Recent Progress in Applying Gauge/Gravity Duality to Quark-Gluon Plasma & Nuclear Physics

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"Holography"

what is it?

Holography = Solvable Toy Model

Solvable models of strong coupling dynamics.

- Study Transport, real time
- Study Finite Density
- Explore paradigms "beyond Landau"

(Challenging in real QCD, experimentally relevant)

(this is interesting for a different audience)

Gives us qualitative guidance/intuition.

Not QCD! Expect errors of order 100%

(better than extrapolating perturbation theory to $\alpha_s \sim 1$??)

Holographic Theories:

Examples known:

- in d=1, 2, 3, 4, 5, 6 space-time dimensions
- with our without super-symmetry
- conformal or confining
- with or without chiral symmetry breaking
- with finite temperature and density

Holographic Theories:

Holographic toy models have two key properties:

"Large N": theory is essentially classical

"Large λ": large separation of scales in the spectrum

$$m_{\text{spin-2-meson}} \sim \lambda^{1/4}\, m_{\text{spin-1-meson}}$$

QCD: **1275 MeV** **775 MeV**

(note: there are some exotic examples where the same parameter N controls both, classicality and separation of scales in spectrum)

Successes and recent developments

- Viscosity and Hydrodynamics
- Energy Loss
- Thermalization

Viscosity and Hydrodynamics

Viscosity

Viscosity can be quantified:

water: 1 centipoise (cp)
air: 0.02 cp
honey: 2000-10000 cp

(1 cp = 10^{-2} P = 10^{-3} Pa·s)

Measuring Viscosity - an example

Pitch drop experiment

Started in 1930

8 drops fell so far

but no one has ever witnessed a drop fall

2005 Ig Nobel Prize in Physics

Viscosity of pitch: 230 billions times that of water

($2.3\ 10^{11}$cp)

Measuring Viscosity - an example

Recall: Viscosity of pitch: ~ 2.3 10^{11}cp

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RHIC's measurement of QGP (confirmed by LHC):

$$\eta \sim \frac{\hbar}{4\pi} s \sim \frac{10^{-27}\mathsf{erg} \cdot \mathsf{s}}{(10^{-13}\mathsf{cm})^3} \sim 10^{14}\mathsf{cp}$$

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BNL press release 2005:

"The degree of collective interaction, rapid thermalization, and extremely low viscosity of the matter being form at RHIC makes this the most nearly perfect liquid ever observed."

Viscosity in Holography:

In a large class of systems:

$$\frac{\eta}{s} = \frac{\hbar}{4\pi} \qquad \text{(KSS)}$$

- pinpoints correct observable
- gives ball-park figure
- large at weak coupling: bound?

Viscosity – Recent Developments

Not a bound! (Kats, Petrov, 2007)

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 - \frac{1}{2N}\right)$$

$\mathcal{N} = 2$ Sp(N)
4 fundamental
1 antisymmetric traceless

Higher Curvature corrections violate bound.

(Brigante, Liu, Myers, Shenker, Yaida, Buchel, Sinha, ….)

Calculations only reliable if violations are small.

Hydro – Recent Developments

Viscosity is not the only hydro transport coefficient that
can be calculated holographically.

- 2nd order hydro
  - Calculated in 2007 (Romatschke et. al., Batthacharyya et. al.)
  - Needed for stable hydro simulation (causality!)
  - Holographic values/structure routinely used
- anomalous transport

Anomalous Transport in Hydro

(following Kharzeev and Son)

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

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J: conserved current

1) Baryon Number or

2) Electric Charge

Anomalous Transport in Hydro

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B: magnetic field
“Chiral Magnetic Effect”

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ω: vorticity (= curl of velocity)
"Chiral Vortical Effect"

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$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

axial chemical potential
(requires non-zero axial charge)

$$\langle \mu_5 \rangle = 0$$

$$\langle {\mu_5}^2 \rangle \neq 0$$

relies on event
by event fluctuations

Anomalous Transport in Hydro

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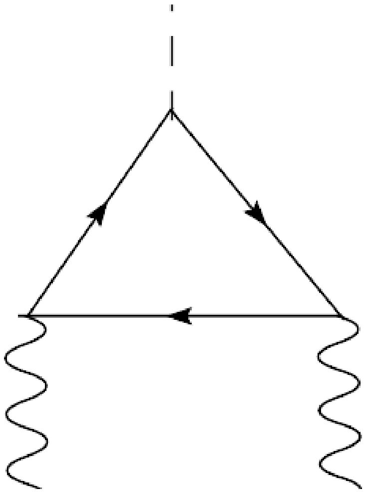


Coefficients determined by anomaly!

