Holography and heavy ion collisions

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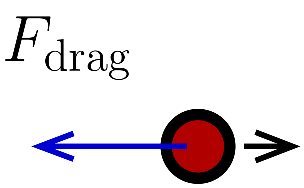
Special thanks to P. Arnold, M. Heller, P. Chesler, W. Horowitz, A. Ficnar, B. Muller

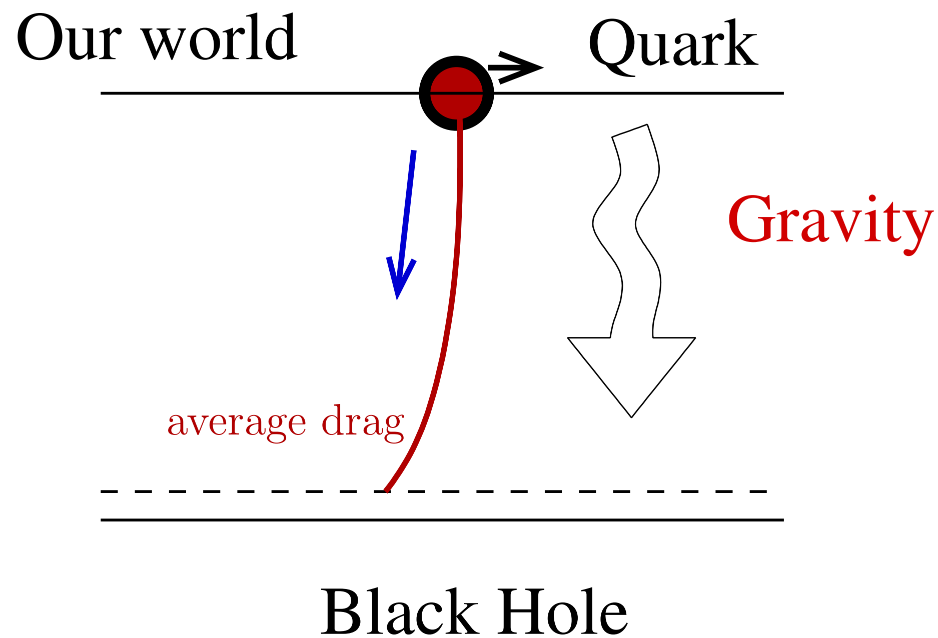
The AdS/CFT Correspondence:

Quark Drag



$$M\frac{dv}{dt} = -\eta v$$

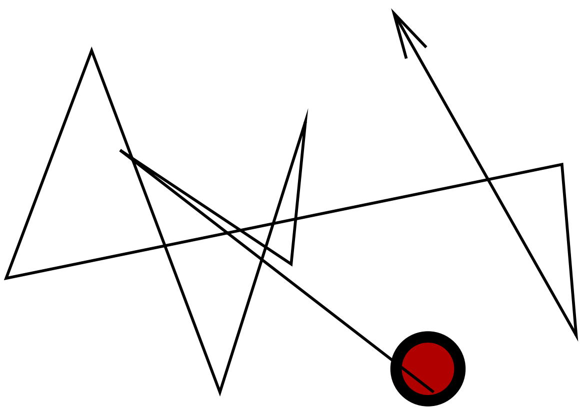
String Pulling on Quark



Its physics not math!

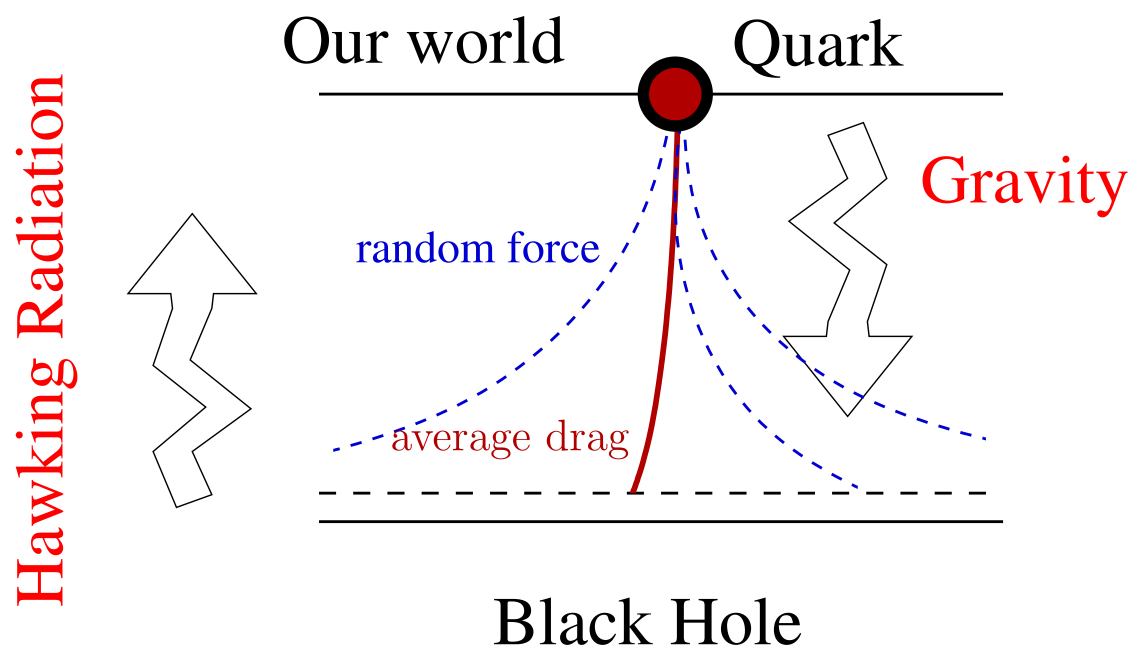
The AdS/CFT Correspondence

Brownian Quark



$$M\frac{dv}{dt} = -\eta v + \xi(t)$$

Stochastic String Pulling on Quark



5D equilibrium is a competition between dissipative gravity and hawking radiation:

classical probability $\propto e^{-\beta H[x,\pi_x]}$

Again, its physics not math!

Outline:

