

Quantum Liquids in space and in collider

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Quantum Liquids

- Here I will present two easy pieces associated with quantum liquids that might be connected to string theory:
One for dark matter, and
the other for QuarkGluonPlasma.
- The reasons why two are QL are very different: small mass//strong int.

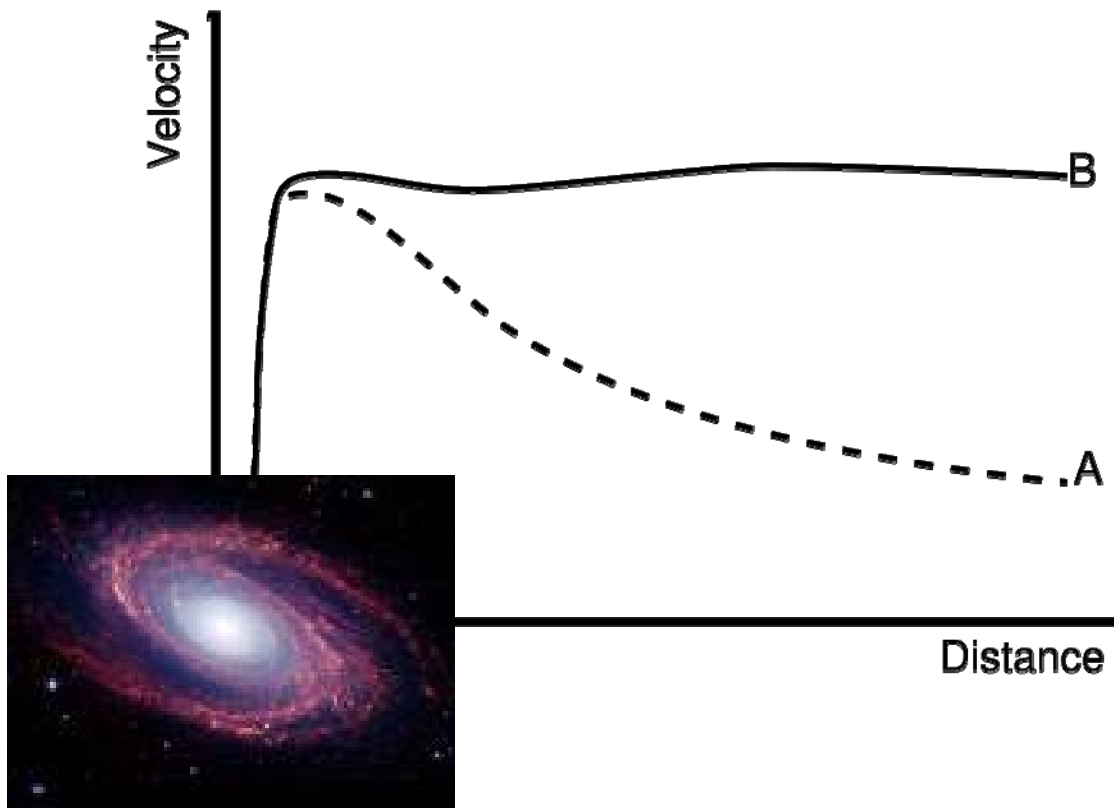
I. Quantum Dark Matter

1992 at UF. PRD

- Majority of mass of the universe is invisible.

Rotation curve

$$v^2 = GM/r$$



$$M(r) = \int_0^r dr' 4\pi r'^2 \rho(r')$$

What DM is made of and where is it

- Assume they are Bosons of extremely small mass $\sim 10^{-24}$ eV
 \Rightarrow compton length ~ 10 pc.
- galactic dark matter density $\sim 10^{-25}$ gram/cc \Rightarrow Density $\sim 1/\text{fm}^3$
- They are overlapping and compactly fill this room. These are wave like not particle like. QM nature dominate!

Many particle system

- Consider a particle moving in a potential generated by all other particles.

- Energy

$$E = \frac{1}{2}mv^2 + \int_0^r dr' \frac{GmM(r')}{r'^2}, \text{ where } M(r) = \int_0^r dr' 4\pi r'^2 \rho(r')$$

- Problem: determine the distribution

- Quantum mechanically it is easier if we assume coherency.

