Analysis of Bound States in Holographic Conductors

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We report a relationship between lifetime of a bound state and non-linear conductivity in holographic conductors.

Introduction: Non-linear conductivity

$\frac{\partial J}{\partial E} > 0$: Positive differential conductivity (PDC), a "conventional" behavior.

$\frac{\partial J}{\partial E} < 0$: **Negative differential conductivity (NDC)**,
It was also observed in strongly-correlated insulators.
Important for Industrial applications, *e.g.* thyristor.

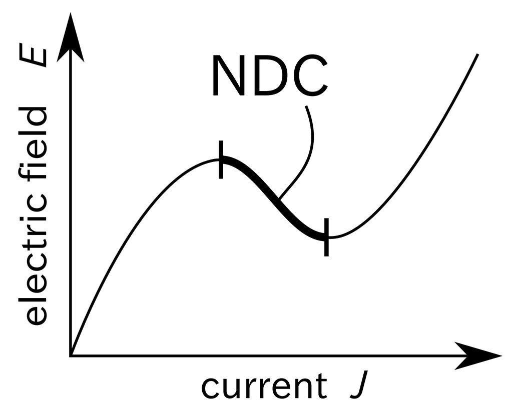


Fig. 1. *The typical J-E characteristic of ("S"-shaped) NDC.*

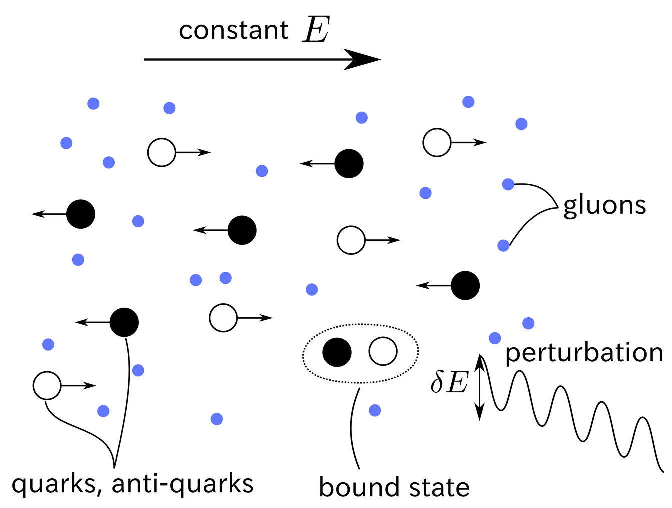


Fig. 2. *The system settings.*

Holographic conductors

D3-D7 model

[A. Karch, A. O'Bannon, JHEP 024 (2007), 0709]

- D3-brane → AdS-Schwarzschild black hole with T (**thermal bath**)
- D7-brane → probe brane (**system of charged particles**)

We apply constant electric field E. → Non-equilibrium steady state (NESS)

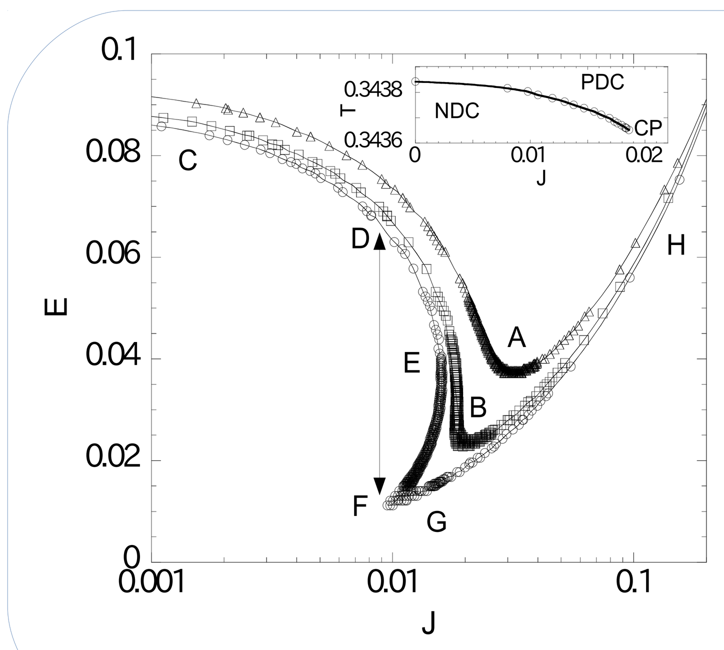


Fig. 3. *NDC J-E characteristics in D3-D7 model.*

[S. Nakamura, PTP 124 (2010), 1105]
[S. Nakamura, PRL 109 (2012), 120602]

