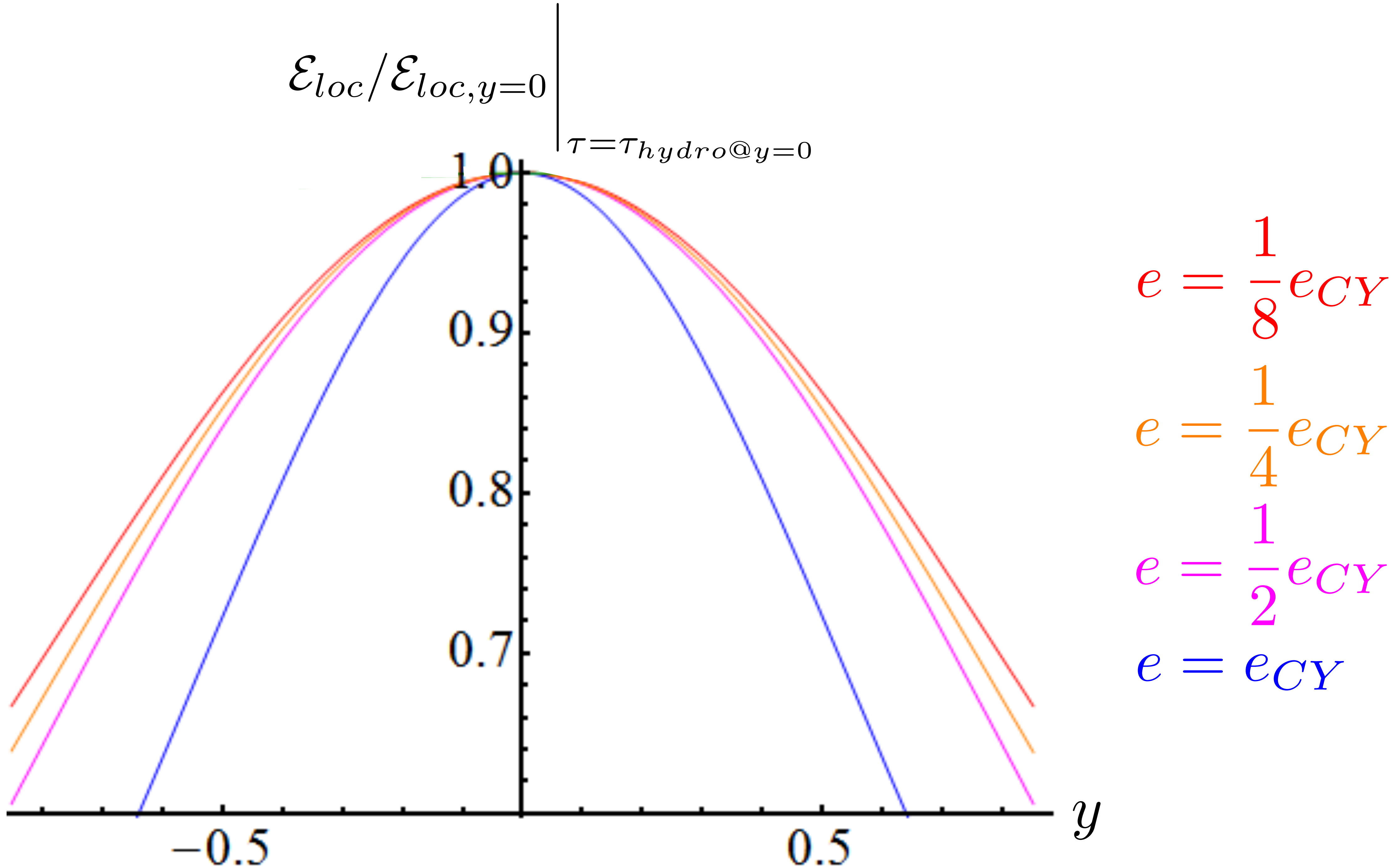
$\left.\mathcal{E}\right|_{\tau=0} \sim 1$ leads to $\left.\frac{\mathcal{P}_L}{\mathcal{E}}\right|_{\tau=0} = -1$ and $\left.\frac{\mathcal{P}_T}{\mathcal{E}}\right|_{\tau=0} = 1$

$\boxed{\left.\mathcal{E}\right|_{\tau=0} \sim \tau^2 \text{ leads to } \left.\frac{\mathcal{P}_L}{\mathcal{E}}\right|_{\tau=0} = -3 \text{ and } \left.\frac{\mathcal{P}_T}{\mathcal{E}}\right|_{\tau=0} = 2}$

plasma creation!