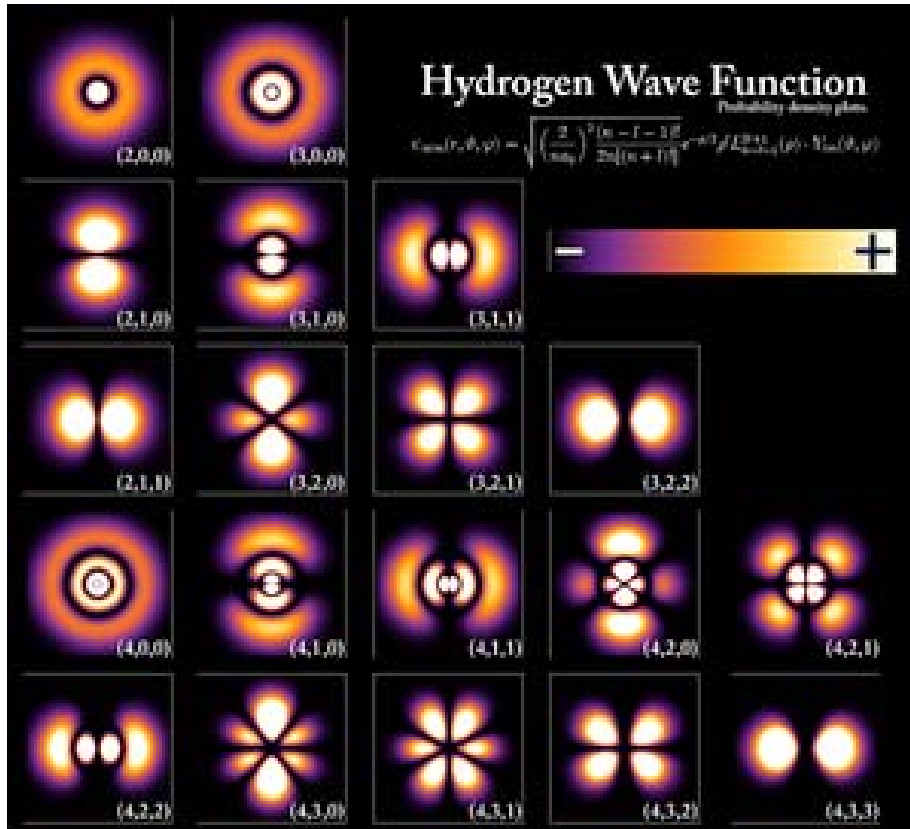
We consider wave function describing collective behavior:

$$i\hbar\partial_t\psi = -\frac{\hbar^2}{2m}\Delta^2\psi + GmM_0 \int_0^r dr' \frac{1}{r'^2} \int_0^{r'} dr'' 4\pi r''^2 |\psi|^2 \cdot \psi(r)$$

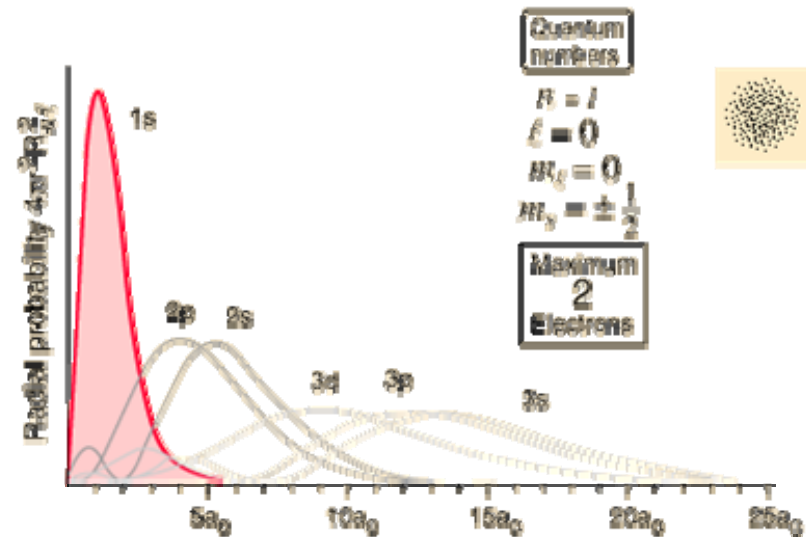
$$M = M_0 \int dr 4\pi r^2 |\psi|^2$$

- Qualitatively it is similar to the hydrogen atom wave function.

