Non-spherical collapse & Early Thermalization,

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1302.1277 with Eunseok Oh,

hep-th/0511199 with Shuryak,Zahed

Announced title was
Thermal Mass and Plasmino

Based on

1205.3377; 1305.1446

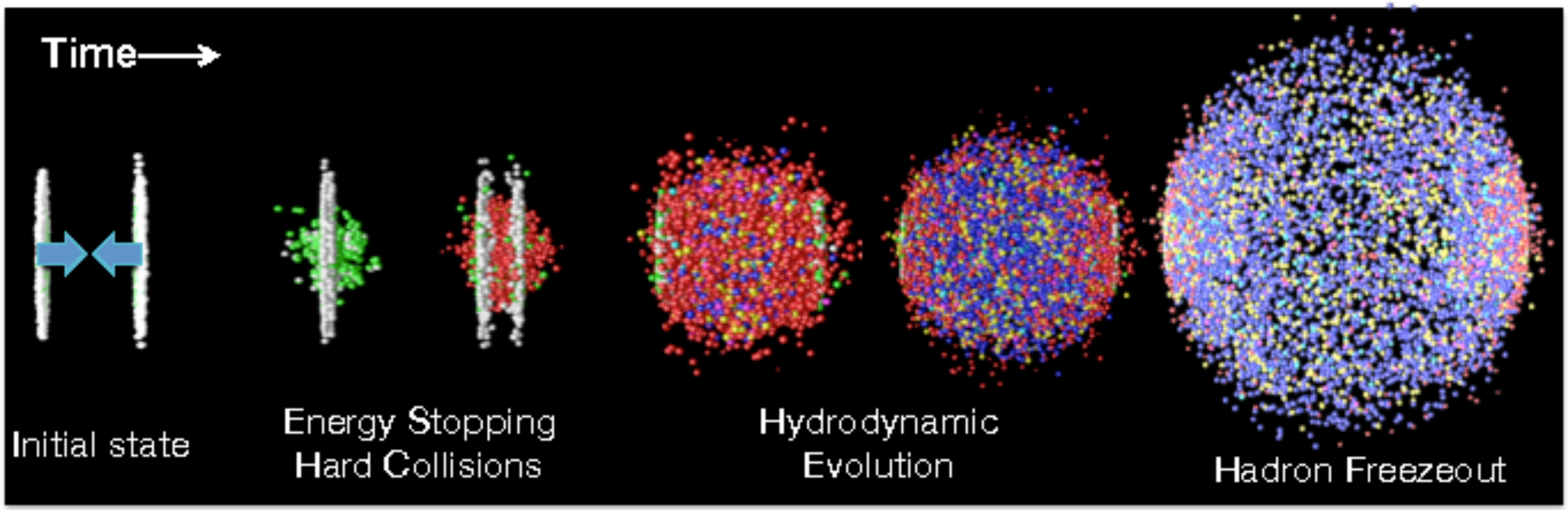
with Yunseok Seo + Yang Zhou

I will talk about this as second topic.

Early thermalization.

- Is one of the puzzles in RHIC : Heavy ion collision fireball equilibrate just in passing time

  t~ 1 fm/c



This is one of the evidence that QGP in RHIC exp. is sQGP!

Other evidences for sQGP:
small eta/s, elliptic collective flow,
Jet quenching

Why strong? Asymptotic freedom + Rapid particle creation.

Initial E=200GeV/particle, T=200MeV.

In gravity dual,

- Thermalized state = BH, so

  Early thermalization means, Easy BH formation.

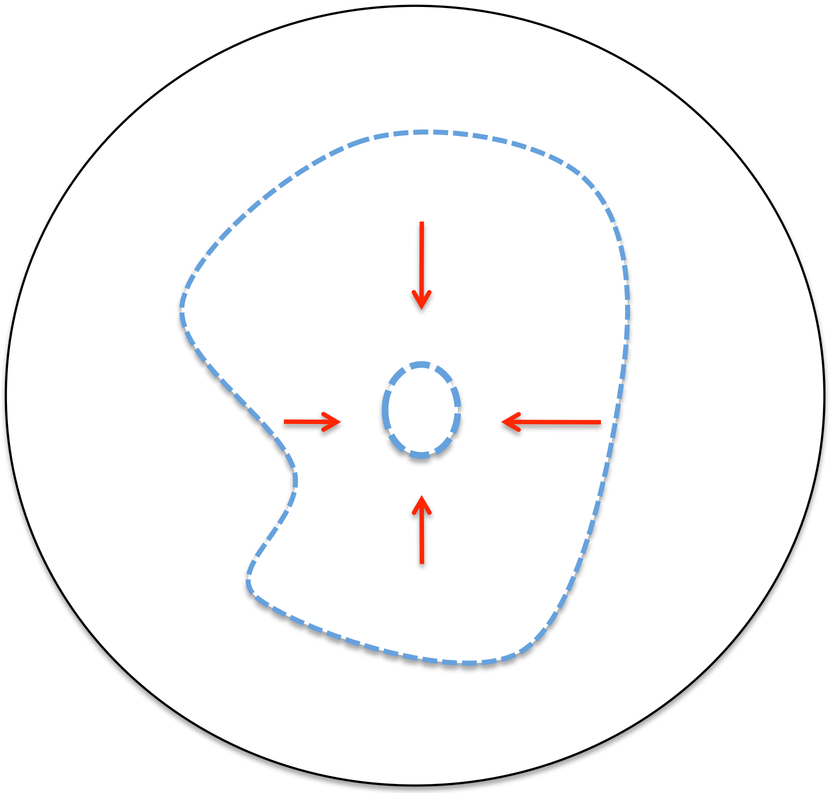
  So Our question will be:
  Can a generic collapse in AdS give a BH
  in ONE dynamical time?
- many works are done!

  Aharony, Bucher, Chesler,…,Gubser, Minwalla,
  …. Yaffe, Zayas
  My work with Shuryak and Zahed ('05) **hep-th/0511199**

Claim and conclusion

- Any shape of dust particle distribution will collapse into Black hole in a time less than the one Falling time.
- This is the mechanism of Early Thermalization. (review of 0511199)

In AdS space



In flat space,

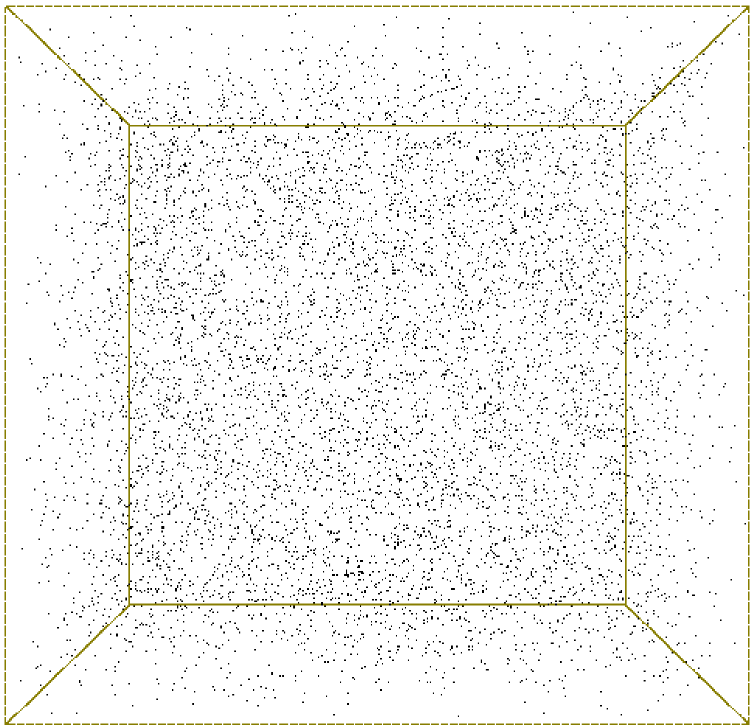


Figure 1: The system of particles after initialization.

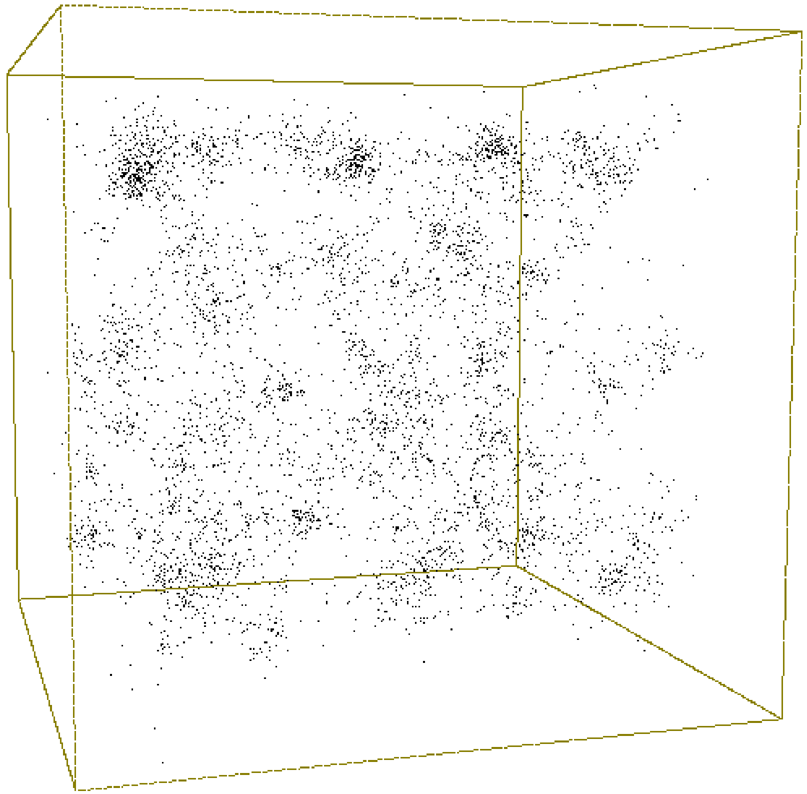


Figure 2: The system of particles after the simulation has run for 2.5 days nonstop.

