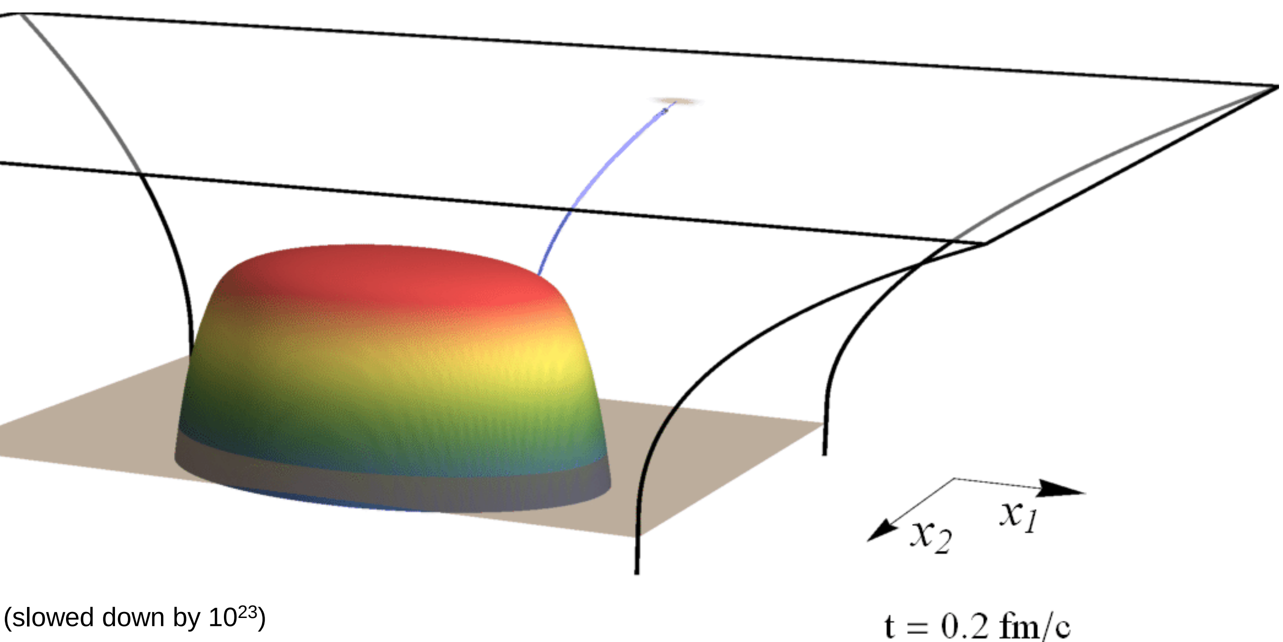
Universiteit Utrecht

HYDRODYNAMIZATION AND JET ENERGY LOSS IN HOLOGRAPHY

TOWARDS QUANTITATIVE RESULTS FROM HOLOGRAPHY

Based on work with Michał Heller, David Mateos, Jorge Casalderrey, Miquel Triana, Paul Romatschke, Björn Schenke, Krishna Rajagopal, Andrey Sadofyev, Jasmine Brewer, Umut Gürsoy and Aron Jansen

Review references: 1802.04801 (general) and 1501.04952 (holography)



(slowed down by 10^{23})

Wilke van der Schee

ALICE Journal Club

21 February 2018

OUTLINE

Holography to model QCD

- AdS/CFT: first principle non-perturbative QFT computations
- Limitations: QCD(-like) theory with intermediate coupling is hard

Two simple models

- Colliding lumps of energy in super-Yang-Mills theory
  - Obtain early hydrodynamics + rapidity distribution
  - Finite coupling corrections
- Shoot ensemble of jets through expanding and cooling sQGP
  - Extract influence QGP on jet shape + dijet asymmetry

An outlook

- Time permitting: small systems
- More refined models, more realistic phenomenology

INITIAL STAGE + JET ENERGY LOSS

Hydrodynamics needs initial conditions

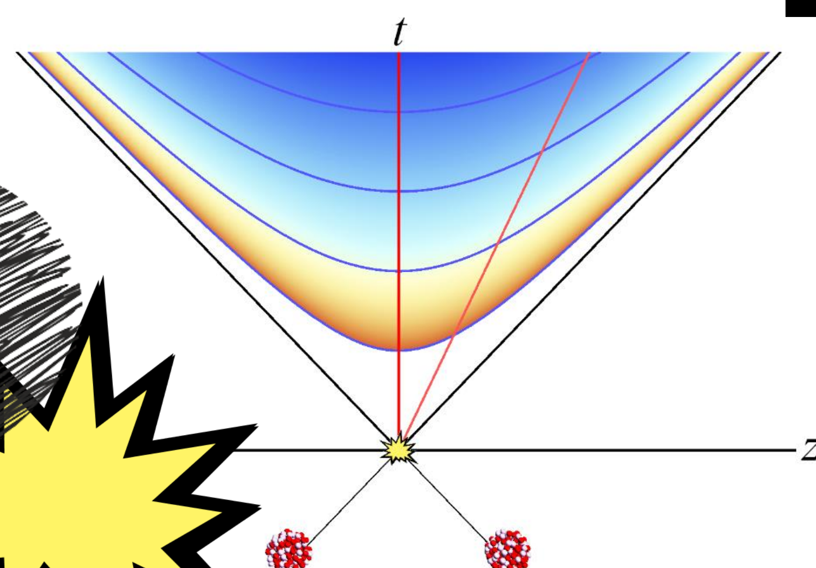
- Energy density, velocity, as function of space at initial time
- (Gradient tensors for 2^{nd} order hydro)

Energy loss of quark/gluon

- Temperature/path length
- Wave function of quark?

QCD is well understood theory??

- Perhaps at weak coupling

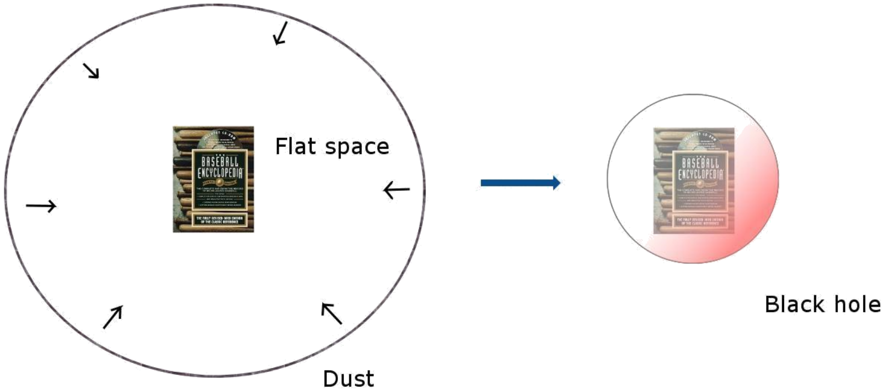


THE WORLD AS A HOLOGRAM

A very curious fact: black hole entropy proportional to area!

$$S_{BH} = A/4$$

Thought experiment: collapse entropy to black hole



Intuition: gravity provides UV cut-off in space due to BH formation

Jacob Bekenstein, Black holes and entropy (1973)
Stephen Hawking, Particle creation by black holes (1975)
Gerard ’t Hooft, Black hole quantization and a connection to string theory (1990)

A PICTURE OF ADS/CFT

Strongly coupled planar QFT = classical gravity in a box (of d+1)

Strongly coupled QFT lives on boundary

Distance to boundary = dynamics at certain scale

NB: only self-similar (conformal) in vacuum state

Maurits Cornelis Escher, Circle Limit III (1960) and Regular Division of the Plane VI (1962)

HOLOGRAPHY MORE PRECISELY

Exact equivalence between string theory and quantum field theory

$$\mathcal{Z}_{bulk}\left[\phi(\vec{x},z)|_{z=0}=\phi_0(\vec{x})\right]=\langle e^{\int d^4x\,\phi_0(\vec{x})\mathcal{O}(\vec{x})}\rangle_{\text{Field Theory}}$$

$$\langle\mathcal{O}\rangle=-i\frac{\delta Z_{\text{bulk}}[\phi_{(0)}]}{\delta\phi_{(0)}}\overset{N\to\infty}{=}\frac{\delta S[\phi_{(0)}]}{\delta\phi_{(0)}}$$

Holography synonyms:
AdS/CFT, gauge/gravity duality, gauge/string duality

Dictionary:

- Original: type IIB string theory $AdS_5\times S_5\sim\mathcal{N}=4\,\mathrm{SU}(N_c)$ SYM on $\mathbb{R}^4$
- Near-boundary metric of AdS ~ stress tensor
- Black hole ~ thermal state
- **Fundamental string ~ Quark-antiquark pair**

Most famous result: $\eta/s=\frac{1}{4\pi}$ **(from black hole horizon)**

Also: insights information paradox, fast thermalization, ... (16000+)

Juan Maldacena, The large-N limit of superconformal field theories and supergravity (1997)

ADS/CFT AND HEAVY IONS

Exact equivalence between certain string theories and certain QFTs

- String theory only simple in large N_c and infinite 't Hooft coupling
- Several examples known, but no known 'real world' QFT (yet?)

