Hydrodynamic Response to Energetic Particles

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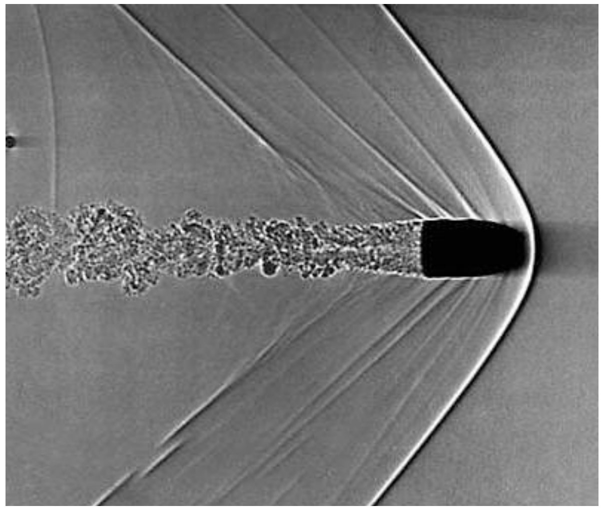
Outline

- Introduction: Sound and diffusion mode.
- Models for jet-plasma interaction
- Consequence for particle correlations.
- Lessons from strong coupling calculations
- Space like meson from gravity duals (work in progress)

Hydrodynamic Modes



- Sound mode: Propagating mode with velocity c_s. Supersonic particles lead to Mach Cones.
- Diffusion mode: not propagating mode related and remembers the source direction.
- In non relativistic fluids the macroscopic shape of the object sets how much each mode is excited.
- Microscopic particles couple to hydro modes but the hydro evolution depends on an unknown source

$$\partial_\mu T^{\mu\nu} = J^\nu$$

JCS, Shuryak, Teaney

Scenario 1: Non Isentropic

- Simple source (small perturbation)

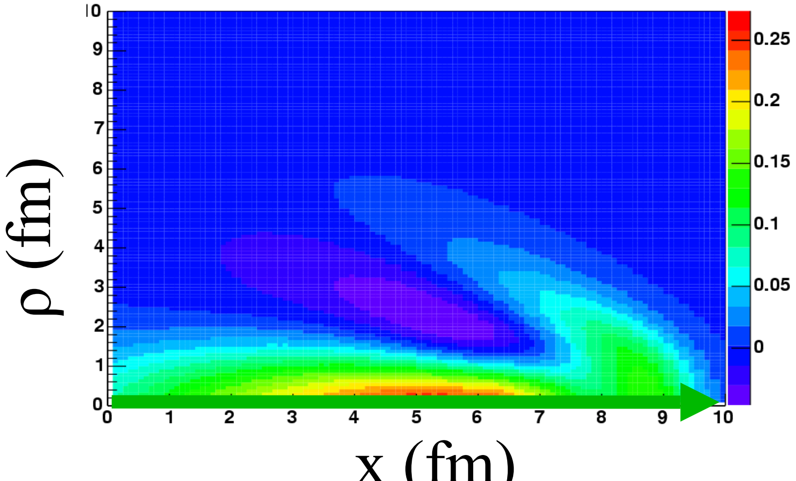
$$J^\mu(x) = \lambda\, F(x - x_{jet})\,(1,1,0,0)$$

strength normalizable function

- The energy loss and the hydro field amplitude are controlled by the same parameter

$$\frac{dE}{dx} = \int d^3x J^0(x) = \lambda$$

- This type of sources always produce a wake



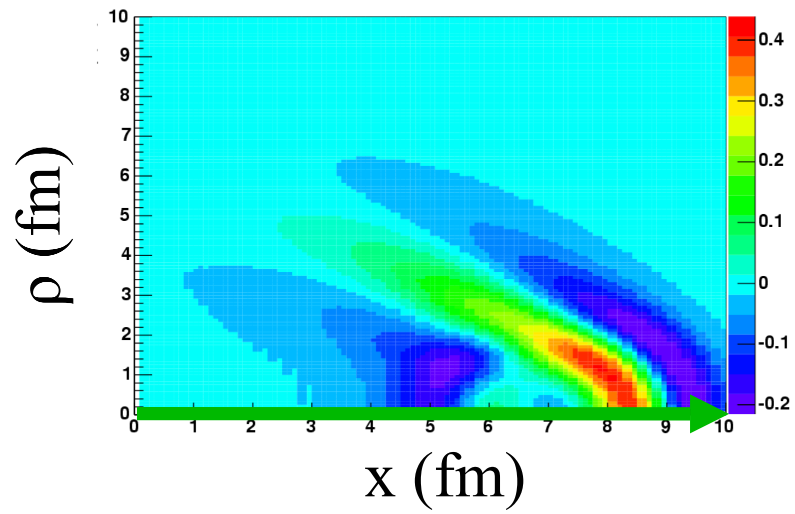
Scenario II: Isentropic

- Source of the type:

$$J^{\mu}(x) = \lambda\left(0, \partial^{i} F(x - x_{jet})\right)$$

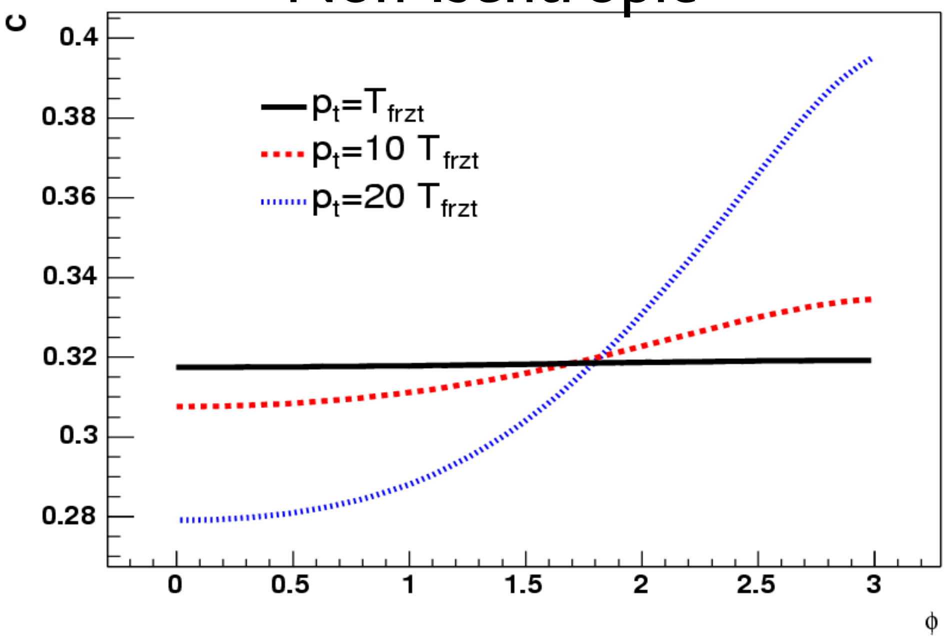
- This source has zero integral. Energy loss is zero to linear order.
- Non linear correction in the hydro fields carry energy: Energy loss from sound waves is quadratic in amplitude!

- This type of source produces sound waves only.

