Fluid model of black hole/string transition

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Black hole is fluid of strings

Black hole/string transition near string scale (Hagedorn temp.)

String bound state (self-gravitating string) $\overset{\text{transition}}{\Longleftrightarrow}$ Black hole

Temperature of strings effectively exceeds Hagedorn temperature

$\Rightarrow$ Strings approximately become fluid in the bound state

We derive geometry of string fluid

High temperature: bound state of strings

Low temperature: approximately black hole (horizonless)

Plan of Talk

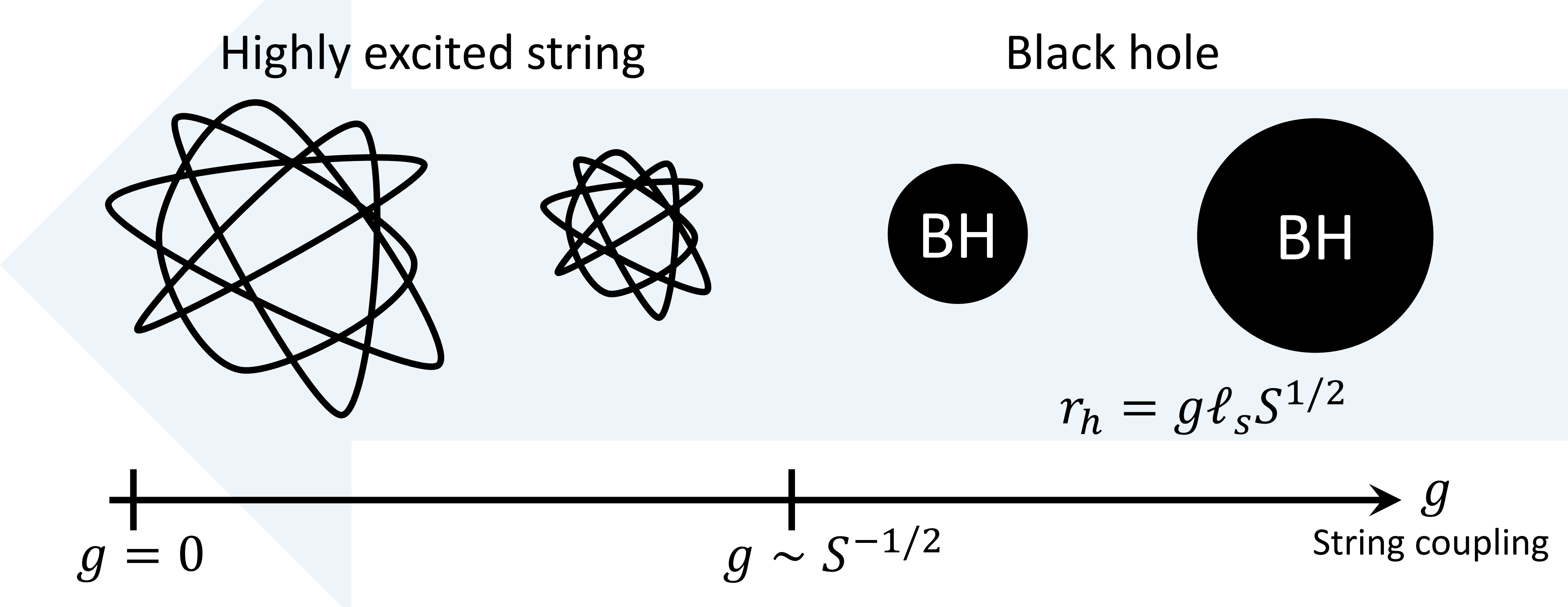
1. Black hole/string transition
    - String becomes black hole by self-gravitation
    - Horowitz-Polchinski model: Self-gravitating winding string
    - Temperature effectively exceeds Hagedorn temperature

2. Fluid model of self-gravitating strings

String become black hole by self-gravitation

[Susskind, arXiv:hep-th/9309145, arXiv:2110.12617]

