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

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### 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? Astrophysical tests "gravitational waves "not studied in MG using Black Holes

## Motivation

#### **BH Hair**

Many ST theory: No-hair theorem mass

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

mass, charge, angular momentum

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

## Dressing BH in Shift-symmetric ST theory

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

#### Assumptions

 $ds^{2} = -h(r)dt^{2} + \frac{dr^{2}}{f(r)} + r^{2}d\Omega^{2}$   $J^{r} = 0 \longrightarrow \text{Current} J^{2} = J_{\mu}J^{\mu} \text{ regular at the horizon}$   $\phi(t, r) = qt + \psi(r) \longrightarrow \text{Space-time is static in}$  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**  $\Lambda$  **does not appear!** we do not conceive huge bare  $\Lambda$  through the metric

## 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 $f(r) = h(r) = 1 - \frac{\mu}{r} \qquad \mu : \text{const.}$ $\phi_{\pm} = qt \pm q\mu \left[ 2\sqrt{\frac{r}{\mu}} + \log \frac{\sqrt{r} - \sqrt{\mu}}{\sqrt{r} + \sqrt{\mu}} \right] + \phi_0$

Self-tuned Schwarzschild-de-sitter

$$f(r) = h(r) = 1 - \frac{\mu}{r} + \frac{\eta}{3\beta}r^{2} \longrightarrow \Lambda_{\text{eff}} = -\frac{\zeta\eta}{\beta}$$
$$\psi(r)' = \pm \frac{q}{h(r)}\sqrt{1 - h(r)} \qquad \Lambda > \Lambda_{\text{eff}}$$

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)

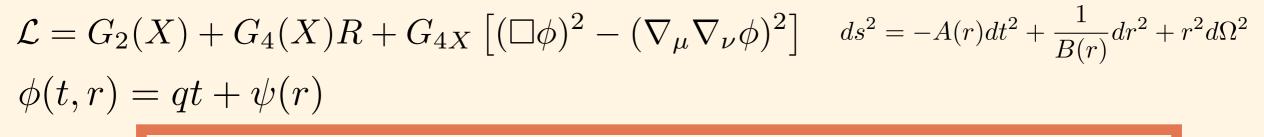
HO, Kobayashi, Suyama in preparation

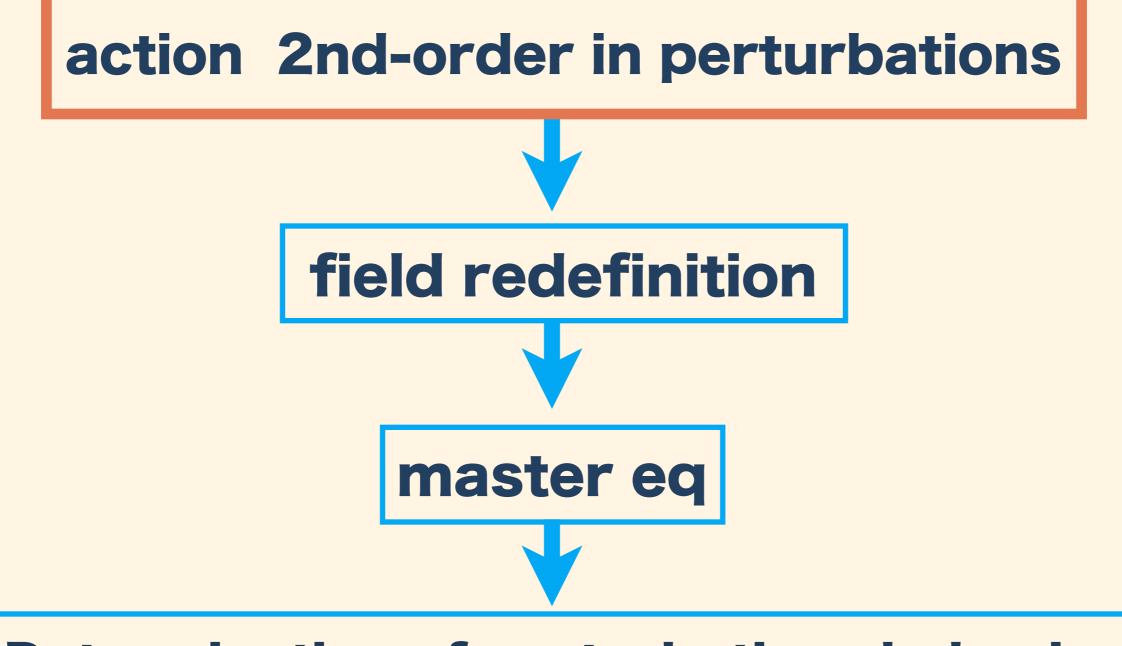
#### The most general 2nd-order theory with shift & reflection symmetries

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

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

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





#### **Determination of perturbations behavior**

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

action 2nd-order in perturbations

time-dependent scalar(my result) mixing term!  $\dot{h}_i := \frac{\partial h_i}{\partial t}, \quad h'_i := \frac{\partial h_i}{\partial r}$  $\frac{2l+1}{2\pi}\mathcal{L}^{(2)} = A_1h_0^2 + A_2h_1^2 + A_4h_0h_1$  $+A_3\left(\dot{h}_1^2 - 2h_0'\dot{h}_1 + h_0'^2 + \frac{4}{r}h_0\dot{h}_1\right)$ static scalar(Kobayashi, Motohashi, Suyama(2012))  $\frac{2l+1}{2\pi}\mathcal{L}^{(2)} = a_1h_0^2 + a_2h_1^2$  $+a_3\left(\dot{h}_1^2-2\dot{h}_1h_0'+h_0'^2+\frac{4}{r}\dot{h}_1h_0\right)$ 

$$\mathcal{L} = G_2(X) + G_4(X)R + G_{4X} \left[ (\Box \phi)^2 - (\nabla_\mu \nabla_\nu \phi)^2 \right] \quad ds^2 = -A(r)dt^2 + \frac{1}{B(r)}dr^2 + r^2 d\Omega^2$$
  
$$\phi(t,r) = qt + \psi(r) \qquad \qquad \frac{2l+1}{2\pi}\mathcal{L}^{(2)} = A_1h_0^2 + A_2h_1^2 + A_4h_0h_1$$

#### time-dependent

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

$$\begin{aligned} \frac{2l+1}{2\pi} \mathcal{L}^{(2)} = &A_1 h_0^2 + A_2 h_1^2 + A_4 h_0 h_1 \\ &+ A_3 \left( \dot{h}_1^2 - 2h'_0 \dot{h}_1 + h'_0^2 + \frac{4}{r} h_0 \dot{h}_1 \right) \\ \frac{2l+1}{2\pi} \mathcal{L}^{(2)} = &a_1 h_0^2 + a_2 h_1^2 \\ &+ a_3 \left( \dot{h}_1^2 - 2\dot{h}_1 h'_0 + {h'_0}^2 + \frac{4}{r} \dot{h}_1 h_0 \right) \end{aligned}$$

#### static

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

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