Relative size of baryon versus charge asymmetry unambiguous.

Anomaly and the CVE

connection between CME and anomaly was quantitatively understood before (Kharzeev, …)

How does the anomaly know about vorticity?

Erdmenger et. al, Banerje et. al:

In holographic models CVE completely determined in terms of
Chern-Simons term = anomaly.

Anomaly and the CVE

How does the anomaly know about vorticity?

Son, Surowka: True in general.

axial anomaly in background electromagnetic fields

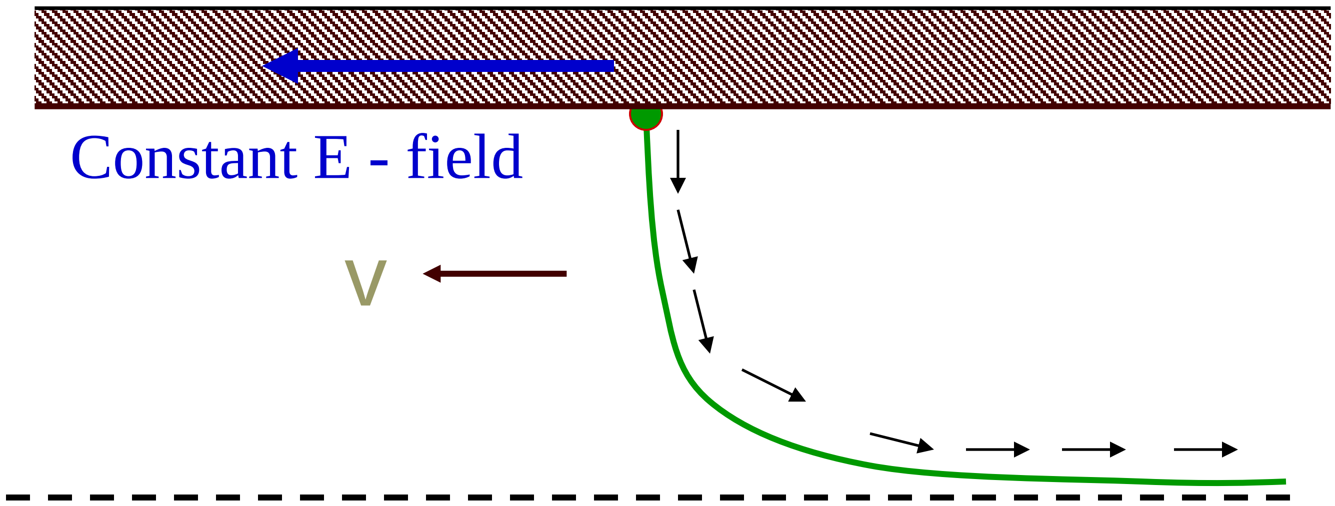
+

entropy current with non-negative divergence

= CVE

Energy Loss

Energy Loss (2006): Heavy quarks

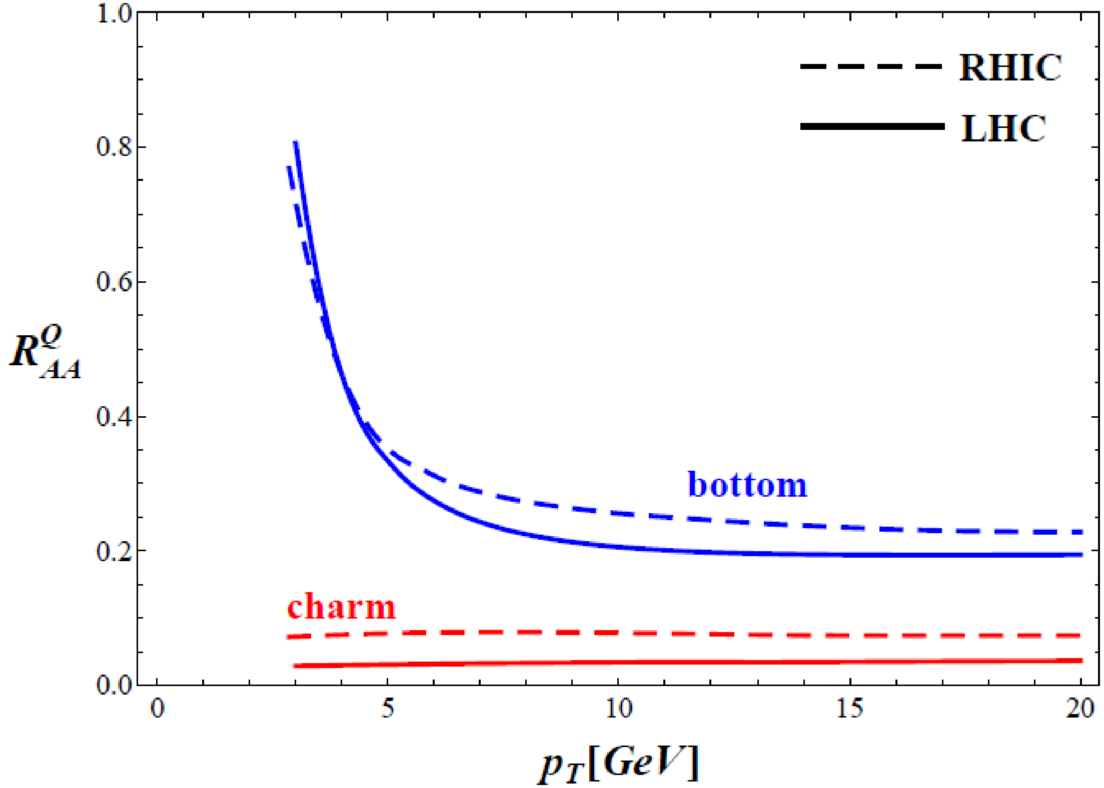


$$\frac{dp}{dt} = -\mu\, p \qquad \mu = \pi T\, \frac{\Delta m(T)}{m} \qquad \Delta m(T) \equiv \tfrac{1}{2}\sqrt{\lambda}T$$

(Casalderrey-Solana & Teaney, HKKKY, Gubser)

Energy Loss, Recent Developments:

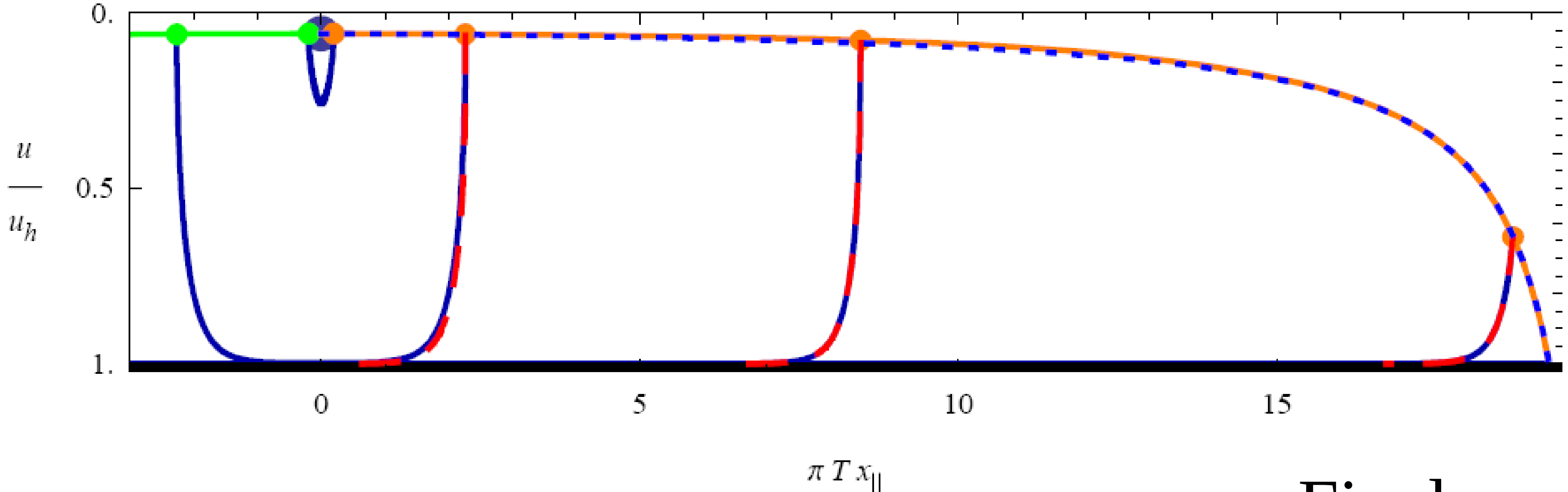
Use holographic models to make LHC “predictions”:



(Ficnar, Noronha, Gyulassy)

Energy Loss, Light Quarks (2010)

(Chesler, Jensen, AK, Yaffe; Gubser, Gulotta, Pufu, Rocha)

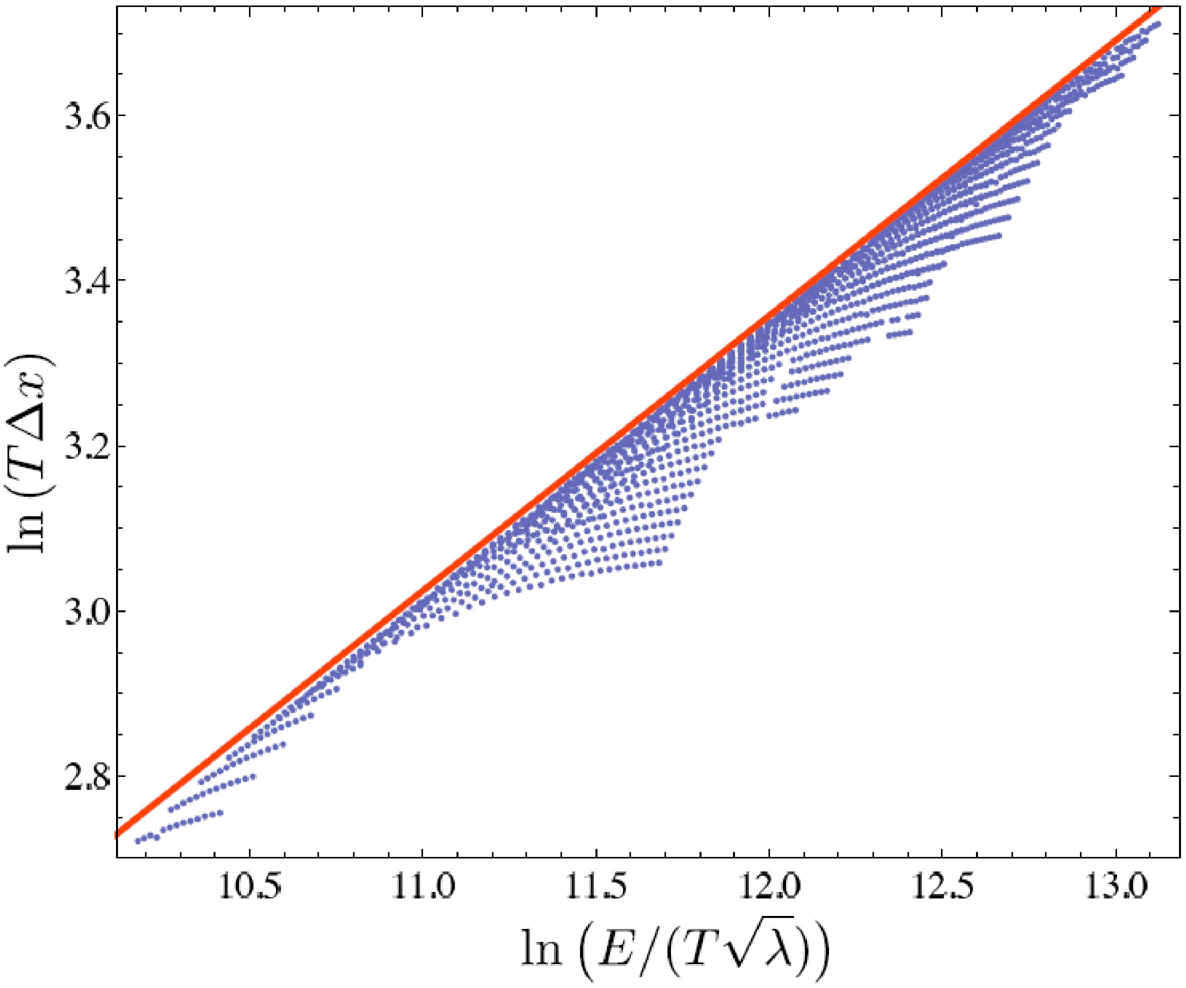


Zero T
Jets

Quasiparticle in Plasma
(for E >> T)

Final
Diffusion

Stopping Distance vs Energy



(Chesler, Jensen, AK, Yaffe)

Stopping Distance:

Perturbative QCD: **$L \sim E^{1/2}$** (BDMPS, …)

Holography:

Maximal Stopping Distance: **$L \sim E^{1/3}$**

Typical Stopping Distance: **$L \sim E^{1/4}$**

(Arnold, Vaman - 2011)

Experiment: **1/3 preferred over 1/2 ???** (Renk, …)

Stopping Distance: **Exponents!**

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Thermalization

Why does the QCD fireball thermalize so rapidly?