A typical strategy: start with `canonical' example $\mathcal{N}$=4 SYM

- Theory non-confining, but confining analogues exist
- Requires large N_c, but $1/3^2$ seems small from lattice QCD
- Can compute some corrections, e.g.: $\eta/s = \frac{1}{4\pi}\left(1 + \frac{15}{\lambda^{3/2}}\zeta(3) + \frac{5}{16}\frac{\lambda^{1/2}}{N_c^2}\right)$

Holography provides a unique perspective

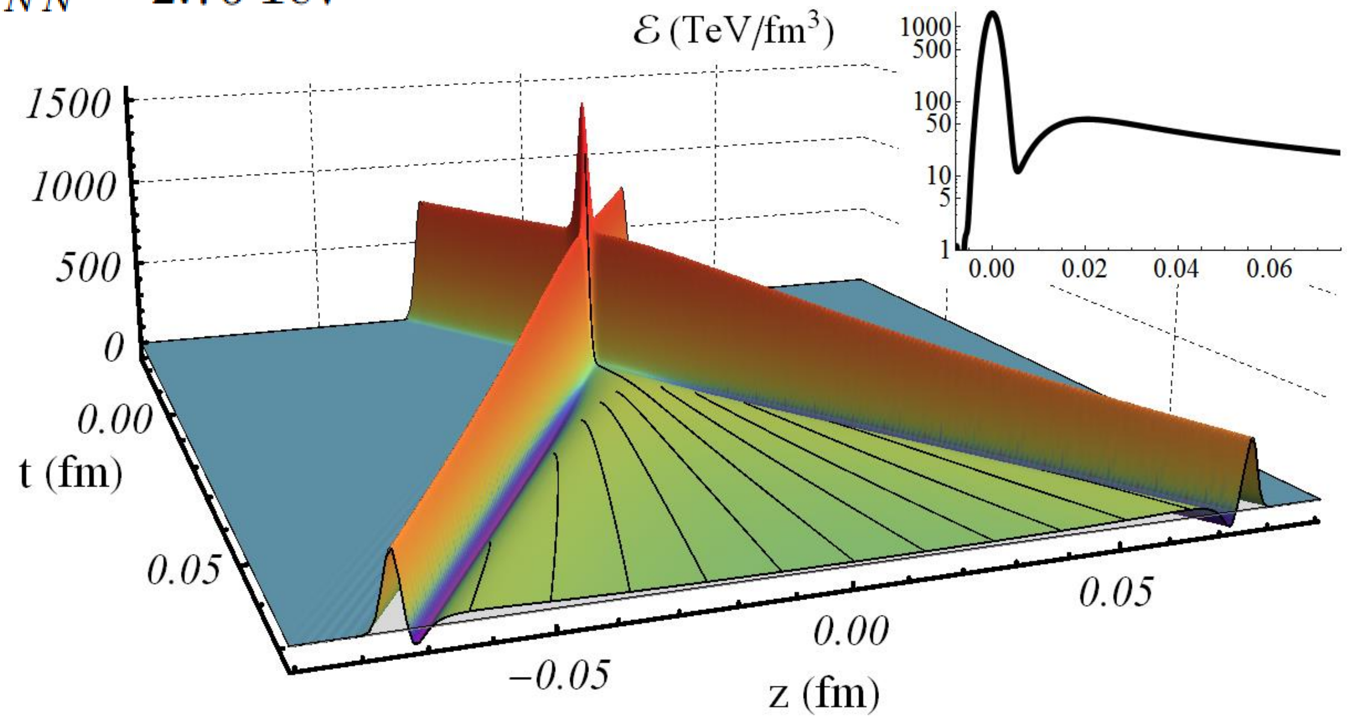
- Only way of computing far-from-equilibrium non-perturbative dynamics
- Study rich dynamics of general strongly coupled theories

Real world heavy ions most likely interplay between weak and strong

COLLISIONS AT INFINITELY STRONG COUPLING

- Match longitudinal profile of energy density to nuclei
- Approximately homogeneous in transverse plane

$\sqrt{s_{NN}} = 2.76\,\text{TeV}$



Benchmark: $T_{\text{max}} = 2.6\ \text{GeV}$

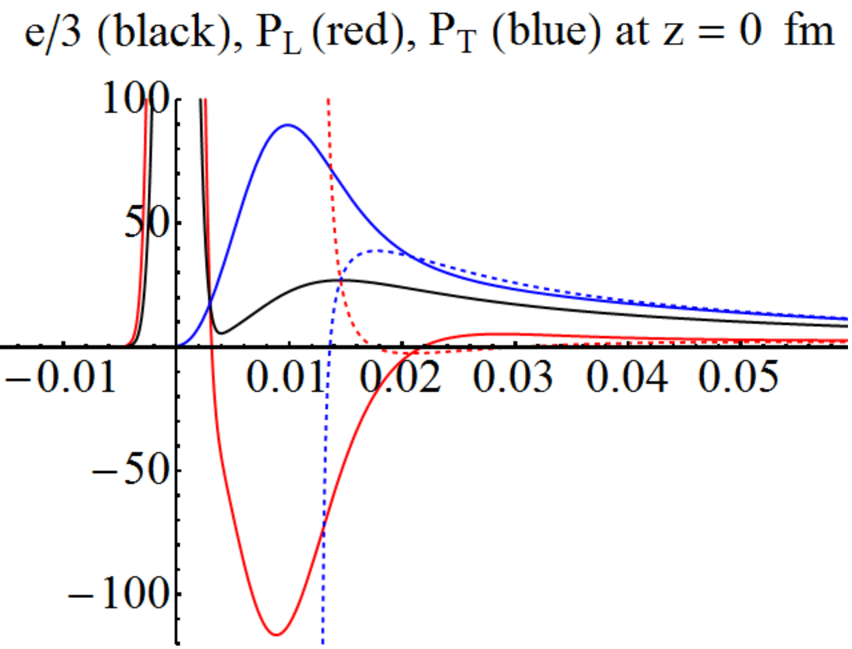
J. Casalderrey-Solana, M.P. Heller, D. Mateos and WS, From full stopping to transparency in a holographic model of heavy ion collisions (PRL 2013)

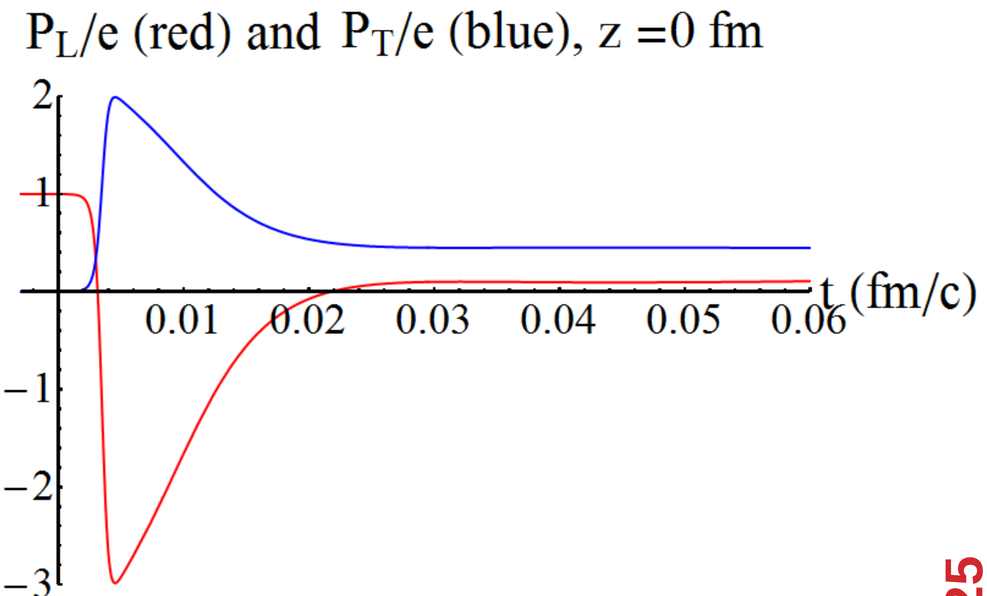
THERMALISATION/PRESSURES

Pressures, energy starts at zero, grows (unique to holography?)

Thermalises very fast (hydro applies in perhaps 0.02 fm/c)

- Thermalisation = relaxation non-hydro modes (or **hydrodynamization**)
- Gradients + viscous corrections are big



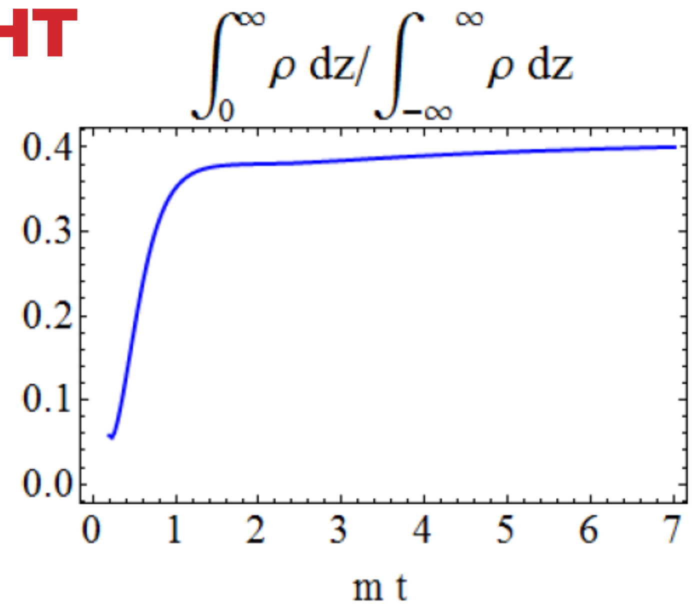


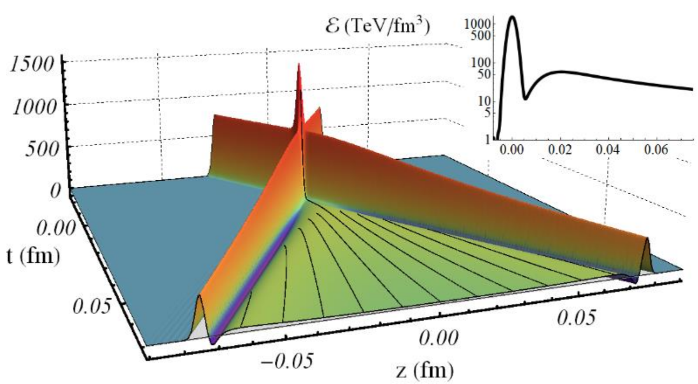
J. Casalderrey-Solana, M.P. Heller, D. Mateos and WS, From full stopping to transparency in a holographic model of heavy ion collisions (2013)

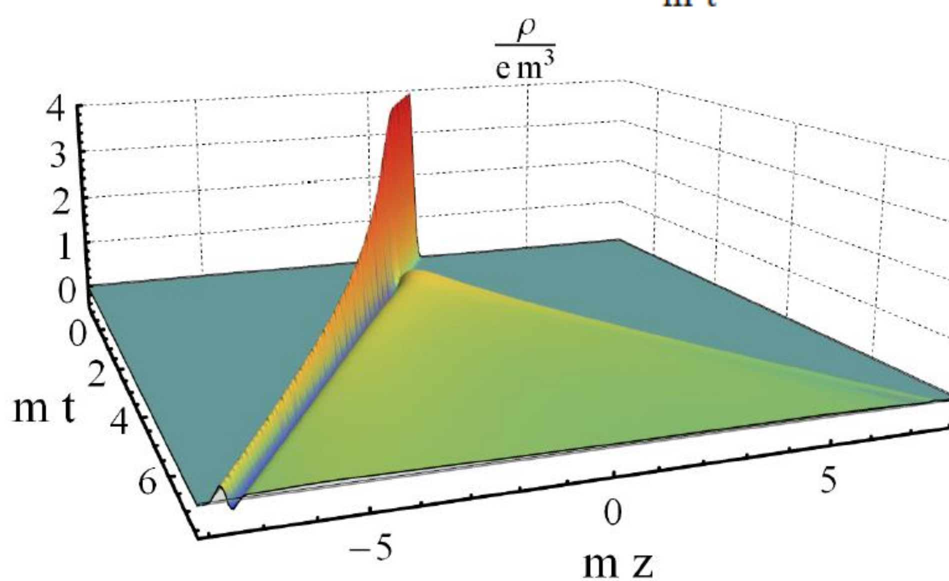
A NEW QUANTITATIVE INSIGHT

- Collide shocks with energy and charge
- Now collide neutral with charged shock
- 41% of charge changes direction