- hydrogen atom wave functions.



$$M(r) = \int_0^r dr' 4\pi r'^2 \rho(r')$$

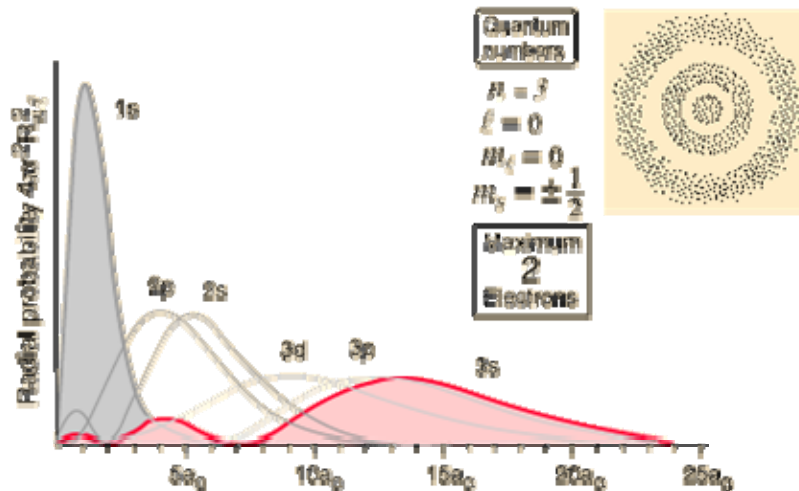


For ground state

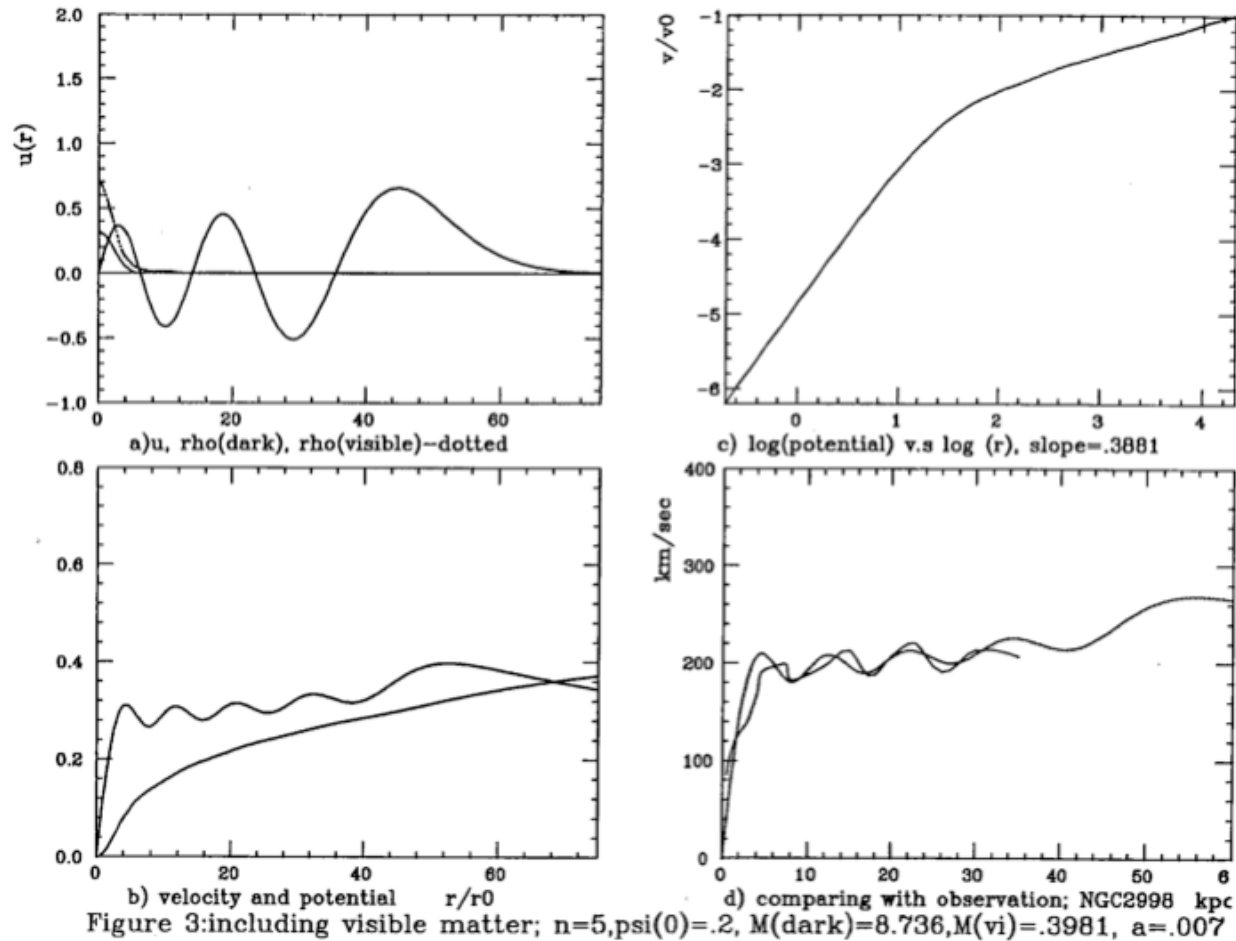
- The corresponding states are called Bose star. The galactic rotation curve for it will be similar to the Keplerian. So not interesting....

