Holographic approaches for HIC

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Outline

- Review Shockwave collisions in GR
- Review older results obtained with Albacete and Kovchegov
- Trapped surface analysis, an elementary introduction
- ~~Flat backgrounds, applications to BHs production at the LHC and extra dimensions~~
- AdS backgrounds and applications to QGP production at the LHC
- Summary/conclusions/take home message

Review Shockwave collisions

- Studied by many authors in both backgrounds

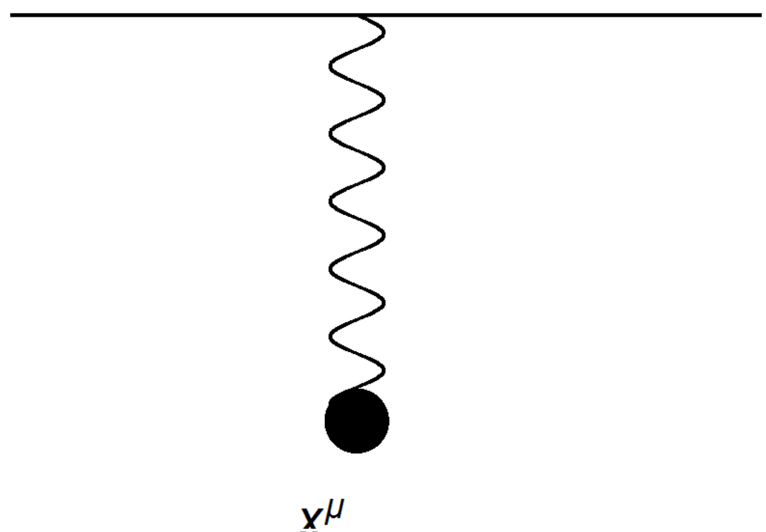
[Ads:,Albacete,Kovcegov,Taliotis;Romatscke,Mateos-Solana-van der Schee, ,Heller,Janik,Peschanski,Wu, Chesler,Yaffe…, Flat:'t Hooft,D'Eath, Payne,Giddings,Tomaras,Taliotis, Herdeiro et.al…]

- Single shock wave geometry

Simplest example of shock in AdS

$$ds^2 = \frac{-2dx^+dx^- + dx_\perp^2 + Ez^4 f(x^-)(dx^-)^2}{z^2/L^2}$$

$$R_{--} + \frac{4}{L^2} g_{--} = 0$$



- # What does this describe in gauge theory?

Can show $g_{--}|_{bdry} \sim T_{--}$. Since $g_{--}|_{bdry} \sim \delta(x^-)$

It implies that this geometry describes a thin fast glueball along x- which generally can have a transverse profile .