1. What are strong strongly coupled plasma like?

   - What are QCD plasmas like? Lattice spectral densities

2. Thermalization of strongly coupled plasmas

   - Hydro everywhere, but viscous corrections important

3. Equilibration of high (???) momentum modes

   - Limitations – Large N_c and λ

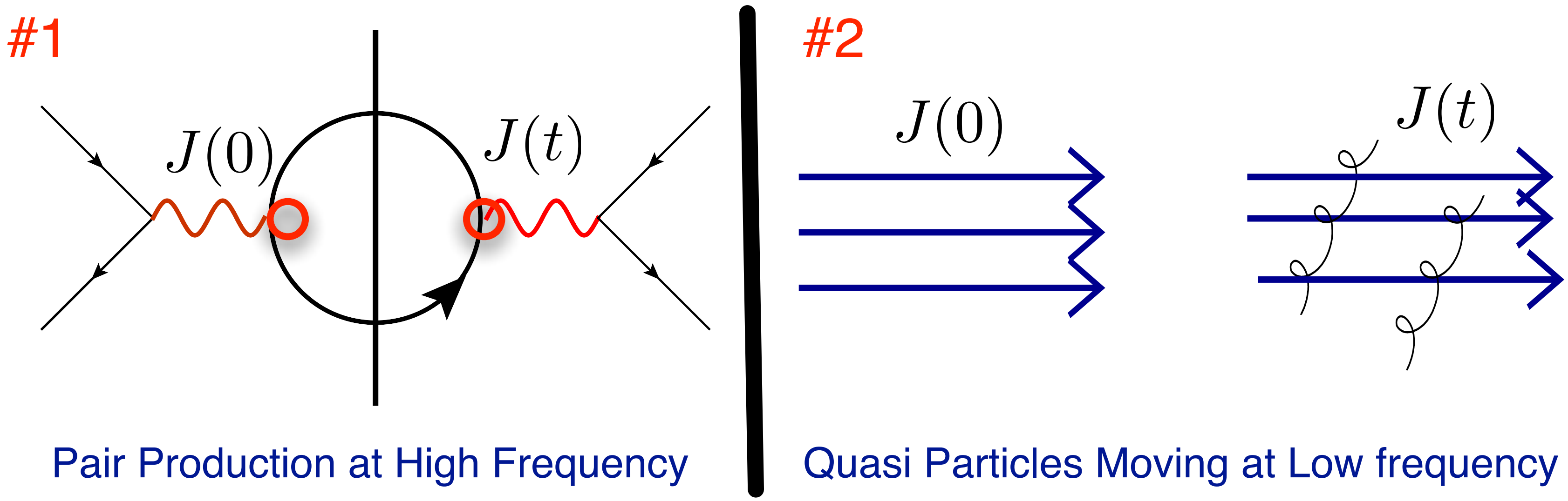
Strongly Coupled Plasmas and Lattice

QCD Lattice – Weak versus strong coupling how to tell?

- Lattice "measures" current-current correlation functions

$$\rho_{JJ} = \langle [J(t), J(0)] \rangle$$

- Weakly coupled picture consists of two processes:



Pair Production at High Frequency | Quasi Particles Moving at Low frequency

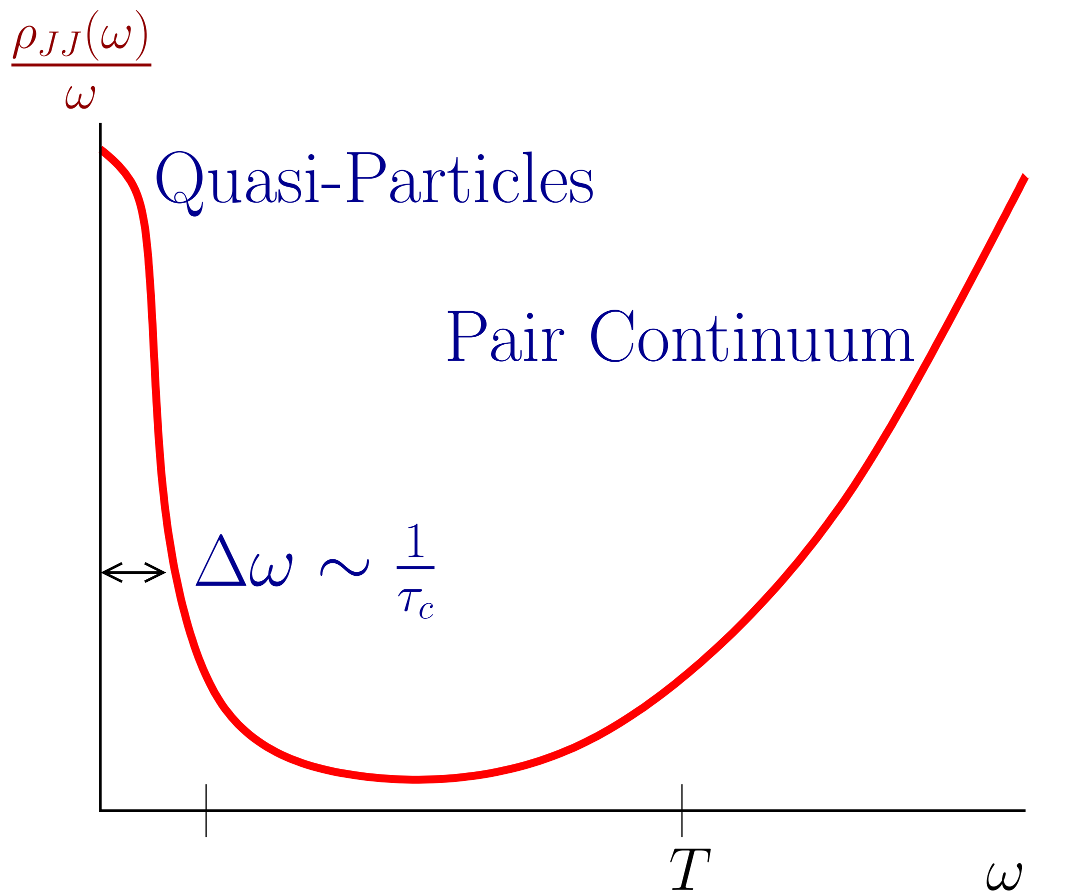
Duration that quasi-particles move set by the collisional time scale

$$\tau_c \sim \frac{1}{\alpha_s^2 T}$$

Spectral functions weak and strong coupling

$$\rho_{JJ}(\omega) = \int_{-\infty}^{\infty} \mathrm{d}t e^{i\omega t} \, \langle [J(t), J(0)] \rangle$$

Weak Coupling



Width of peak set by collisional time scale $\frac{1}{\tau_c} \propto \alpha_s^2$

Spectral functions weak and strong coupling

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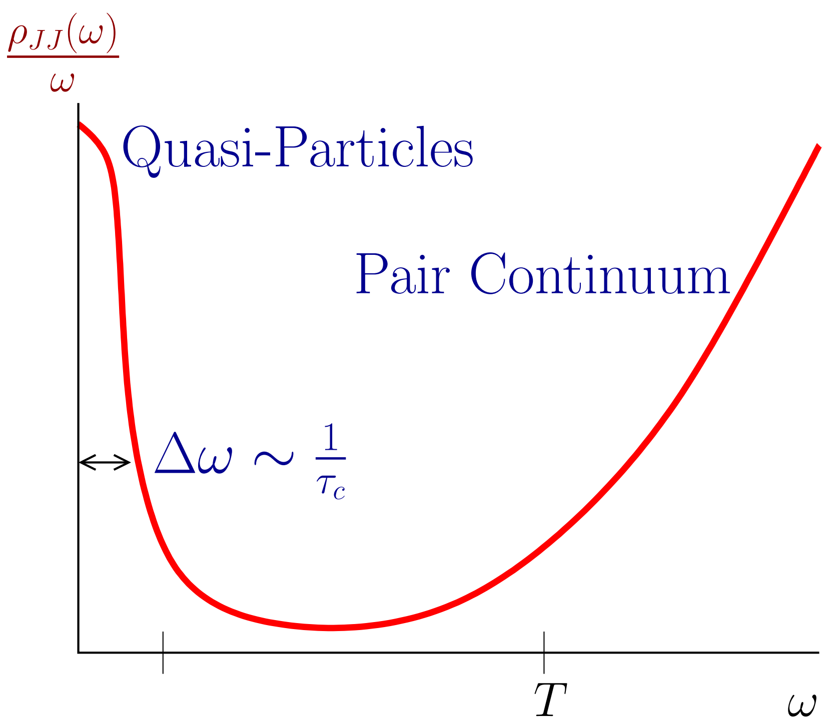
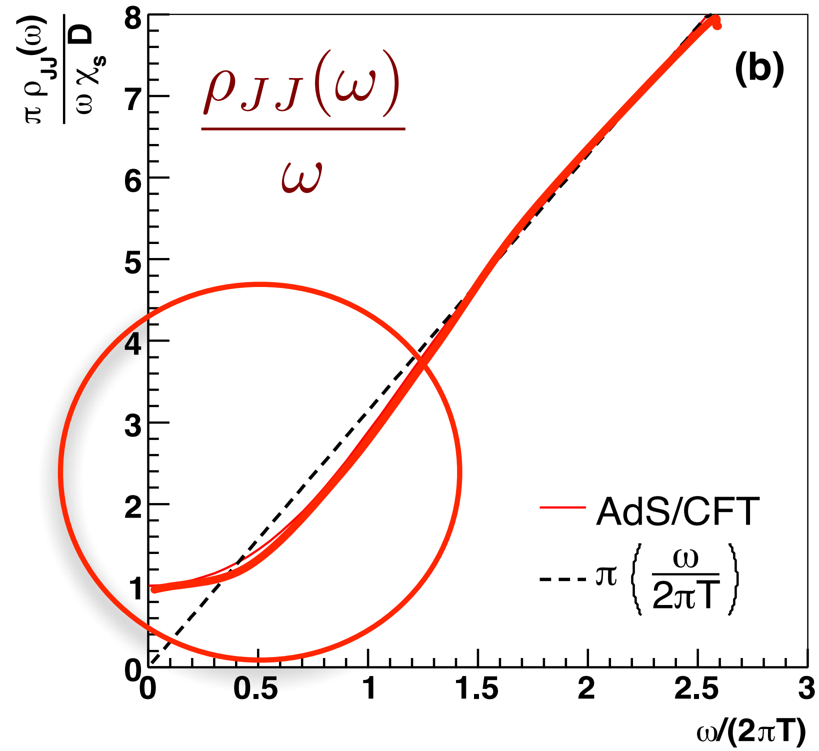
Weak Coupling