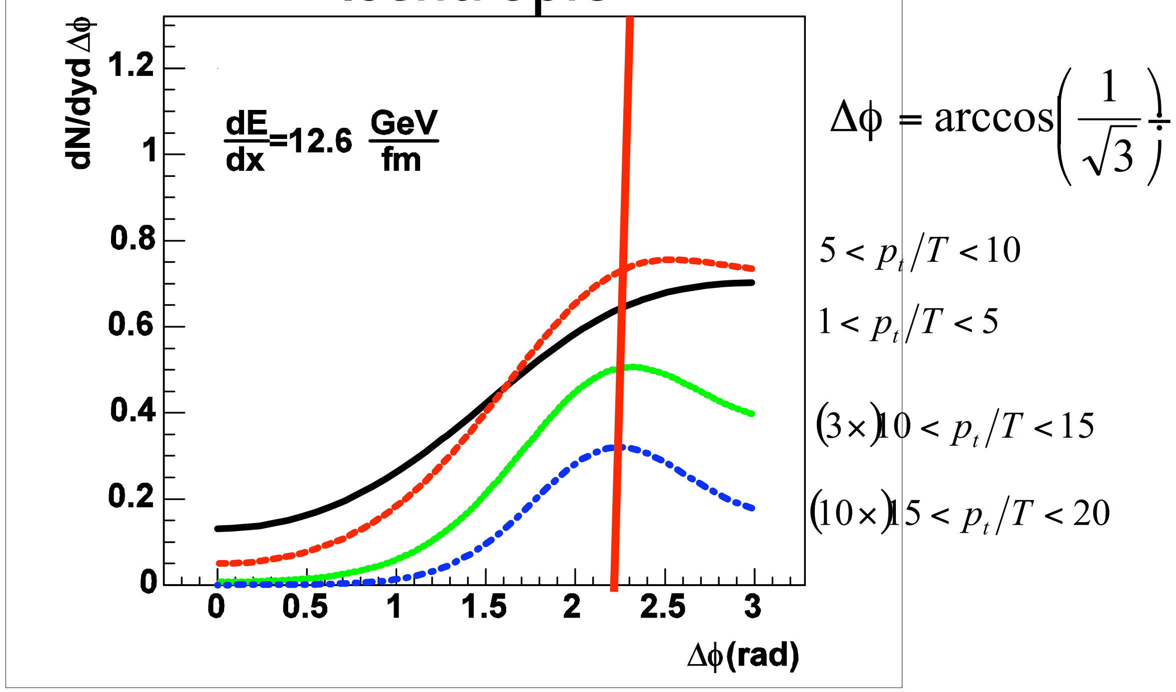


Correlations

Non-Isentropic



Isentropic



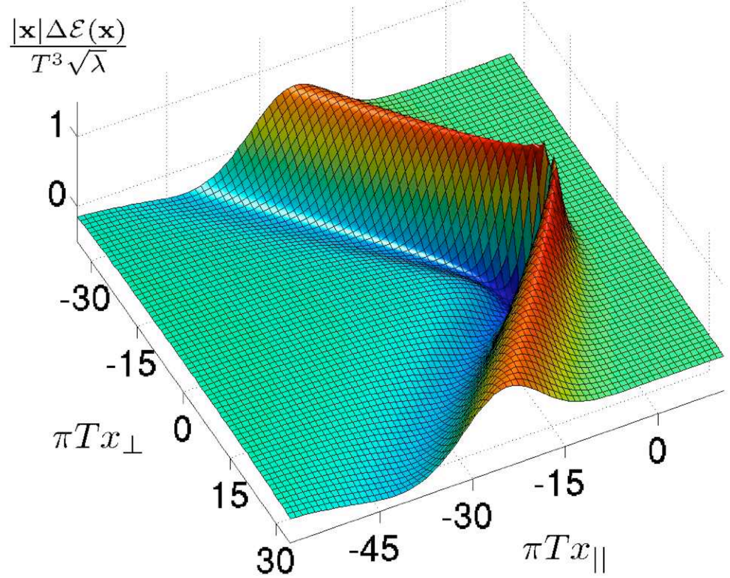
- Only if the diffusion mode is not excited, jet associated particle distribution reflect the Mach Cone.
- In static medium, unrealistically large energy loss are needed. Expansion effects may solve this problem (JCS, Shuryak)
- When present, the Mach Cone signal leads to a p_t^{assoc} independent peak position. The width of the peak grows with increasing p_t^{assoc}.

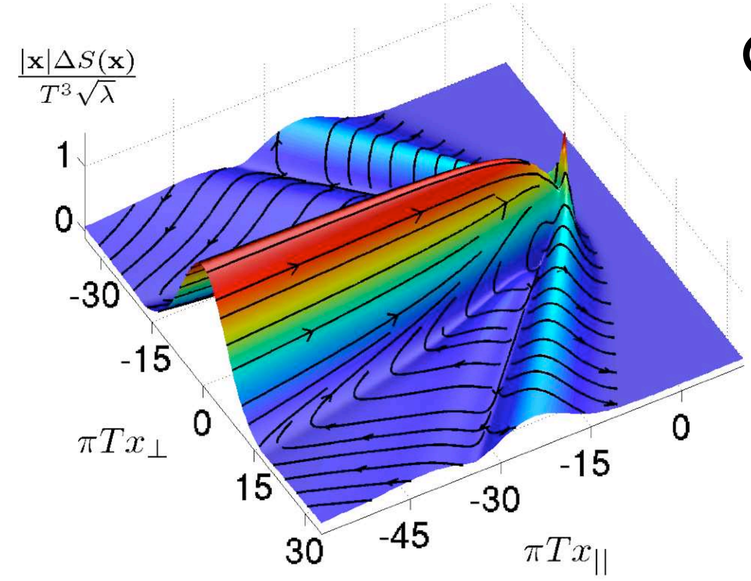
Remarks

- Even if energetic particles couple to hydro modes it is not guarantee that the Mach Cone is reflected in data.
- There are many qualitative features that agree with the Mach Cone formation (see Renk's talk)
- Quantitative comparison is hard... there are many effects to consider.
- But the Mach Cone only can explain data if the source is the correct one!
- Can we find a physical system with the correct source?