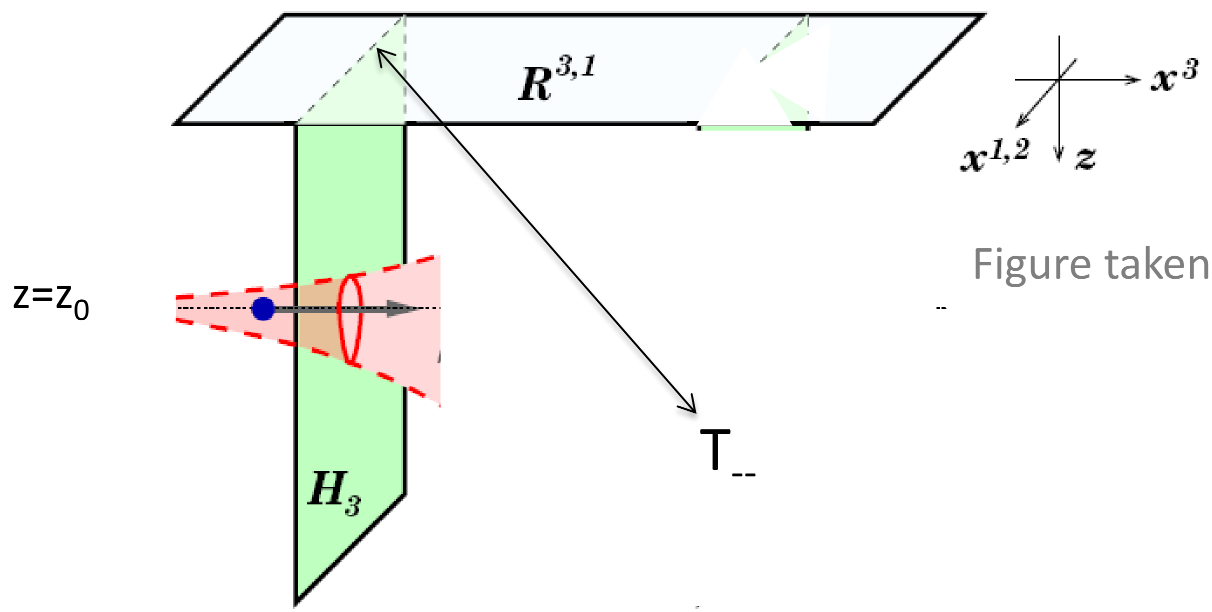


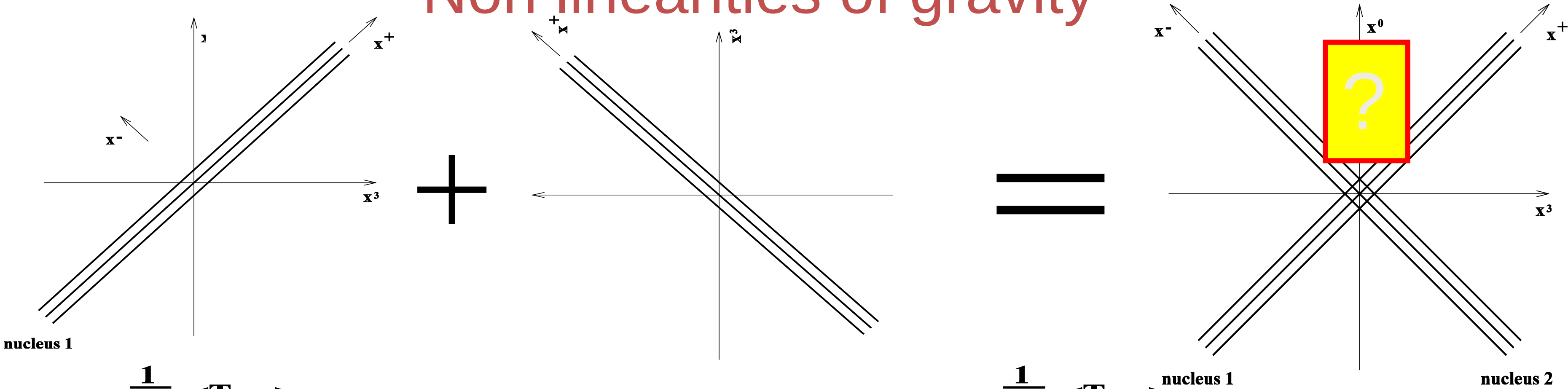
Figure taken from GYP

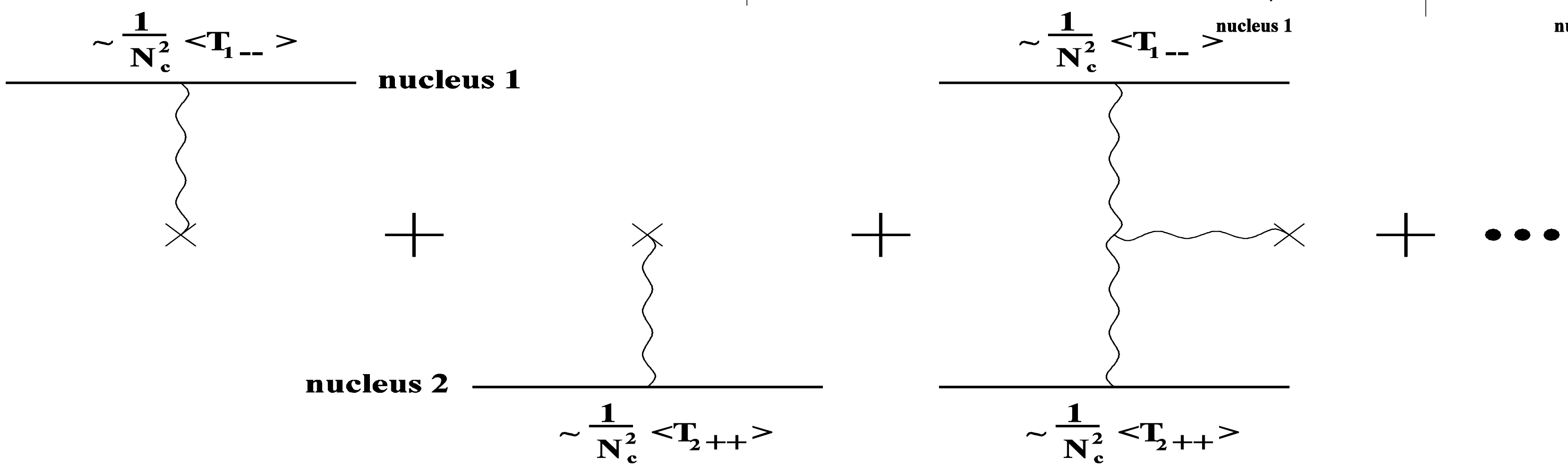
2008-09 results: Albacete, Kovchegov, AT

JHEP 0807 (2008) 100 **arXiv:0805.2927 [hep-th]**
JHEP 0905 (2009) 060 **arXiv:0902.3046 [hep-th]**

Superposition of two shockwaves

Non linearities of gravity





$$ds^2 = \frac{L^2}{z^2}\Big[\underbrace{-2\,dx^+dx^- + dx_\perp^2 + dz^2}_{\text{A}} + \underbrace{\frac{2\pi^2}{N_C^2}\langle T_{1--}(x^-)\rangle z^4\,dx^{-2}}_{\text{B}} + \underbrace{\frac{2\pi^2}{N_C^2}\langle T_{2++}(x^+)\rangle z^4\,dx^{+2}}_{\text{C}} + \ldots\Big]$$

Flat AdS

One graviton ex.

Higher graviton ex.

