Perturbations of Hairy Black Holes in Shift-symmetric Scalar-Tensor theories

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Hiromu Ogawa

Tsutomu Kobayashi

Rikkyo Univ.

Teruaki Suyama

RESCEU the Univ of Tokyo

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Introduction

General Relativity (GR) 100th anniversary

most successful gravitational theory **"now"**

Modified Gravity (MG) explains accelerating Universe

additional field, higher dimension, Lorentz violation,etc…

How to compare MG with GR?

"gravitational waves

"not studied in MG

Astrophysical tests

using Black Holes

Motivation

BH Hair

Many ST theory: No-hair theorem **mass**, **charge**, **angular momentum**

(Brans Dicke,K-essence,Galileon, etc…)

Bekenstein (1995); Hui, Nicolis(2014)…

Shift-symmetric ST theory **with time-dependent scalar field**

→ BH solution found with non-trivial **scalar hair**

(this scalar is regular at the horizon)

Bavichev, Charmousis(**2014**)

Stealth Schwarzschild

Schwarzschild metric with nontrivial configuration of the scalar field

Self-tuned Schwarzschild-de-sitter

screening of the bare huge cosmological constant

Motivation

However…

GR Schwarzschild Stealth Schwarzschild

Distinguishable?

↓

Perturbation

Stability?

Can exist?

Gravitational waves?

Dressing BH in

Shift-symmetric Scalar-Tensor Theory

Bavichev, Charmousis(2014)

Dressing BH in Shift-symmetric ST theory

Shift & reflection symmetry: $\phi \to \phi + \mathrm{const.}, \quad \phi \to -\phi$

$$\mathcal{L} = [\zeta R - \eta(\partial\phi)^2 + \beta G^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - 2\Lambda]$$

$\zeta > 0, \eta, \beta : \mathrm{const}$

$\Lambda :$ cosmological constant

Shift symmetry

$\phi \to \phi + \mathrm{const.}$ → EOM for scalar

$$\nabla_\mu J^\mu = 0$$

$$J^\mu = (\eta g^{\mu\nu} - \beta G^{\mu\nu})\partial_\nu\phi$$

Assumptions

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

$J^r = 0$ → Current $J^2 = J_\mu J^\mu$ regular at the horizon

$\phi(t, r) = qt + \psi(r)$ → **Space-time is static in Shift-symmetric theory**

Dressing BH in Shift-symmetric ST theory

$$\mathcal{L} = [\zeta R - \eta(\partial\phi)^2 + \beta G^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - 2\Lambda] \qquad \phi(t,r) = qt + \psi(r)$$

Stealth Schwarzschild

$$f(r) = h(r) = 1 - \frac{\mu}{r} \qquad \mu : \text{const.}$$

$$\phi_\pm = qt \pm q\mu\left[2\sqrt{\frac{r}{\mu}} + \log\frac{\sqrt{r}-\sqrt{\mu}}{\sqrt{r}+\sqrt{\mu}}\right] + \phi_0$$

Self-tuned Schwarzschild-de-sitter

$$f(r) = h(r) = 1 - \frac{\mu}{r} + \frac{\eta}{3\beta}r^2 \longrightarrow \Lambda_{\text{eff}} = -\frac{\zeta\eta}{\beta}$$

this metric represent Schwarzschild BH
in the presence of cosmological constant

present model Λ does not appear!

we do not conceive huge bare Λ through the metric

Bavichev, Charmousis(2014)

Dressing BH in Shift-symmetric ST theory

$$\mathcal{L} = [\zeta R - \eta(\partial\phi)^2 + \beta G^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - 2\Lambda]$$

Stealth Schwarzschild

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Self-tuned Schwarzschild-de-sitter

$$f(r) = h(r) = 1 - \frac{\mu}{r} + \frac{\eta}{3\beta}r^2 \quad \longrightarrow \quad \Lambda_{\text{eff}} = -\frac{\zeta\eta}{\beta}$$

$$\psi(r)' = \pm\frac{q}{h(r)}\sqrt{1-h(r)} \qquad \Lambda > \Lambda_{\text{eff}}$$

Babichev, Charmousis(2014) can be generalized

$$\mathcal{L} = G_2(X) + G_4(X)R + G_{4X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$

Kobayashi, Tanahashi(2014)