Strong Coupling



No distinction between transport and continuum!

The most important strong coupling prediction!

Lattice Measurements

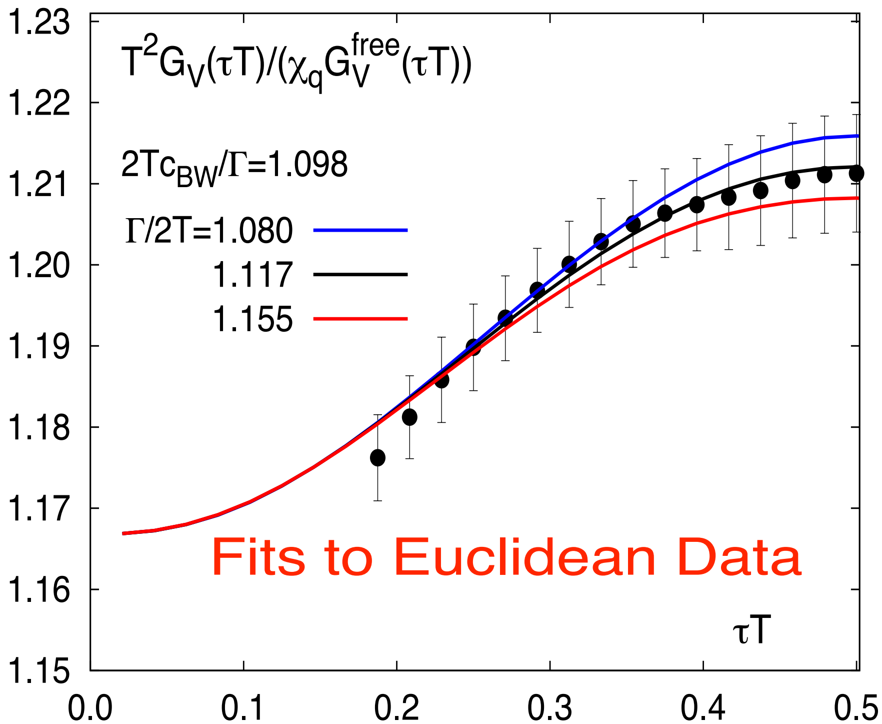
1. Lattice measures integrals of ρ

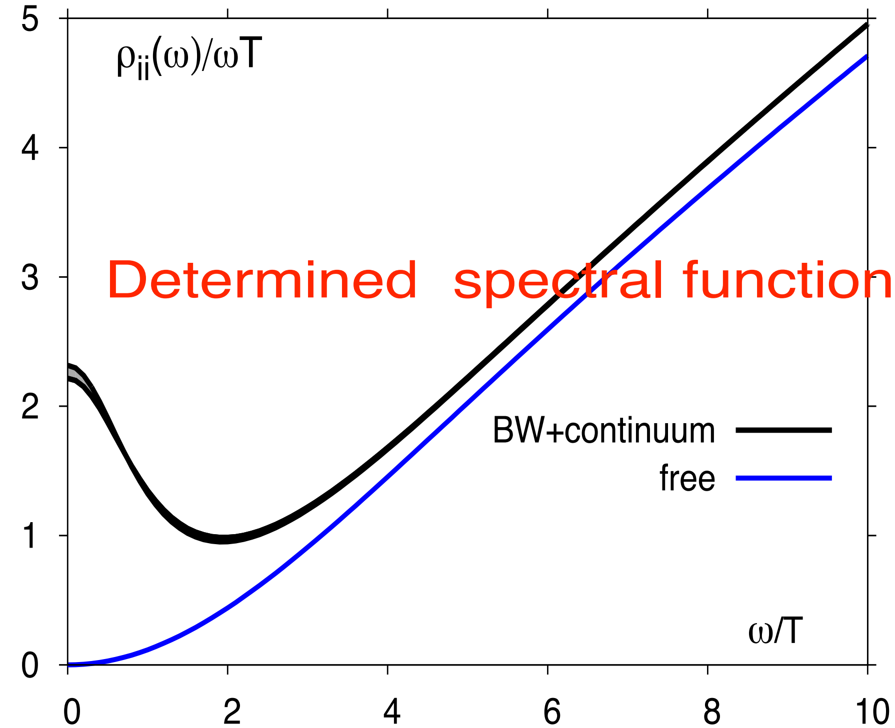
$$\underbrace{G_{JJ}(\tau)}_{\text{lattice measurements}} = \int_0^\infty \frac{d\omega}{2\pi} \underbrace{\frac{\rho_{JJ}(\omega)}{\omega}}_{\text{what we want}} \frac{\omega \cosh \omega(\tau - 1/2T)}{\sinh(\omega/2T)}$$

2. Always suffers from systematics

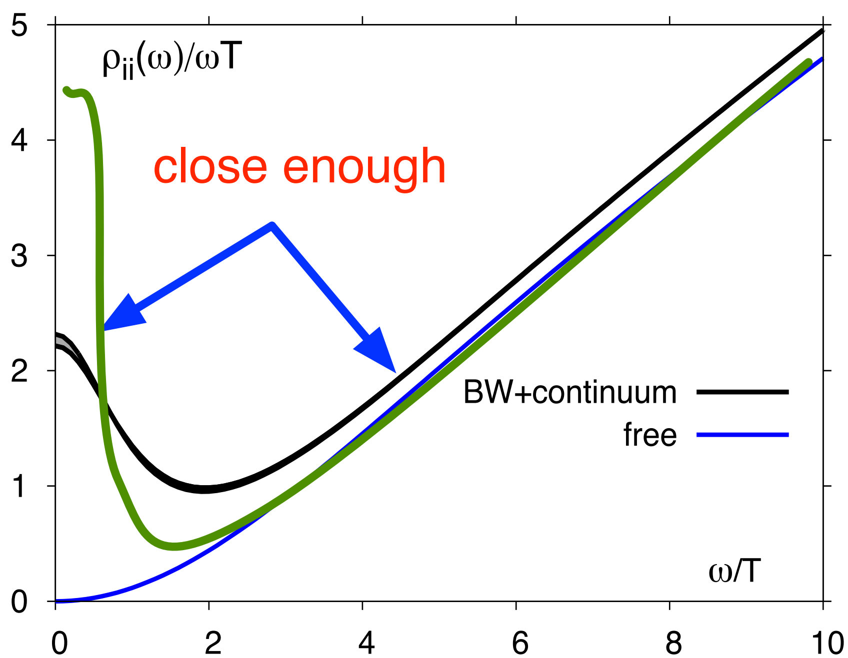
3. As good as it will get for a good while: Brookhaven-Bielefeld group, Ding et al arXiv:1012.4963