Notice, however,

- For dark matter, there is no mechanism to lose the potential energy, the wave function must be highly excited state. This makes the rotation curve flat or rising.



numerical results



ripple wavelength and the rotation velocity,

$$m = 3.3 \cdot 10^{-23} \text{ eV}, \text{ and } M_0 = 0.69 \cdot 10^{12} M_{\odot}.$$

$$\rho_c = 1/4\pi |\hat{\psi}_0|^2 (M_0/r_0^3) = 1.08 \cdot 10^{-22} \text{ g/cm}^3.$$

Prediction/merit

- If a galactic halo is quantum liquid of very light boson, dark matter is wave like, and rotation curve must have wave like feature as well.
- Central cusp of the cold dark matter can be avoided.

Origin of the ultra light boson?

- Not in SM.
- In string theory: moduli fields, dilaton.

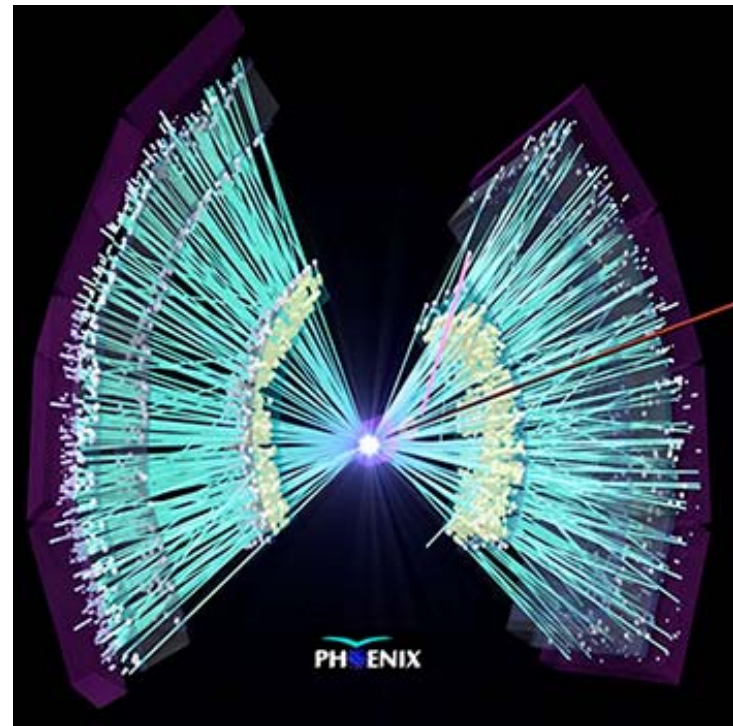
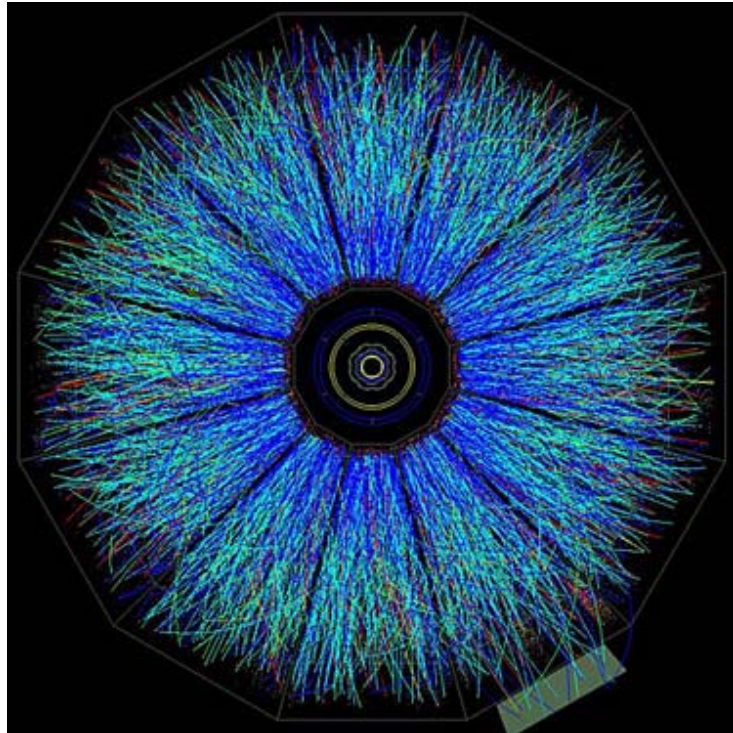
II. Quantum Liquid in RHIC/LHC collider