Then Why in ads?   1302.1277

- Consider a free fall of a massive particle in ads.

$$ds^2 = -(1 + r^2/R^2)c^2dt^2 + r^2d\Omega^2 + \frac{dr^2}{1 + r^2/R^2}$$

$$S = -m \int \sqrt{-g_{\mu\nu}\dot{x^\mu}\dot{x^\nu}}dt, \text{ with } \dot{x} = \frac{dx}{dt}.$$

$$\dot{r}^2 + (m/E)^2(1 + r^2)^2(1 + r^2 - E^2/m^2) = 0$$

The equation of motion turns out to be integrable.

With change of variable

$$r = \frac{v}{\sqrt{1-v^2}}$$

The equation of motion become SHO:

$$\dot{v}^2 + v^2 = v_c^2 := 1 - (m/E)^2$$

Solution

$$r = \frac{v_c \cos t}{\sqrt{1 - v_c^2 \cos^2 t}}.$$

$$E = \frac{m}{\sqrt{1 - v_c^2}}$$

r_0 is the initial radial position.

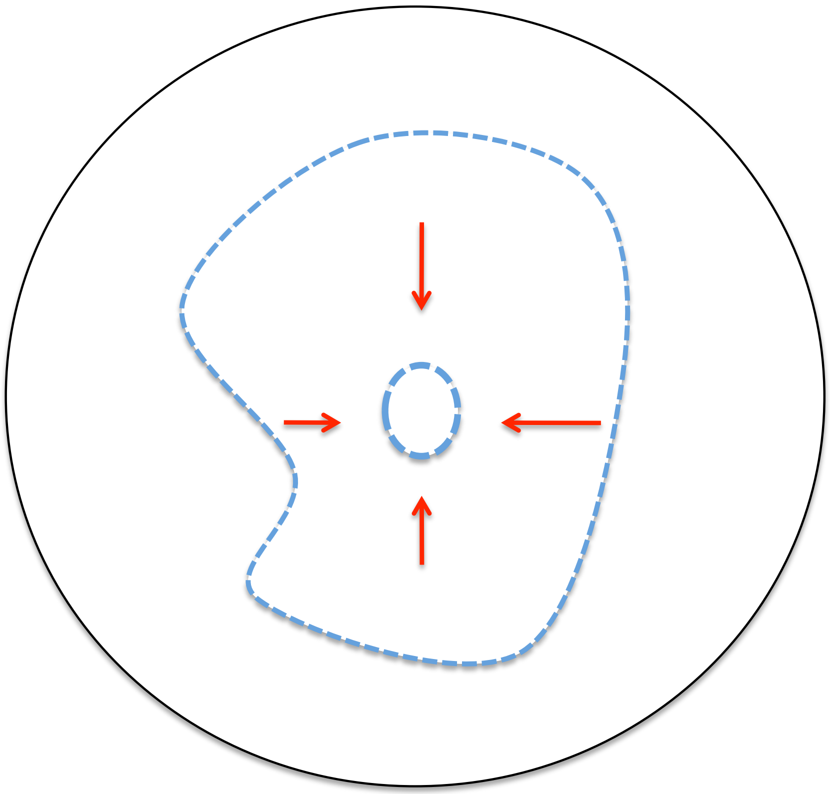
v_c is the velocity at the center.

Falling time is the same independent of the initial condition of particle.

$$T_{fall} = \frac{\pi}{2}\frac{R}{c}.$$

This means what I claim.

Generic collapse will give a black hole, provided that they start from static configuration.



Status on BH making in AdS
see Ishibashi's talk.

1 scalar field collapse ➔ turbulant instability

If one can wait long, OK

But if you need to form BH in one dynamical time,
➔ even spherical collapse is not easy, not to mentioning the generic shell.

Is this a contradiction to what I said?
No. I used dust.
Wave is hard to localize! This in particle QM is uncertainly principle.

- 2. Spherical initial condition➔ even in the case one get BH in one falling (remember BIG shell), such fine tuned Initial Condition is not of no use for RHIC exp.

II. Is this the Mechanism of early thermalization?

- Q1. What/Why dust ?
- Q2. Why fall?
- Q3. Why non-interacting dust?
- Q4. Poincare patch?
- Q5. What is the initial velocity effect?
- Q6. What happen if we add interaction?
- Q7. Any prediction?

- Q8. Where is entropy generation?
- Q9. back reaction of gravity?
- Q10. Is this mechanism universal?
- Q11.What is wrong with Shock wave?

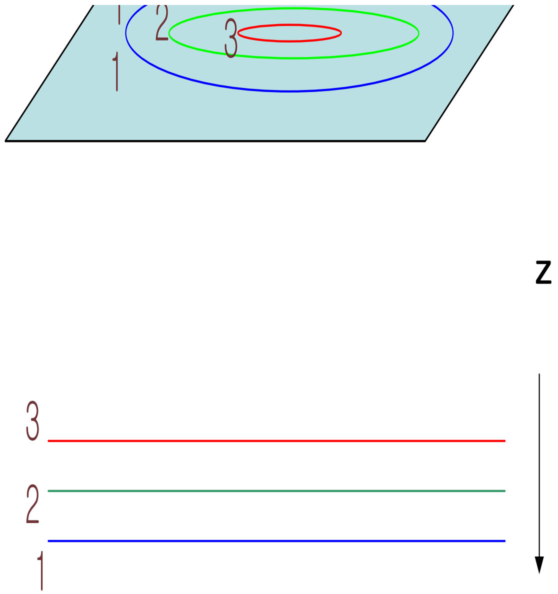
………etc.……

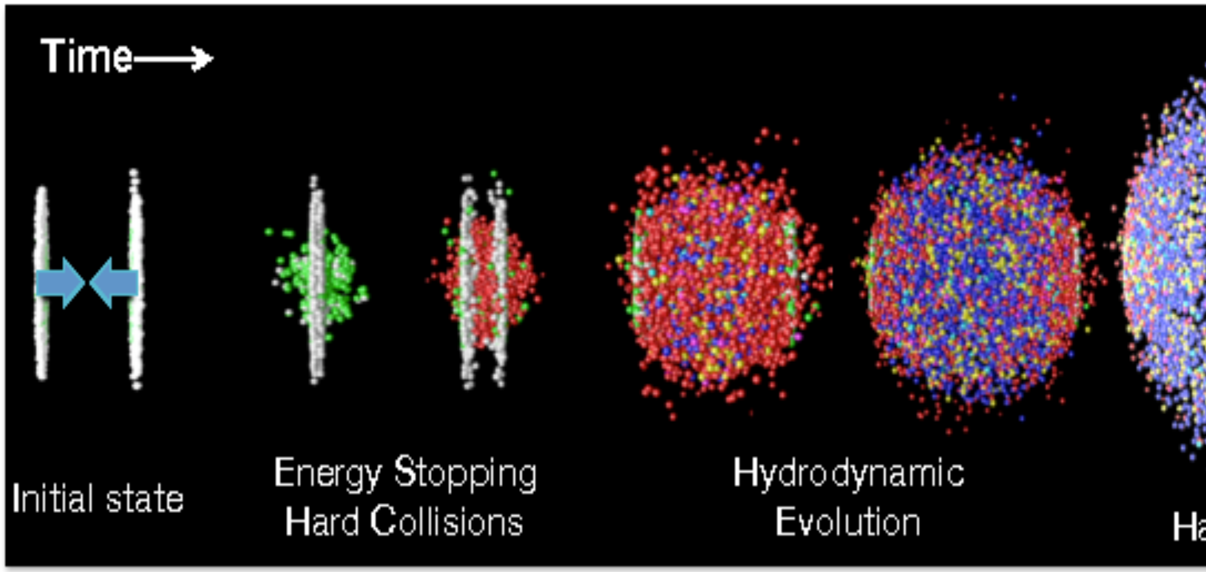
Q1. What/Why dust?

- The holographic image of the created particles is the dust in the bulk.
  Since they are NOT in a coherent state or Bose condensation state, it is better not to be described as a non-trivial field configuration of scalar or any tensor.
- More proper discussion should involve Particle creation mechanism in string theory. Open string scattering can pinch off closed string.
- But we start from the creation of 5000 particles.

Q2. Why Fall ?
1. It equilibrates after some Expansion

- Accodring to UV/IR relation,
  Expansion @bdry is dual to the Falling in bulk.





Why Fall? continued

2. Because holographic image of a created particle is at r> 0.

Polchinski+Strassler (hep-th/0109174)
Maximum contribution to scattering amplitude is from a definite height.)

$$r_{scat} \sim R^2 p.$$

Shuryak, SS, Zahed (hep-th/0511199)
Look at Maximum probability to find created particle of given 4 momentum to get similar result.

$$P(z) = \sqrt{g}|\phi(z)|^2. \qquad \phi(z) = z^2 I_\nu(kz) \quad for \quad k^2 > 0.$$

Q3. Why non-interacting dust?

- All the gluon mediated interactions are transformed away as background gravity
  → dusts are free particle in a ads background.

- But non-gluonic interactions should be remained and will be discussed later.

Q4. Poincare Patch?

- Motion not periodic. Falling time is infinite.

$$r = \frac{\epsilon R}{\sqrt{(\epsilon t/R)^2 + 1}} = R^2/t - (R/t)^3/2\epsilon^2 + \mathcal{O}(t^{-5}),$$

- Initial condition dependence rapidly disappear. → Synchronization effect is still there.