   - $128^3 \times 48$ lattice. Very precise $\lesssim 1\%$. Continuum extrapolated

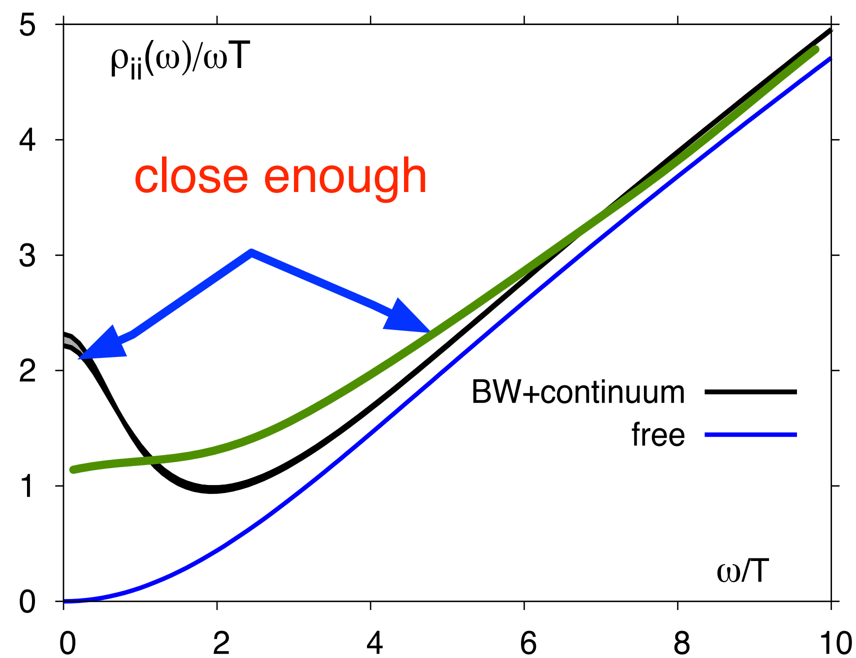

T2GV(τT)/(χqGVfree(τT))
2TcBW/Γ=1.098
Γ/2T=1.080
1.117
1.155
Fits to Euclidean Data
τT
1.23
1.22
1.21
1.20
1.19
1.18
1.17
1.16
1.15
0.0
0.1
0.2
0.3
0.4
0.5


ρii(ω)/ωT
Determined spectral function
BW+continuum
free
ω/T
5
4
3
2
1
0
0
2
4
6
8
10

Weak View



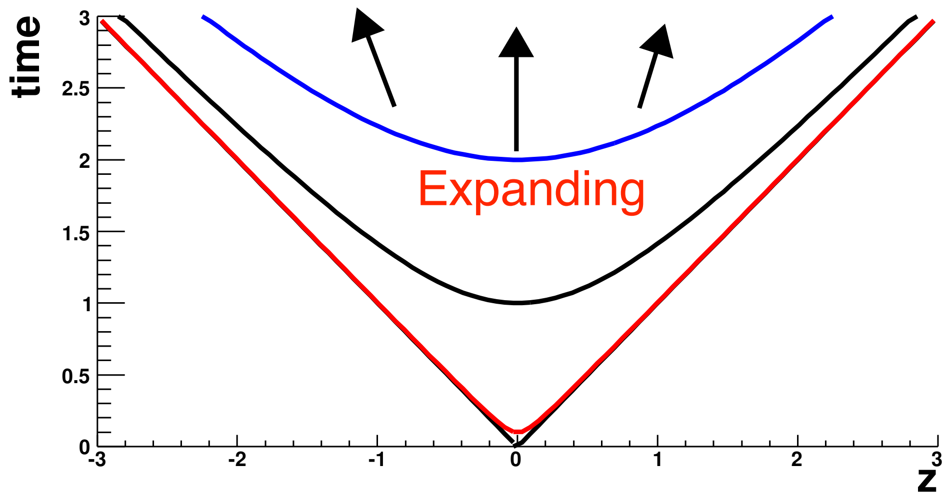
Strong View



Lattice data are disastrously in between weak and strong

Thermalization of Strongly Coupled Plasmas

Bjorken Expansion at weak coupling:



- Condition for hydro to apply:

$$\underbrace{\text{Collision rate}}_{\sim\alpha_s^2 T_o} \gg \underbrace{\text{Expansion Rate}}_{\sim 1/\tau_o}$$

Find:

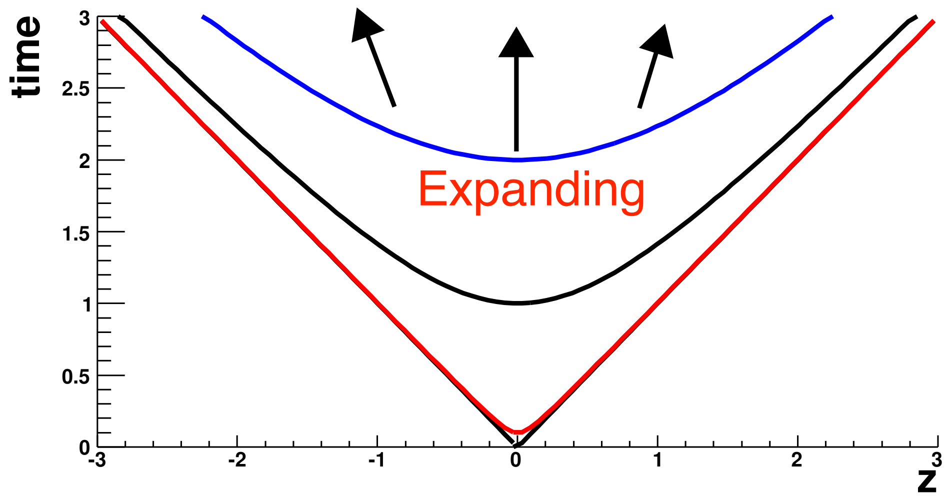
1. Not easy to reconcile with weak coupling with hydro

$$\alpha_s^2 \gg 0.66 \times \frac{(1\,\mathrm{fm})(300\,\mathrm{MeV})}{\tau_o T_o}$$

2. For a fixed coupling α_s, need $T\tau$ larger enough to have hydro

$$\frac{1}{\alpha_s^2} \ll \tau T$$

Bjorken Expansion at weak coupling:



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What about when $\alpha_s \to \infty$???