Thermalization

Why does the QCD fireball thermalize so rapidly?

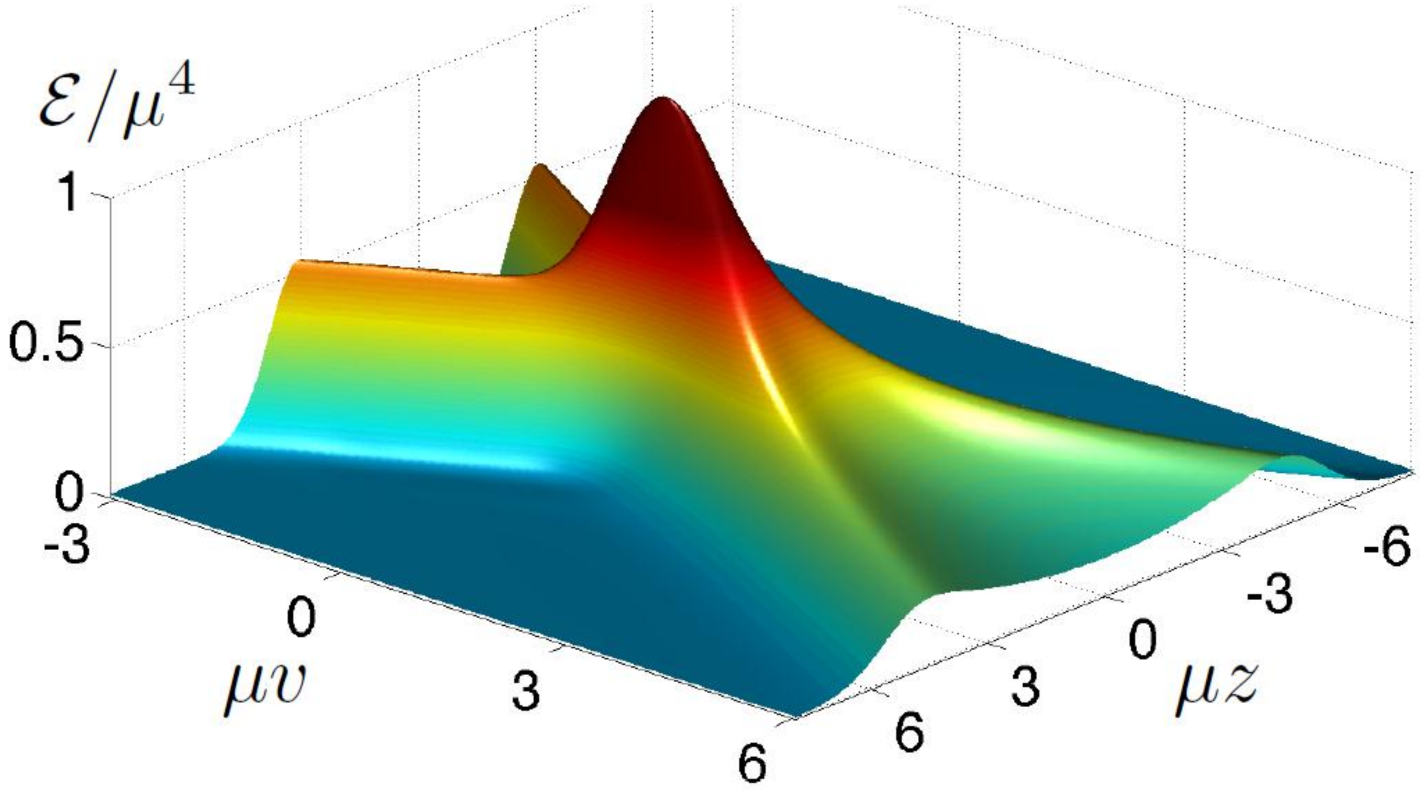
too hard!

Thermalization

How quickly does the holographic fireball thermalize?