Lessons From Strong Coupling

Quarks at Strong Coupling

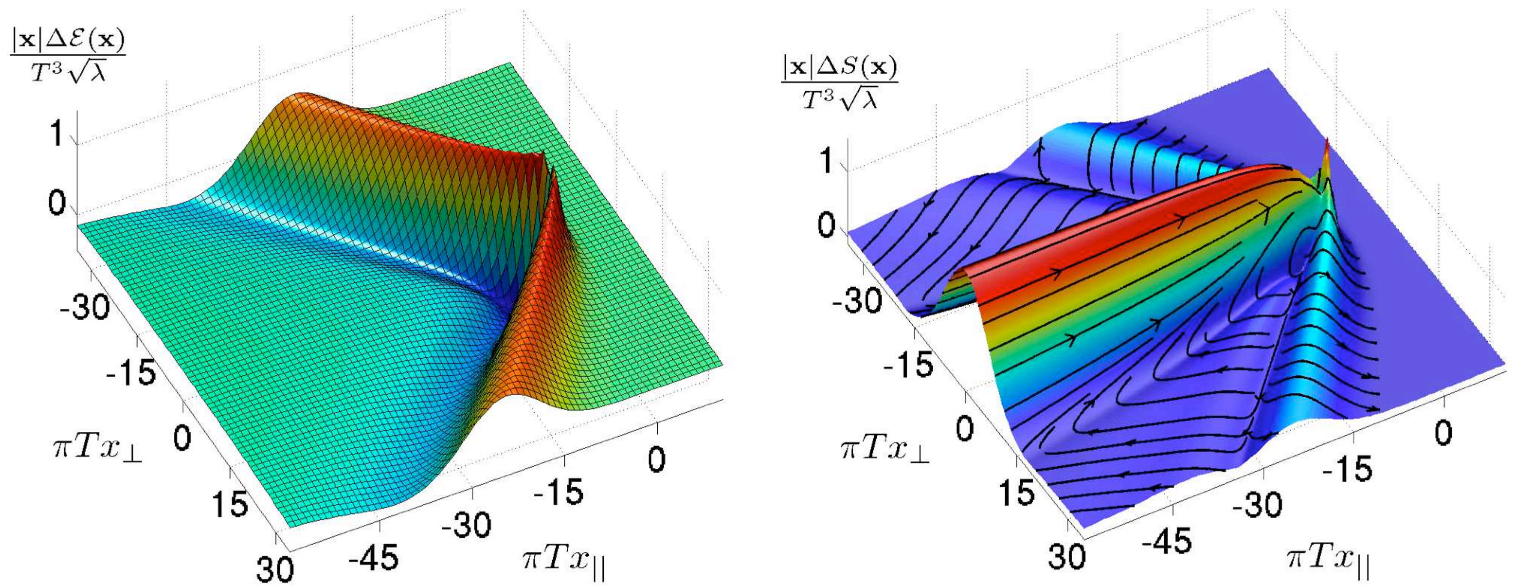




Chesler & Yaffe
Gubser et al
Yarom

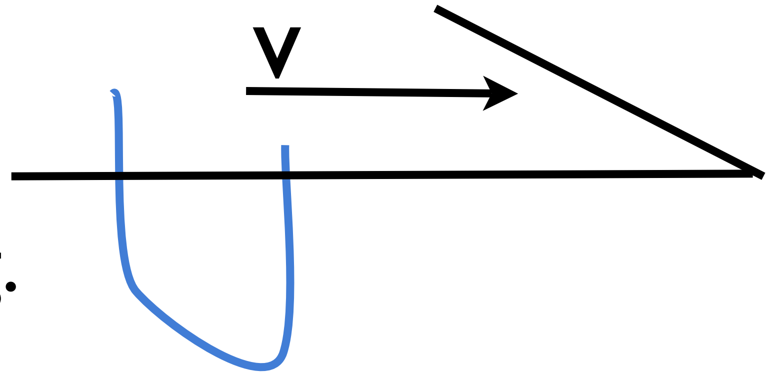
- The AdS/CFT resolves all scales.
- Supersonic quarks ⇒ Mach cones. Proof of principle
- The energy lost by the quark is thermalized quickly
    - Hydrodynamics agrees with the computed fields up to a distance r≈1.5/T.
- Strong wake ⇒ two particle correlations with this source do not reflect the Mach Cone. (Betz, Noronha, Gyulassy, Torrieri)

Parameter Counting



- Energy density is proportional to $\lambda^{1/2}$
- Total E-loss also proportional to $\lambda^{1/2}$
- The integral of the energy density matches the energy loss. It is proportional to $\lambda^{1/2}$
- For the quark, the "microscopic" mechanism for energy loss is the same as for medium excitation (they are controlled by the same parameter).

Mesons at Strong Coupling



- Mesons can be represented by a string.

- Unlike the quark, the meson string does not bend back

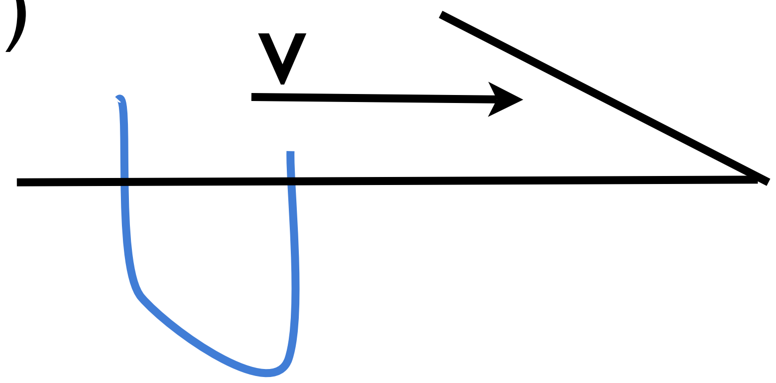
- No energy loss to leading order, ie, proportional to $\lambda^{1/2}$.