Strong coupling answer: (M. Heller et al, PRL)

- Find at strong coupling must have

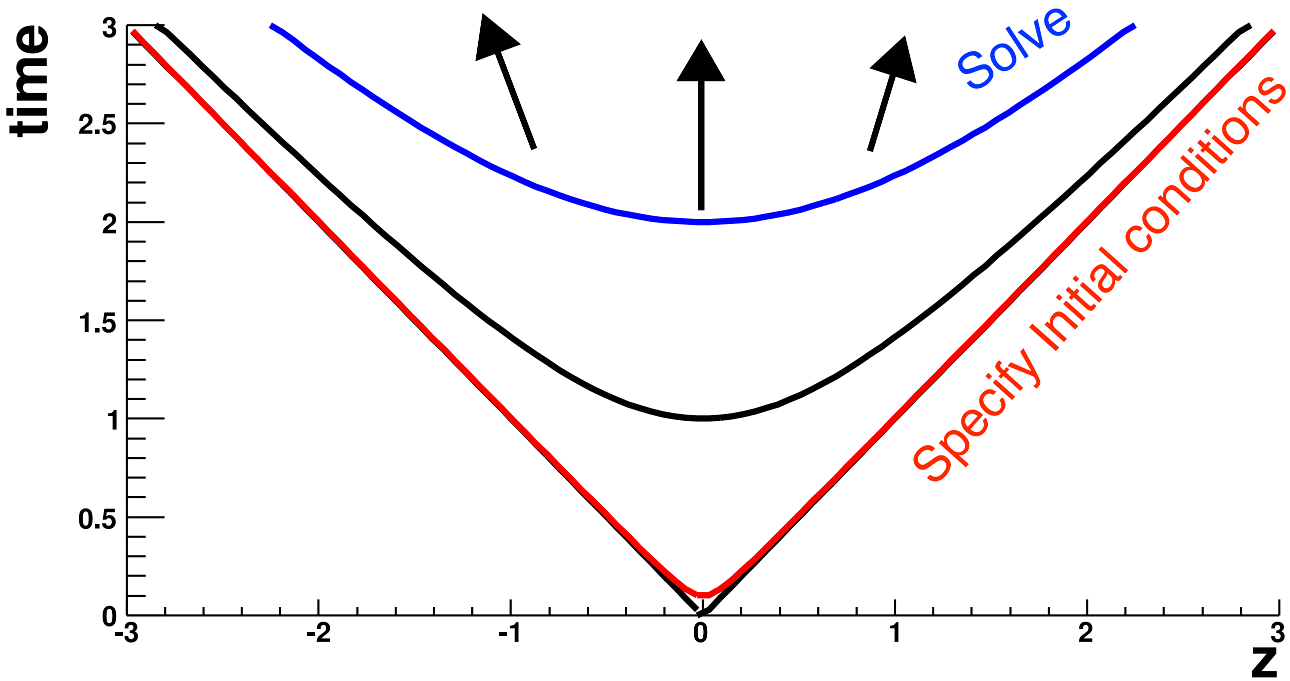
$$0.65 \lesssim \tau_o T_o$$

before we can use (viscous) hydro

  - I will review work of Michal Heller, R. Janik, R. Pechanski
  - See also P. Chesler and L. Yaffe, lots of PRLs

The setup

- Specify intial conditions and solve

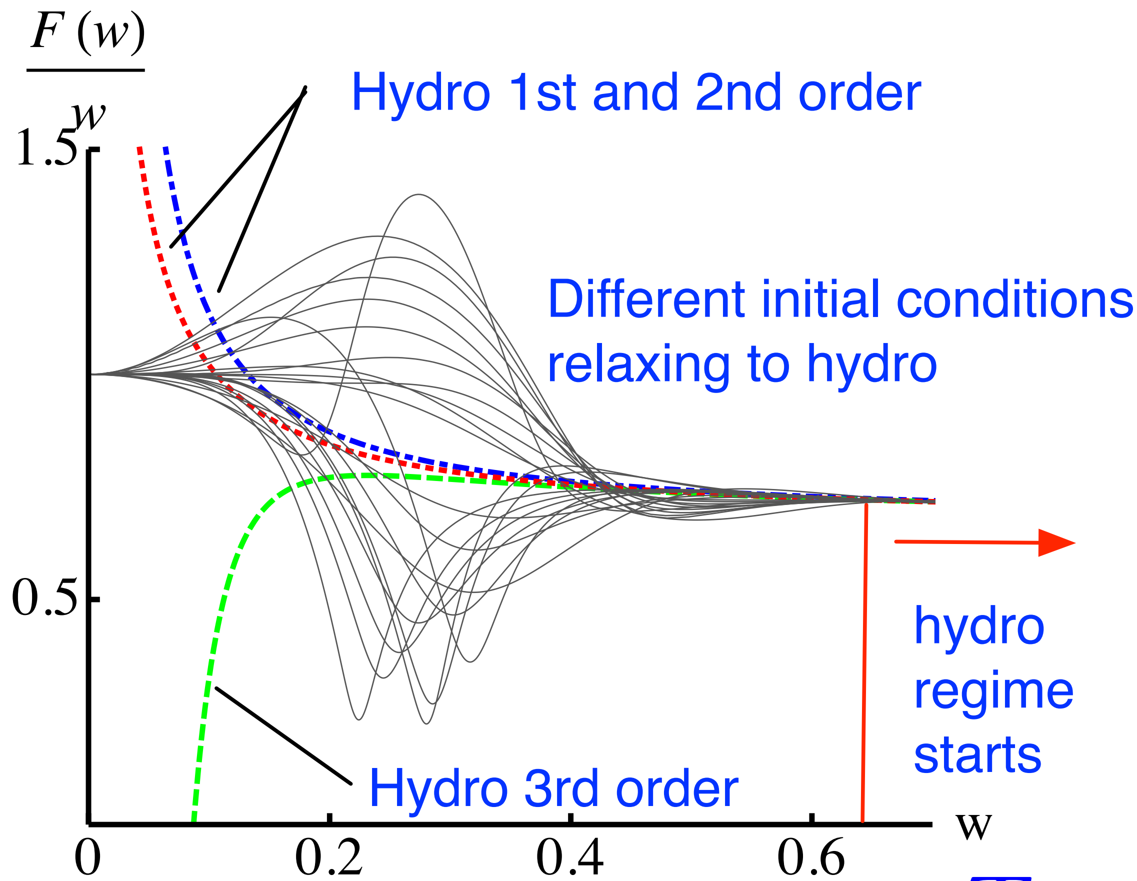


- Immense number of initial conditions with the same initial energy density
  - * Specify initial conditions in the fifth dimension
- Specify an effective temperature $T_{\rm eff}(\tau)$ from the EOS at all times

$$\text{energy density}(\tau) \;\propto\; (T_{\rm eff}(\tau))^4$$

Result:

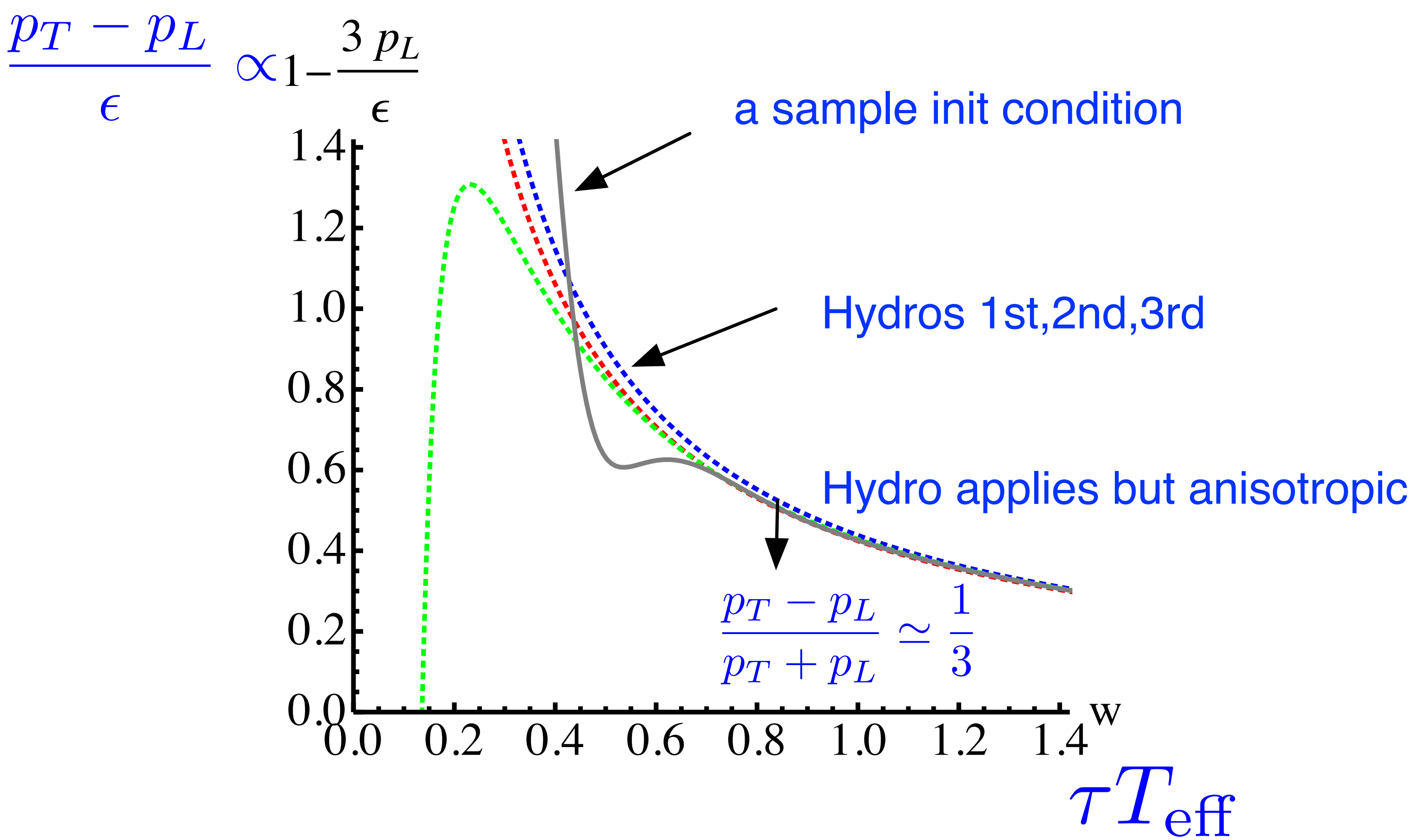
$$\frac{d\log(\tau T_{\text{eff}})}{d\log\tau}$$



τT_{eff}

Remarkably fast convergence to the universal hydro regime

But, viscous corrections are important for everything



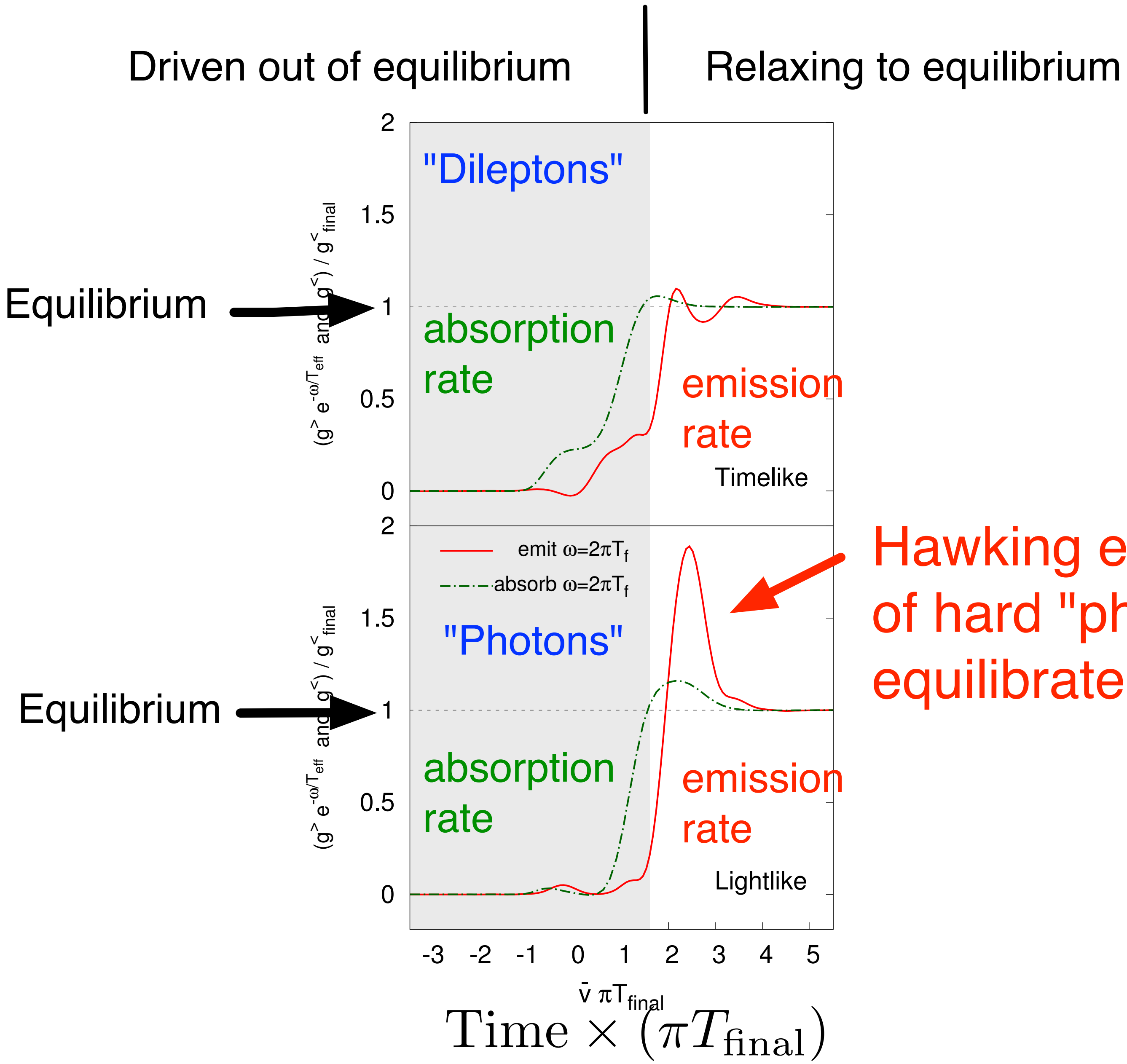
Viscous corrections are important for <u>all</u> observables

- Photon production has important viscous correction (Dusling and Shu)
- Jet quenching parameters, *i.e.* $\hat{q}$, gets important-anisotropic viscous corrections

Emission rate of non-equilibrium "Photons" and "Dileptons"

(P. Chesler and DT)

- In equilibrium – Rate to emit $= e^{-\omega/T} \times$ Rate abosrb



Hawking emission rate of hard "photons" equilibrates last

High momentum lightlike modes and “Jets”

