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FCT

Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

一般化された Proca 理論 におけるブラックホール

南辻真人

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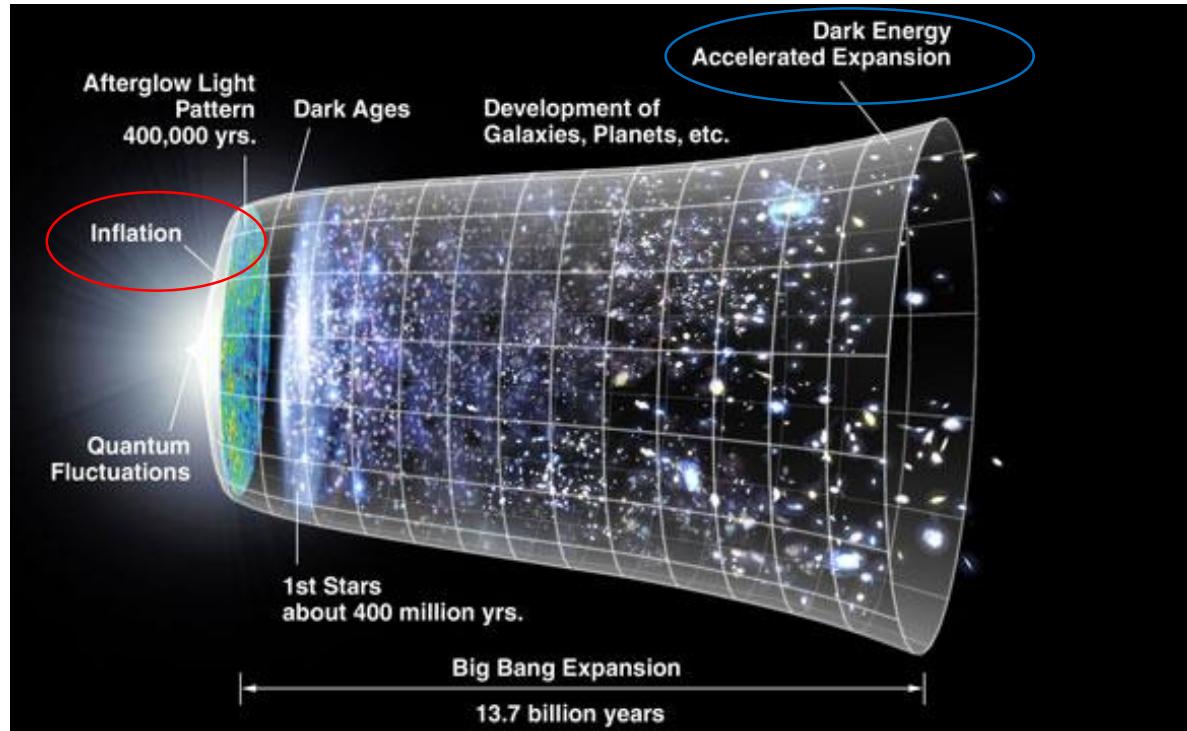
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導入

修正重力模型

暗黒エネルギー

インフレーション



$$G_{\mu\nu}(g) = 8\pi G \left(T_{\mu\nu}^{(SM+DM)} + T_{\mu\nu}^{(\phi)}(g, \phi) \right)$$

↓

$$G_{\mu\nu}(g) + H_{\mu\nu}(g, \phi) = 8\pi G T_{\mu\nu}^{(SM+DM)}$$

新たな自由度 ⇒ スカラー・テンソル理論
 $(g_{\mu\nu}, \phi)$

Horndeski 理論

Horndeki (74)

Deffayet, Deser and Esposito-Farese (09)

Kobayashi, Yokoyama and Yamaguchi (11)

$$S = \sum_{i=2}^5 \int d^4x \sqrt{-g} \mathcal{L}_i \quad X = -\frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi \quad \text{正準運動項}$$

$$\mathcal{L}_2 = G_2(\varphi, X)$$

$$\varphi_{\mu\dots\nu} = \nabla_\mu \dots \nabla_\nu \varphi$$

$$\mathcal{L}_3 = -G_3(\varphi, X) \square \varphi$$

$$\mathcal{L}_4 = G_4(\varphi, X) R + G_{4X}(\varphi, X) [(\square \varphi)^2 - \varphi_{\mu\nu}^2]$$

$$\mathcal{L}_5 = -G_5(\varphi, X) G_{\mu\nu} \varphi^{\mu\nu} - \frac{G_{5X}(\varphi, X)}{6} [(\square \varphi)^3 + 2\varphi_{\mu\nu}^3 - 3\varphi_{\mu\nu}^2 \square \varphi]$$

