Black hole/string transition in black hole evaporation

Yoshinori Matsuo

Kindai University

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and work in progress

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Evaporation of black hole can be described by time evolution of massive string fluid

Fluid model of black hole/string transition

At high T, a black hole turns into a bound state of strings

Black hole is also described by a bound state of strings

Q: Does black hole consist of massive strings?

A: The Hagedorn transition occurs during gravitational collapse

Evaporating black hole is time-dependent string fluid

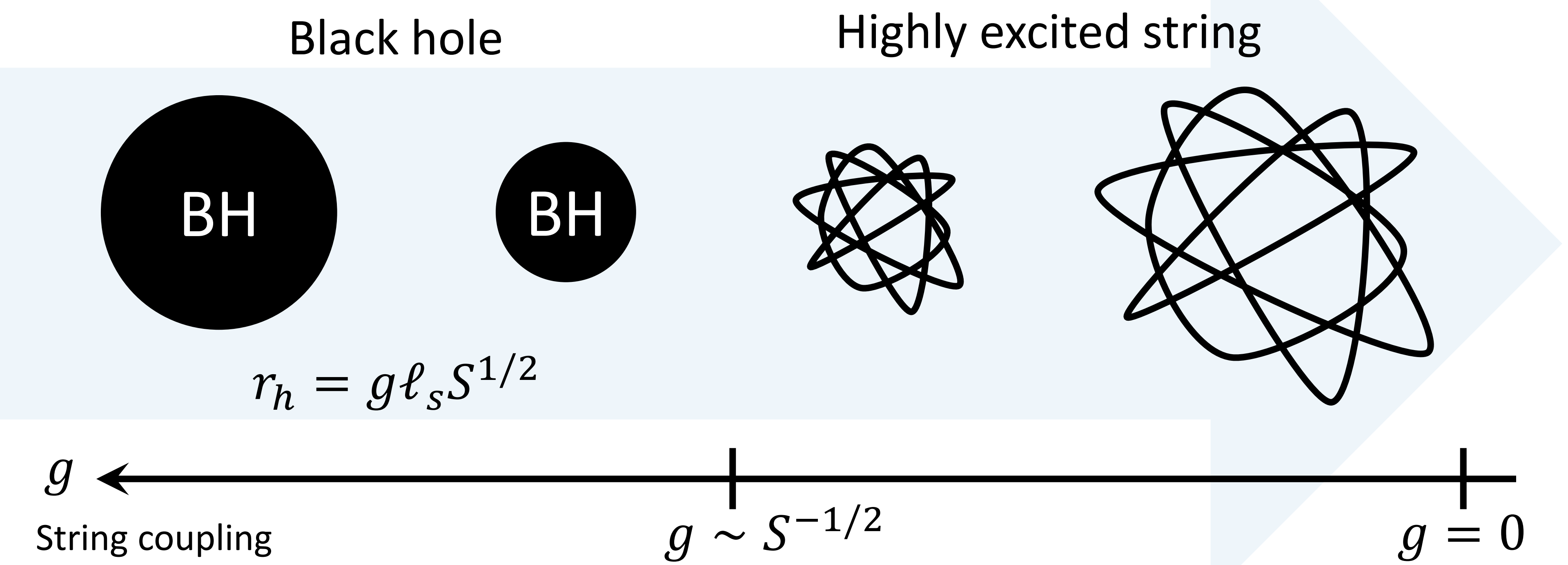
Black hole phase is described by using derivative expansion

String phase has similar structure to dust solution

Black holes turn into string bound state near the Hagedorn temperature

[Susskind,93]

Susskind's proposal



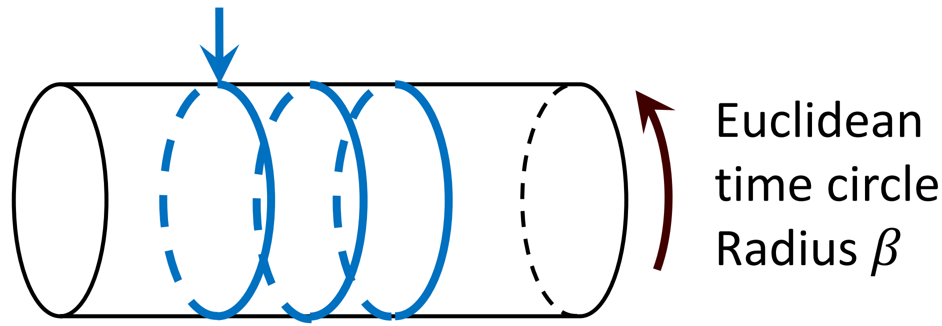
If string coupling is so weak, gravity cannot trap string inside horizon