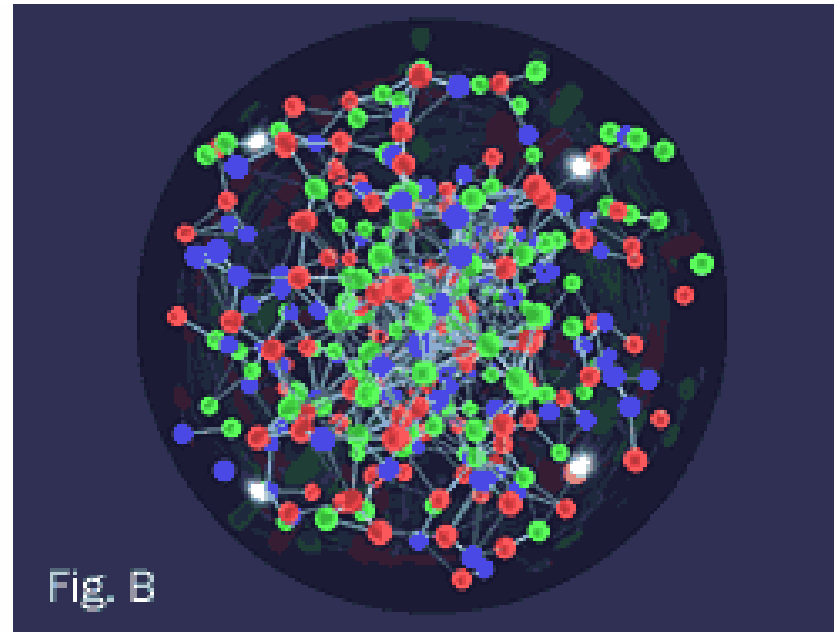
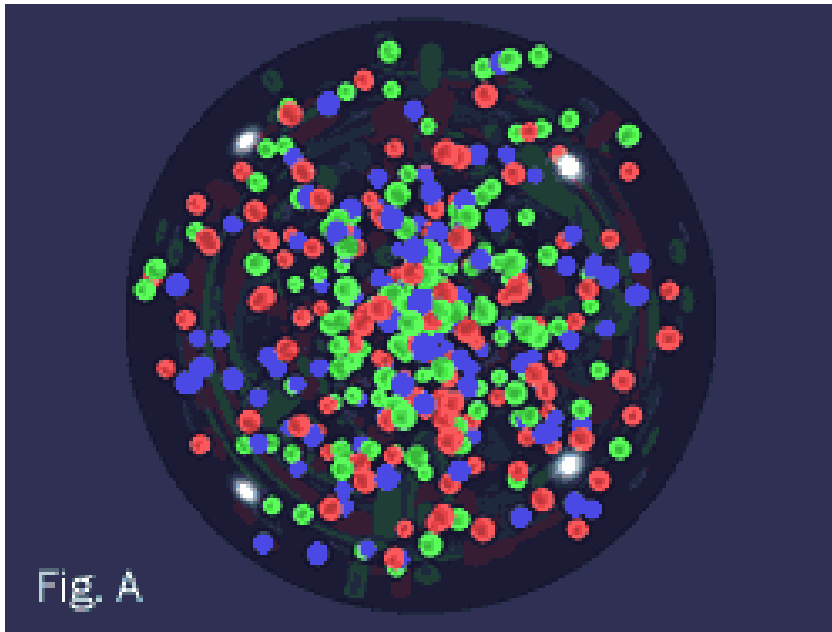
- Au-Au collision to make QGP