運動方程式が2階微分方程式で記述される
最も一般的な(单一場)スカラー・テンソル理論

一般相對論 + 宇宙項: $R - 2\Lambda$

$$\Rightarrow G_2 = -2\Lambda, \quad G_4 = 1, \quad G_3 = G_5 = 0$$

k-essence: $R - K(X, \varphi)$ ⊃ quintessence $R - X - V(\varphi)$

$$\Rightarrow G_2 = -K(X, \varphi), \quad G_4 = 1, \quad G_3 = G_5 = 0$$

非最小結合: $F(\varphi)R + \dots \Rightarrow G_4 = F(\varphi), \dots$

$$\supset f(R)$$

Galileon: $-G(X, \varphi)\square\varphi + \dots$

$$\Rightarrow G_3 = -G(X, \varphi), \dots$$

非最小微分結合: $\zeta R + \eta G^{\mu\nu} \partial_\mu \varphi \partial_\mu \varphi + \dots$

$$\Rightarrow G_4 = \zeta + \eta X, \dots$$

Einstein-dilaton-Gauss-Bonnet 理論: $R + X + f(\varphi)R_{GB}$

$$R_{GB} := R^2 - 4R_{\mu\nu}^2 + R_{\mu\nu\alpha\beta}^2$$

$$\Rightarrow G_2 = X + 8f^{(4)}X^2(3 - \ln X), \quad G_3 = 4f^{(3)}X(7 - 3\ln X),$$

$$G_4 = \frac{1}{2} + 4f^{(2)}X(2 - \ln X), \quad G_5 = -4f^{(1)}\ln X$$

$$f^{(n)} = f^{(n)}(\varphi)$$

シフト対称な Horndeski 理論 : $\varphi \rightarrow \varphi + c$

$$S = \sum_{i=2}^5 \int d^4x \sqrt{-g} \mathcal{L}_i \quad X = -\frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi$$

$$\mathcal{L}_2 = G_2(X)$$

$$\mathcal{L}_3 = -G_3(X) \square \varphi$$

$$\mathcal{L}_4 = G_4(X)R + G_{4X}(X)[(\square \varphi)^2 - \varphi_{\mu\nu}^2]$$

$$\mathcal{L}_5 = -G_5(X)G_{\mu\nu}\varphi^{\mu\nu} - \frac{G_{5X}(X)}{6}[(\square \varphi)^3 + 2\varphi_{\mu\nu}^3 - 3\varphi_{\mu\nu}^2 \square \varphi]$$

運動項のみの依存性を残す

ブラックホールの無毛性 に関する議論

仮定1) 漸近平坦な静的球対称時空 Hui and Nicolis (11)

$$ds^2 = -A(r)dt^2 + \frac{dr^2}{B(r)} + r^2(d\theta^2 + \sin\theta^2 d\phi^2)$$

$$A, B \rightarrow 1 \quad (r \rightarrow \infty), \quad A(r_h) = B(r_h) = 0$$

- シフト対称性 \Rightarrow 保存カレント $J^\mu := \frac{\delta S}{\delta \partial_\mu \varphi}$

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

仮定2) スカラー場が時空と同じ対称性を持つ

$$\varphi = \varphi(r) \Rightarrow J^\mu = (0, J^r, 0, 0)$$

漸近平坦性 $r \rightarrow \infty \Rightarrow \varphi' \rightarrow 0$

仮定3) 正則性 $J^2 = J^\mu J_\mu = \frac{1}{B} (J^r)^2 < \infty$

仮定4) $G_i(X)$ の微分が X の0または正幕しか含まない

$$\begin{aligned} J^r &= -BG_{2X}\phi' + \frac{B^2\phi'^2}{2} \left(\frac{A'}{A} + \frac{4}{r} \right) G_{3X} + \frac{2B^2\phi'}{r} \left(\frac{A'}{A} - \frac{1}{Br} + \frac{1}{r} \right) G_{4X} \\ &\quad - \frac{2B^3\phi'^3}{r} \left(\frac{A'}{A} + \frac{1}{r} \right) G_{4XX} - \frac{B^3\phi'^2}{2r^2} \frac{A'}{A} \left(\frac{3B-1}{B} \right) G_{5X} + \frac{A'}{A} \frac{B^4\phi'^4}{2r^2} G_{5XX} \end{aligned}$$