- Formation of trapped surface in "finite time" seems "obvious".

Q5. Effect of initial velocity

- Holographic Image at its creation moment does not have radial velocity.
- Work in Poincare patch.

$$\frac{mr^2}{\sqrt{r^2(1-\dot{x}^2)-\dot{r}^2/r^2}}=E,\ \frac{mr^2\dot{x}}{\sqrt{r^2(1-\dot{x}^2)-\dot{r}^2/r^2}}=p, \quad V=p/E,$$

$$r=\frac{\epsilon(1-V^2)}{\sqrt{1+(\epsilon(1-V^2)t/2)^2}}.$$

Remarkably the large time behavior of the radial position is independent of

all of the initial conditions m, E, p.

Q6. Non-gluonoc Interaction effect

- Newtonian potential in AdS.

$$V(\{x_i, y_i\}) = \int\int d^5x d^5y J(x) G(x,y) J(y),$$
$$= G_N \sum_{i<j} \int dt \frac{(x_{i0}x_{j0})^{2\Delta}}{\left(|x_i(t) - x_j(t)|^2 + |x_{i0}(t) - x_{j0}(t)|^2\right)^{\Delta - 1/2}}$$

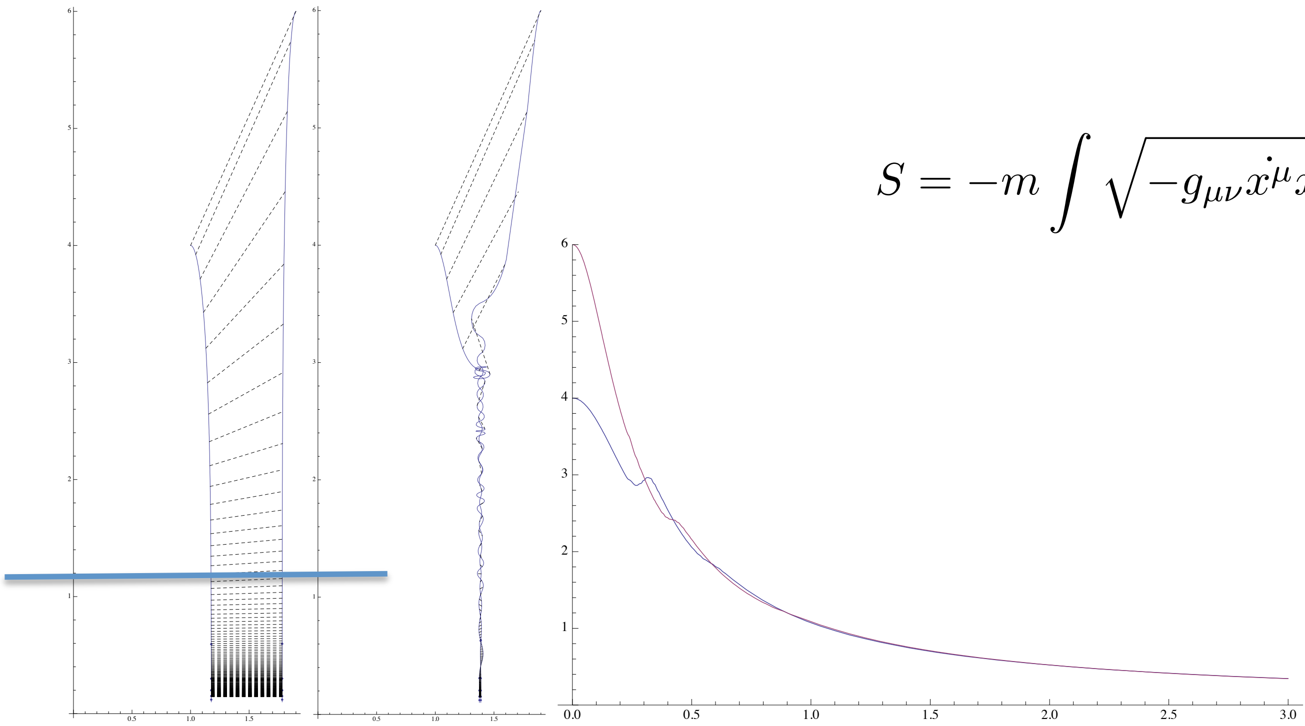
. from $G \sim \left(\frac{1}{u(2+u)}\right)^{\Delta}$ with $u = \frac{(x-y)^M (x-y)_M}{2x_0 y_0}$

$$ds^2 = \frac{1}{x_0^2}(dx_0^2 + dx^\mu dx_\mu), \text{ with } x_0 = 1/r$$

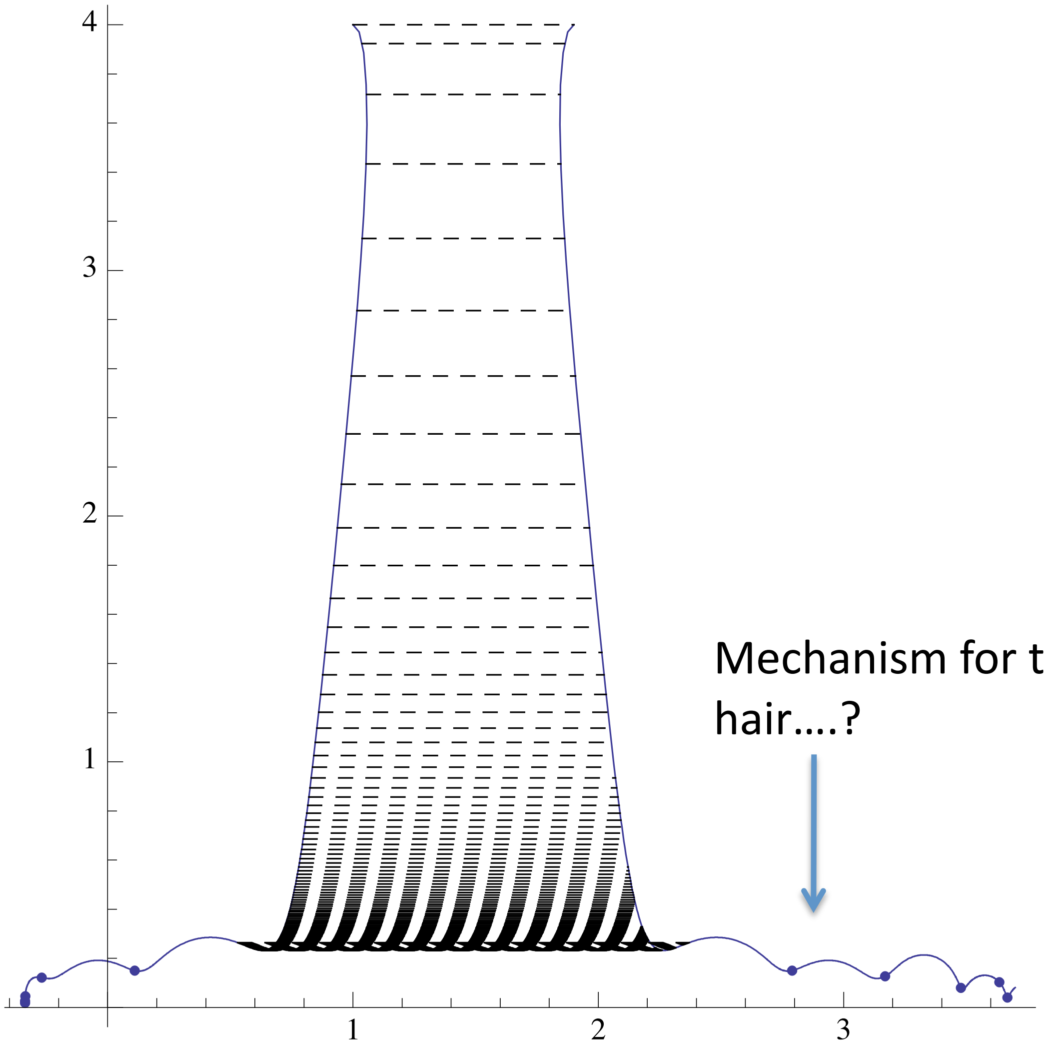
Q6. Interaction (non-gluonic) effect I:

- Interaction is not so important if attractive.