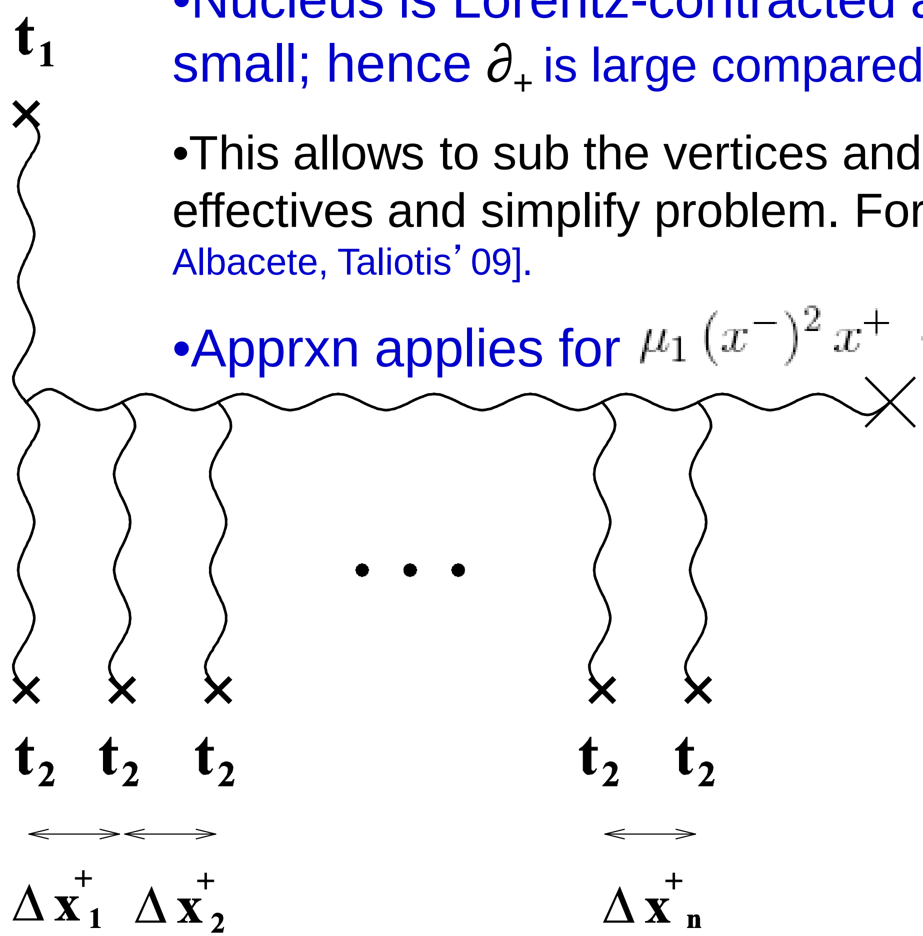
Due to non linearities

Eikonal Approximation and Resummation techniques

•Nucleus is Lorentz-contracted and so $\Delta x_i^+ \sim 1/p_2^-$ are small; hence ∂_+ is large compared to ∂_- and ∂_z.

•This allows to sub the vertices and propagators with effectives and simplify problem. For more see [Kovchegov, Albacete, Taliotis' 09].

•Apprxn applies for $\mu_1 (x^-)^2 x^+ \ll 1, \quad \mu_2 (x^+)^2 x^- \sim 1$



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Results

$$\mu_1\,(x^-)^2\,x^+ \;\ll\; 1, \quad \mu_2\,(x^+)^2\,x^- \sim 1$$

$$\langle T^{++}\rangle \;=\; -\frac{N_c^2}{2\,\pi^2}\,\frac{4\,\mu_1\,\mu_2\,(x^+)^2\,\theta(x^+)\,\theta(x^-)}{[1+8\,\mu_2\,(x^+)^2\,x^-]^{3/2}},$$

$$\langle T^{--}\rangle \;=\; \frac{N_c^2}{2\,\pi^2}\,\theta(x^+)\,\theta(x^-)\,\frac{\mu_1}{2\,\mu_2\,(x^+)^4}$$

$$\times\;\frac{3-3\sqrt{1+8\,\mu_2\,(x^+)^2\,x^-}+4\,\mu_2\,(x^+)^2\,x^-\left(9+16\,\mu_2\,(x^+)^2\,x^- - 6\sqrt{1+8\,\mu_2\,(x^+)^2\,x^-}\right)}{[1+8\,\mu_2\,(x^+)^2\,x^-]^{3/2}}$$

$$\langle T^{+-}\rangle \;=\; \frac{N_c^2}{2\,\pi^2}\,\frac{8\,\mu_1\,\mu_2\,x^+\,x^-\,\theta(x^+)\,\theta(x^-)}{[1+8\,\mu_2\,(x^+)^2\,x^-]^{3/2}},$$

$$\langle T^{\,ij}\rangle \;=\; \delta^{ij}\,\frac{N_c^2}{2\,\pi^2}\,\frac{8\,\mu_1\,\mu_2\,x^+\,x^-\,\theta(x^+)\,\theta(x^-)}{[1+8\,\mu_2\,(x^+)^2\,x^-]^{3/2}}.$$

Conclusions

[Mateos,Solana,Heller, van der Schee, 2013]

- ***Not Bjorken hydro***
  Indeed instead of $T^{\perp\perp}=p \sim 1/\tau^{4/3}$ it is found that $p \sim \frac{1}{(x^+)^2\sqrt{x^-}} \sim \frac{e^{-(3/2)\eta}}{\tau^{5/2}}$

- ***Negative energy densities*** which we conjectured that can be hidden behind sufficiently fat initial profiles.

- ***Proton stopping in pA:*** for AA, it was initially found that

$$\left\langle T^{++}(x^+ >> a, x^- = a/2)\right\rangle = \frac{\mu}{a} - 2\mu^2 x^{+2}$$

(Landau Hydro??)

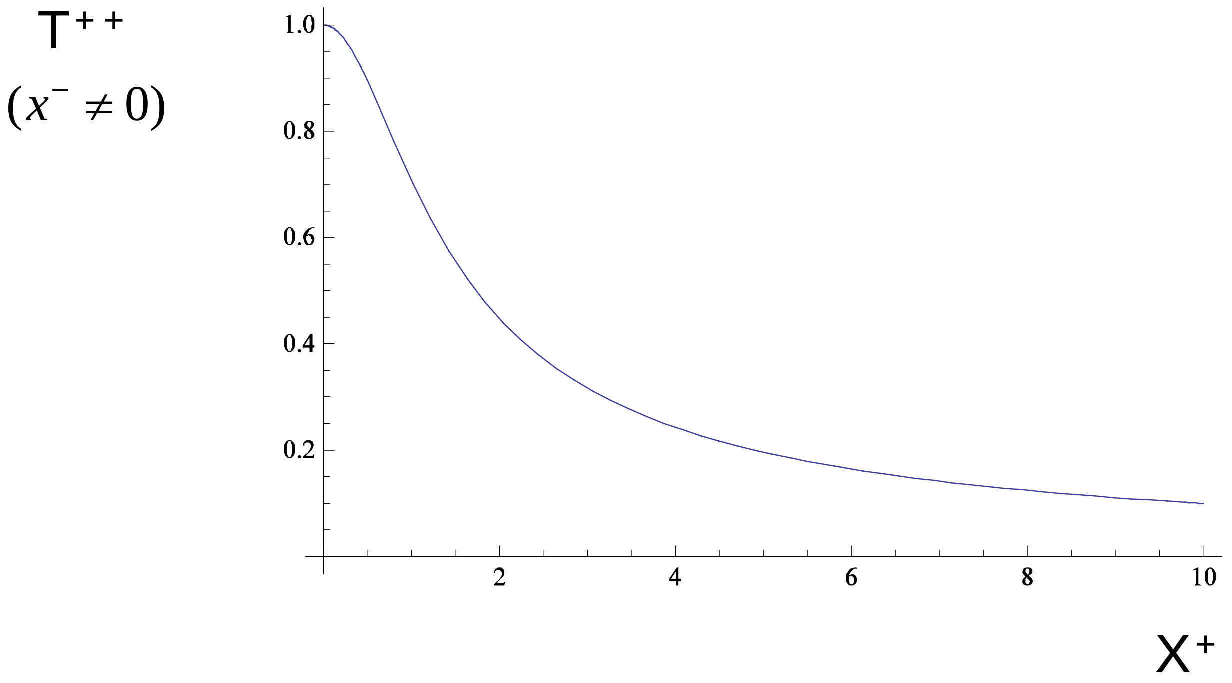
with estimation stopping given by $x^+ = \sqrt{1/2\mu a}$. Same result is recovered here by expanding the total-ressumed T^{++} to $O(\mu_2; x^- = \alpha/2)$:

$$\langle T^{++}_{tot}\rangle = \langle T^{++}_{orig}\rangle + \langle T^{++}_{prod}\rangle = \frac{N_c^2}{2\pi^2}\frac{\mu_1}{a_1}\frac{1}{\sqrt{1+8\,\mu_2\,(x^+)^2\,x^-}}, \quad \text{for} \quad 0 < x^- < a_1$$

- ***Energetic nuclei stop faster*** in a quantified manner.

Proton Stopping

(Landau Hydro??)



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New results in HICs: main part of the talk

Essential formulas

- Restricted SO(3) invariant shocks:

$$ds^2 = \frac{-2dx^+dx^- + dx_\perp^2 + EG_5 z\phi(q(z,x_\perp))\delta(x^-)(dx^-)^2}{z^2 / L^2}$$

$$q = \frac{x_\perp^2 + (z - z_0)^2}{4zz_0}$$

$$R_{--} + \frac{4}{L^2} g_{--} \sim \delta(x^-)\nabla_q^2\phi = 8\pi G_5 J_{--} = EG_5\rho(q)\delta(x^-)$$

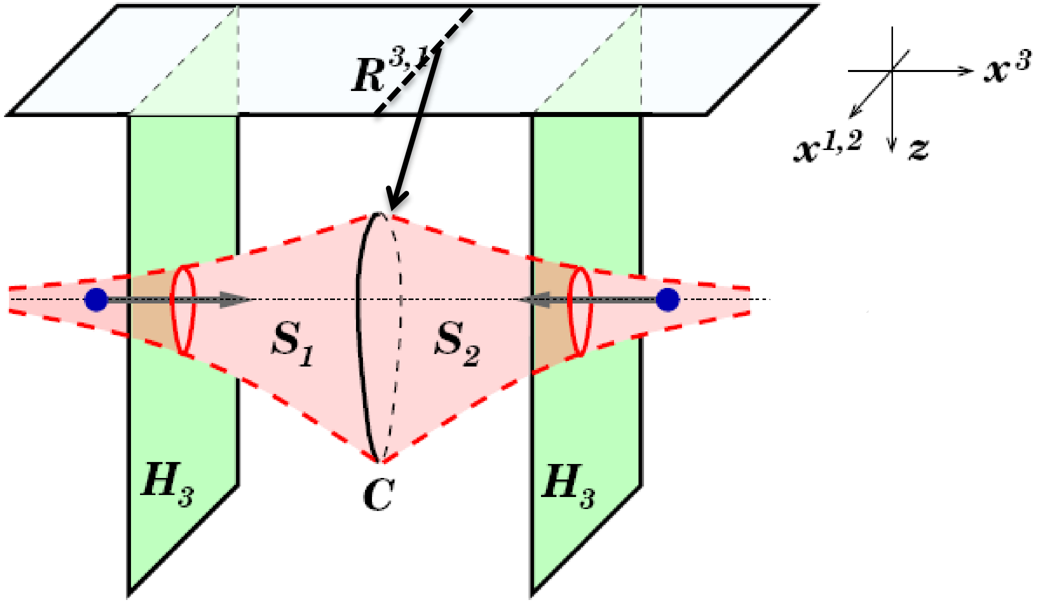
- z_o estimates the center of ρ in the 5th dimension.

- z_o is also the width of $T_{\mu\nu}$ in gauge theory side. Although expected, NOT trivial to show this for any ρ.

- Superimpose two shocks: Add another one along the opposite direction

- Shocks talk each other at $x_{-}>0$, $x_{+}>0$

2D Plasma at t=0=>
Highly anisotropic



Introduction to TS

Important Clarifications

- What this method does not do: does NOT provide info for $g_{\mu\nu}$ on future LC

- What this method can do: provides a suggestion that a BH is formed by reducing to unusual BV problem. In what follows we will assume that a BH is always formed.

- TS yields a lower bound on entropy production $S_{trap} \leq S_{prod}$
  [Giddings,Eardly,Nastase,Kung,Gubser,Yarom,Pufu,Kovchegov,Shuryak,Lin,kiritsis,Taliotis,Aref'eva,Bagrov,Joukovskaya Veneziano Alvarez-Gaume,Gomez,Vera,Tavanfar,Vazquez-Mozo, Romatscke...]

Trapped surface analysis introduction (D=4, flat backgrounds)

If there is a function ψ and some curve C s.t.

$$\nabla_\perp^2(\psi-\varphi)=0 \qquad \psi|_C = 0, \; \nabla_\perp\psi.\nabla_\perp\psi|_C = 1$$

then there exists a trapped surface and it is enclosed inside the curve C.