$$\Rightarrow J^r = B * \varphi' * F(g, g', g'', \varphi')$$

無限遠方で正準運動項の寄与が支配 $G_2 = \alpha X + O(X^2)$

$$\Rightarrow J^r \rightarrow \alpha B \varphi' \Rightarrow F = \alpha \rightarrow const$$

- 保存則: $\nabla_\mu J^\mu = 0 \Rightarrow \partial_r \left(\sqrt{\frac{A}{B}} J^r r^2 \right) = 0 \Rightarrow \sqrt{\frac{A}{B}} J^r r^2 = K = \text{const}$

- 地平面 $r = r_h$: $A(r_h) = B(r_h) = 0, \frac{A(r_h)}{B(r_h)} = \text{finite}$

$$\Rightarrow J^2 = J^\mu J_\mu = \frac{1}{B} (J^r)^2 < \infty \Rightarrow J^r(r_h) = 0 \Rightarrow K = 0$$

$$\Rightarrow J^r = 0 \quad \forall r$$

$$J^r = B * \varphi' * F(g, g', g'', \varphi') = 0$$

$$B, F \neq 0 \text{かつ連続的に変化} \Rightarrow \varphi'(r) = 0 \quad \forall r$$

非自明なブラックホール 解

仮定1)-4) のいずれかを破る。

⇒ 仮定1) : 漸近 anti-de Sitter ブラックホール

Rinaldi (12) Minamitsuji (14) Anabalón, Cisterna and Oliva (14)

⇒ 仮定2) : 線形時間依存性を持つスカラ一場

Babichev and Charmousis (14)

$$\varphi = \textcolor{blue}{q}t + \psi(r)$$

$\dot{\varphi} = \textcolor{blue}{q}$, $\ddot{\varphi} = 0 \Rightarrow$ 静的球対称性と矛盾しない

$$-q * J^r = E_{tr} * B(r) = 0 \Rightarrow J^r = 0 \quad \forall r \Rightarrow \psi' \neq 0$$

運動方程式

⇒仮定4) $G_i(X)$ の微分が X の負ベキも含む

例. EdGB理論: $R + X + \alpha\varphi R_{GB}$ Sotiriou and Zhou (14)

$$\Rightarrow G_2 = X, \quad G_3 = 0, \quad G_4 = 1, \quad G_5 = -4\alpha \ln X$$

$$\begin{aligned} J^r &= -BG_{2X}\phi' - \frac{B^3\phi'^2}{2r^2} \frac{A'}{A} \left(\frac{3B-1}{B} \right) G_{5X} + \frac{A'}{A} \frac{B^4\phi'^4}{2r^2} G_{5XX} \\ &\sim \frac{1}{X} \sim \frac{1}{(\phi')^2} \qquad \qquad \qquad \sim \frac{1}{X^2} \sim \frac{1}{(\phi')^4} \\ &= -B\phi' - 4\alpha \frac{A'}{A} \frac{B(B-1)}{r^2} \end{aligned}$$

$$\Rightarrow \varphi' \neq 0 \quad \forall r : Q = Q(M)$$

例) $G^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi$

$$G_4 \sim X$$

Shift-symmetric
Galileons
 $G_i(X)$

例) EdGB φR_{GB}

$$G_5 \sim \ln X$$

G_{iX} contains only
positive powers of X

G_{iX} contains ne-
gative powers of X

Hair with $J^r \neq 0$

Sotiriou-Zhou
 $G_5(X) \propto \ln(X)$

No asymptotic flatness

Asymptotic flatness

Hair with $J^r = 0$

Rinaldi, Anabalon
et al., Minamitsuji,
Babichev *et al.*, etc

No kinetic term

Kinetic term

Hair with $J^r = 0$

Stealth Schwar-
schild black hole

No hair

Hui-Nicolis theorem

$G^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi$ を含む理論
におけるブラックホール解

非最小微分結合

$$S = \int d^4x \sqrt{-g} \left[\frac{m_p^2}{2} (R - 2\Lambda) - \eta g_{\mu\nu} \nabla^\mu \varphi \nabla^\nu \varphi + \beta G_{\mu\nu} \nabla^\mu \varphi \nabla^\nu \varphi \right]$$