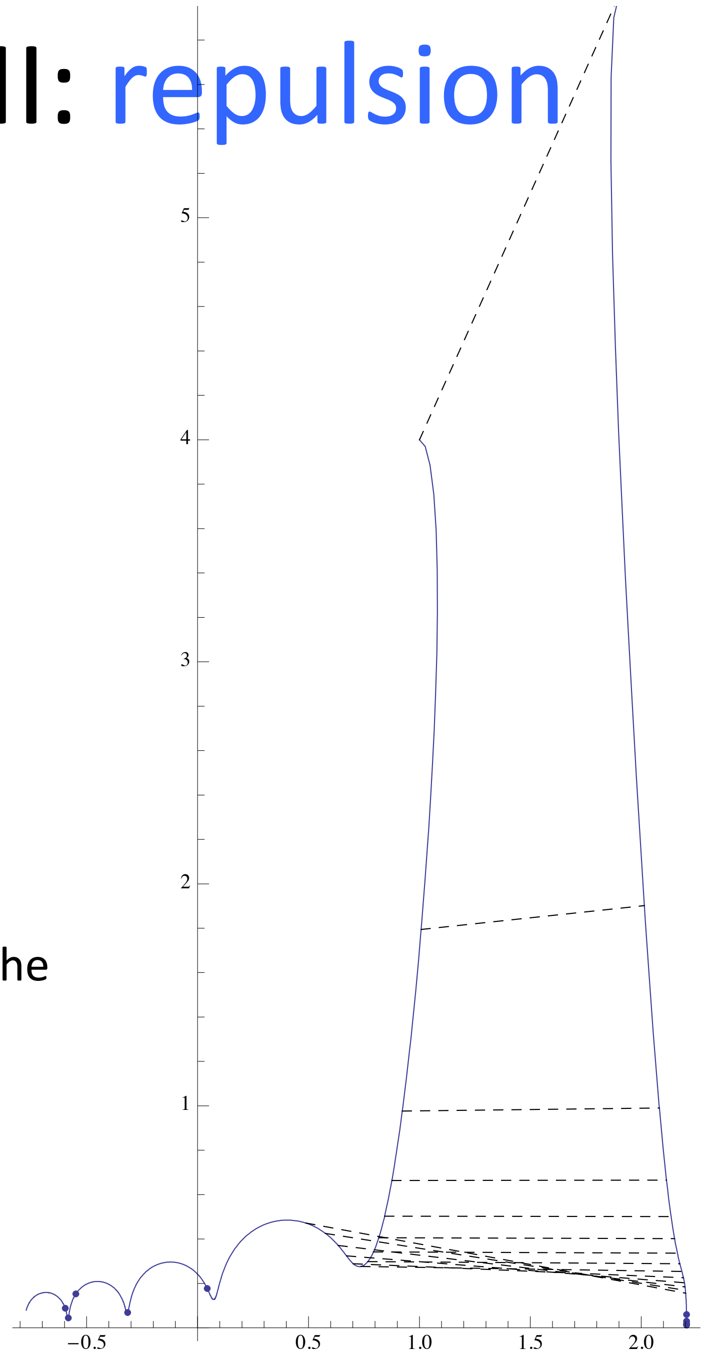
$$S = -m \int \sqrt{-g_{\mu\nu}\dot{x^\mu}\dot{x^\nu}}dt, \ +V(\{x_i, y_i\})$$



Interaction effect II: repulsion



Mechanism for the hair….?



Q7. Prediction

- Thermalization time < One Dynamical time,

$$T_{fall} = \frac{\pi}{2}\frac{R}{c}$$

- Thermalization: Soft first and Hard later.

(for pure gluon int. in the large N.)

higher energy particles arrive at the apparent horizon later.

$$t_{Thermalization} = \sqrt{1/r_H^2 - 1/r_o^2}$$

Future projects.

- Q8. Where is entropy generation?
- Q9. back reaction of gravity?
- Q10. Is this mechanism universal for other background?
- Q11. What is wrong with Shock wave?

………etc.……

Topic II: Thermal Mass and Plasmino for strongly interacting Fermions

With
Yunseok Seo, Yang Zhoua,b

- Massless particle in finite temperature gets mass ~ gT : Thermal mass.

- There are Three scales in weak coupling:
  $T \gg gT \gg g^2 T$
- Q: What will happen to strong coupling?

- Ans: No thermal mass in strong coupling. [See also Maldacena's recent work]

Fermion In hot Medium: T>>m,

$$S(\omega,\mathbf{p}) = \frac{1}{\omega\gamma_0 - \mathbf{p}\boldsymbol{\gamma} - \Sigma(\omega\mathbf{p})}$$

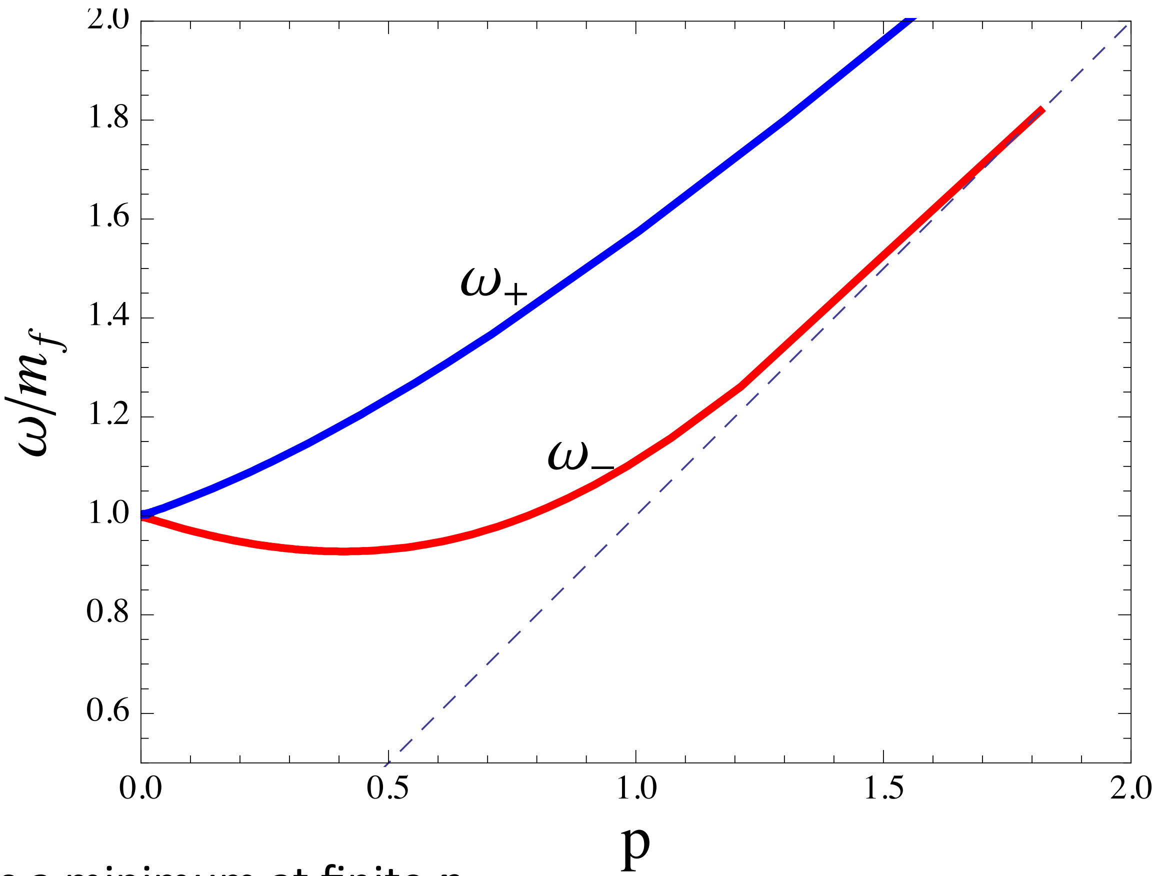
In Hard Thermal loop approximation

1. Thermal mass(Klimov '82, Weldon '83)

$$m_T = \frac{gT}{\sqrt{6}} \qquad m_f^2 = \frac{1}{8} g^2 C_F \left(T^2 + \frac{\mu^2}{\pi^2} \right)$$

2. Plasmino : New collective mode (Braaten, Pisarski '89)

Plasmino



- The plasmino mode has a minimum at finite ***p***.

$$p << m_f \; : \quad \omega_\pm(p) \simeq m_f \pm \frac{1}{3}p + \frac{1}{3m_f}p^2 + \cdots \;\; ,$$

$$p >> m_f \; : \quad \omega_\pm(p) \simeq p \; .$$

Importance

- Van Hove singularity.
  Density of state is enhenced in low dim.

$$
\begin{aligned}
\rho(\omega) &= \sum_n \int \frac{d^3k}{(2\pi)^3} \delta(\omega - \omega_n(k)) \\
&= \sum_n \int \frac{dS}{(2\pi)^3} \frac{1}{\nabla_k \omega_n(k))}
\end{aligned}
$$

New mechanism of SC…..
Enhenced dilepton production …..(Thoma ph/0008218)

However

- Resummation needs ladder approximation,
  not justified for strong coupling.

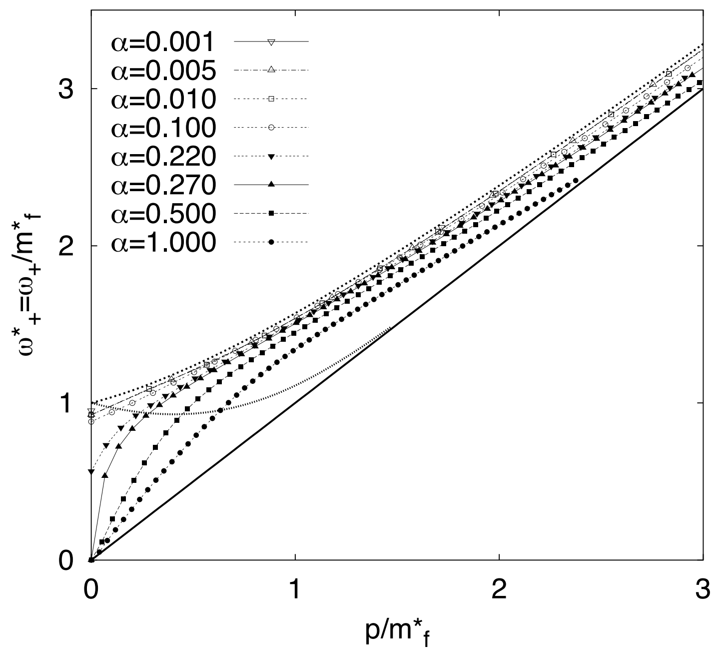
It is not clear whether plasmino continues to exit in the strong coupling limit.