Susskind's proposal



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

Similar phase structure can be found for temperature

Horowitz-Polchinski model: Self-gravitating winding strings

[Horowitz-Polchinski, Phys.Rev.D 57 (1998)]

χ: winding string on Euclidean time circle

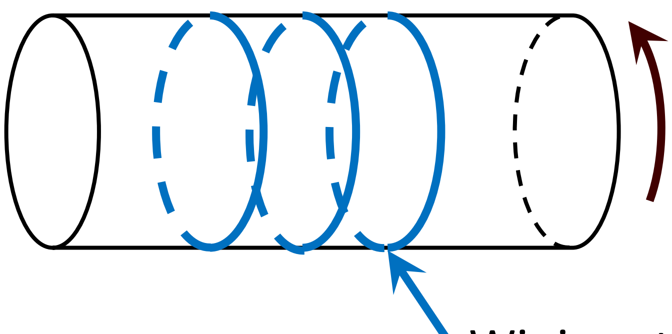
mass:

in gravitational potential

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

Mass from tension

Tachyonic at ground state



Horowitz-Polchinski studied bound state of χ by self-gravitation

Horowitz-Polchinski model:
Self-gravitating winding strings

[Horowitz-Polchinski, Phys.Rev.D 57 (1998)]

$$0 = \nabla^2\chi - 2\varphi\beta^2\chi - (\beta^2 - \beta_H^2)\chi$$

$$0 = \nabla^2\varphi - \beta^2|\chi|^2 \qquad\qquad (\, g_{tt} = -e^{2\varphi} \,)$$

- near Hagedorn temperature
- Linearized gravity
- Numerical solution

We would like to find analytic solution of black hole/string transition

$\Downarrow$

Some approximation/simplification is needed

Temperature of winding strings effectively exceeds Hagedorn temperature

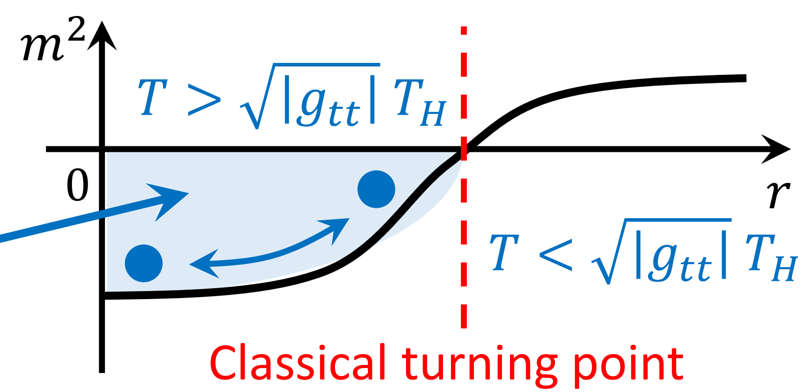
Winding strings is tachyonic beyond Hagedorn temp $T > \sqrt{|g_{tt}|}\, T_H$

EOM of winding string field

$0 = \nabla^2\chi - m^2\chi$ ⇨ Schrödinger eq. in potential $V(r) = m^2$

Classical turning point:
$m^2 = |g_{tt}|\beta^2 - \beta_H^2 = 0$

Winding strings are trapped in this region



Local temp. exceeds Hagedorn temp. inside classical turning point

⇨ Winding condensate beyond Hagedorn temperature

Plan of Talk

1. Black hole/string transition

2. Fluid model of self-gravitating strings

- Winding strings can be approximated by perfect fluid
- Geometry is junction of fluid solution and Schwarzschild
- High T : string bound state $\Longleftrightarrow$ Low T : approx. black hole
- Horizonless geometry is realized by
  negative energy of true vacuum

Winding strings can be approximated by perfect fluid

Bound state of strings is ground state of Horowitz-Polchinski model

⇨ Naively, only mass of winding strings is important

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

Mass terms in energy-momentum tensor (ignoring kinetic terms)

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

EM tensor of perfect fluid

$$T^t{}_t = -\rho \qquad T^i{}_i = P$$

ρ: energy density $\quad P$: pressure

Fluid is in the region $P > 0$

⇨ Local temp. exceeds Hagedorn temp.