- Example: Let the shock $\phi=EG_4 Log(kx_\perp)$ ala AS
- Then $\psi=EG_4 Log(x_\perp/EG_4)$ and $C : x_{\perp;C}=EG_4$
- And $S = A/4G_4 \sim \int d^2x_\perp \sim E^2 G_4$ [Giddings & Eardley, 2002]

AdS Backgrounds and QGP

Trapped Surface Condition

$$\frac{\int_0^{q_c}(1+2q)\sqrt{q(1+q)}\rho(q)dq}{(1+2q_c)(1+q_c)}=\frac{L^3}{G_5}\times\frac{k}{E}$$

- Where $k \equiv 1/z_o$ (the transverse scale if the colliding glue-ball in the QFT side). Note the dimensionless parameter controlling the TS: E/k Vs E × k in flat backgrounds. Interesting!!

- We will classify ρ's under the assumptions

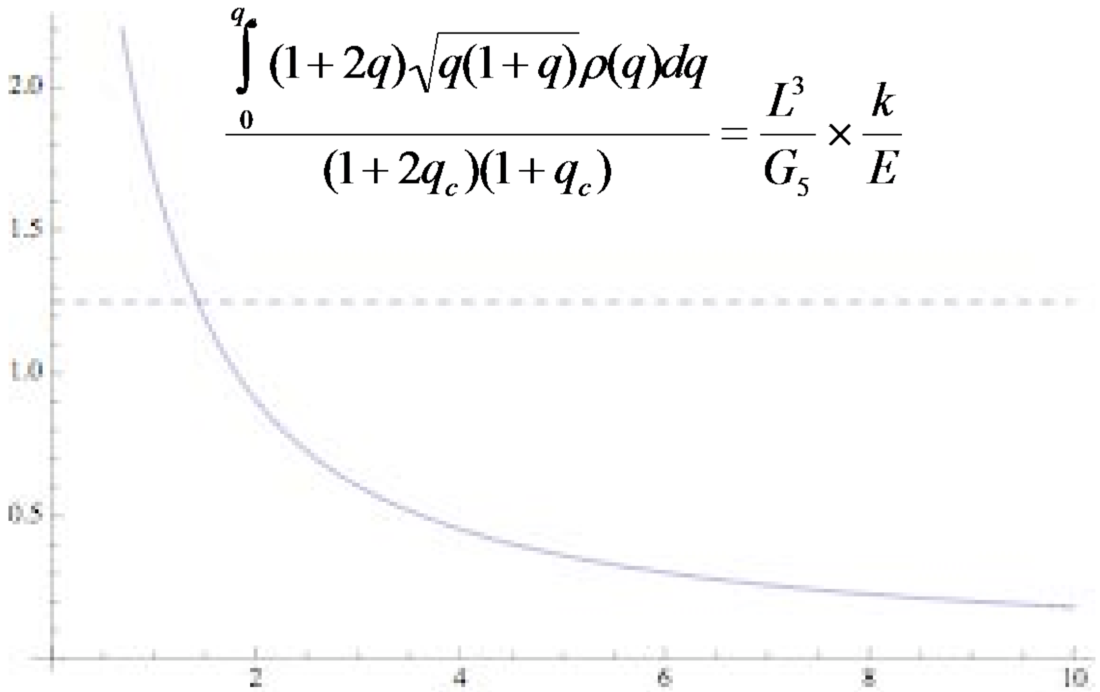
(i) ρ is positive definite
(ii) ρ is integrable. (i)+(ii)=> 3+1 cases
(iii) (qρ(q))'=0 has at most one root in (0, ∞)=> 3 cases

- The classification depends on how ρ behaves at small q's!

Case I. Always a single TS

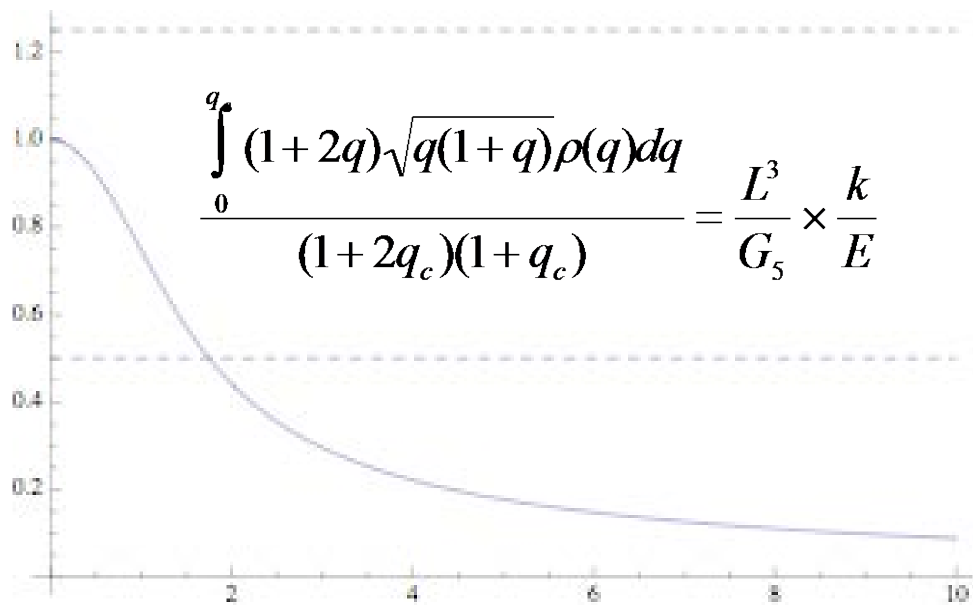
- Case I.: ρ ~ $1/q^n$ +sub-leading, q<<1, 3/2>n>1/2. (always a single TS)

$$\frac{\int_0^{q_c}(1+2q)\sqrt{q(1+q)}\rho(q)dq}{(1+2q_c)(1+q_c)}=\frac{L^3}{G_5}\times\frac{k}{E}$$