Detectors

star / phenix



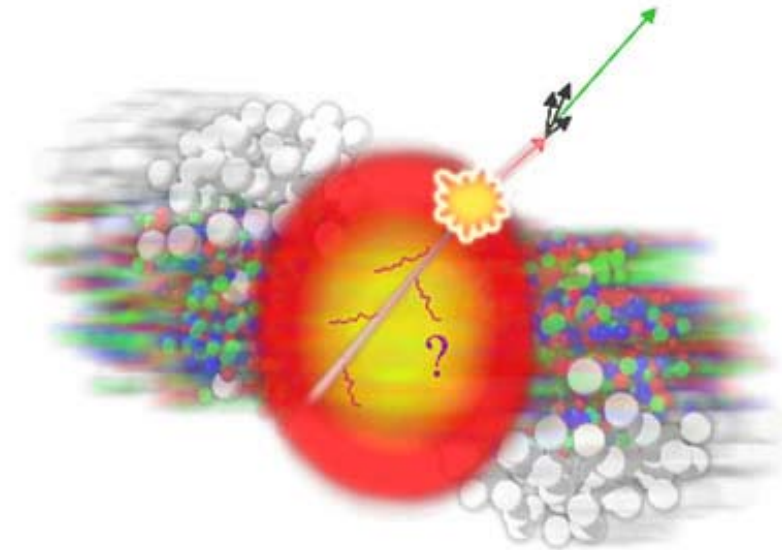
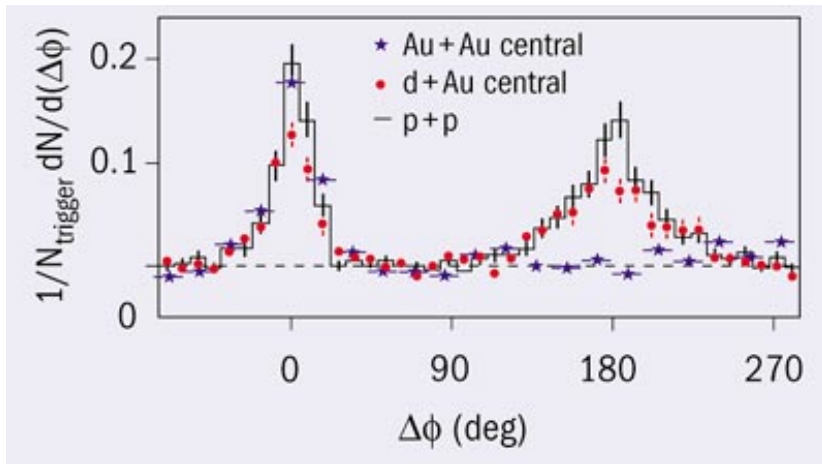
Liquidity due to strong interaction



Evidence and puzzles

- Jet quenching (**hep-th/0607123**)
- Early thermalization (**hep-th/0511199**)
- elliptic flow (**hep-th/0610113**)*
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- These are puzzles from the aspect of AF but clues to use AdS/CFT.