- The E-loss is suppressed by $1/N^2_c$ (Dusling et. al.)

- Naive expectation: If the energy loss controls the stress tensor modification there should not be leading order fields associated to the meson.

Fields Associated to the Meson

(Gubser, Pufu & Yarom)



- The string is a source for gravity to leading order!
- The associated stress tensor is proportional to $\lambda^{1/2}$.
- The integral of the energy density is zero. The calculation is not sensitive to $1/N^2_c$ corrections.
- The field excitation is not controlled by the same dynamics as the energy loss.
- The wake is not required to valance the energy loss.
- The explicit calculation shows that there is no wake associated to the meson propagation! Only sound is emitted to leading order.

Lessons from Strong Coupling

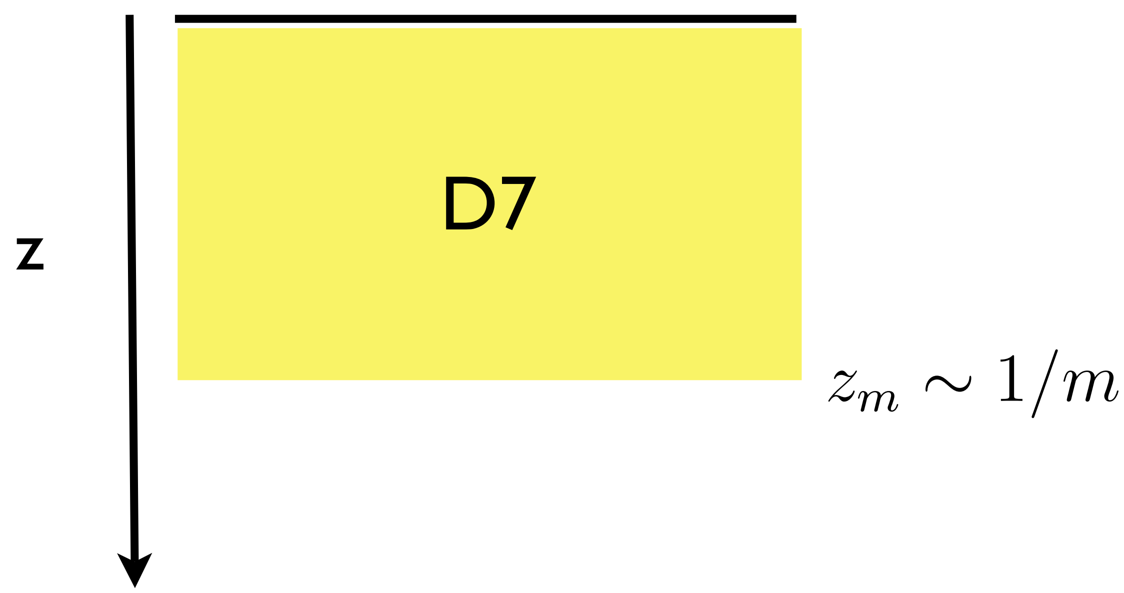
- Sound waves do couple to probes. They must be there in heavy ion collisions.
- The excitations of the plasma quickly become hydrodynamical.
- The energy loss mechanism is not necessarily the same as for the plasma excitation mechanism.
- There is an example of a dynamical system which couples dominantly to sound waves and not to diffusion waves.
- We need to understand what controls the excitation. Is the absence of wake related to string breaking?

Cherenkov Mesons from Gravity Duals

(In progress, JCS, D. Mateos)