  → strong interactions







J. Casalderrey-Solana, D. Mateos, WS and M. Triana, Holographic heavy ion collisions with baryon charge (2016)

COLLISIONS AT FINITE COUPLING

Leading order correction: small curvature squared

- Not for N=4 SYM theory (but that's also not what we want…)
- Einstein-Gauss-Bonnet theory:

$$S_{GB} = \frac{1}{2\kappa_5^2}\int d^5x\sqrt{-g}\left[R - 2\Lambda + \frac{\lambda_{GB}}{2}L^2\left(R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}\right)\right]$$

- Reproduces weak-coupling expectations, i.e. $\eta/s = \frac{1}{4\pi}\left(1 - 4\lambda_{GB}\right)$

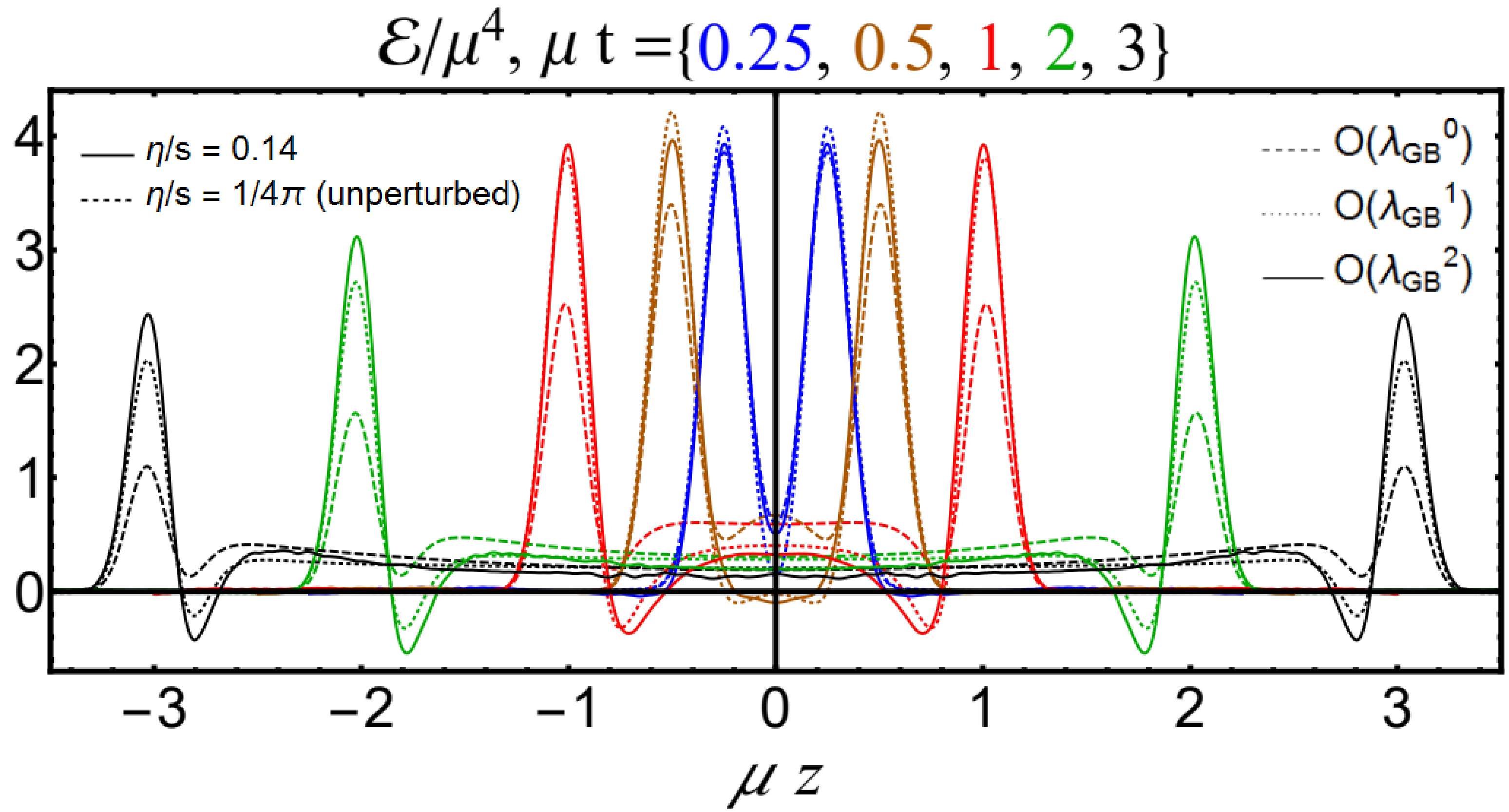
Funny thing: evolution is just as simple as original ☺

- Initial condition remains exact solution of EOM (for some L)
- Nested scheme survives completely (with source terms)

Yevgeny Kats and Pavel Petrov, Effect of curvature squared corrections in AdS on the viscosity of the dual gauge theory (2007)

COLLISIONS AT FINITE COUPLING - NARROW

- Results presented for $\lambda_{GB} = -0.2$ i.e. $\eta/s = 1.8/4\pi$ (solid)
- Initial condition constructed such that energy is the same

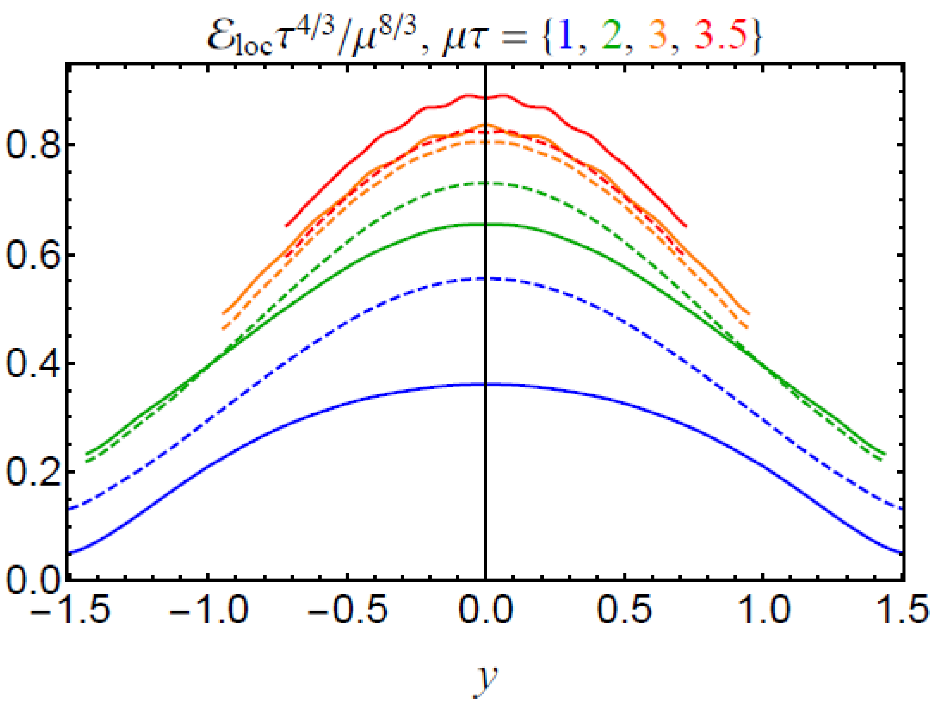


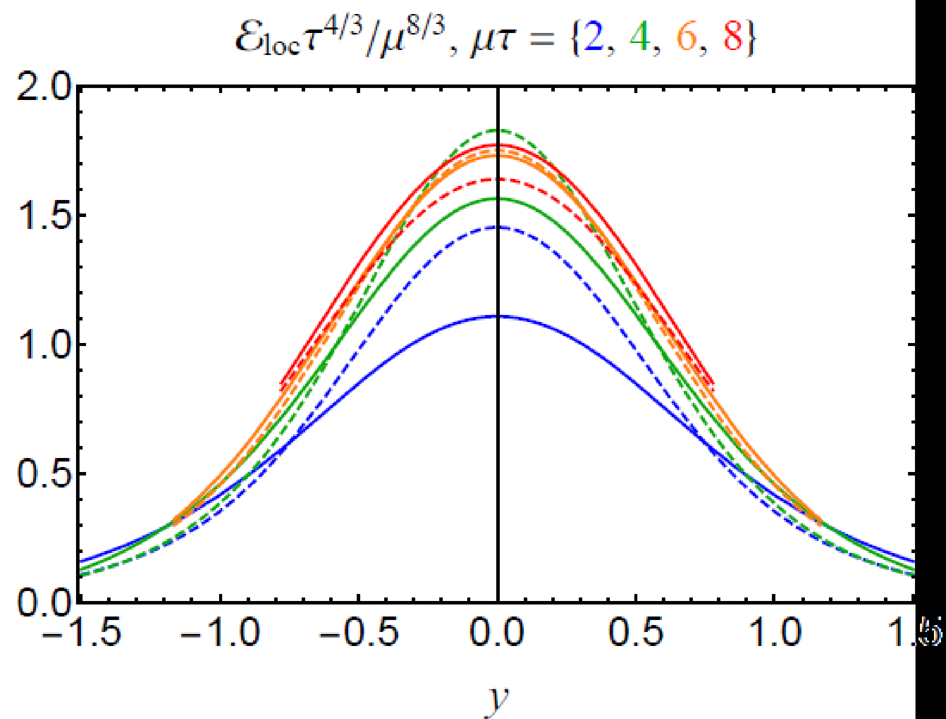
- Much more energy on lightcone (more transparent, less stopping)
- Energy in plasma flatter

Sašo Grozdanov and WS, Coupling Constant Corrections in a Holographic Model of Heavy Ion Collisions (PRL, 2016)

COLLISIONS AT FINITE COUPLING - RAPIDITY

- Initial rapidity shape differs from Gaussian





Narrow
Wider and lower initially (energy on lightcone not shown)
Later similar (time 3), then more entropy, similar width