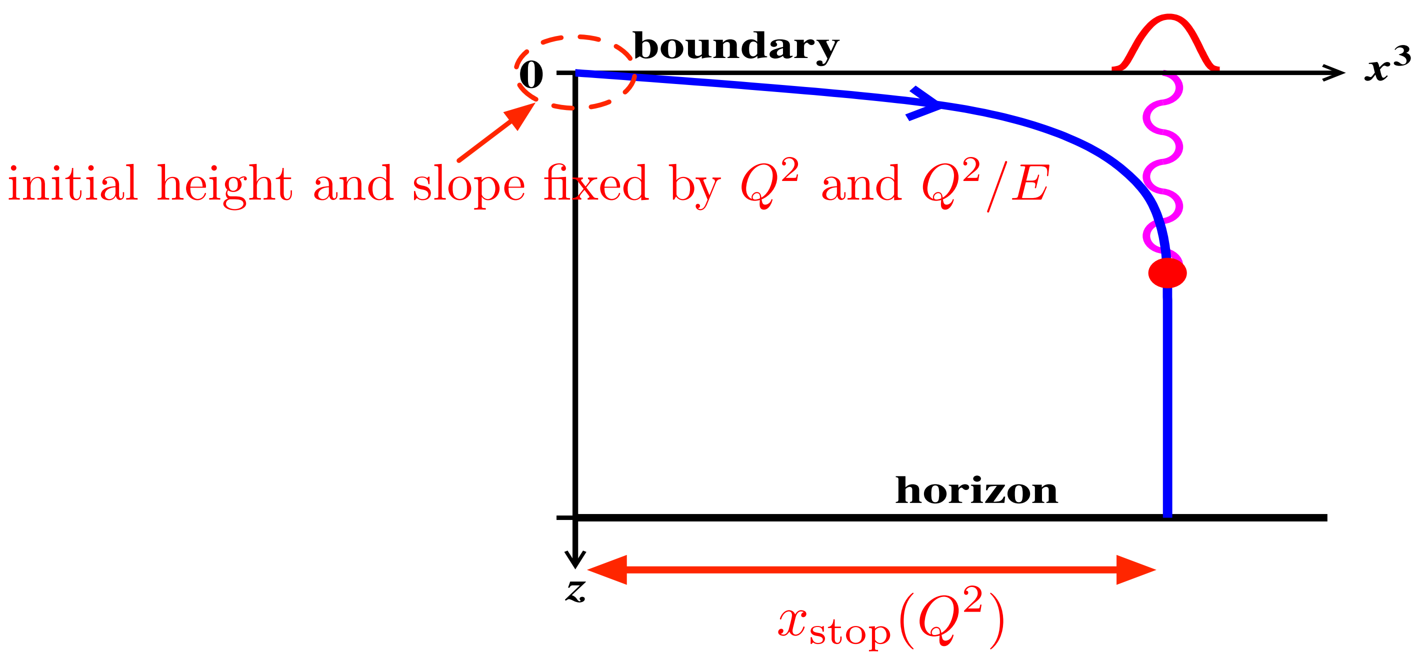
Jets by P. Arnold, D. Vaman (see also Iancu, Mueller; Jensen, Chesler Yaffe)

- Construct a wave packe with energy E and virtuality Q in boundary theory

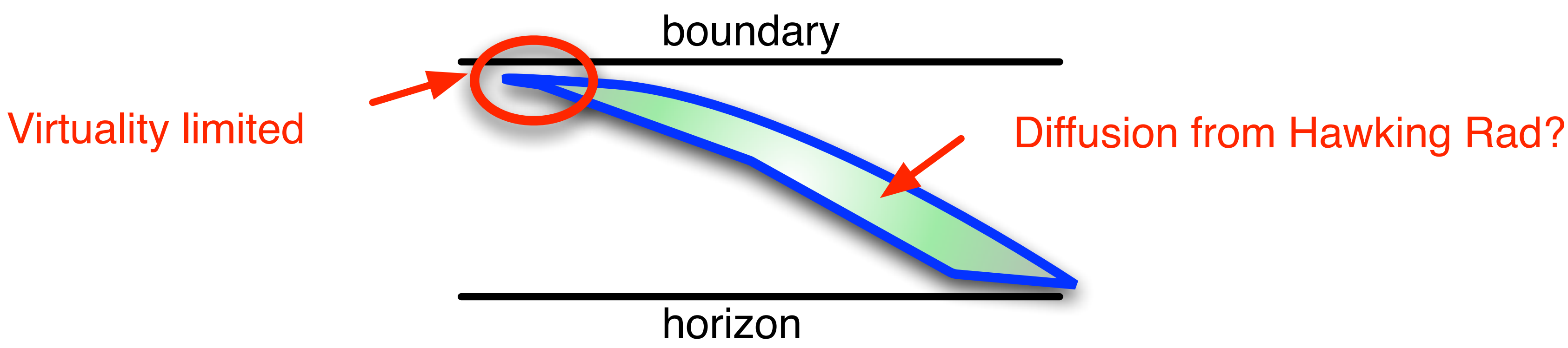
$$Q^{\mu} = (E+\epsilon, 0, 0, E-\epsilon) \Rightarrow Q^2 \simeq 4E\epsilon$$

- This wave packet maps to a bulk wave-packet which follows geodesics

$$x_{\text{stop}}(Q^2) \propto \frac{1}{T}\left(\frac{E^2}{Q^2}\right)^{1/4} \propto \frac{1}{T}\left(\frac{E}{\epsilon}\right)^{1/4}$$



Additional points about AdS theory of Jets



1. For Q^2 large enough classical AdS theory doesn't apply: (P. Arnold, D. Vaman, P. Szepietowski)

   - All curvature higher corrections, e.g. R^4, are the same size

$$\sqrt{Q^2} \ll \sqrt{\lambda} T \left(\frac{E}{\sqrt{\lambda} T} \right)^{1/3}$$

2. Maximum stopping stopping distance set by smallest possible virtuality

$$\text{size of wave-packet} \simeq x_{\rm stop}^{\rm max} \propto \frac{1}{T} \left(\frac{E}{T} \right)^{1/3}$$

AdS/CFT Jet Phenomenology

- What is high momentum?

$$\frac{p}{T} \gg 1$$

- But we have taken:

$$\sqrt{\lambda} \to \infty \qquad N_c^2 \to \infty$$

- This means that we are normally working in a regime where

$$\frac{p}{T\sqrt{\lambda}} \ll 1 \qquad \frac{p}{TN_c^2} \ll 1$$

When $\frac{p}{TN_c^2} \gg 1$ it is largely unkown how to calculate.