Shockwave-collision to black hole

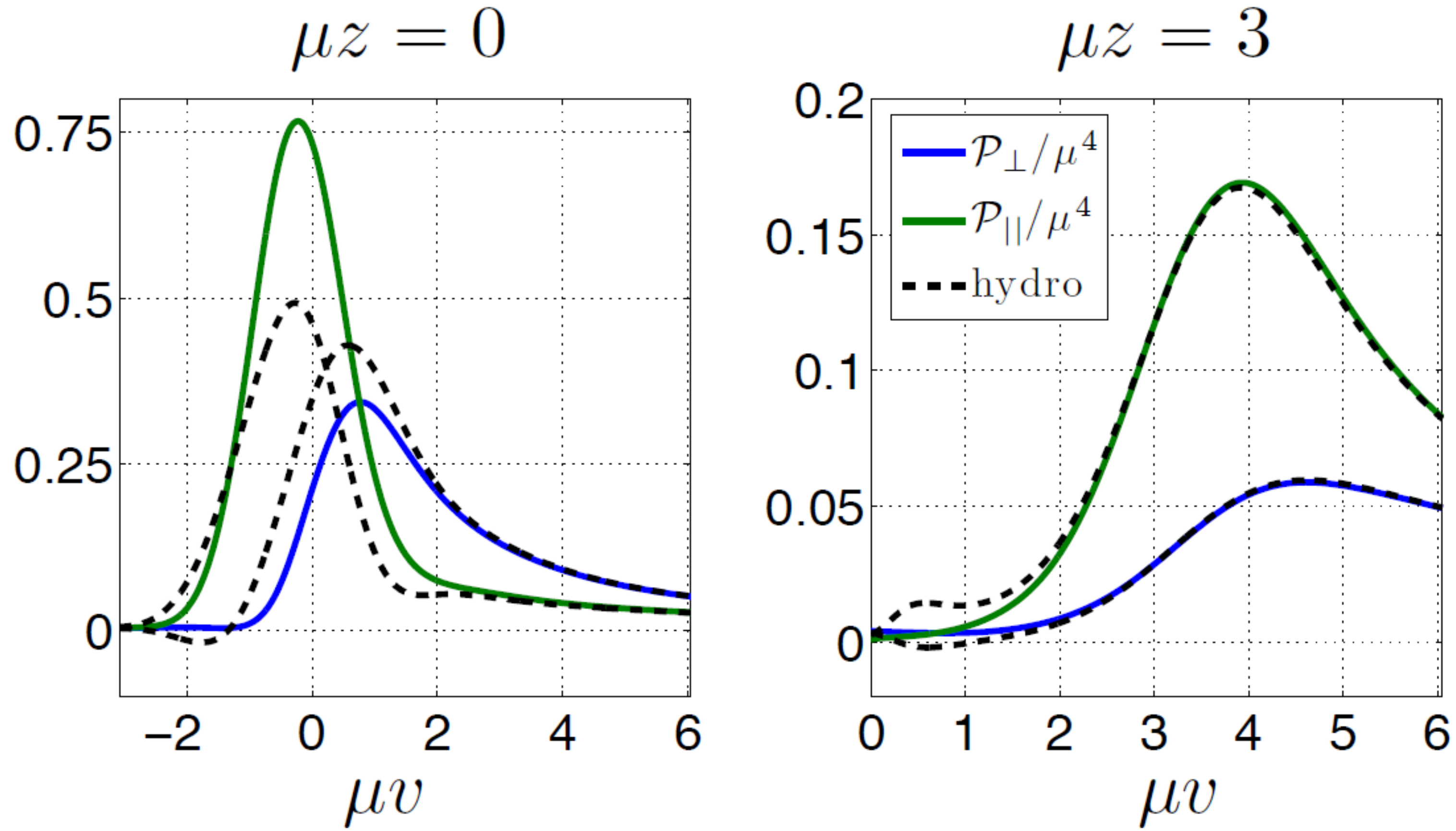
(Chesler, Yaffe)



Energy/area in shock ~ μ^3

Shockwave-collision to black hole

(Chesler, Yaffe)



Shockwave-collision to black hole

(Chesler, Yaffe)

"RHIC":

$\mu \sim 2.3$ GeV

Hydro valid ~ 0.35 fm/c << 1 fm/c

But: there is so much more info in this plot!

What do you want to know?

Summary: recent progress

- Viscosity and Hydrodynamics
- Energy Loss
- Thermalization