Jet-Quenching

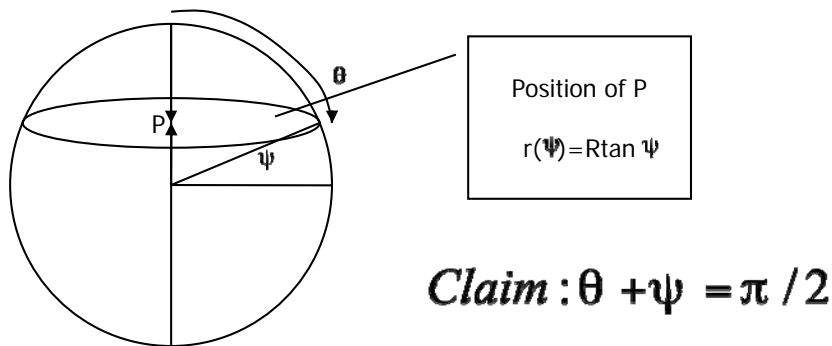


- Energy Loss Problem.

Holography of radiation

SJS with Zahed (hep-th/0407215, PLB)

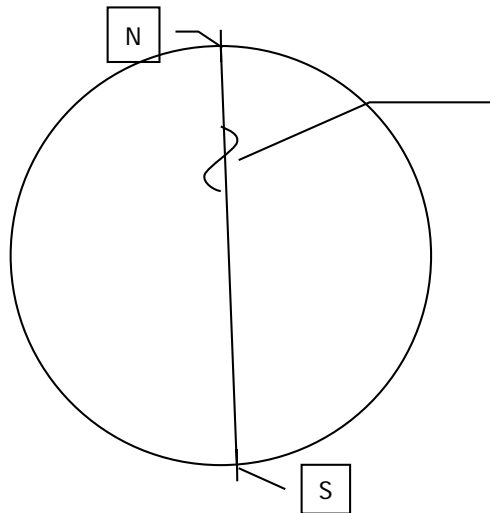
- gluon propagation at boundary v.s. null geodesic along the path passing the center.



- We get point-sphere correspondence.

Evidence

- Mikhailov (hep-th/0305196)



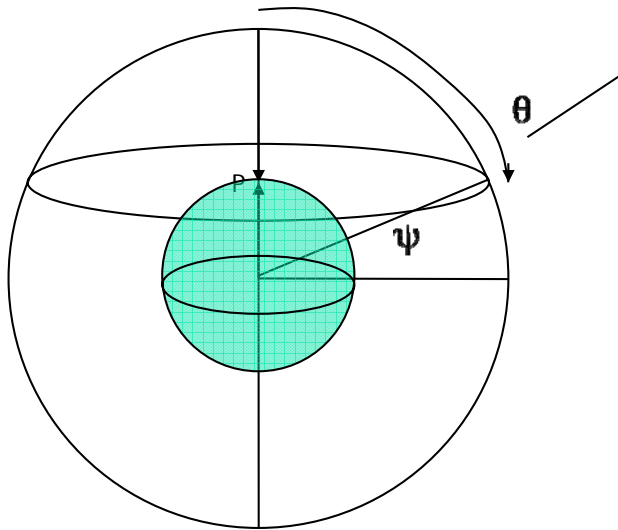
$$E = \frac{\sqrt{\lambda}}{2\pi} \int dt \frac{\dot{a}^2 - (\dot{\mathbf{v}} \times \dot{\mathbf{a}})^2}{(1 - \dot{\mathbf{v}}^2)^2},$$

$$\text{with, } \mathbf{v} = \frac{dx}{dt}, \mathbf{a} = \frac{d^2x}{dt^2}$$

Lienard formular for the radiation
apart from square root

calculated energy of ripple along the string
from N to S passing through the center.

radiation in Black hole background



Maximal propagation distance=
 $1/\pi T$

P will be absorbed into the BH or never get to it
according to the observer.
The dual picture to this is stopping at