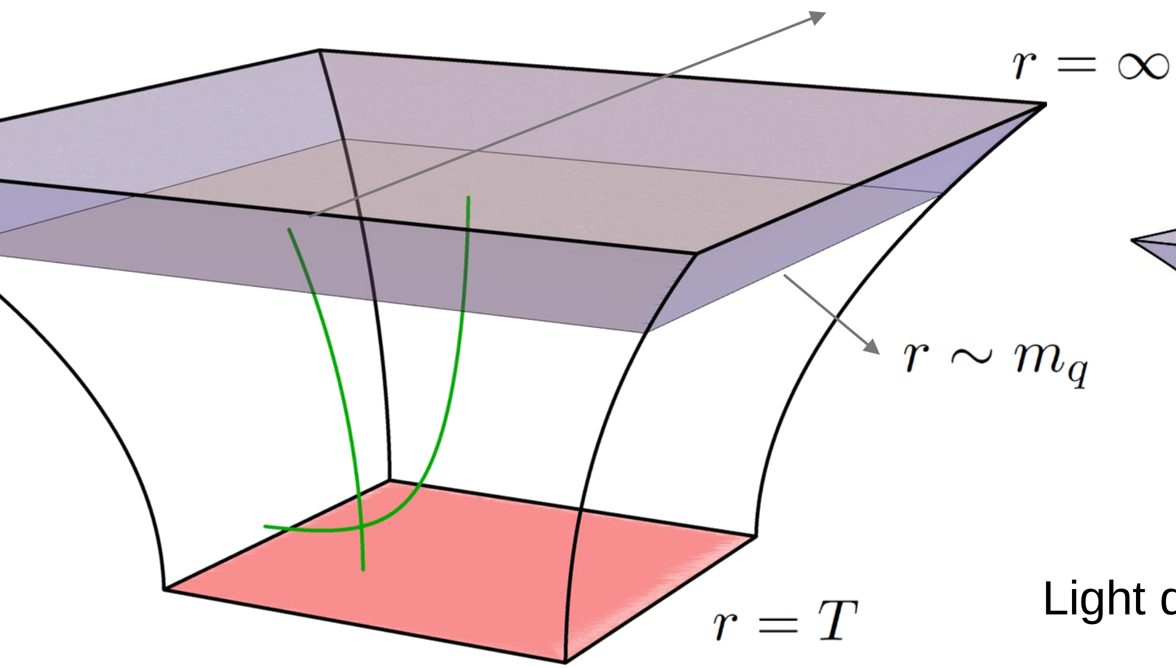
Wide
Almost entirely by hydro + less pile-up:
First lower energies + wider
Viscosity: lower transverse pressure, more entropy

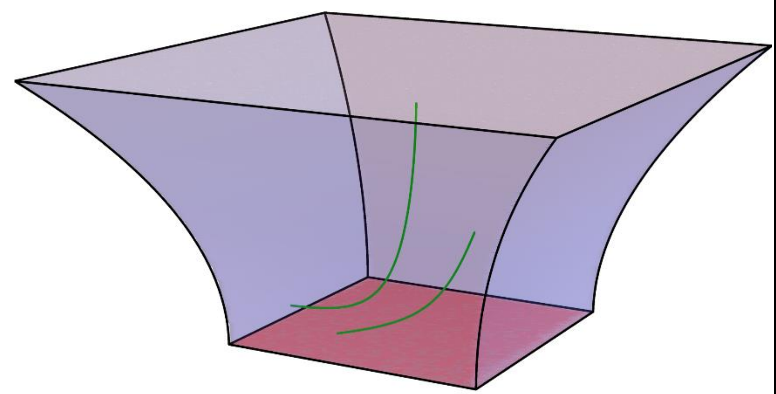
QUARKS IN ADS/CFT

AdS/CFT allows to add fundamental quarks to N=4 SYM

- Classical open strings, but energy proportional to $\sqrt{\lambda}$

Endpoint has to stay on D7-brane, cannot fall





Light quarks; strings falls into black hole

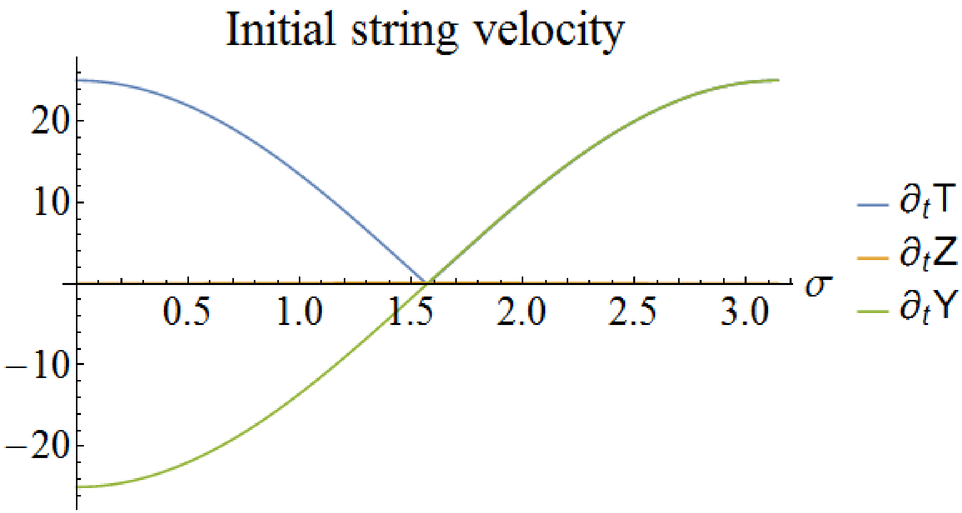
Heavy quarks, if mass>temperature

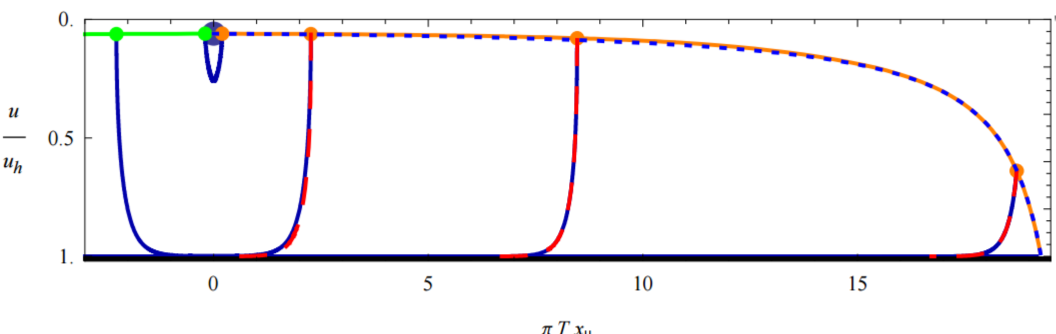
Andreas Karch and Emanuel Katz, Adding flavor to AdS/CFT (2002)

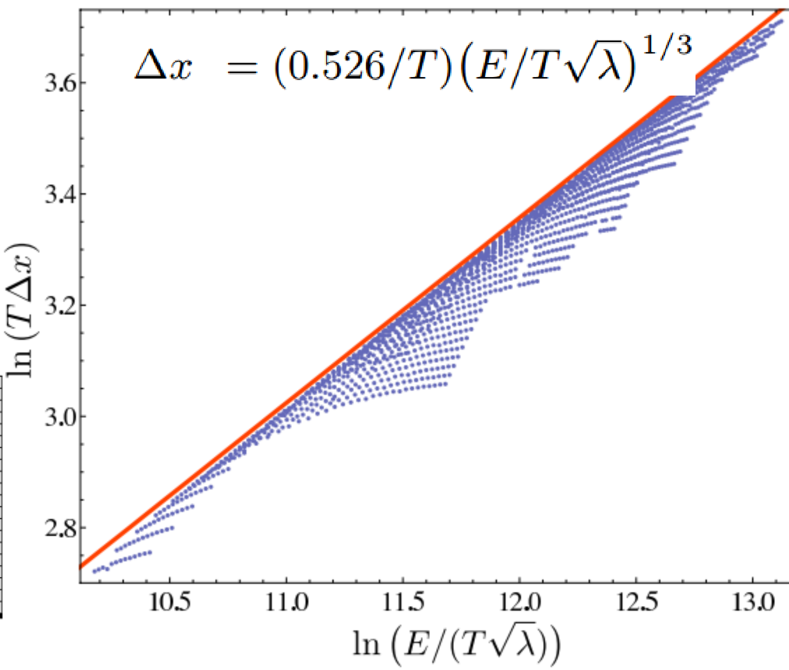
EARLY WORK

$$\partial_\tau Y(0,\,\sigma) = A\, z_0 \cos(\sigma)$$
$$\partial_\tau Z(0,\,\sigma) = z_0(1-\cos(2\sigma))\sqrt{f(z_0)}$$
$$A = 500,\;\; z_0 = 1/20,\;\; f(x) = 1 - x^4$$