$$G_2(X) = 2\eta X - \Lambda m_p^2 \quad G_4(X) = \frac{m_p^2}{2} + \beta X$$

$$G_3(X) = G_5(X) = 0$$

正則な $G_2(X)$ & $G_4(X)$ を含む理論($\varphi \leftrightarrow -\varphi$) の中で最も単純

Self-accelerating 宇宙

真空のエネルギーの突然の変化に対して時空が不变

静的球対称時空

$$ds^2 = -A(r)dt^2 + \frac{dr^2}{B(r)} + r^2(d\theta^2 + \sin\theta^2 d\phi^2)$$

$$\varphi(t, r) = Pt + \psi(r)$$

1) Stealth Schwarzschild 解 : $\eta = \Lambda = 0$ Babichev and Charmousis (14)

$$A(r) = B(r) = 1 - \frac{2M}{r} \quad \text{Schwarzschild時空}$$

$$\psi'(r) = \pm \sqrt{\frac{2M}{r}} \frac{P}{A(r)}$$

スカラー場が時空幾何に寄与しない。

2) Schwarzschild-(A)dS 解 $P = \pm \frac{m_p}{\sqrt{2\eta}} \sqrt{\Lambda + \frac{\eta}{\beta}}$ $\Rightarrow \Lambda \geq -\frac{\eta}{\beta}$
 $\eta \neq 0, \Lambda \neq 0$

$$A(r) = B(r) = 1 - \frac{2M}{r} + \frac{\eta}{3\beta} r^2 \quad \Rightarrow \Lambda_{\text{eff}} = -\frac{\eta}{\beta} \neq \Lambda$$

$$\psi'(r) = \pm m_p \sqrt{\frac{(\eta + \beta\Lambda)(1 - A(r))}{2\beta\eta}} \frac{1}{A(r)}$$

真空のエネルギー Λ は時空幾何に寄与しない。

$\Rightarrow \Lambda$ の変化に対して時空は不变

3) 漸近 AdS 解 $P = 0$ Rinaldi (12) Minamitsuji (14) Anabalón, Cisterna and Oliva (14)

$$A(r) = \frac{1}{3r\beta(\eta - \beta\Lambda)^2} [\eta^3 r^3 - 3r\beta^3 \Lambda^2 + \eta r\beta^2 \Lambda(-6 + r^2\Lambda) + \eta^2 \beta(9r - 2r^3\Lambda - 24M) + 3\frac{\beta^{3/2}}{\eta^{1/2}} (\eta + \beta\Lambda)^2 \arctan\left(\frac{\sqrt{\eta}r}{\sqrt{\beta}}\right)]$$

$$B(r) = \frac{(\eta - \beta\Lambda)^2(\eta r^2 + \beta)^2}{\eta^2(\eta r^2 + \beta(2 - r^2\Lambda))^2} A(r)$$

$$\psi'(r) = \pm \sqrt{-\frac{\eta + \beta\Lambda}{2\beta(\eta r^2 + \beta)B(r)}} m_p r$$

$$r \gg \frac{\sqrt{\beta}}{\sqrt{\eta}} \Rightarrow A(r) \approx B(r) \approx \frac{\eta r^2}{3\beta} \Rightarrow \Lambda_{\text{eff}} = -\frac{\eta}{\beta} < 0 \quad \text{漸近 AdS}$$

低速回転ブラックホール解

Maselli, Silva, Minamitsuji and Berti (15)

$$ds^2 = -A(r)dt^2 + \frac{dr^2}{B(r)} + r^2(d\theta^2 + \sin\theta^2 d\phi^2) - 2r^2\omega(r)\sin\theta^2 dt d\phi + O(\Omega^2)$$

frame dragging

Ω : BH 角速度

$$O(\Omega): E_{t\phi} = 0 \Rightarrow \omega(r) \quad \text{Hartle and Thorne (67)}$$

$$\text{全ての球対称解1)-3)} \Rightarrow \omega(r) = \omega_0 + \frac{2J}{r^3} \quad J: \text{角運動量}$$