We compute the response $J=\sigma E$ by

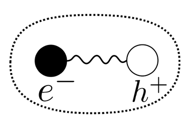
$$J = \frac{\delta S_{D7}}{\delta A_x}\Big|_{\text{bou.}} \quad \because)\ A_x \text{ is conjugate with } J.$$

←NDC is produced!

But its mechanism is not still understood.

- An ionization of the bound state may plays some role?

exciton



We study a lifetime of the bound state.

Lifetime can be read from ***quasi-normal mode's (QNM)*** frequency.

$$e^{-i\omega t} = e^{-i\omega_R t} e^{-(-\omega_I)t} \iff \text{lifetime } \tau \propto 1/|\omega_I|$$

- EoM for *transverse* perturbation field to E

$$\partial_b [\sqrt{-\det(g+F)} g^{\perp\perp} (\partial_d \delta \mathcal{A}_\perp)(g+F)^{(db)}] = 0$$

Fourier transformation of this eq. with
ingoing-wave condition at horizon,
Dirichlet b.c. at boundary, $\delta \mathcal{A}_\perp = 0$.

➡ Eigenvalue problem
Eigenvalue: QNM frequency
$\omega = \omega_R + i\omega_I \in \mathbb{C}$

We compute QNM frequencies as functions of quark-mass, E, J, by using "shooting method".

See also [J. Mas, J. P. Shock, J. Tarrio, JHEP 032 (2009), 0909]
[P. K. Kovtun, A. O. Starinets, PRD 72 (2005), 086009]

Results: QNMs & lifetime of bound state

(We have set $m_q = 1$)

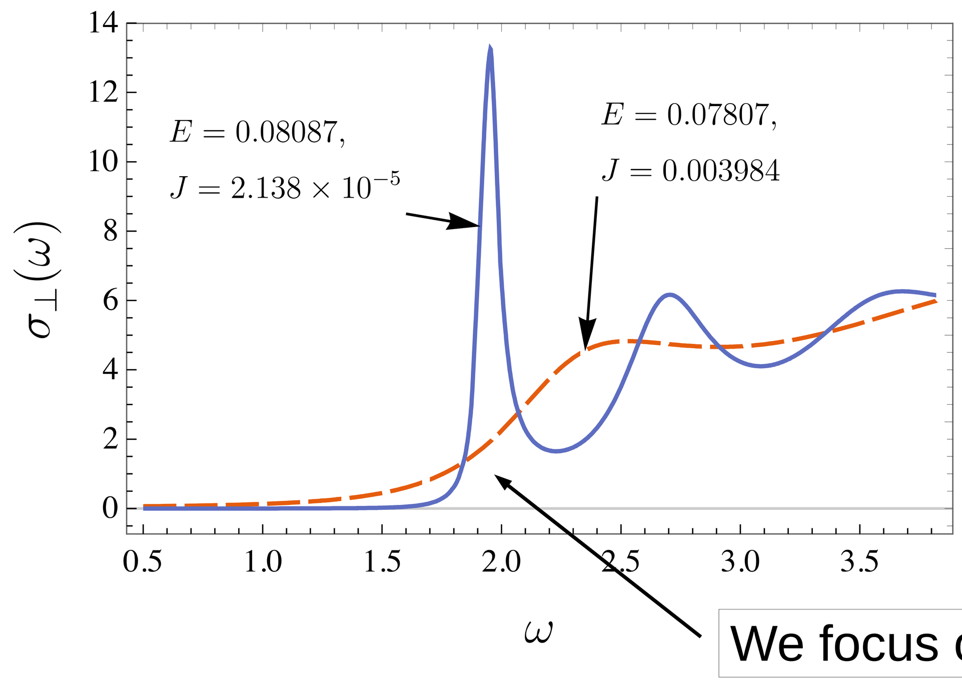


Fig. 4. *AC conductivity spectrum at* $T = 0.343638$.

AC conductivity spectrum has peaks which indicate quasi-particles.