Geometry is given by junction of fluid solution and Schwarzschild

We solve Einstein equation (for $D = 4$)

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

Interior solution: fluid of winding strings

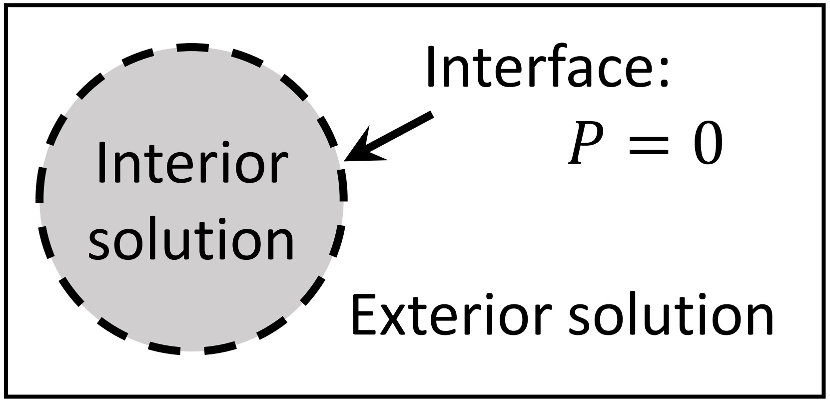
$$T^t{}_t = -(3|g_{tt}|\beta^2 - \beta_H^2)|\chi|^2 \qquad T^i{}_i = (\beta_H^2 - |g_{tt}|\beta^2)|\chi|^2$$

⇨ We obtain an analytic solution [Wyman, Phys.Rev.75 (1949)]

Exterior solution: vacuum

$$T_{\mu\nu} = 0$$

⇨ Schwarzschild solution



High temperature: bound state of strings
Low temperature: approximately black hole

High temperature (near Hagedorn temperature)

- Weakly bounded by gravitation in almost flat spacetime
- Size of bound state (star) $\gg$ Schwarzschild radius r_h
- Consistent with Horowitz-Polchinski solution

Low temperature

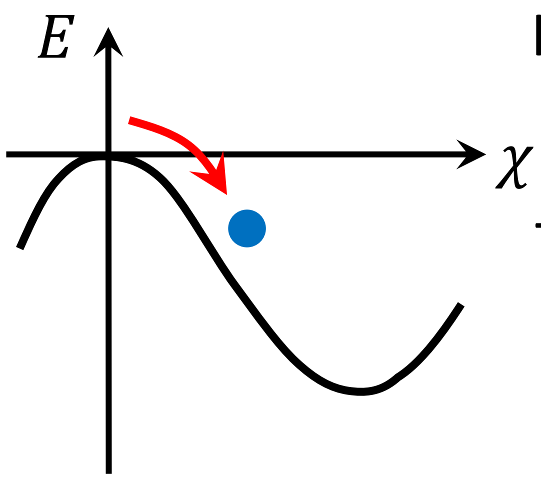
- Almost frozen inside star ($f(r) \ll 1$)
- Size of bound state (star) $\simeq$ Schwarzschild radius r_h
- Temperature of fluid $\simeq$ Hawking temperature
- Approximately Schwarzschild (Mass and entropy approx. agree)

Horizonless geometry is realized by negative energy in true vacuum

Buchdahl theorem: No static star has size of $r_0 \leq \frac{9}{8} r_h$

Assumptions:
- Static Spherically symmetric
- Pressure is isotropic (perfect fluid)
- Energy density is non-increasing outwards

$\Rightarrow$ No negative energy is assumed



In our model, energy is renormalized as

$$E = 0 \text{ for } \chi = 0 \text{ (in } r \to \infty)$$

Temp. in BH exceeds Hagedorn temp. by blue shift

$\Downarrow$ Winding condensate

Negative energy in true vacuum

Horizonless geometry is realized by stringy effect

Black hole is fluid of strings

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Thank you