Case II. A marginal case: A single TS for sufficiently large E x k

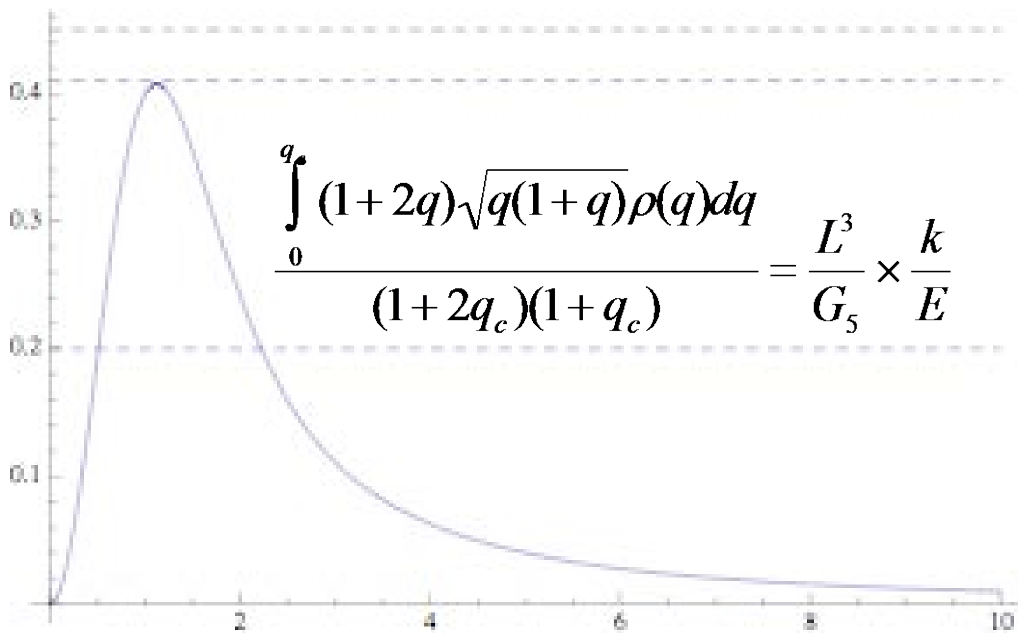
- ρ ~ 1/√q +sub-leading, q<<1 (a single TS if E>>k).



$$\frac{\int_0^{q_c}(1+2q)\sqrt{q(1+q)}\rho(q)dq}{(1+2q_c)(1+q_c)}=\frac{L^3}{G_5}\times\frac{k}{E}$$

Case III. Two TS for sufficiently large E x k

- Case III. ρ ~ 1/q^n +sub-leading, q<<1, n<1/2. (2 co-eccentric TSs if E>>k)