Rapidity distribution at hydrodynamization

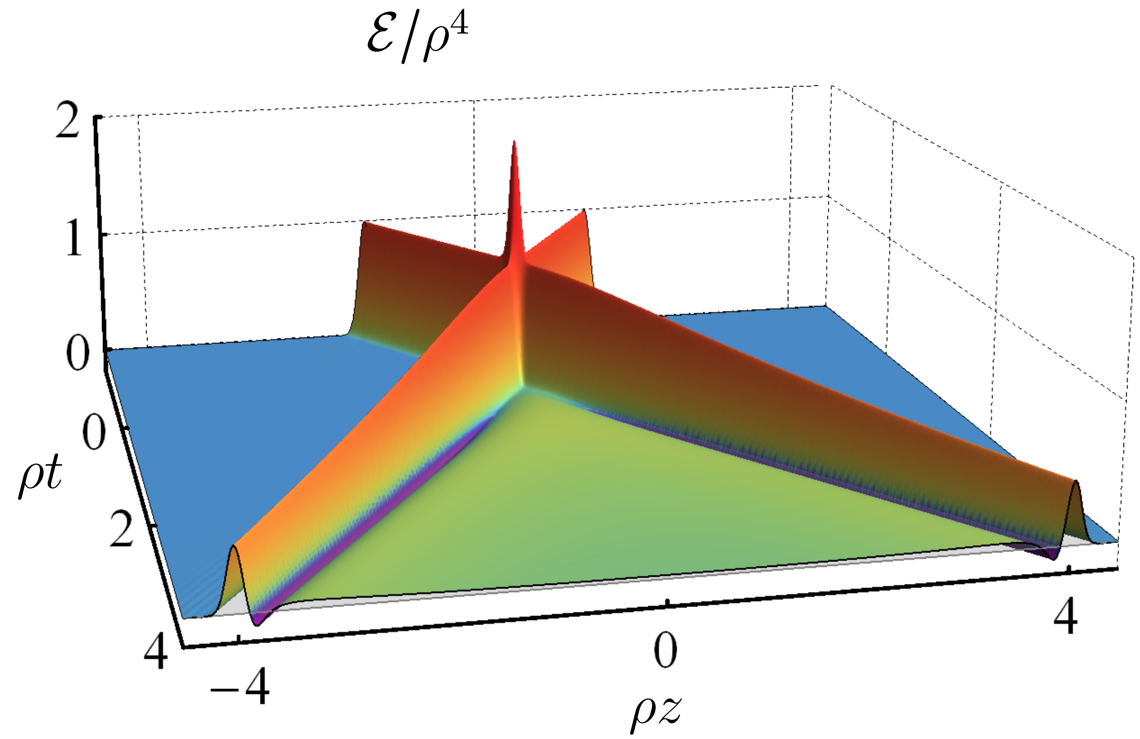
1305.4919 [hep-th] Casalderrey-Solana, MPH, Mateos, van der Schee



The dynamics is not boost-invariant in the sense introduced by Bjorken but nevertheless with decreasing e the rapidity distribution flattens out.