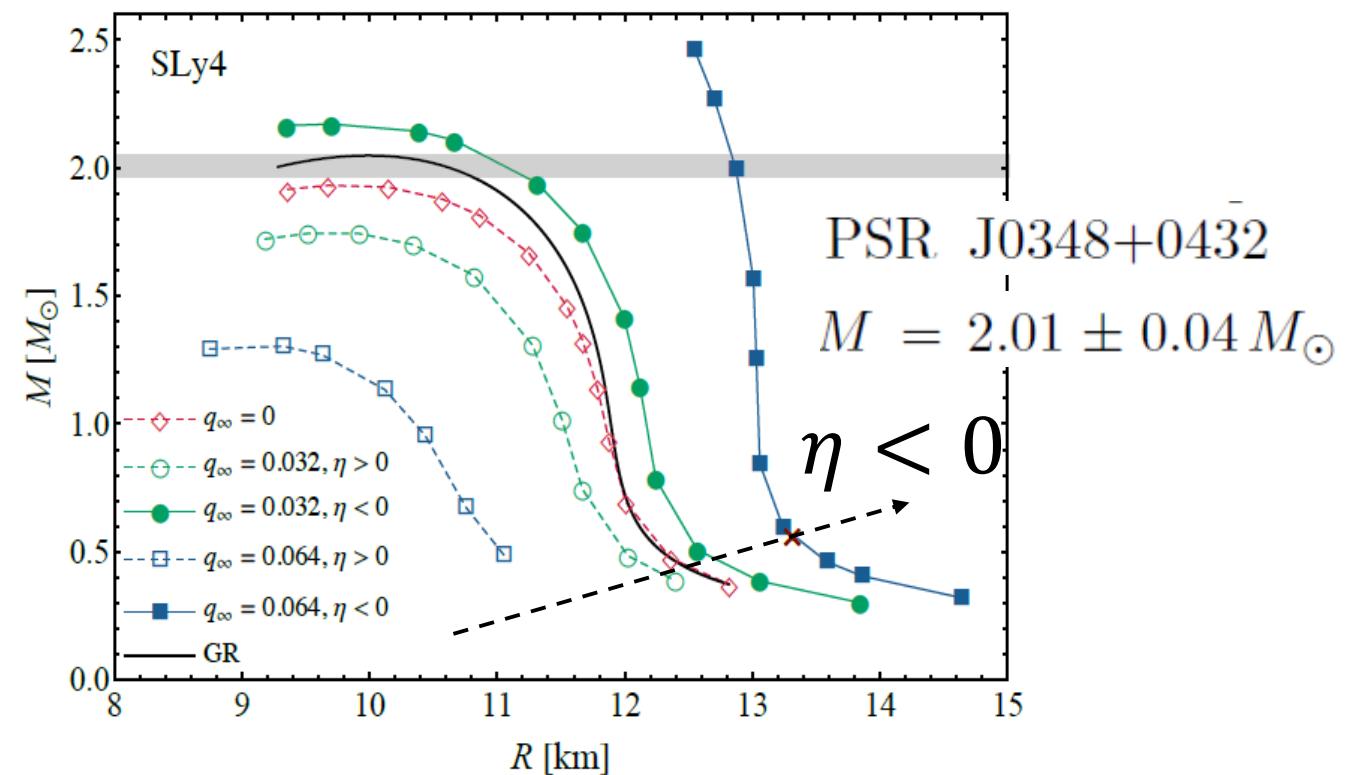
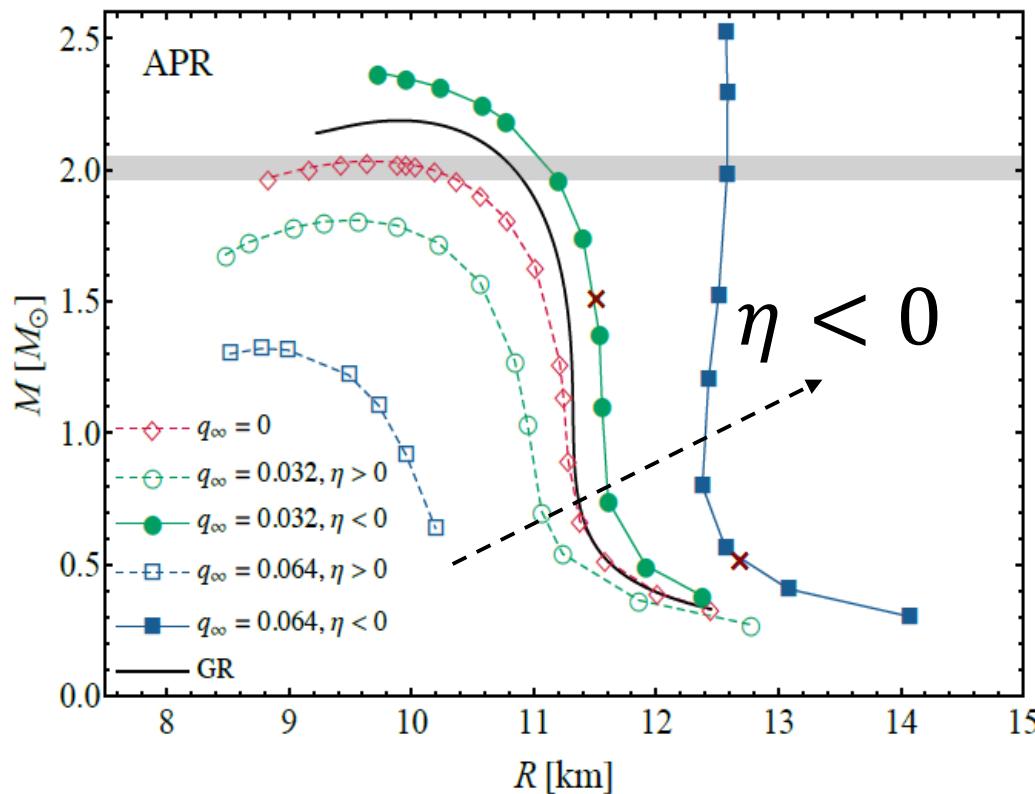
= Kerr 解の低速回転極限