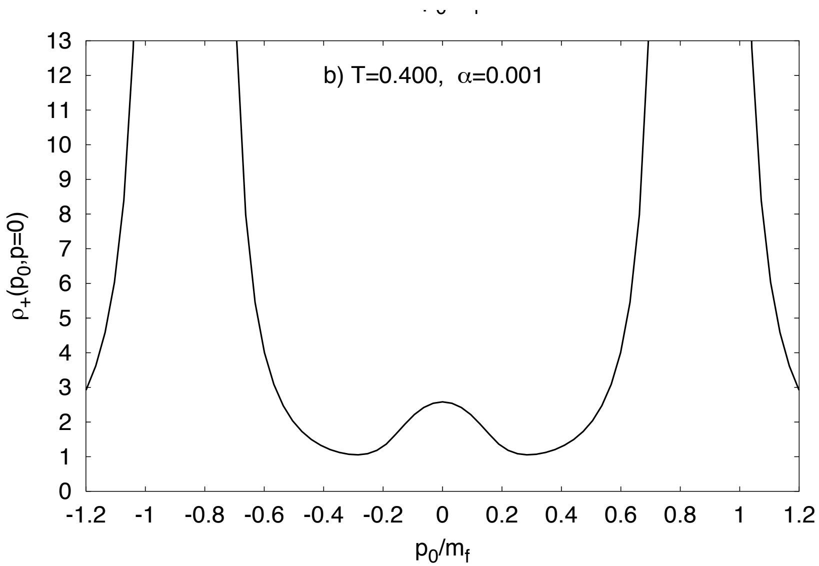
& .....

Evidence

An interesting Numerical study suggested m_T=0.

ArXiv: 1111.0117 , Nakkagawa et.al.





However, this work is also based on SD idea.

Set up

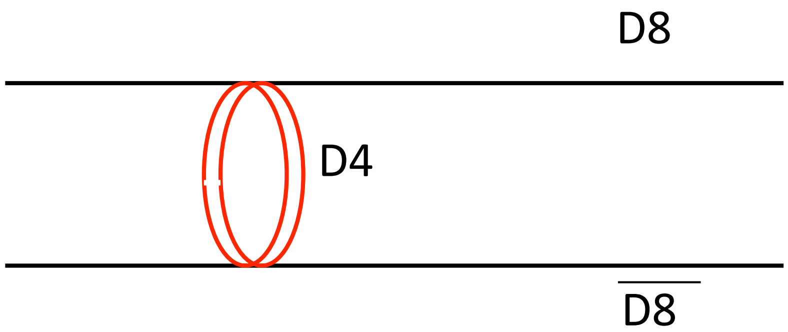
- Use D4/D8/D8bar : SS model :
  Confinement(cf): by solitonic bg.
  Deconfinement (dcf): Black hole bg.

- Chiral Symmetry breaking: Joined D8/D8bar

- Density/chemical potential: U(1) gauge field (sourced by the strings emanating from horizon of the BH or compact D4 (baryon vertex).)

The D4-D8-$\overline{D8}$ System

Sakai,Sugimoto

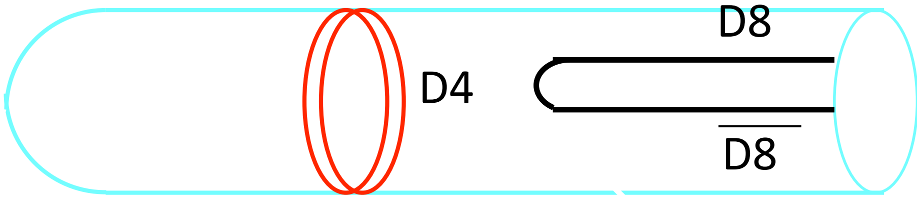


	0	1	2	3	4	5	6	7	8	9
D4	x	x	x	x	x					
D8	x	x	x	x		x	x	x	x	x

The D4-D8-$\overline{\text{D8}}$ System

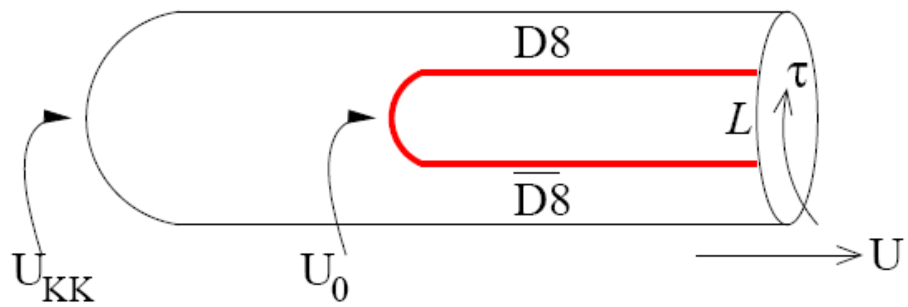
Sakai,Sugimoto;

Aharony,Sonnenschein,Yankielowicz



	0	1	2	3	4	5	6	7	8	9
D4	x	x	x	x	x					
D8	x	x	x	x		x	x	x	x	x

D4 brane geometry



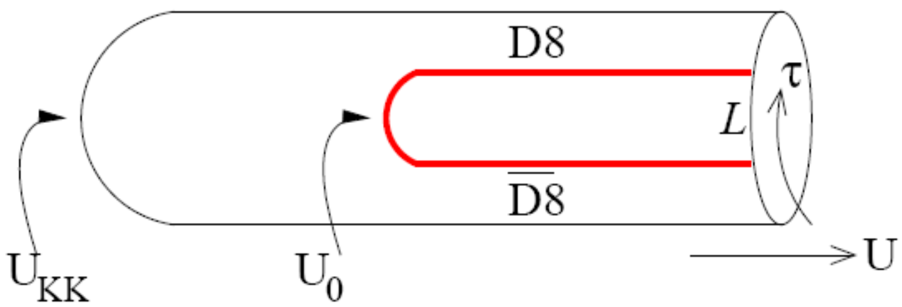
$$ds^2 = \left(\frac{U}{R}\right)^{3/2}\left(\eta_{\mu\nu}dx^\mu dx^\nu - f(U)d\tau^2\right) - \left(\frac{R}{U}\right)^{3/2}\left(\frac{dU^2}{f(U)} + U^2\, d\Omega_4^2\right)$$

$$f(U) = 1 - \frac{U_{KK}^3}{U^3} \qquad R^3 = \pi g_s N l_s^3$$

τ period: $4\pi R^{3/2}/(3U_{KK}^{1/2})$

Probe brane limit $N_f \ll N_c$

Karch,Katz



D8-brane action

$$S_{DBI} = -T \int d^9x\, e^{-\phi} \sqrt{\det g_{MN}} \qquad e^{\phi} = g_s \left(\frac{U}{R}\right)^{3/4}$$

Stationary Solution:
$$f(U) + \left(\frac{R}{U}\right)^3 \frac{U'(\tau)^2}{f(U)} = \frac{U^8 f(U)^2}{U_0^8 f(U_0)}$$

$$ds^2 = \left(\frac{U}{R}\right)^{3/2} \eta_{\mu\nu} dx^\mu dx^\nu - \left(\frac{R}{U}\right)^{3/2} U^2\, d\Omega_4^2 - \left(\frac{R}{U}\right)^{3/2} \left[\frac{1}{f(U)} + \left(\frac{U}{R}\right)^3 \frac{f(U)}{U'(\tau)^2}\right] dU^2$$

Fermion on D8

- Fermion =mode of D4-D8 string
  = bi-fundamental field ψ_i^a
- When D4 is replaced by a gravity, color index is interpreted as "averaged over"
  so that D8 fermions are color averaged quarks.
- Here only 1 flavor.
- Remark: NOT a "bulk" fermion, No ads/cft.

Fermion action and eq. of M

- Ignore S4: D8 becomes effectively 5d with one dimension compactified. → 3+1 d theory.

$$S = \int d^5x\sqrt{-g}\; i\left(\bar{\psi}\Gamma^M D_M\psi - m_5\bar{\psi}\psi\right) \;,$$

$$D_M = \partial_M + \tfrac{1}{4}\omega_{abM}\Gamma^{ab} - \; iqA_M .$$

$$\psi = (-gg^{rr})^{-1/4} e^{-i\omega t + ik_i x^i}\Psi$$

$$\sqrt{g_{ii}/g_{rr}}(\Gamma^{\underline{r}}\partial_r - m_5\sqrt{g_{rr}})\Psi + iK_\mu\Gamma^{\underline{\mu}}\Psi = 0 \;,$$

$$K_\mu = (-v(r), k_i) \text{ and } v(r) = \sqrt{-g_{ii}/g_{tt}}(\omega + qa_0).$$

Def. of Green function

$$\Psi = (\Phi_1, \Phi_2) = (y_1, z_1, y_2, z_2)^T$$

$$G_1(r) := y_1(r)/z_1(r) \text{ and } G_2(r) := y_2(r)/z_2(r)$$

Then,

$$\sqrt{\frac{g_{ii}}{g_{rr}}}\partial_r G_\alpha + 2m_5\sqrt{g_{ii}}G_\alpha = (-1)^\alpha k + v(r) + \left((-1)^{\alpha-1}k + v(r)\right) G_\alpha^2 \ .$$

Finally,

$$G^R_{1,2} = \lim_{\epsilon\to 0} e^{-\frac{1}{2}m_5 R r^{1/4}} G_{1,2}(r)|_{r=1/\epsilon}$$

For retarded green fct, we need Boundary condition:

IR Boundary condition: 1. deconfinging case

- BC← horizon regularity
- Retarded Green function:

$$G_{1,2}(r_0) = i \ ,$$

$$v(r) = (\omega + q a_0(r)) / \sqrt{f}$$

$$a_0(r) = \mu + \int_\infty^r d\hat{r} \left(\frac{D'^2}{\hat{r}^5 + D'^2} \right)^{1/2}$$

$$\mu = \frac{m}{q} + \int_{r_0}^\infty a_0'(r)\ dr.$$

IR Boundary condition:
2. confinging case

- For retarded(advanced) green fct

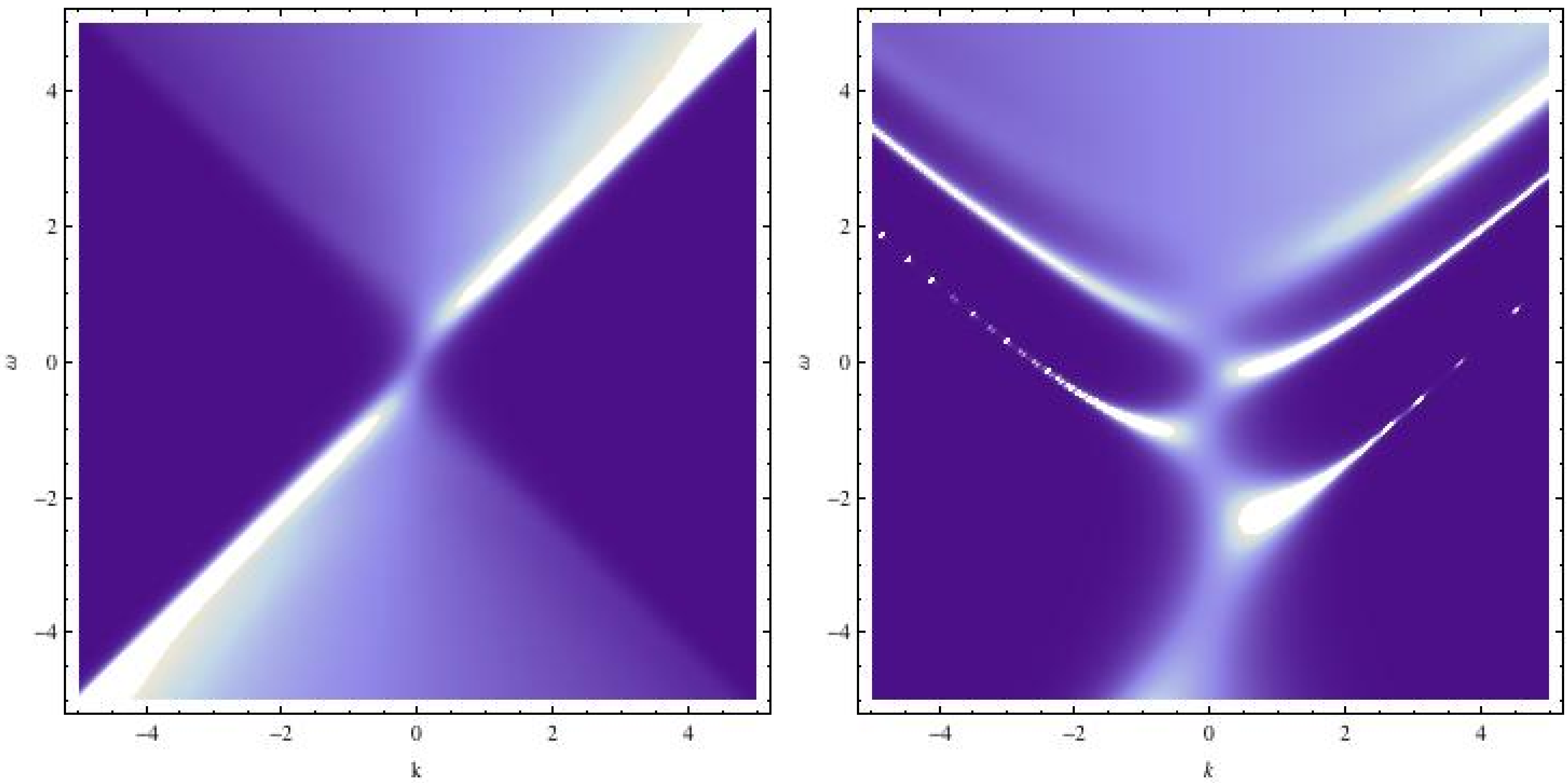
$$G_\alpha(r_0) = \frac{-mR + \sqrt{m^2R^2 + k^2 - \hat{\omega}^2}}{(-1)^\alpha k - \hat{\omega}} \ ,$$

where $\hat{\omega} = \omega + m_*$ and $m := m_5 r_0^{3/4}$

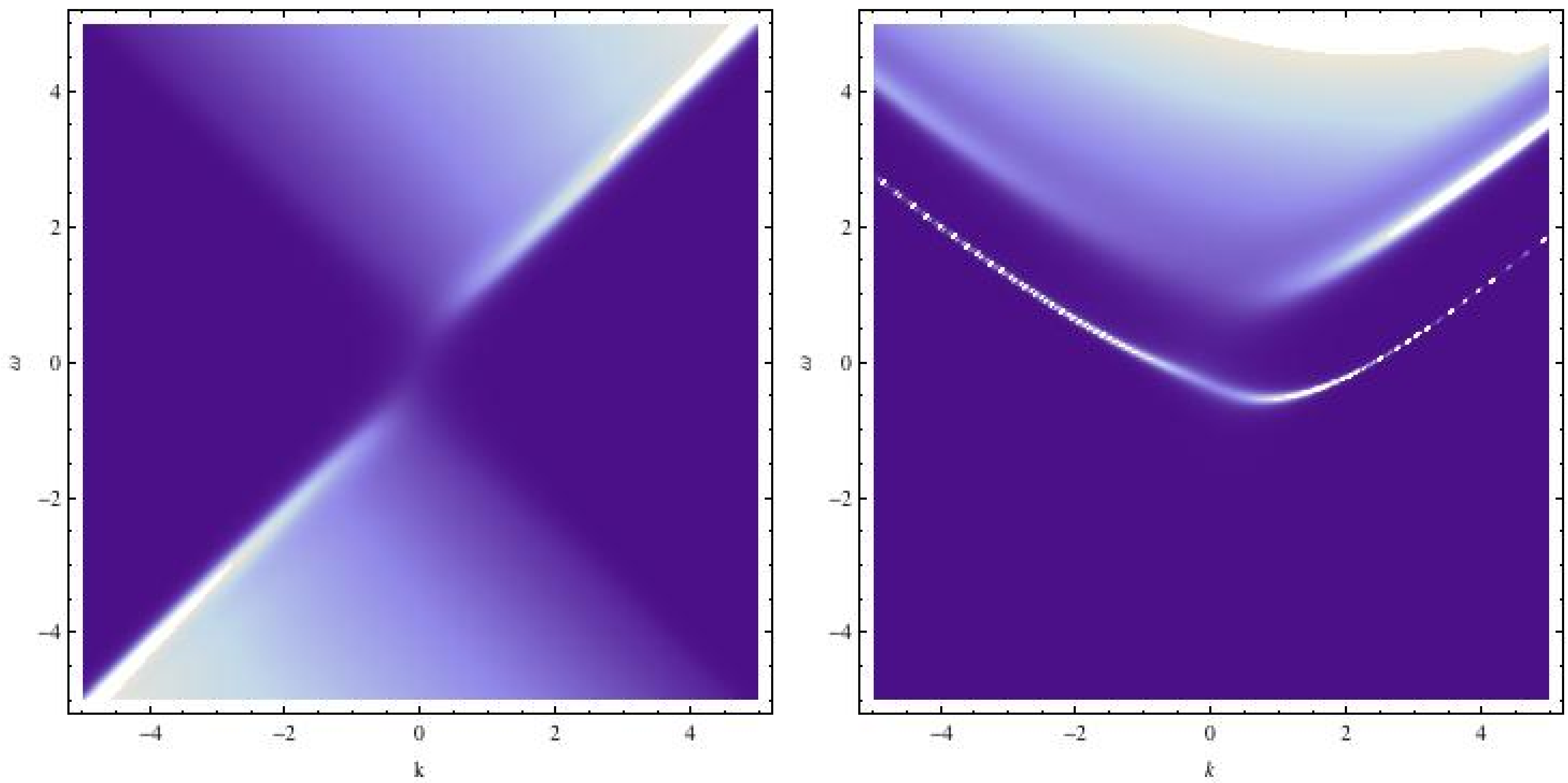
$$\omega \ \to \ \omega + i\epsilon \ (\omega \ \to \ \omega - i\epsilon).$$

Deconfing case, massless fermion.