Similar phase structure can be found for temperature

String bound state is described by winding strings

[Horowitz-Polchinski,98]

χ: winding string on Euclidean time circle



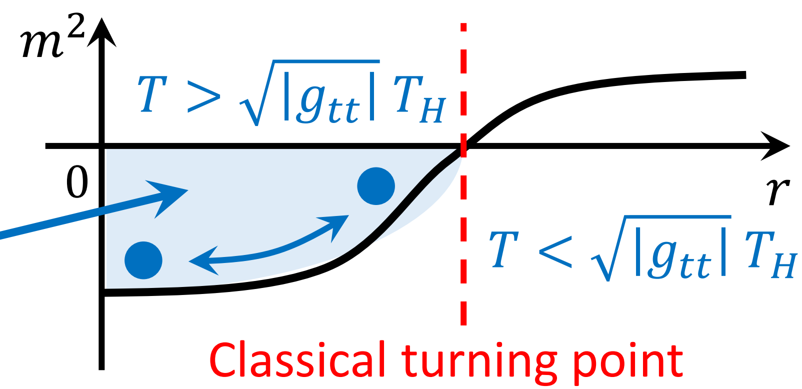
$$0 = \nabla^2 \chi - m^2 \chi$$

$$m^2 = |g_{tt}|\beta^2 - \beta_H^2$$

Mass from tension

Tachyonic at ground state

Classical turning point: $m^2 = 0$



Winding strings are trapped in this region

Local temp. exceeds Hagedorn temp. inside classical turning point

Fluid model of black hole/string transition

Effects of winding string mass gives EM tensor of perfect fluid

$$T^t{}_t = -\underline{(3|g_{tt}|\beta^2 - \beta_H^2)|\chi|^2} \qquad T^i{}_i = \underline{(\beta_H^2 - |g_{tt}|\beta^2)|\chi|^2}$$

$$= \rho \qquad\qquad = P$$

Static solution of Einstein equation for winding string fluid

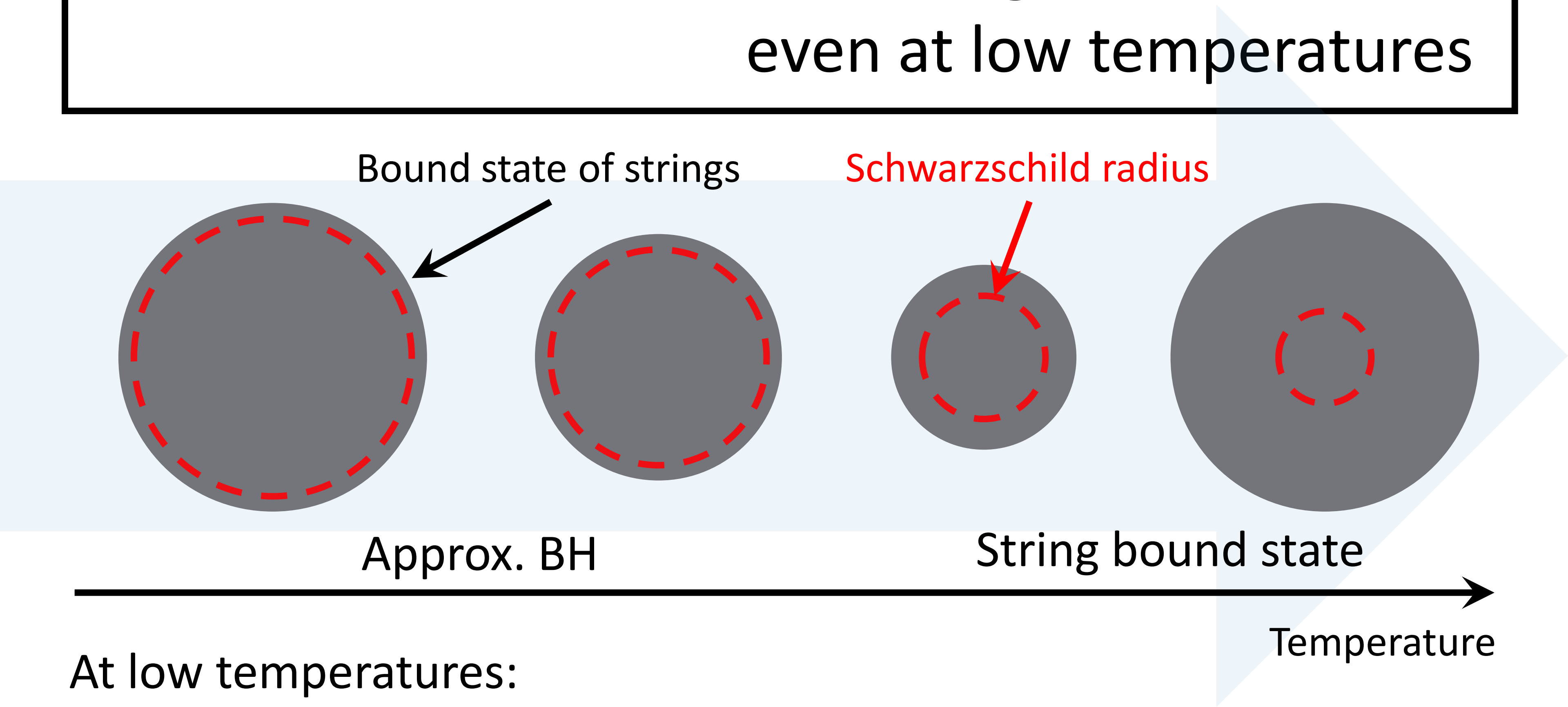
$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)h(r)} + r^2 d\Omega^2$$