Mesons in AdS/CFT

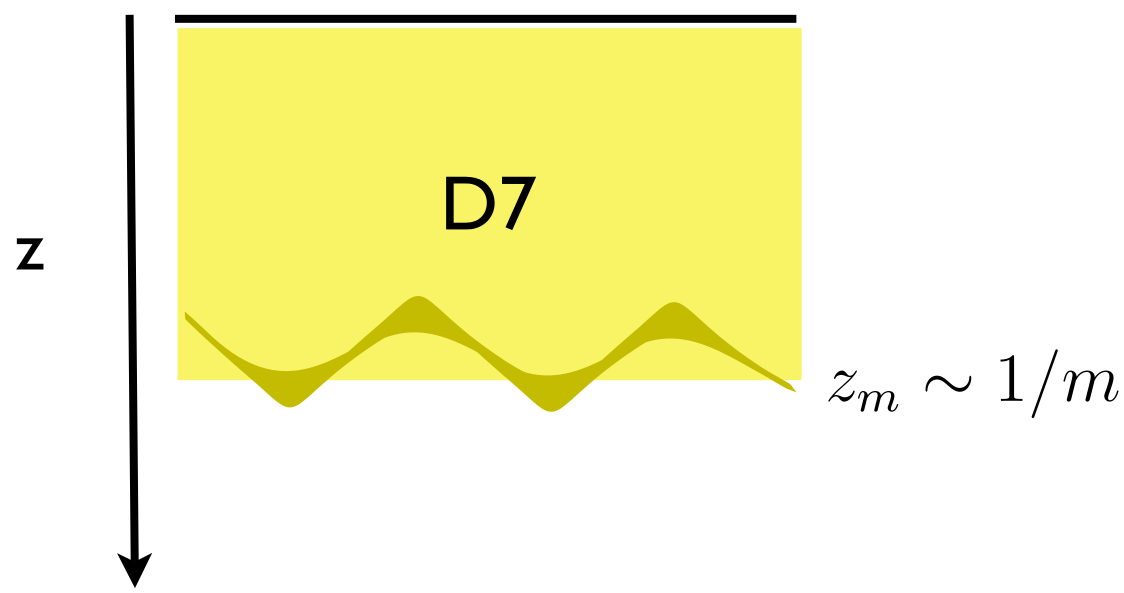
Mateos, Myers, Thomson



- Fundamental matter by D7 branes: "memebranes" that end at a scale 1/m.
- Mesons are (quantized) vibrations of the membrane. The vibration modes are the meson masses.
- These mesons survive the deconfining transition.
- We use AdS/CFT as a model for the dynamics of mesons in a hot deconfined gauge theory.

Mesons in AdS/CFT

Mateos, Myers, Thomson



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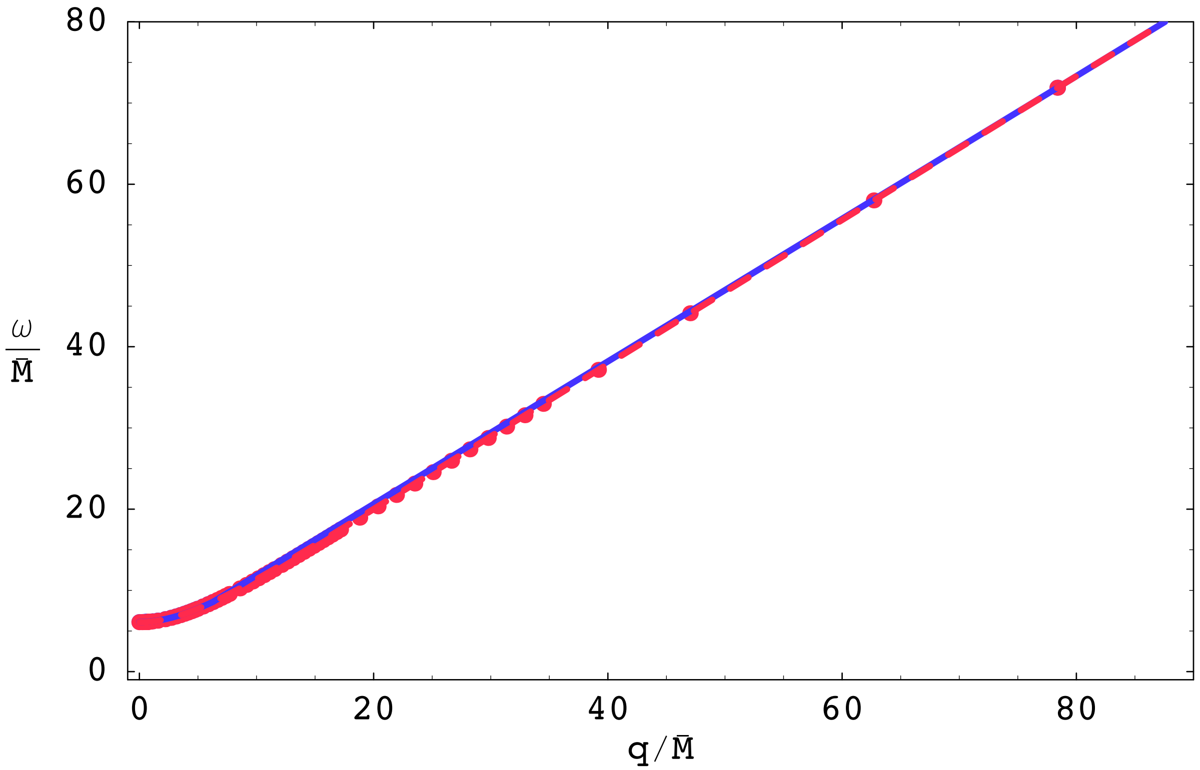
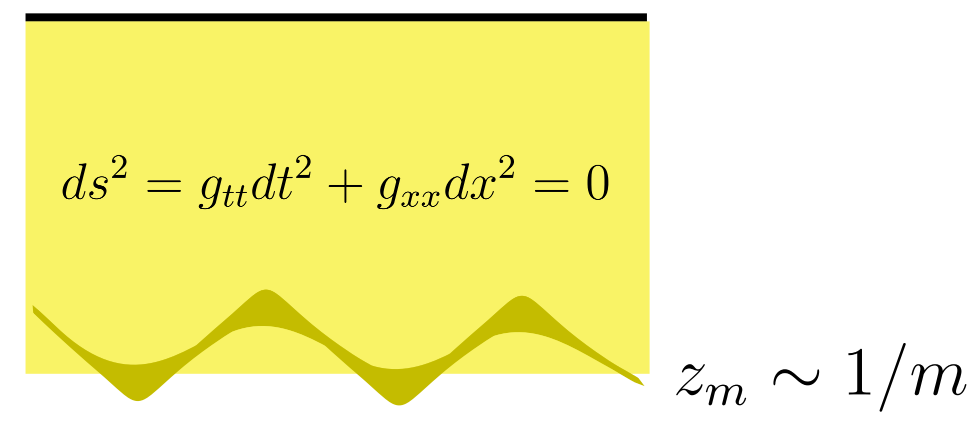
Dispersion Relations