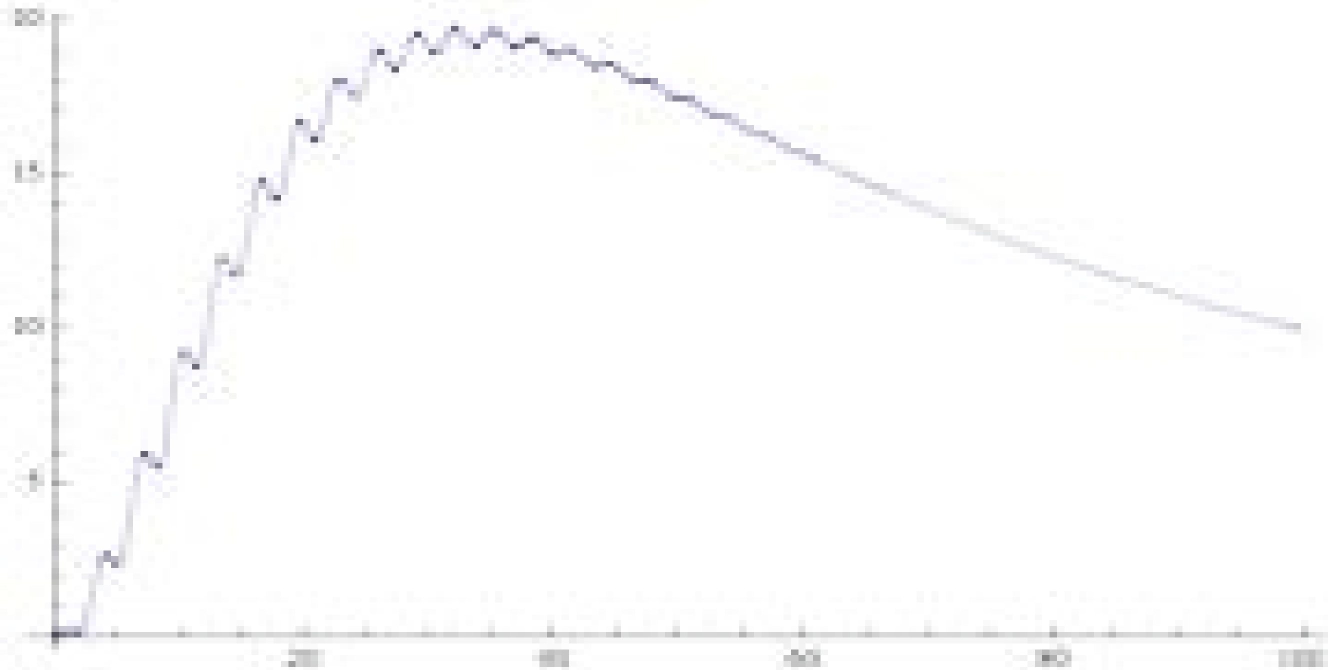


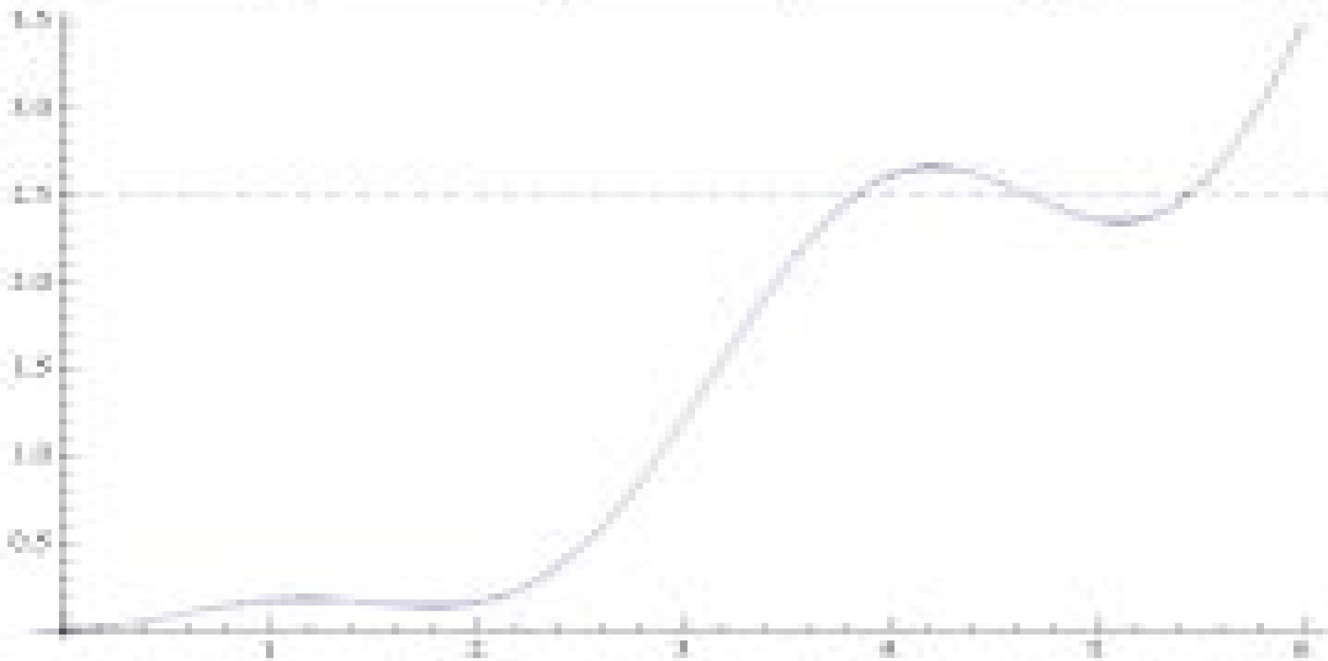
$$\frac{\int_0^{q_c}(1+2q)\sqrt{q(1+q)}\rho(q)dq}{(1+2q_c)(1+q_c)}=\frac{L^3}{G_5}\times\frac{k}{E}$$

- "RN-like" scenario in the absence of charge

[Mureika,Nicoli,Spallucci;Taliotis]

Remove the $(x\rho(x))'=0$ has a single root





Universal Results

Can show that any ρ:

- Yields a ϕ s.t. at $q>>1$ decays as $1/q^3$ as dictated by holographic renormalization considerations [Skenderis, Papadimitriou, de Haro, Solodukhin,…].
- The TS, in the HE limit: $k/E<<1$, grows as $q_c^3=E/k$ with k NOT dropping out.
- In the HE limit can show $S \sim q_c^2$ and so $S\sim (E/k)^{2/3}$.

Desired feature captured

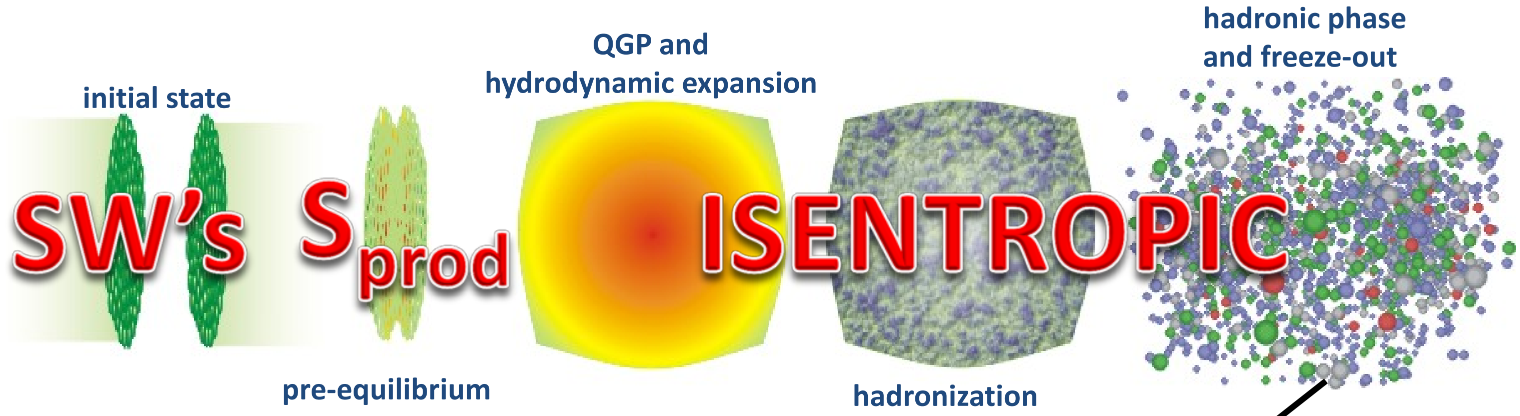
- Seen that a BH, hence QGP, may exist if E>>k.
- But k is the transverse scale of the SE tensor in QFT; that is scale of colliding glue-balls.
- Tempted to identify k with Λ_{QCD}
- This would imply forming QGP⇔E>>Λ_{QCD}
- Although expected, it is first time in literature such feature is described theoretically; in present context holographically.