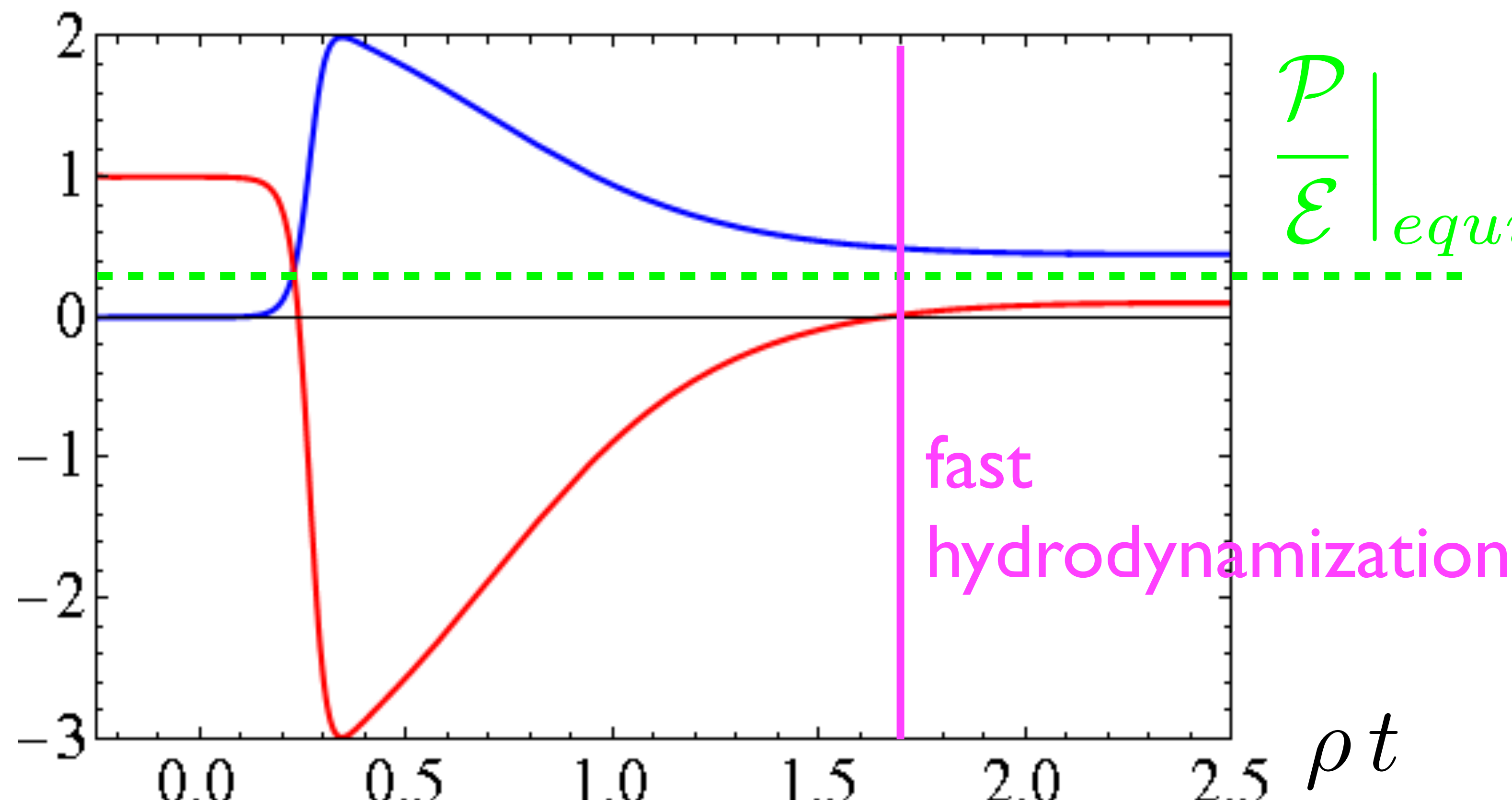
Summary

Dispels the myth that strong coupling necessarily leads to stopping*



Plasma creation and hydrodynamization ($\neq$ isotropization!)

$\frac{\mathcal{P}_L}{\mathcal{E}}$ & $\frac{\mathcal{P}_T}{\mathcal{E}}$



$$\left.\frac{\mathcal{P}}{\mathcal{E}}\right|_{equilibrium} = \frac{1}{3}$$