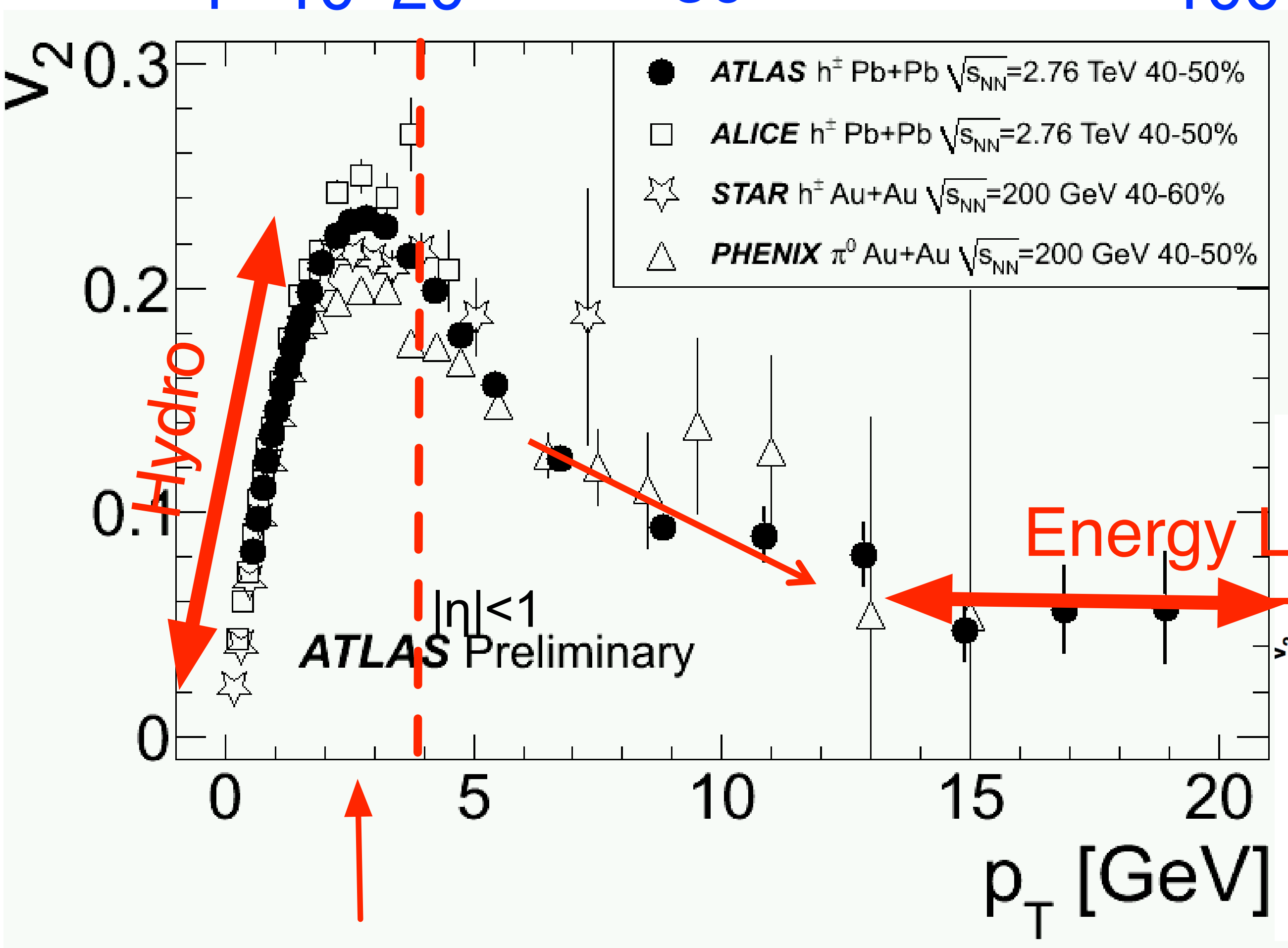
AdS Phenom for the timid

Ads Phenom for the Brave!

$P/(T\sqrt{\lambda}) < 1?$

$P/(TN_c^2) \gg 1!!!$

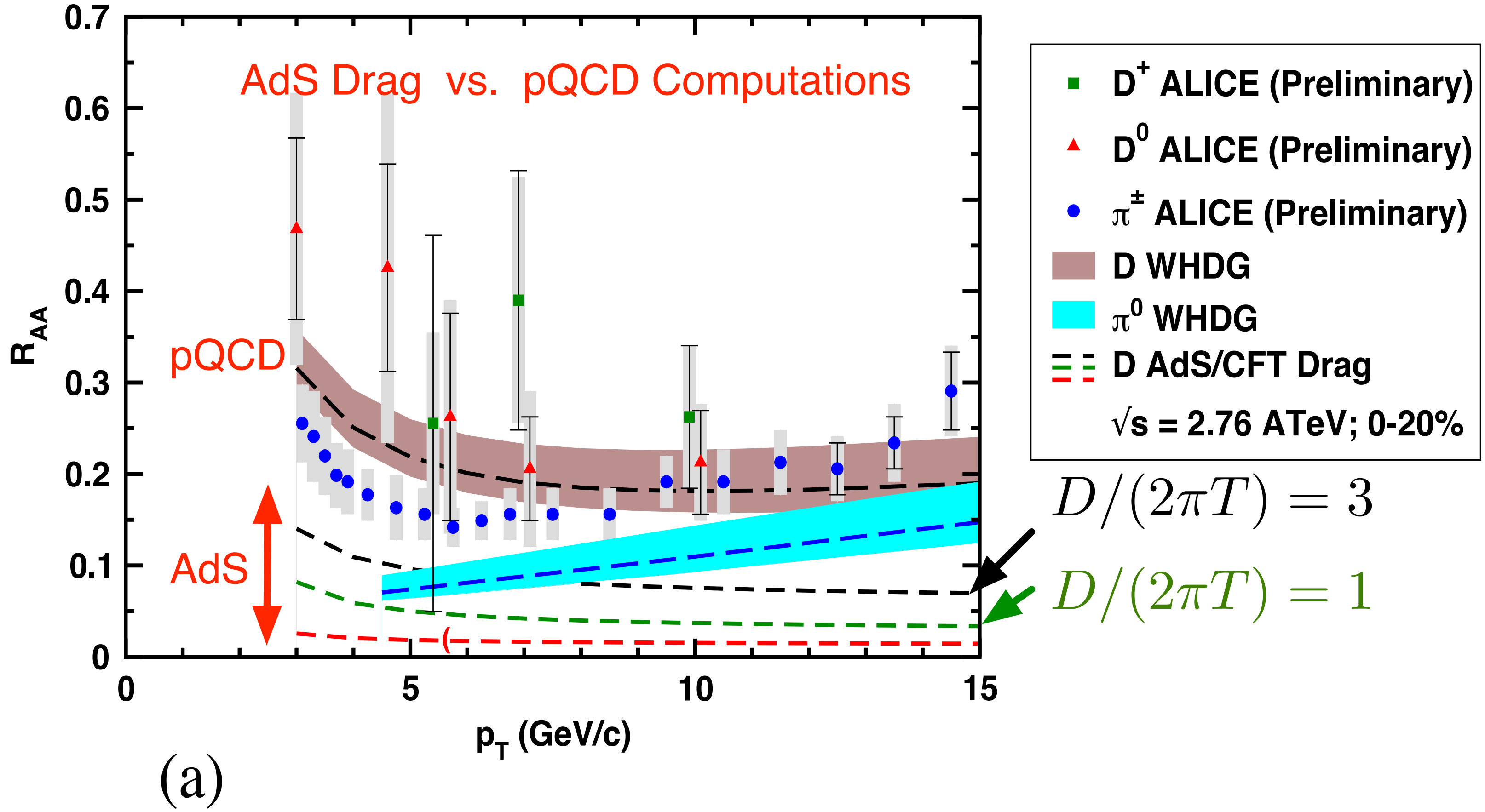
1 10 20 50 100 P_T/T



Use AdS light quark e-loss results here?

AdS/CFT vs. Peturbation Theory for heavy quarks – Slide by W. Horowitz

- Comparison with ALICE data – I kind of hoped it would work better



How much do (strong) longitudinal fluctuations effect this result?

Conclusions

1. Holography can be a useful foil to perturbative thinking about plasma physics

   - Are there soft quark and gluons quasi-particles?

2. Holography yields valuable insight into thermalization and hydrodynamics

3. Real QCD jets are not well described by holography.

4. Need to see holography “break-down” in a systematic way:

   - Increased fluctuations at higher p_T