Initial string at point, velocity profile → stopping distance

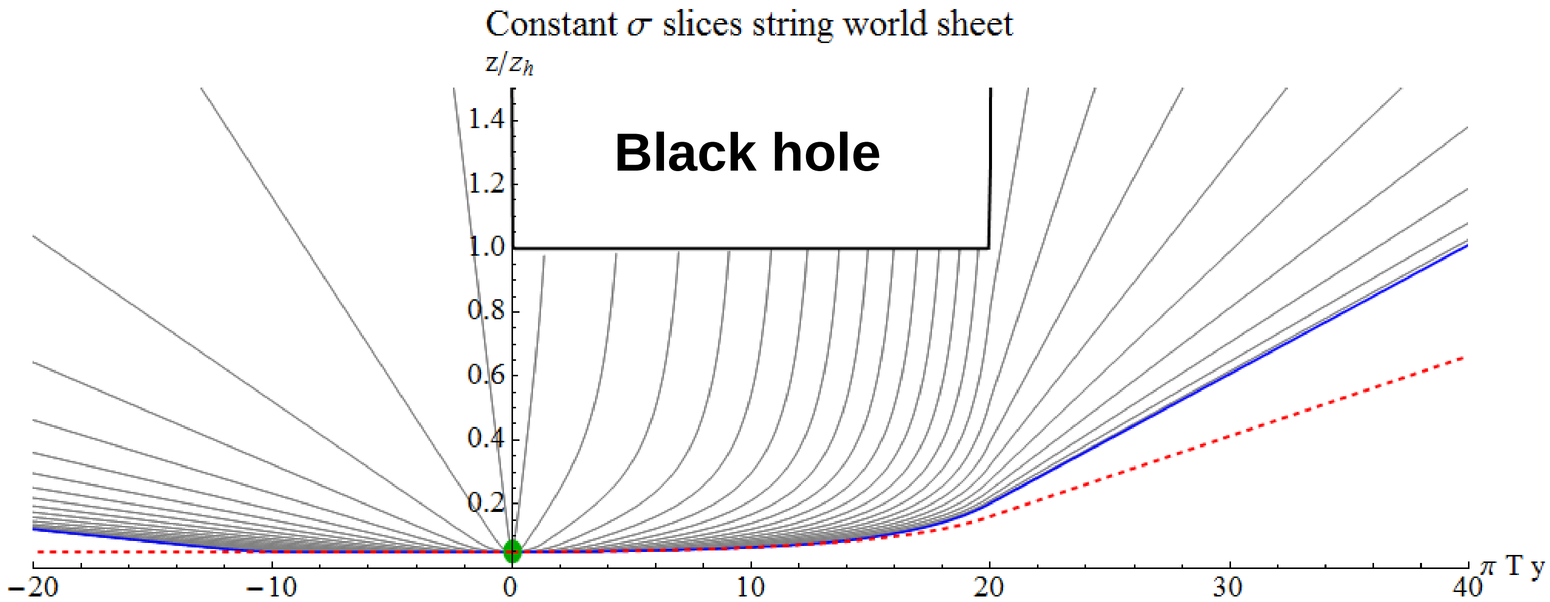






P.M. Chesler, K. Jensen, A. Karch and L.G. Yaffe, Light quark energy loss in strongly-coupled N = 4 supersymmetric Yang-Mills plasma (2008)

STRING EVOLUTION: EXAMPLE



Old problem: how to define energy loss in terms of string?

- In particular, real jets lose order 10% energy
- Natural definition: size black hole = size QGP, shoot jet through

Model evolution more realistically

- Part of string falls in black hole: dissipates into hydro modes

Attractive: final string in vacuum AdS is well understood

- Angle in AdS ≈ jet angle (?)

INCLUDING FLUCTUATIONS

So far strings were optimised to minimise energy loss

- Phenomenologically well motivated, but not so realistic

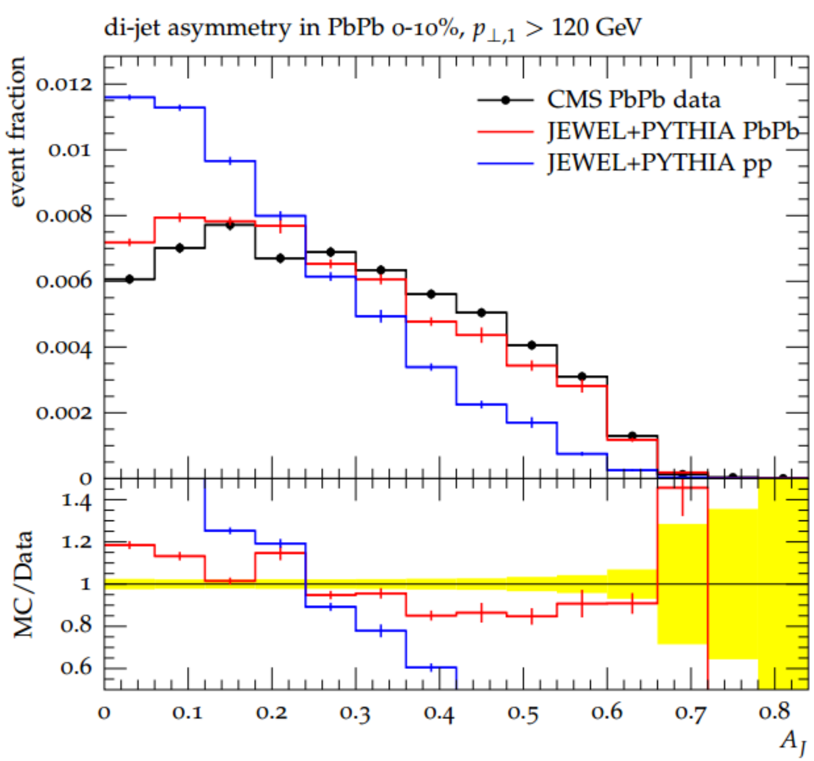
Try including more realistic string initial conditions

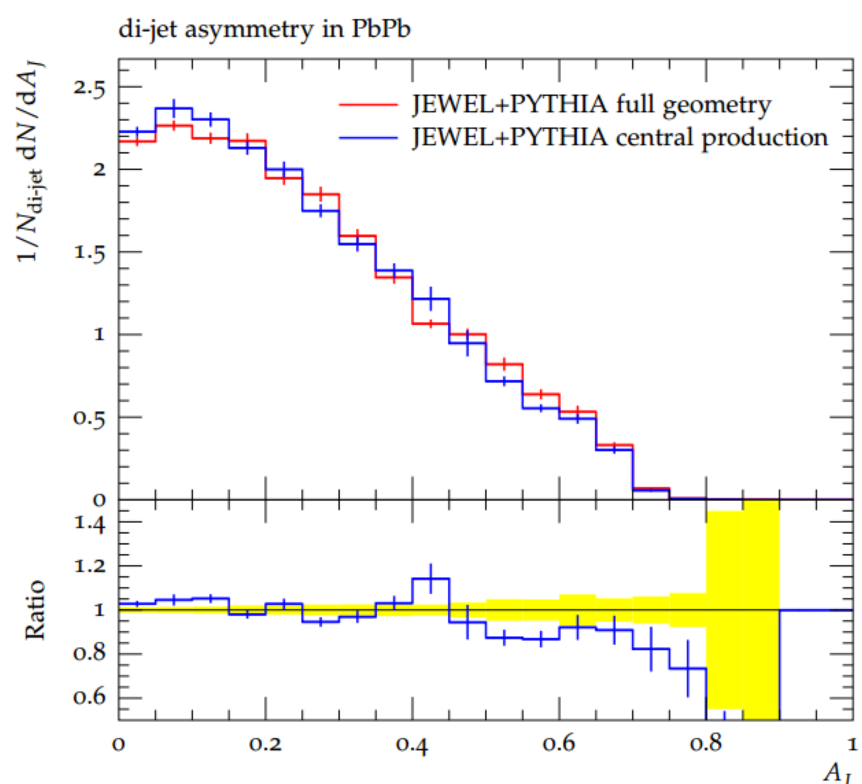
- Jets fluctuate, have probability distribution for energy loss
- Not necessarily straightforward at large N and strong coupling
  - Jets are not spray of particles before hadronization; more properly energy flow with energy correlators
- Different jets, however, characterised by different string profile
- Ignoring 1/N and 1/coupling effects for now…

FLUCTUATIONS IN JEWEL

Jet dijet modification thought to arise from path length fluctuations

- One jet loses more energy than other jet: larger asymmetry
- Intuition turns out not to be quite right: single jet fluctuation dominates
  - Compare r=0 central jets, to regularly distributed jets





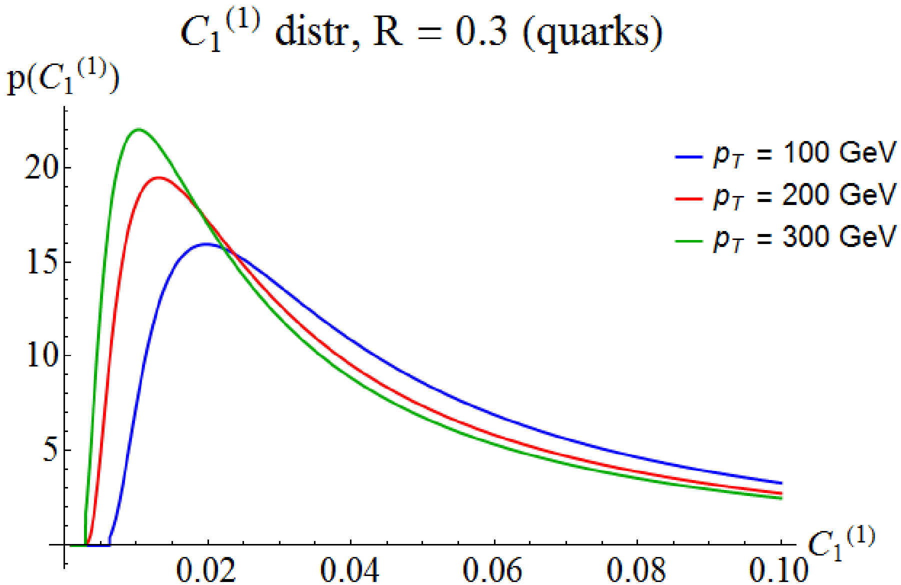
Guilherme Milhano and Korinna Zapp, Origins of the di-jet asymmetry in heavy ion collisions (2015)

MATCHING BOTH JET ENERGY AND JET WIDTH

Initial conditions in literature: minimize energy loss

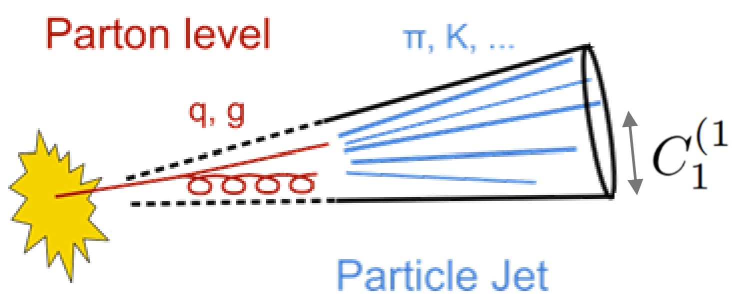
Would like to mimic distribution of real QCD jets

- Extra motivation: how is distribution affected by QGP?
- Take from pQCD (compares well with PYTHIA)



$$C_1^{(\alpha)} \equiv \sum_{i,j} z_i z_j \left(\frac{|\theta_{ij}|}{R} \right)^{\alpha}$$

z_i: fraction of jet energy
θ_{ij}: angle between particle *i* and *j*
R: jet radius parameter