$$f(r) = \frac{\beta_h^2}{\beta^2}\left\{\frac{1}{h_0} + 1 - \frac{\sqrt{r_m^2 - r^2}}{r}\left[\sin^{-1}\left(\frac{r}{r_m}\right)\right]\right\}$$

$$h(r) = \frac{\beta^2}{\beta_H^2} h_0 \left(1 - \frac{r^2}{r_m^2}\right)$$

Parameters h_0 and r_m are functions of β

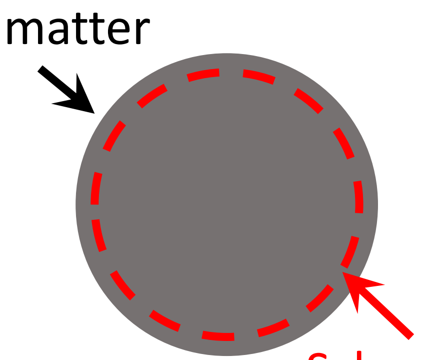
Black hole is bound state of strings even at low temperatures



At low temperatures:

- Size of the star is slightly larger than Schwarzschild radius
- Temperature, mass, entropy are almost same to Schwarzschild
- Interior: almost frozen $|g_{tt}| \ll 1$, very small volume $g_{rr} \ll 1$

Hagedorn transition occurs during gravitational collapse



In gravitational collapse of ordinary matter
red shift factor becomes very small when
the size approaches the Schwarzschild radius