Vanishing thermal mass: 0 or non-0 density



Deconfing case, massive fermion.
0 / non-0 density

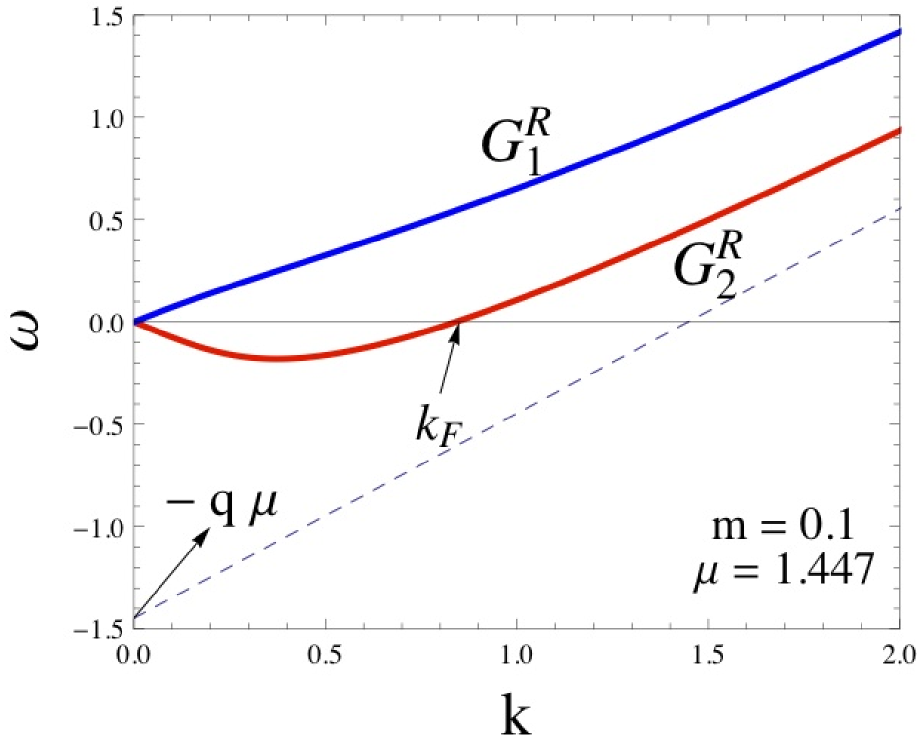


Confining case

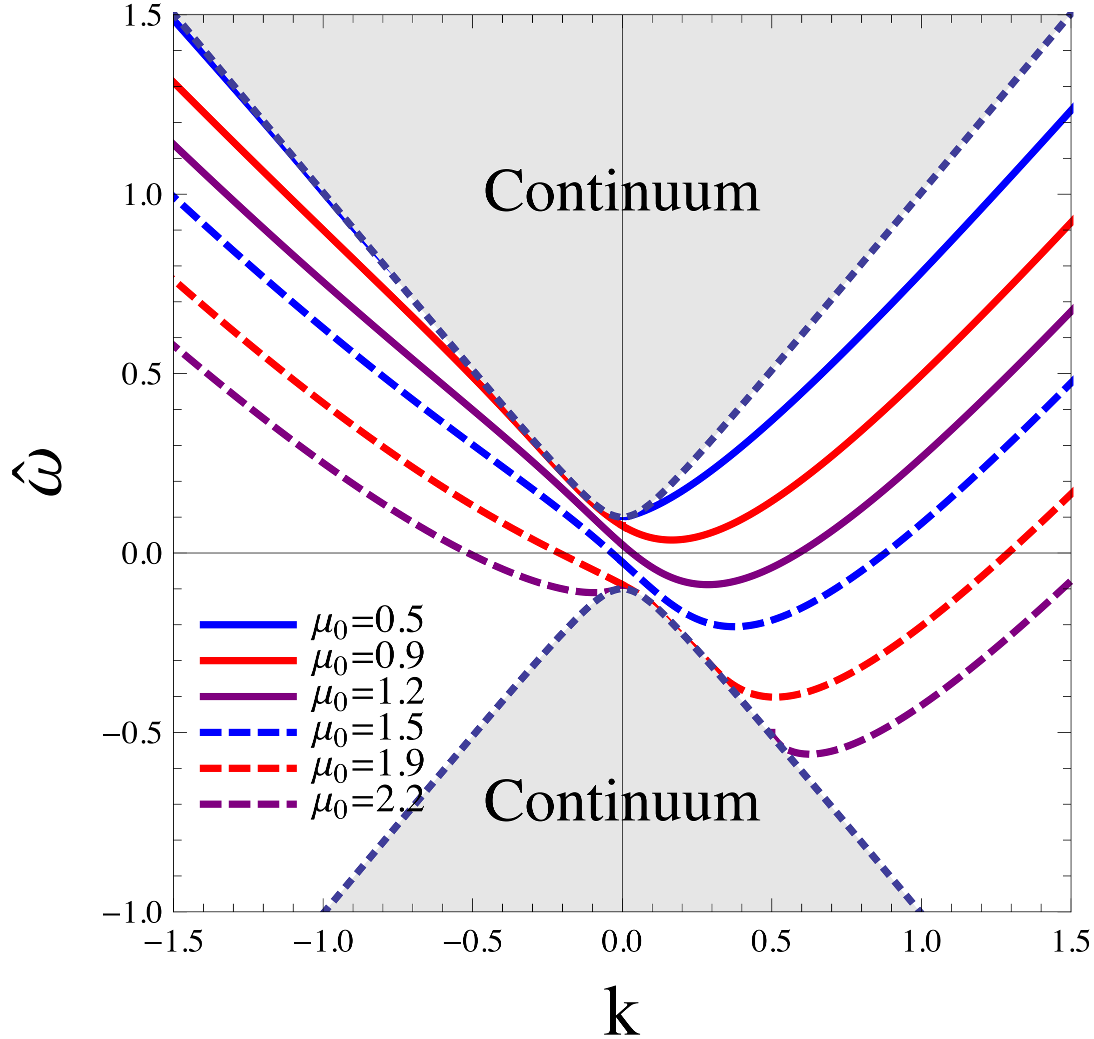
There is Plasmino only for large but not too large chemical potential.

$$\mu_1 \leq \mu \leq \mu_2.$$

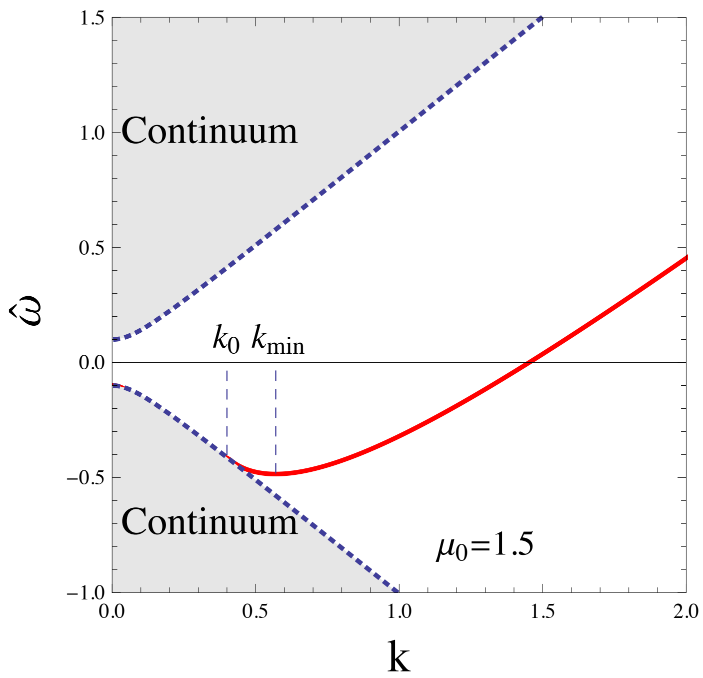
. Extreme high density behavior is very complex and rich and will not be presented here.