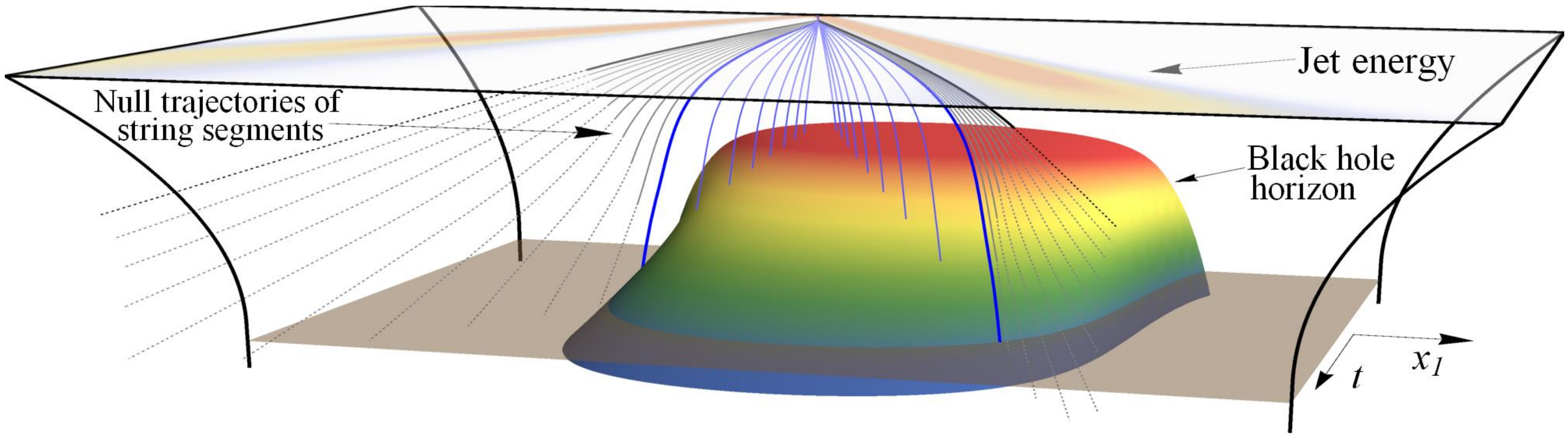


Link jet width to AdS angle

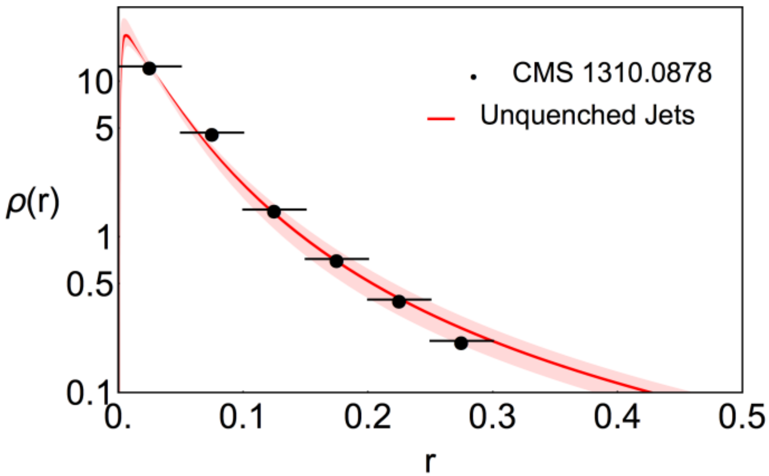
A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft drop (2014)

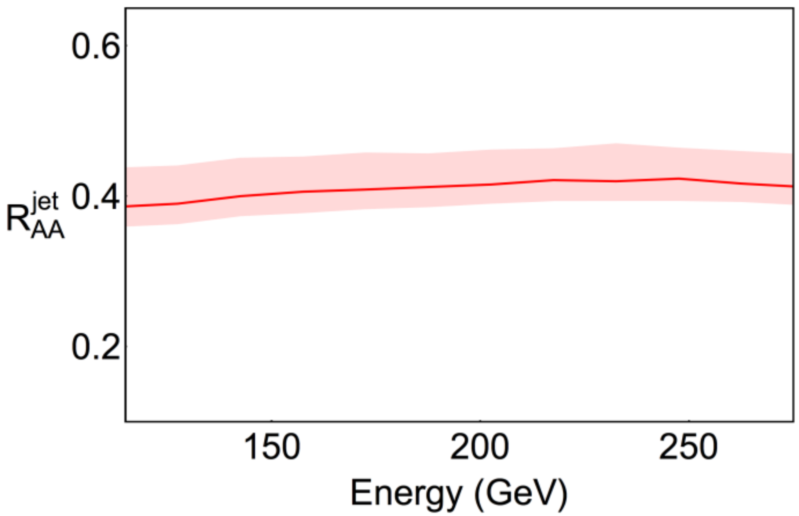
MODEL PARAMETERS

Wilke van der Schee, MIT/Utrecht



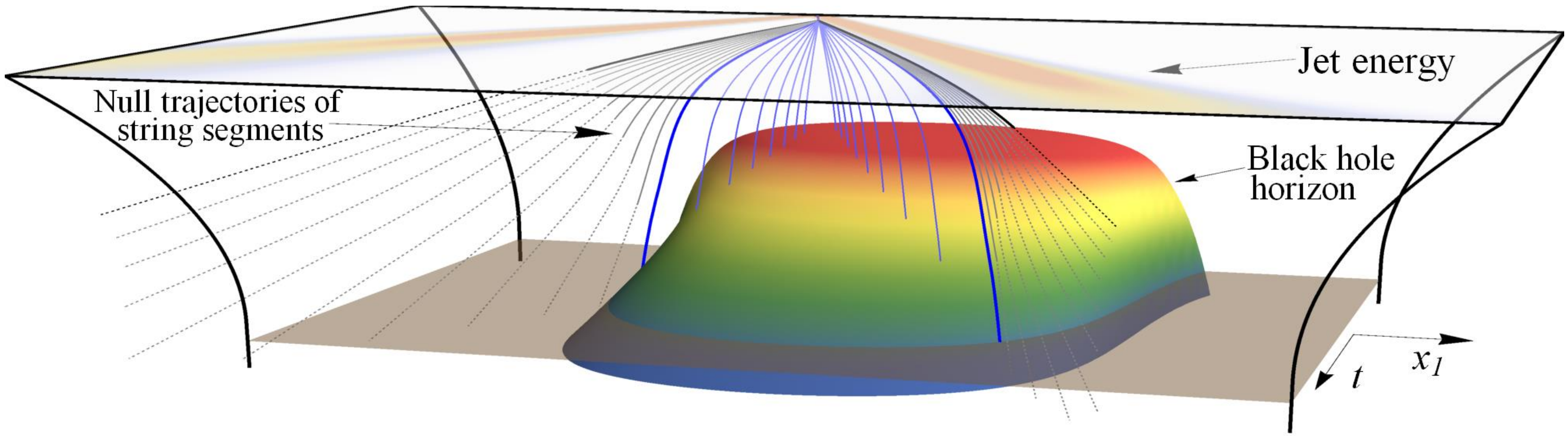
Two parameters fitted by data (~scaling T and scaling $\langle C^{(1)}{}_1 \rangle$):



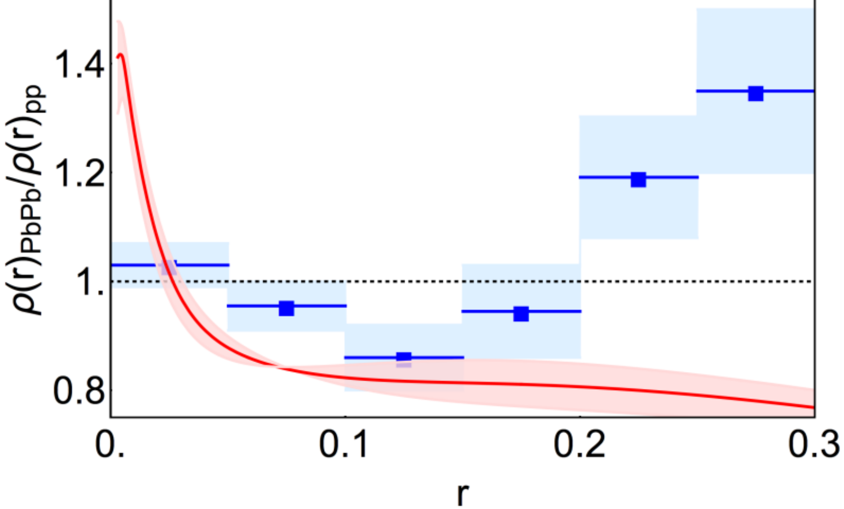


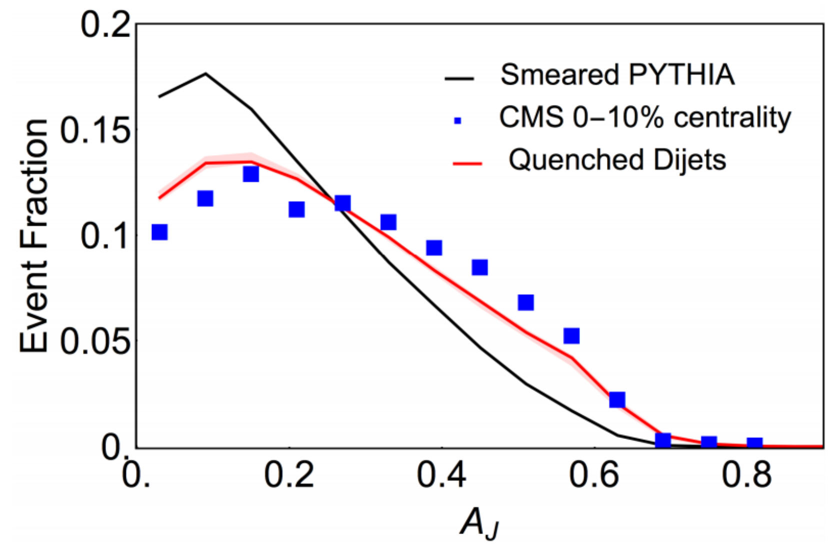
J. Brewer, K. Rajagopal, A. Sadofyev and WS, Jet Shape Evolution in a Strongly Coupled Plasma (2016)

EVOLUTION IN QGP:



Resulting modification in jet shape + dijet asymmetry:



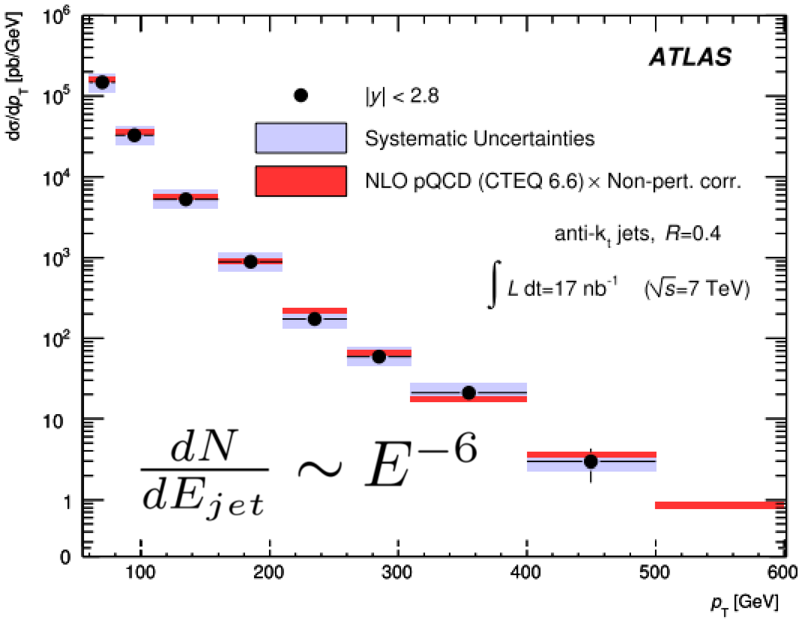


J. Brewer, K. Rajagopal, A. Sadofyev and WS, Jet Shape Evolution in a Strongly Coupled Plasma (2016)

TWO COMPETING EFFECTS

1. **Every jet widens**

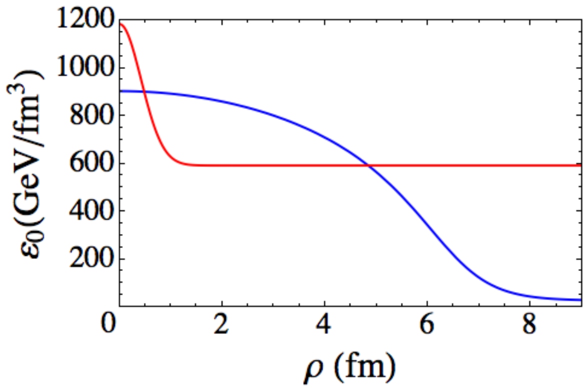
2. **Energy distribution falls steeply (~E^{-6})**
   - Wide jets lose (much) more energy
   - → selection bias on narrow jets

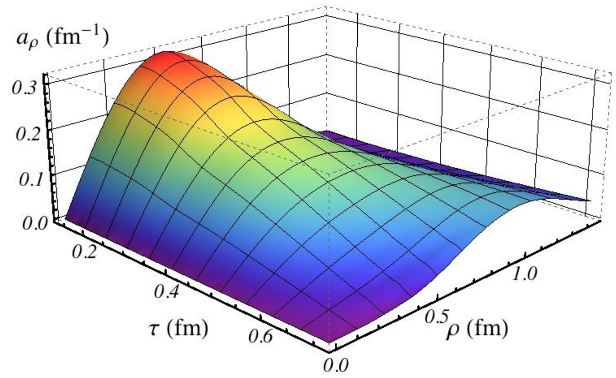


ATLAS, Measurement of inclusive jet and dijet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy (2011)

TWO COMPUTATIONS FOR SMALL SYSTEMS

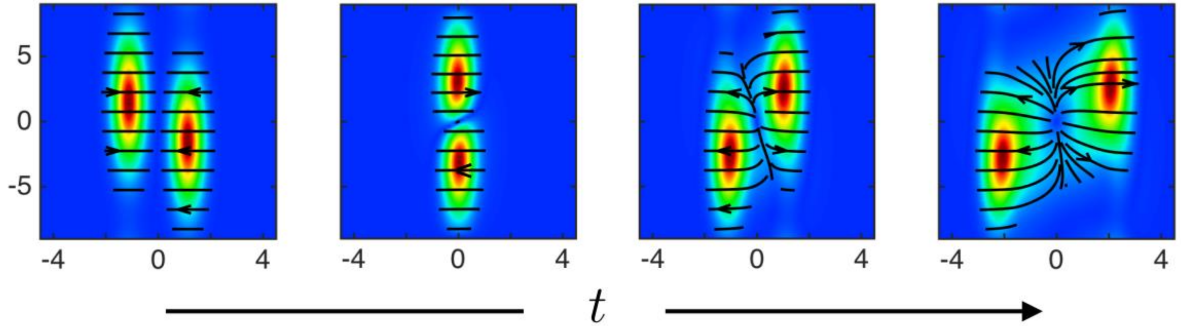
A fluctuation in a thermal bath:





- Hydro works within 0.2 fm/c, for system of size 0.5 fm.

A full-blown off-center `p-p collision':



- Hydro found to work in a system with R ~ 1/T

WS, Holographic thermalization with radial flow (2012)
Paul Chesler, How big are the smallest drops of quark-gluon plasma? (2016)

AN ESTIMATE

For p-Pb and p-p collisions only few particles produced

- Naïve estimate: $s \approx 16T^3$ gives $N_{ch} \approx Vs/7.5 \approx 2.1VT^3$
- Volume per rapidity: $R^2 \tau_{ini}$
- When $R > 1/T$ (and $\tau_{ini}T > 1$) then dN_{ch}/dy > 4
- Note that R increases faster than $1/T$ (τ versus $\tau^{1/3}$)
  - Hydro works better at later times
  - Flow requires time to develop, i.e. 4 is `optimistic' estimate

WS, Early hydrodynamisation, energy loss and small systems in holographic heavy ion collisions (2016)
Paul Romatschke, Do nuclear collisions create a locally equilibrated quark-gluon plasma? (2016)

DISCUSSION

Holography and heavy ion collisions

- AdS/CFT essential tool for insights in strongly coupled matter
- Complementary with weak coupling modelling

Qualitative lessons and quantitative modelling

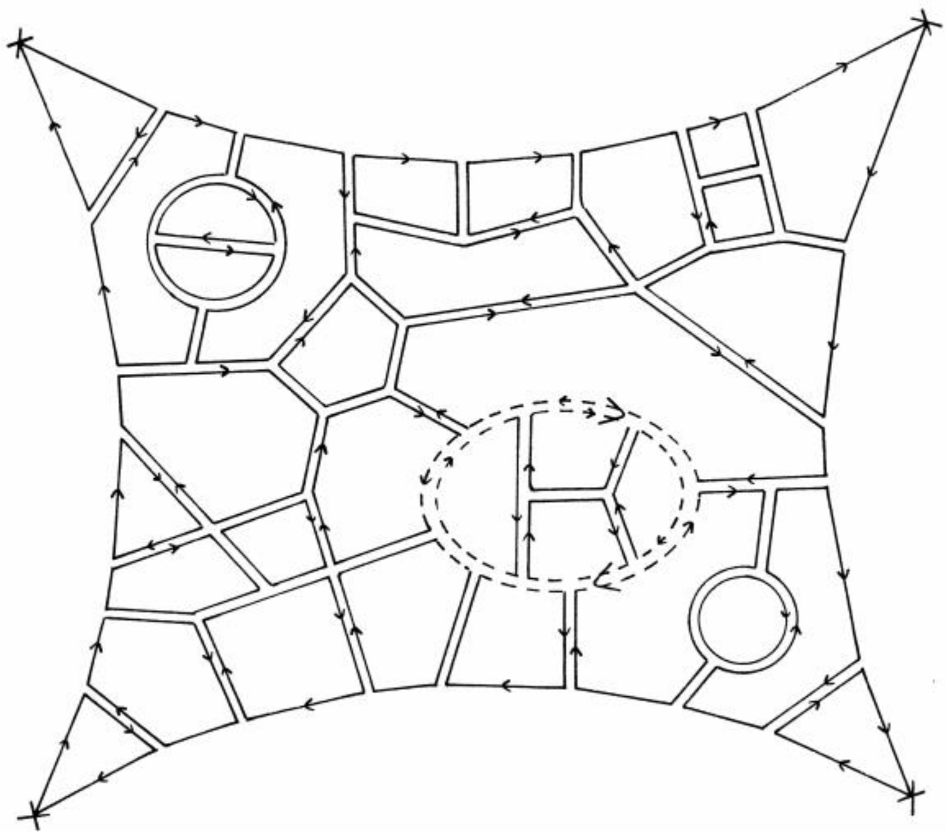
- Fast applicability of hydrodynamics
- Most of energy stopped at moderate rapidity, Gaussian shape
- Less stopping and broader rapidity profile at finite coupling
- Energy loss jet has crucial interplay with jet width
- Hydro in small systems feasible at strong coupling

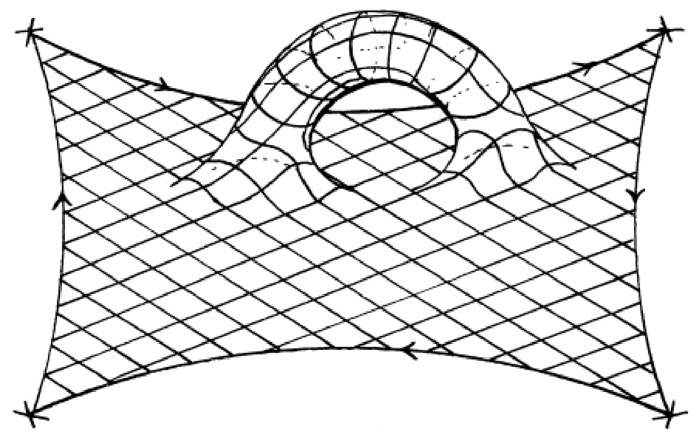
Outlook

- More quantitative comparisons with experiment, perhaps fitting width rapidity spectrum etc, improved models closer to QCD
- Computing non-local energy loss with varying T and varying flow

LARGE N GAUGE THEORIES

At strong coupling we can get GR





Planar limit:

$\lambda = g^2 N$ fixed

$N \to \infty$

Gerard 't Hooft, A planar diagram theory for strong interactions (1974)

ADS/CFT AND HOLOGRAPHY

Heavy ion physics: a weak/strong coupling interplay?