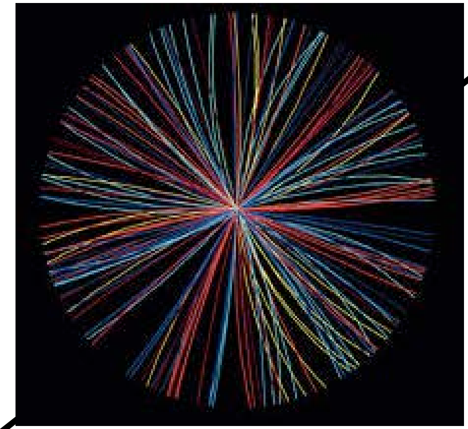
Incorporating strong-weak coupling physics and saturation scale: a phenomenological approach

Attempting to fit RHIC and LHC data

- A phenomenological approach
- Relate S with total multiplicities N
- Use CGC model, in particular the saturation scale.
- Incorporate weak-strong coupling physics.

Multiplicities N_{ch}





$$N_{ch} = \sum_i N_{ch;i} = \sum_i \int \frac{d^3 N_{ch;i}}{dy \; d^2 p_T} \; dy d^2 p_T$$

Relating S with N_{ch}

- Since $N_{CH} \sim S_{GT}$=AdS/CFT=$S_{ST}>S_{TS}$. Numerical works [Hogg,Romatschke,Wu] show $S_{ST}=bS_{TS}$ where b is collision energy independent

- On the other hand, overall constants (gravity parameters s.t. $G5/L^3$) must be fitted with data. Hence schematically work as

$$N_{ch} = (\text{fit } b)\times S_{TS}$$

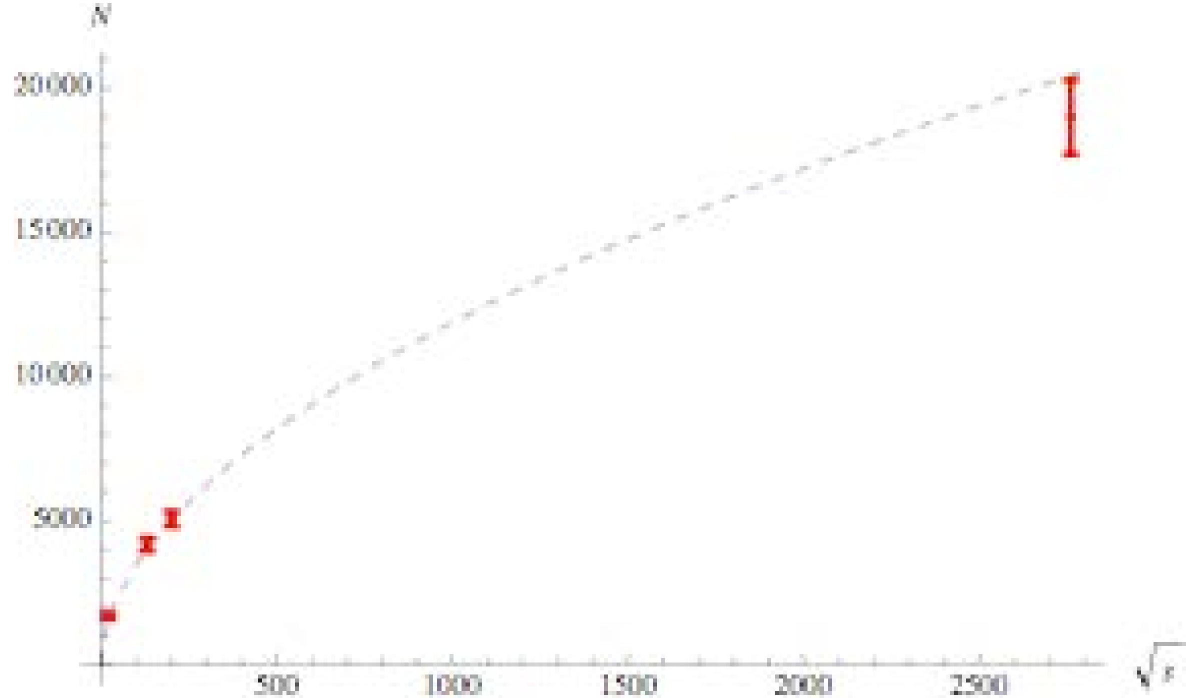
Connection with data

- Seen that $N_{CH} \sim S \sim (E/k)^{2/3}$
- k could generally be E dependent
- Take $k=Q_s(E)$ and use Q_s from pQCD results
- This means that the transverse scale of colliding ultra-fast pancakes is set by Q_s rather than Λ_{QCD}.

- Then N ~ $(E/Q_s(E))^{2/3}$ ~ $(s/\Lambda_{QCD})^{1/3(1-\lambda)}$, λ=[0.1,0.2] where λ~0.2 for AA collisions

$$Q_s^2(s_{NN}) = (0.2 GeV)^2 A^{1/3} \left(\sqrt{s_{NN}}\right)^{2\lambda}$$

- Hence N ~ $(s/\Lambda_{QCD})^{0.26}$ and fit constant using the data. Choosing the (s independent) constant ~300 yields



Summary

- Presented 2008-09 results [Albacete,Kovchegov,AT] that qualitatively agree with the accurate numerical results obtained later-independently.
- Gave an elementary intro to TS/review known results.
- Classified transversally symmetric distributions according to the TSs that can create (for flat and AdS backgrounds).
- Found universal results in both, the geometries at large arguments and at the S in the HE limit.

Take home messages

- Applied to BHs at LHC: No ED=>No BHs but ED=>BHs open scenario (did not study this here).
- QGP⇔ E>>Λ_{QCD}. First time to be described theoretically.
- My explanation (applies even in confining geometries [Kiritsis, AT]): infinitely dense Vs diluted distributions in the bulk.

Thank you

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