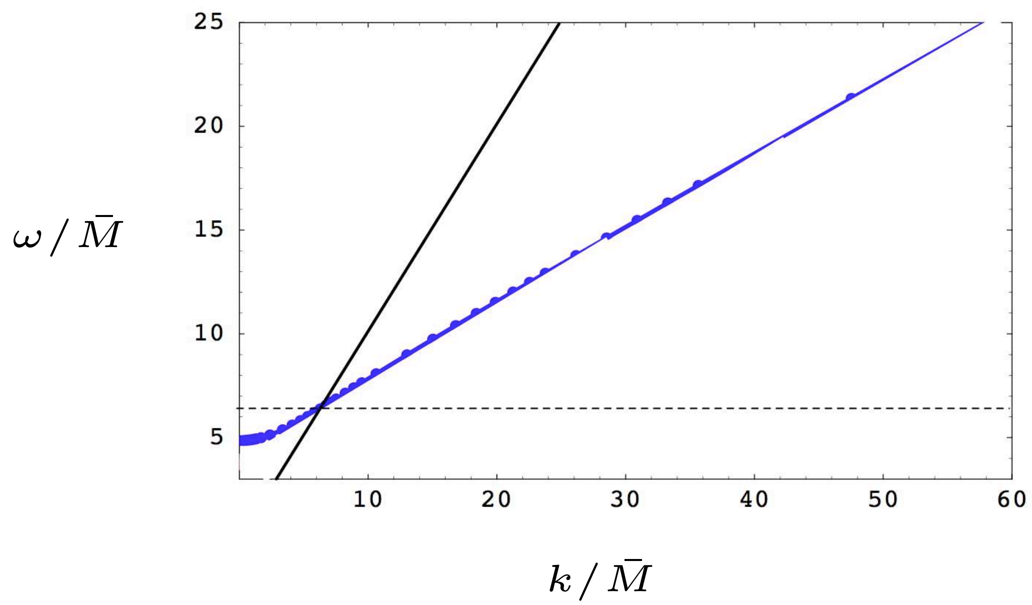


$$c(z) = \sqrt{\frac{g_{tt}}{g_{xx}}}$$

- There is a maximum speed of propagation
- It is determined by the speed of light at the tip of the deformed brane
- This is a universal feature for meson probes in any theory with a gravity dual with $N_c \to \infty$

Space Like Mesons

JCS, D. Mateos



- The dispersion relation always crosses the light cone!

- Mesons (not gluons) can be spontaneously excited by fast particles. They lead to Cherenkov-like radiation

$$\cos(\theta) = v_{lim}$$

- The limiting velocity is temperature (and model) dependent. It grows as the system cools down

- In the D3/D7 model $v_{lim} \geq 0.2$

Consequences

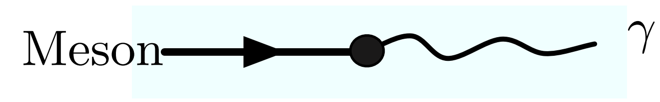
- If mesons survive the deconfining transition:
  - We expect conical emission of meson due to a high energy particle
  - Emission can happen only above certain momentum (the crossing point)
  - At higher p_T the angle would be independent of the momentum
- Obvious candidate would be J/ψ associated to high energy particles (hard to measure...)
- If light mesons do survive, this could have consequences for the double hump.