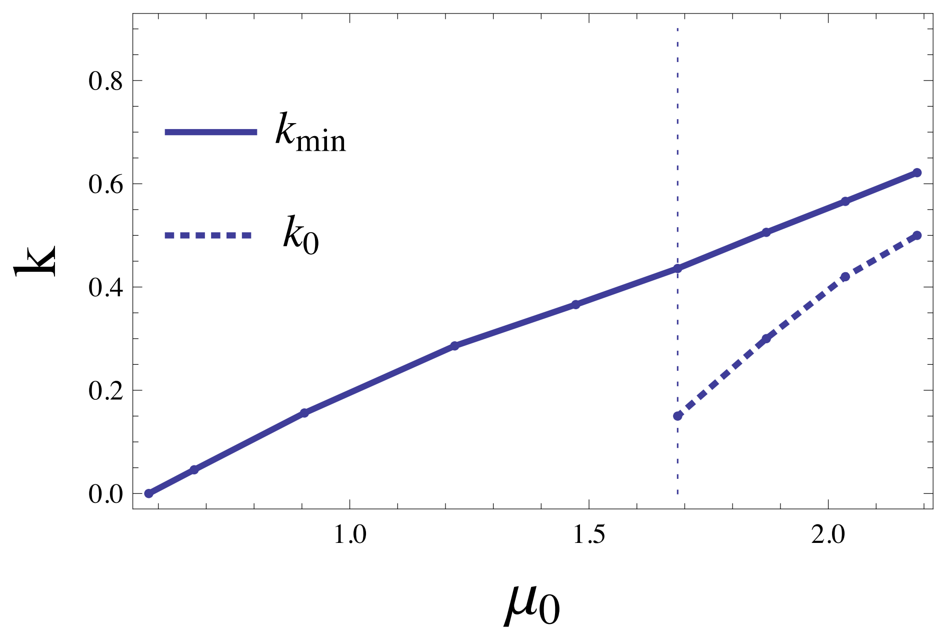


Confinging case

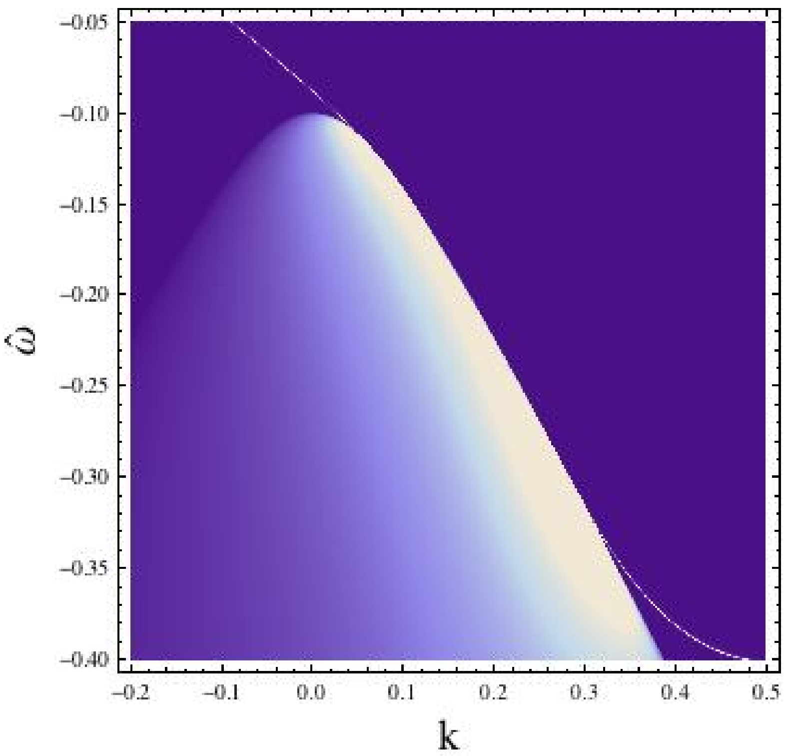


Confining case

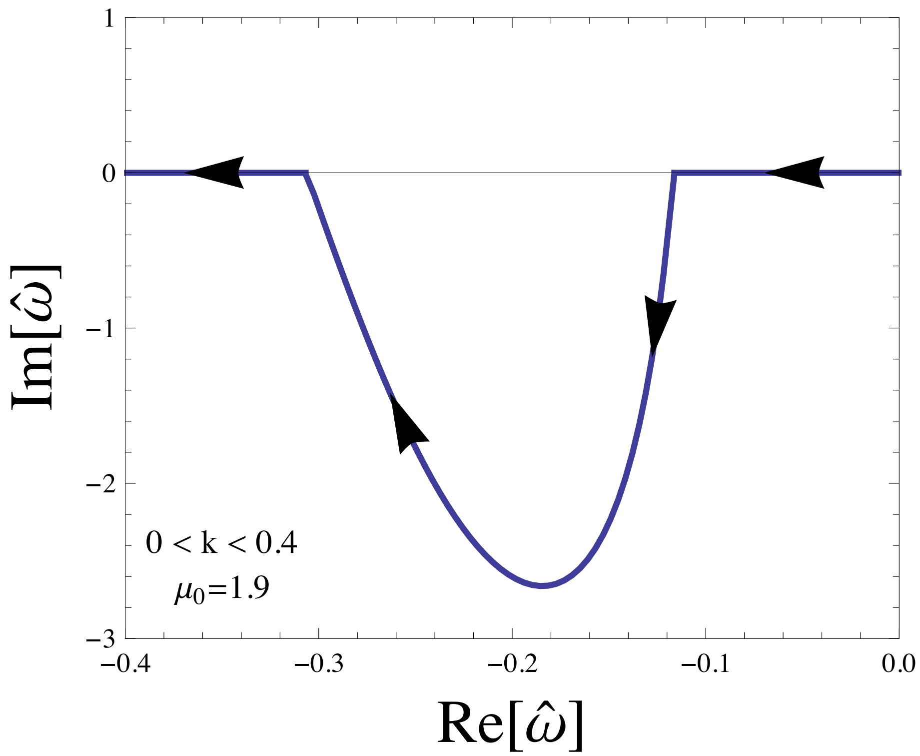




Spectral function



(a)



(b)

Density dependence of plasmino slope at k=0.

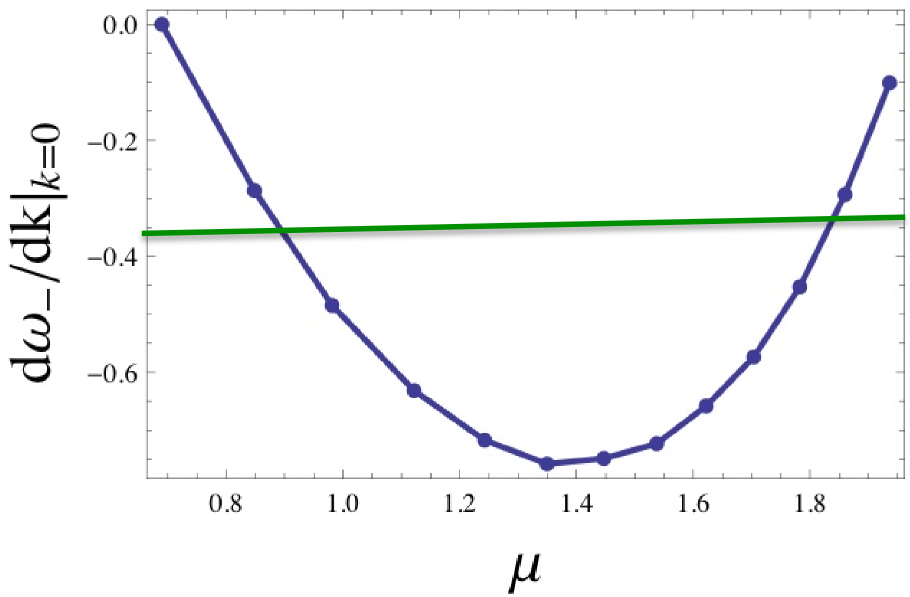


FIG. 3. μ dependence of α. The curve is plotted only in the density window where there is plasmino, namely $\mu_1 \le \mu \le \mu_2$.

Cf: HTL

$$p << m_f : \quad \omega_\pm(p) \simeq \pm\frac{1}{3}p \; ,$$

$$p >> m_f : \quad \omega_\pm(p) \simeq p \; .$$

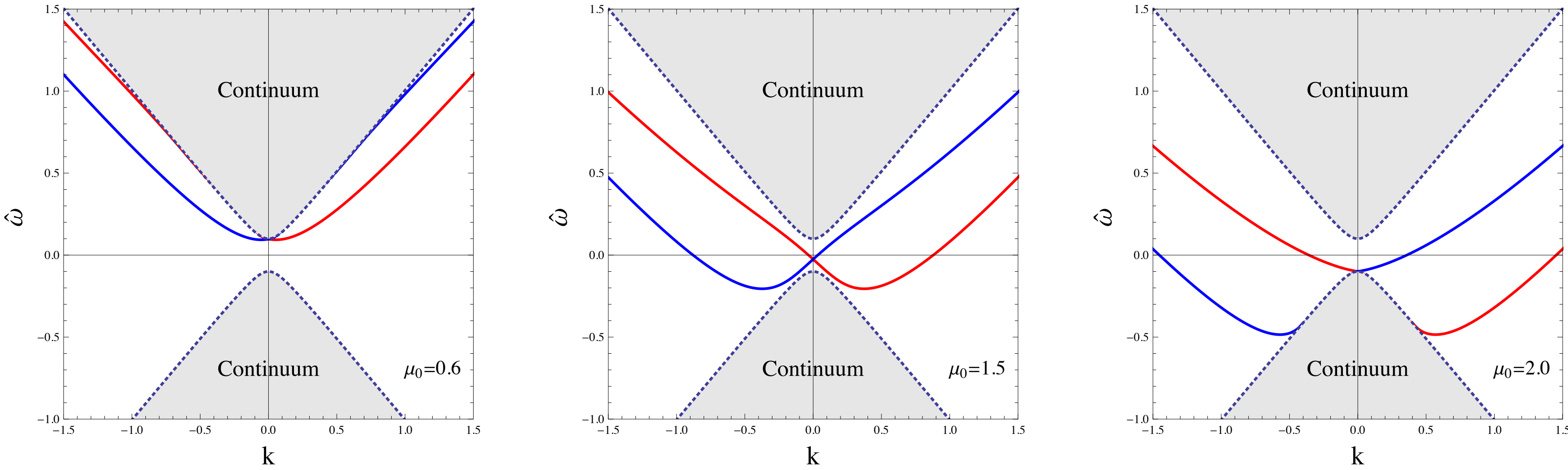
Plasmino as Dual Rashiba effect Herzog et.al (1204.1518)

- Bulk field can couple to fermion spin

$$H_{\pm} = \frac{k^2}{2m_{eff}(r)} + \alpha E(r) \times \sigma \cdot k + \ldots,$$

- What is the field theory Dual?
  Ans Density generated plasmino

Density and plasmino



(a) (b) (c)

Figure 8. Density dependence of dispersion curves for G_1^R and G_2^R. Blue solid line denotes G_1^R and red line denotes G_2^R.

Summary

Parameter		Top down		Bottom up	
		Confining	Deconfining	Confining	Deconfining
Fermion mass	$= 0$				
	> 0		$\circledcirc$		$\circledcirc$
Chemical potential	$< \mu_c$				
	$> \mu_c$	$\circledcirc$	$\circledcirc$	$\circledcirc$	$\circledcirc$

Conclusion .

- Plasmino is present only in the presence of density and mass.
- Plasmino exist only for a window of density in Confining case.

- Thermal mass is 0, in deconfined case even at zero mass limit→ non-fermi liquid.

- High Density seems to restore the fermi liquid character.

Thank you

Review hep-th/0511199

- Poincare coordinate:
  Radial motion is Harmonic oscillator in proper time.
- So each particle has the same period in proper time pi/2 independent of the initial height.
- However, different particle has different proper time. Pi/2 in proper time is infinite real time.

$$t = R/\epsilon \cdot \tan(\tau/R)$$

However

- Initial condition dependence rapidly disappear. → we called it "syncronization".

$$r = \frac{\epsilon R}{\sqrt{(\epsilon t/R)^2 + 1}} = R^2/t - (R/t)^3/2\epsilon^2 + \mathcal{O}(t^{-5}),$$

Dictionary in Poincare Patch

$$p = r_0 \frac{m v_x}{\sqrt{1 - v_x^2}}$$
$$E = r_0 \frac{m}{\sqrt{1 - v_x^2}}$$

This is polchinski-strassler ansatz.

Notice that p, E are conserved one. v_x are language of Bulk.
The radial velocity goes to 0 unlike the global coordinate.
It is clear that r_0 is the parameter which sets the energy scale.

Q11. Shock wave approach.

- Chesler+ Yaffe, Gubser,….
- Good in mimicking the boosted beam, which look like pancake, collision.
- Intuitively, shock wave originally was used to make black hole/brane in real space rather than ads space by t'Hooft, Giddings, …
- Particle creation does not do any role.