Idea of Early Thermalization

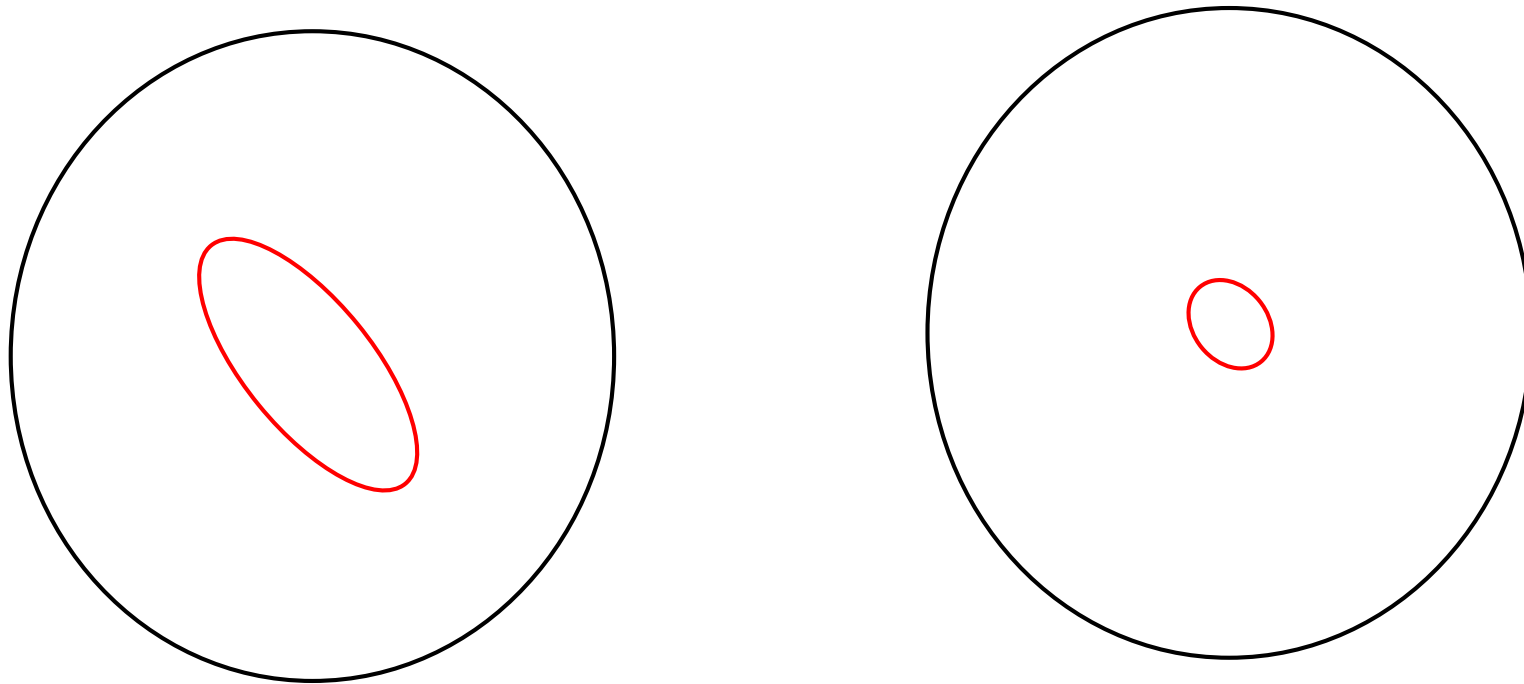
(hep-th/0511199)

Dual Q: why BH is easily formed in ads?

Scattering and particle creation in the boundary has its dual creation at the bulk. It is peaked at some hight and fall.

The point is that the **proper time to fall to the center in ads is the same no matter where you start.**

Falling in AdS and time-focusing effect



It enhances black hole formation in AdS compared with flat spacetime.

Conclusion II

- There is maximal distance independent of initial energy of the gluon $\sim 1/T$
- If this is smaller than the size of the fireball,
then Jet quenching is explained for gluon jet. Since this is statement of propagation of particle in the medium, not much difference between quarks and gluons.
- Problem of energy Loss
=> Problem of Propagation in medium.

Holographic Hydrodynamics

- Maldacena: gauge/gravity duality
- Witten: finite temperature plasma~
ads_BH
- RHIC fireball is expanding.
The dual of expanding plasma=Falling
matter in AdS.
(Shuryak, SJS, Zahed `05)

- Janik, Peschansky: a gravity dual of the expanding SYM plasma= sol. with falling horizon
- Nakamura, SJS: first correction to the JP solution gives the viscosity term.
- Minwalla et.al : Navier-Stokes at the boundary is dual to the Einstein eq. in the bulk.

Holographic chemical Potential

- particle number chemical potential as the boundary value of the 5d electric potential on the brane.
- For deconfinement phase: charge=end of string connecting BH horizon and the probe brane.
- For confinement phase: Baryon vertex touching the probe branes

What next?

- ads/caos?
- ads/superconductivity?
- ads/finance?
-

Happy,
Happy birth day!

Stanley