$$|g_{tt}| = \epsilon^2 \simeq \frac{\ell_P^2}{r_h^2}$$

Entropy of massive strings

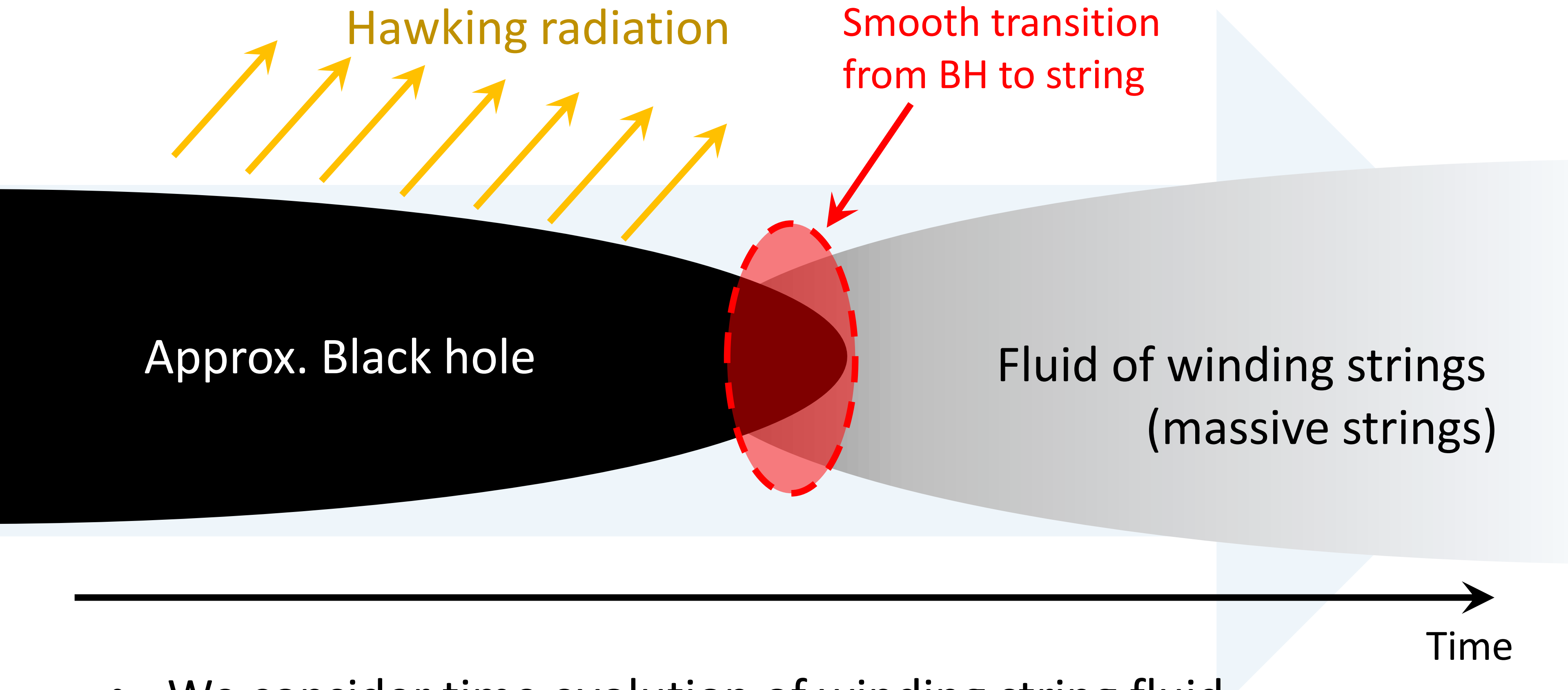
$S = \beta_H E$ ⇨ Temperature is always at $T = \left(\frac{dS}{dE}\right)^{-1} = \beta_H^{-1}$

Temperature of ordinary matters: $T \sim \epsilon^{-1} M \simeq \frac{r_h}{\ell_P} M \gg \beta_H^{-1}$

⇨ Heat transfer from collapsed matters to massive strings

Collapse of ordinary matter gives a bound state of strings

Black hole evaporation can be described by time evolution of massive string fluid



- We consider time evolution of winding string fluid.
- Effect of Hawking radiation should be considered.

Time evolution in black hole phase can be introduced by derivative expansion

Time evolution by emission of Hawking radiation

Very slow ⇨ Derivative expansion for small ∂_t

$$ds^2 = -f(r,t)dt^2 + \frac{dr^2}{f(r,t)h(r,t)} + r^2 d\Omega^2$$

Assume local equilibrium ⇨ Outgoing non-zero fluid velocity

$$T_{\mu\nu} = (\rho + P)u_\mu u_\nu + P g_{\mu\nu} \qquad u^\mu = f^{-1/2}\delta^\mu{}_t + v^r \delta^\mu{}_r + \mathcal{O}(\partial_t^2)$$

We found that the metric is the same form to the static case but

- temp. $\beta(t)$ and int. const. are now functions of t.
- velocity $v^r = \mathcal{O}(\partial_t)$ and the metric has $\mathcal{O}(\partial_t^2)$ corrections.

String phase can be approximated by dust

At high temperature

- Spacetime is almost flat.
- Density of fluid is very small, $|\chi|^2 \sim (\beta - \beta_H)^3$.
- Pressure $P \sim (\beta_H^2 - |g_{tt}|\beta^2)$ is small.

Fluid approximately behave as a dust

Ansatz of the metric

$$ds^2 = -e^{2\varphi}dt^2 + a(t)\left(e^{2\psi}dr^2 + r^2 d\Omega^2\right)$$

⇨ Expanding fluid $a(t) \propto t^{2/3}$

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Thank you