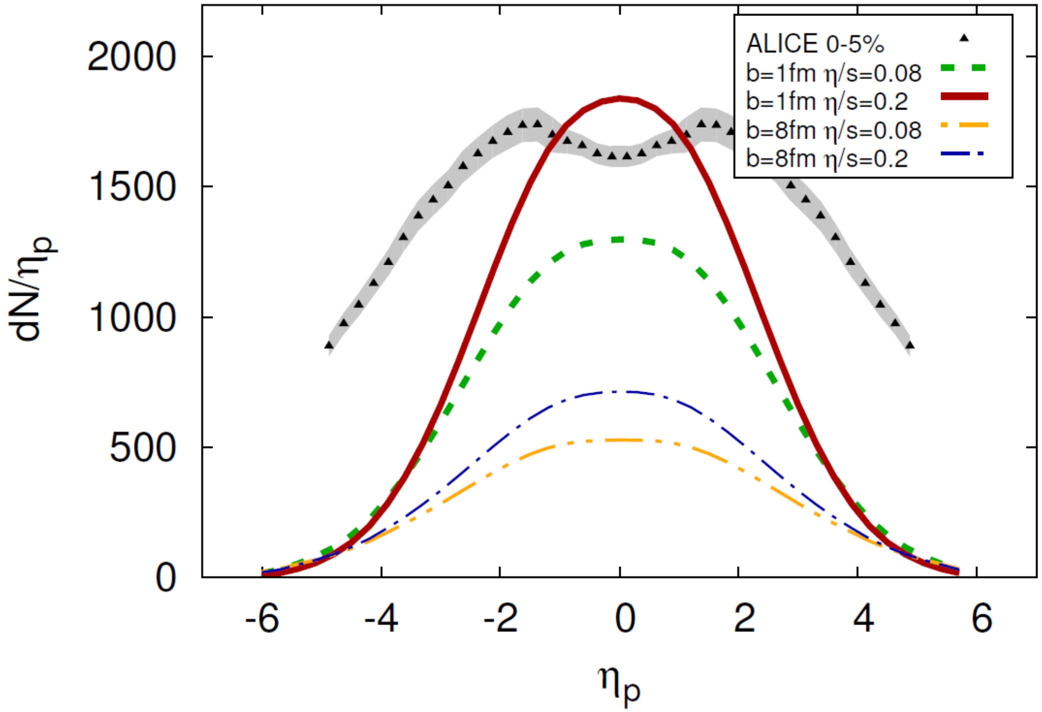
- A ‘hybrid’ approach: make a model inspired by strong and weak models
- Bolder approach: strong coupling entirely
  - Qualitative/quantitative trends can inspire better modelling
  - In either approach some amount of fitting is required

Viscosity is good example: $\eta/s = \frac{1}{4\pi}$

- Canonical theory gives benchmark value
- Qualitative insight: viscosity scales as entropy
- Possible to compute corrections: $\eta/s = \frac{1}{4\pi}\left(1 + \frac{15}{\lambda^{3/2}}\zeta(3) + \frac{5}{16}\frac{\lambda^{1/2}}{N_c^2}\right)$
  - Expected range: 0.08 – 0.12, link with weak coupling result?

RAPIDITY PROFILE + MUSIC

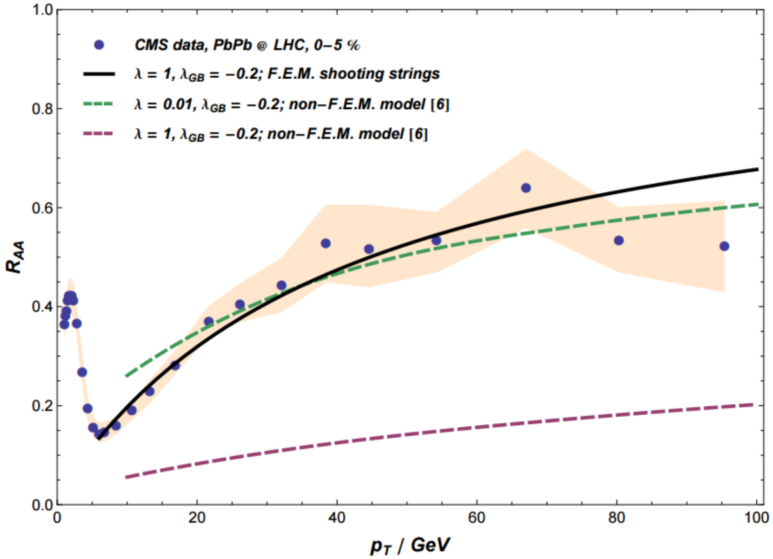
Particle spectra in longitudinal direction:

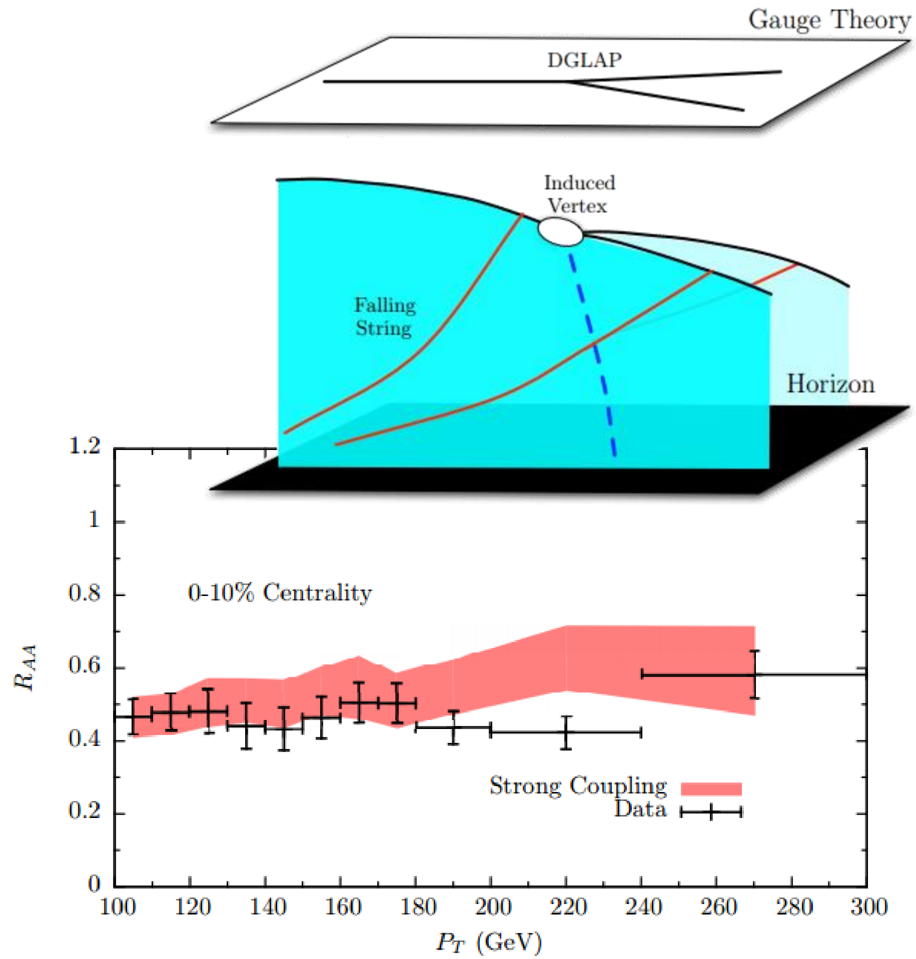


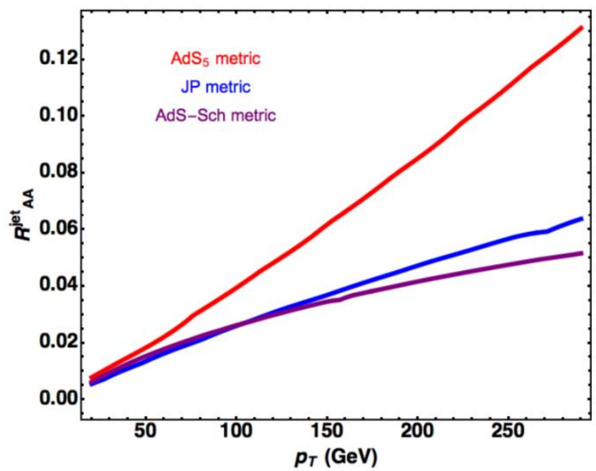
- **Rescaled initial energy density by factor 20**
- **Profile is about 30% too narrow**

WS and B. Schenke, Rapidity dependence in holographic heavy ion collisions (2015)
ALICE, Bulk Properties of Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured by ALICE (2011)

RECENT HOLOGRAPHIC JET STUDIES







J. Casalderrey, D. Can Gulhan, J. Guilherme Milhano, D. Pablos and K. Rajagopal, A Hybrid Strong/Weak Coupling Approach to Jet Quenching
R. Morad, W.A. Horowitz, Strong-coupling Jet Energy Loss from AdS/CFT (2014)
A. Ficnar, S.S. Gubser and M. Gyulassy, Shooting String Holography of Jet Quenching at RHIC and LHC (2013)

ENERGY LOSS BY A SLAB OF PLASMA

Old problem: how to define energy loss in terms of string?

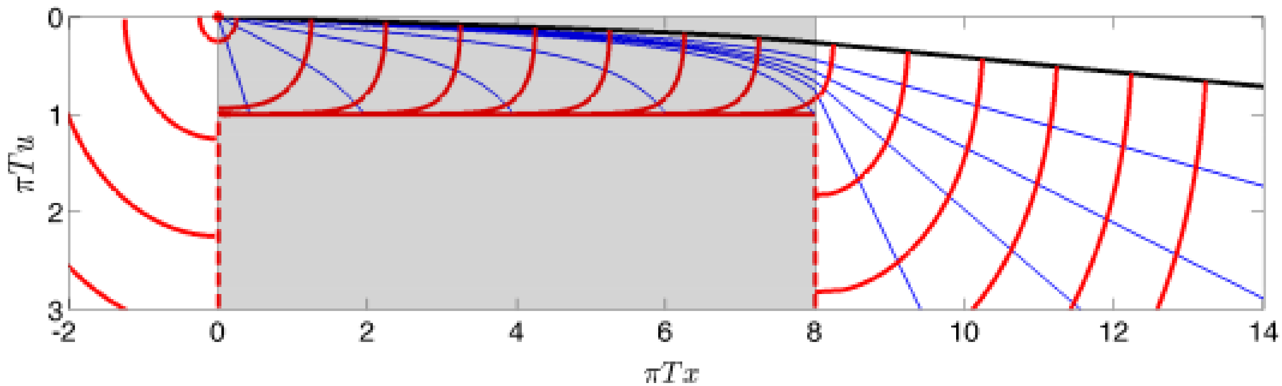
- In particular, real jets lose order 10% energy
- Natural definition: size black hole = size QGP, shoot jet through

Model evolution more realistically

- Part of string falls in black hole: dissipates into hydro modes

Attractive: final string in vacuum AdS is well understood

- Angle in AdS ≈ jet angle (?)



P.M. Chesler and K. Rajagopal, Jet quenching in strongly coupled plasma (2014)