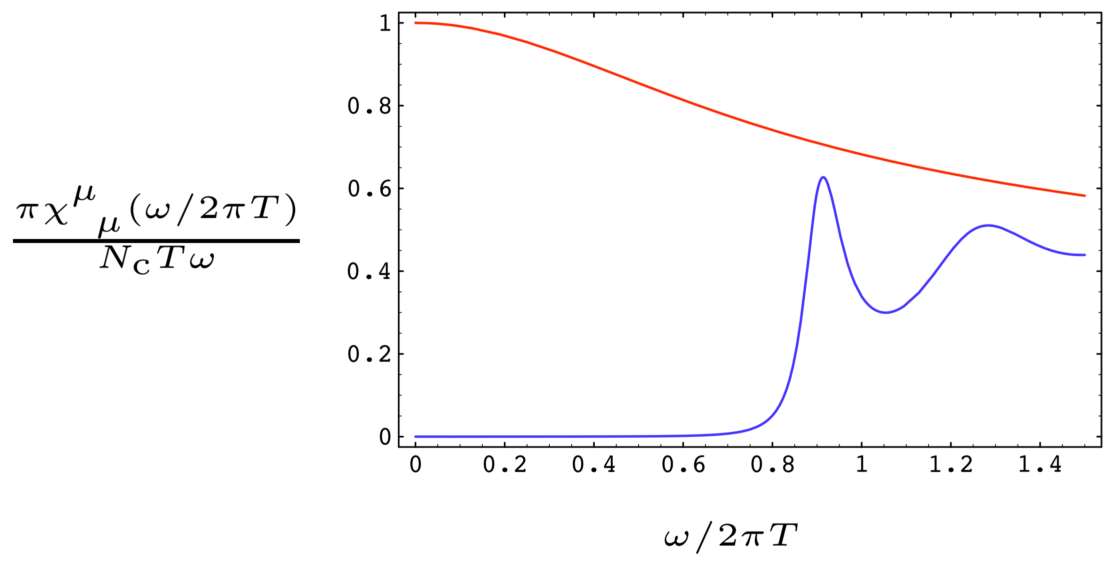
Conclusions

- The interactions of energetic particles with the hydro modes is complicated.
- If the data are only explained by Mach Cones, we must understand how they are produced
- There is one physical system in which only sound waves are excited: mesons in AdS/CFT
- There are other sources for conical emission such as space like mesons.
- These are a universal prediction of any gauge theory with a gravity dual.

Back up

Fixed T



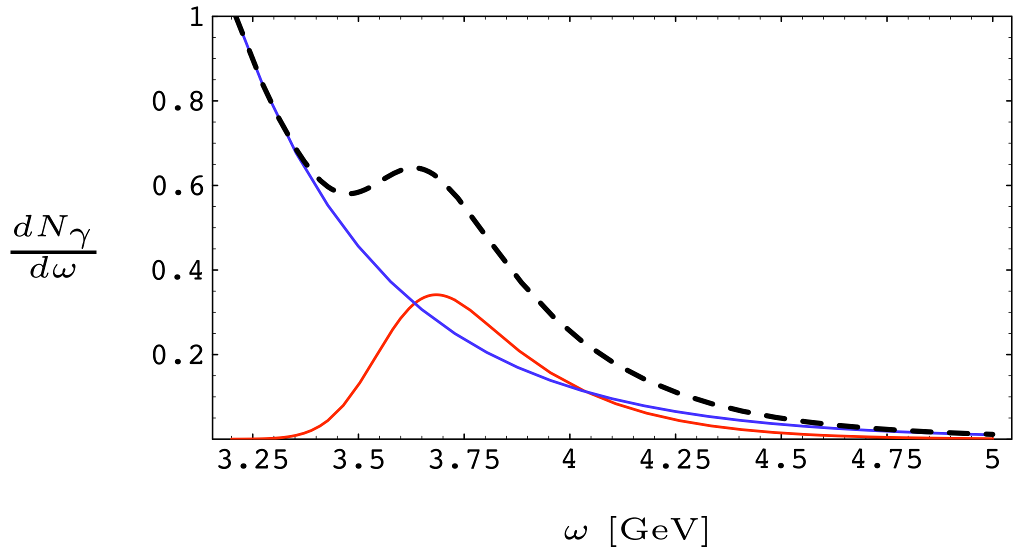


- At a fixed temperature there is a peak in the photon spectrum

- The magnitude (in this model) is comparable with the (strongly coupled) light quark thermal emission.

- The enhancement is a consequence of the modified dispersion relation.
- This feature must be there for all models with gravity duals!

Photons from J/ψ



Crossing at $\omega_{peak} \geq M_{J/\psi}$

ω_{peak} grows as T decreases

$v_{lim} \rightarrow 1$

- We expect and enhancement in the photon spectrum (even a peak) in the region of 3-4 GeV
- Uncertainties in in-medium J/ψ makes quantitative predictions hard...
- From the models in the market, we searched from a scenario in which a peak is observed at the LHC

  (statistical hadronization with the largest possible c-c cross section)
- The magnitude depends a lot on the model
- The observation of the peak would signal the modified dispersion relation