Peaks are corresponding to QNMs.

We focus on the first excited bound state.

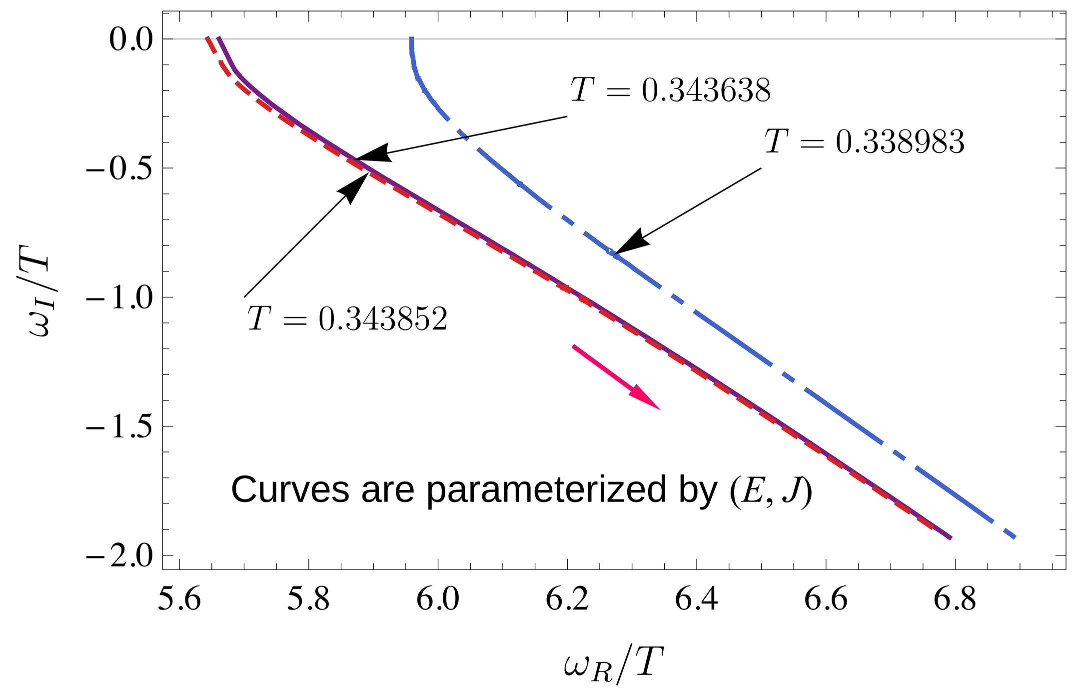


Fig. 5. *The location of the first QNM frequencies.*

Curves are parameterized by (E, J)

Narrow peak (Long lifetime)