BH perturbations with
time-dependent scalar

HO, Kobayashi, Suyama
in preparation

BH perturbations with **time-dependent scalar**

The most general 2nd-order theory with shift & reflection symmetries

$$\mathcal{L} = G_2(X) + G_4(X)R + G_{4X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$

$$\phi(t,r) = qt + \psi(r)$$

Perturbations can be written as following eq (odd-parity)

$$g_{\mu\nu} = g^{(0)}_{\mu\nu} + h_{\mu\nu}$$

$$h_{tt} = 0, \quad h_{tr} = 0, \quad h_{rr} = 0$$

$$h_{ta} = \sum_{l,m} h_{0,lm}(t,r) E_{ab}\partial^b Y_{lm}(\theta,\varphi)$$

$$h_{ra} = \sum_{l,m} h_{1,lm}(t,r) E_{ab}\partial^b Y_{lm}(\theta,\varphi)$$

$$h_{ab} = \sum_{l,m} h_{2,lm}(t,r)[E_a{}^c\nabla_c\nabla_b Y_{lm}(\theta,\varphi) + E_b{}^c\nabla_c\nabla_a Y_{lm}(\theta,\varphi)]$$

$$ds^2 = -A(r)dt^2 + \frac{1}{B(r)}dr^2 + r^2 d\Omega^2$$

$$E_{ab} = \sqrt{\det\gamma}\,\epsilon_{ab}$$

γ_{ab} two-dim metric on the sphere

ϵ_{ab} Levi-Civita symbol

Detail:Suyama san's poster"BH perturbations in Horndeski theory"

BH perturbations with **time-dependent scalar**

$$\mathcal{L} = G_2(X) + G_4(X)R + G_{4X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right] \qquad ds^2 = -A(r)dt^2 + \frac{1}{B(r)}dr^2 + r^2 d\Omega^2$$

$$\phi(t,r) = qt + \psi(r)$$

action 2nd-order in perturbations

↓

field redefinition

↓

master eq

↓

Determination of perturbations behavior

BH perturbations with **time-dependent scalar**

$$\mathcal{L} = G_2(X) + G_4(X)R + G_{4X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right] \qquad ds^2 = -A(r)dt^2 + \frac{1}{B(r)}dr^2 + r^2 d\Omega^2$$

$$\phi(t,r) = qt + \psi(r)$$

action 2nd-order in perturbations

time-dependent scalar(my result)

mixing term!

$$\dot{h}_i := \frac{\partial h_i}{\partial t}, \quad h_i' := \frac{\partial h_i}{\partial r}$$

$$\frac{2l+1}{2\pi}\mathcal{L}^{(2)} = A_1 h_0^2 + A_2 h_1^2 + A_4 h_0 h_1 + A_3\left(\dot{h}_1^2 - 2h_0'\dot{h}_1 + h_0'^2 + \frac{4}{r}h_0\dot{h}_1\right)$$

static scalar(Kobayashi, Motohashi, Suyama(2012))

$$\frac{2l+1}{2\pi}\mathcal{L}^{(2)} = a_1 h_0^2 + a_2 h_1^2 + a_3\left(\dot{h}_1^2 - 2\dot{h}_1 h_0' + {h_0'}^2 + \frac{4}{r}\dot{h}_1 h_0\right)$$

BH perturbations with **time-dependent scalar**

$$\mathcal{L} = G_2(X) + G_4(X)R + G_{4X}\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)^2\right]$$

$$\phi(t,r) = qt + \psi(r)$$

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$$\frac{2l+1}{2\pi}\mathcal{L}^{(2)} = a_1 h_0^2 + a_2 h_1^2 + a_3\left(\dot{h}_1^2 - 2\dot{h}_1 h_0' + {h_0'}^2 + \frac{4}{r}\dot{h}_1 h_0\right)$$

time-dependent

$$A_3 = G_4 - \left(\frac{q^2}{A} - B\Psi'^2\right)G_{4X}$$

static

$$a_3 = G_4 - B\Psi'^2 G_{4X}$$

other coefficients are modified similarly but not in exactly the same way

→ **Implications (difference time-dependent between static)**

propagation of speed changes?

stability conditions changes?

Summary and Outlook

BH with time-dependent scalar

found some interesting Black Hole solutions

BH stability in Shift-symmetric ST theory

obtained action up to 2nd-order in perturbations

BH stability conditions may change

Outlook

derive master equation

obtain BH stability conditions