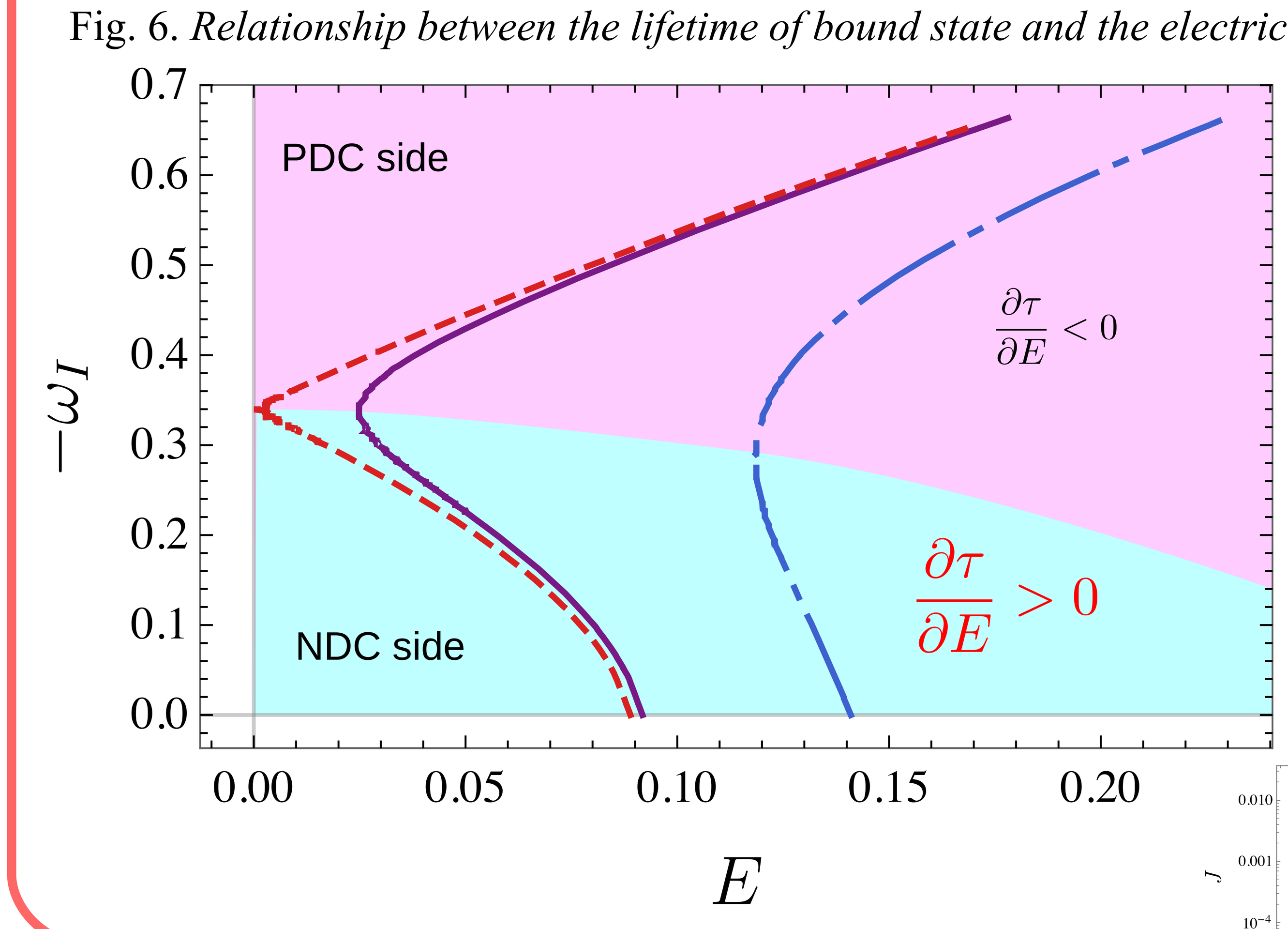
Broad peak (Short lifetime)

The imaginary part of QNM frequency is related to the lifetime of the bound state by $\tau \propto 1/(-\omega_I)$

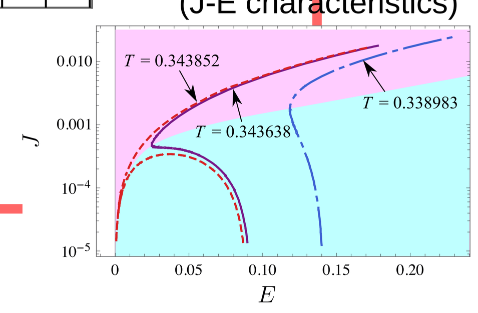
We summarize the relationship between E and $-\omega_I$.

[S. Ishigaki, S. Nakamura in progress]

Fig. 6. *Relationship between the lifetime of bound state and the electric field.*



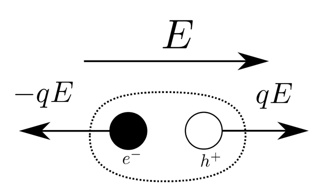
(J-E characteristics)



PDC region : $\frac{\partial(-\omega_I)}{\partial E} > 0 \iff \frac{\partial \tau}{\partial E} < 0$

Lifetime decreases as E increases.

➡ E breaks bound states.



NDC region : $\frac{\partial(-\omega_I)}{\partial E} < 0 \iff \frac{\partial \tau}{\partial E} > 0$

Lifetime grows as E increases.

➡ **E stabilizes bound states.**
↳ **The key feature in NDC**

Conclusion

We find that the lifetime of the bound state is longer as the electric field increases in the NDC region.
It seems to be a key feature in NDC.

Discussion

- Possible interpretations of our results?
  →variation of effective mass, effective trap potential …
- Any phenomenological models?
- parallel perturbation to electric field?
  →inhomogeneous instability?