Stealth Sch. を外部時空を持つ中性子星

$$R + \eta G_{\mu\nu} \nabla^\mu \varphi \nabla^\nu \varphi$$

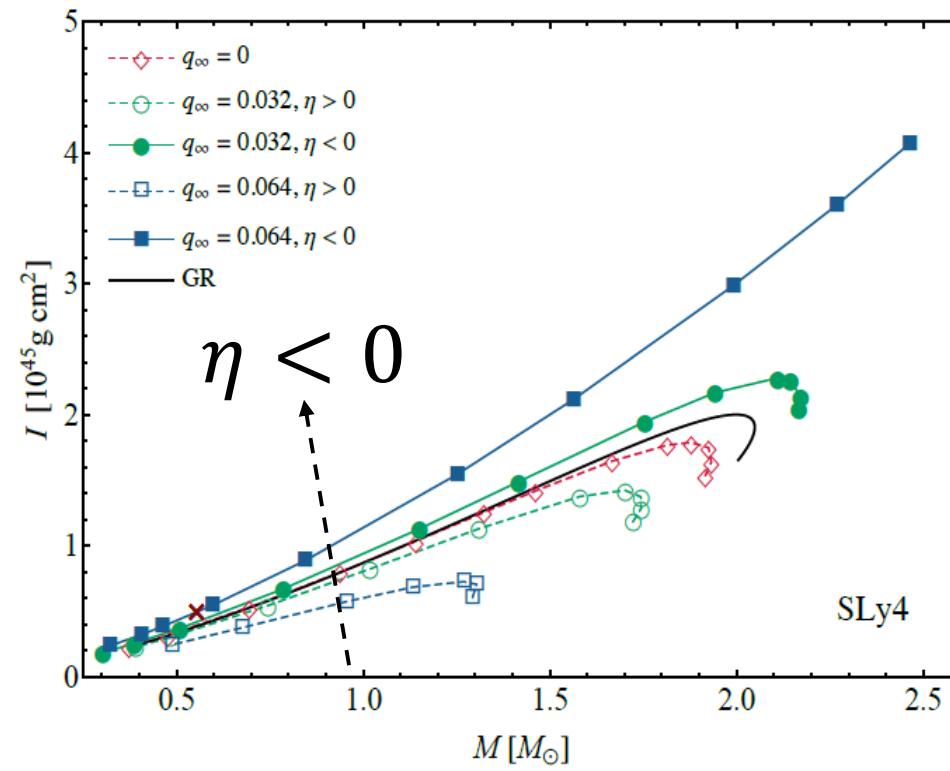
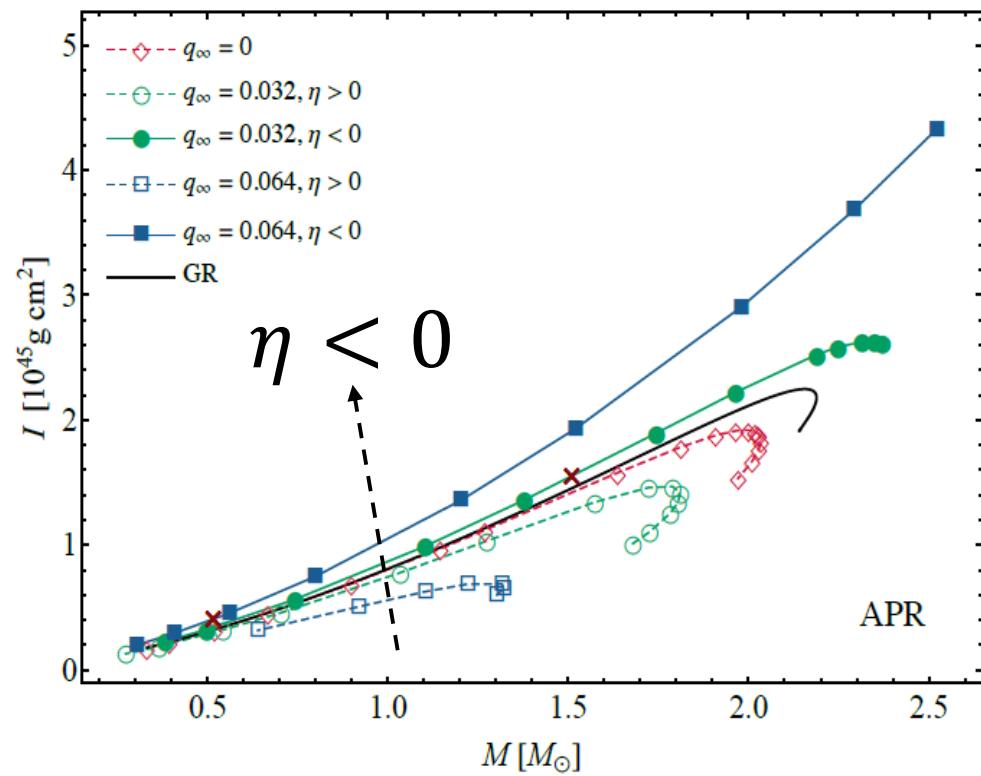
Cisterna, et. al (15,16)
Maselli, Silva, Minamitsuji and Berti (16)

- 質量・半径関係



低速回転星

- 惯性モーメント



$G^{\mu\nu} A_\mu A_\nu$ を含む理論
におけるブラックホール解

Einstein-Proca 理論

$$\mathcal{L} = \sqrt{-g} \left[\frac{m_p^2}{2} (R - 2\Lambda) - m^2 g_{\mu\nu} A^\mu A^\nu - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \right]$$

ゲージ対称性破る

$$F_{\mu\nu} := \nabla_\mu A_\nu - \nabla_\nu A_\mu$$

5 自由度 = (1 longitudinal + 2 transverse) + 2 tensor

$$A_\mu \rightarrow \nabla_\mu \varphi$$

$$\Rightarrow \mathcal{L} = \sqrt{-g} \left[\frac{m_p^2}{2} (R - 2\Lambda) - m^2 g_{\mu\nu} \nabla^\mu \varphi \nabla^\nu \varphi \right]$$

一般化された Proca 理論

Tasinato (14) Heisenberg (14)
 Allys, Peter and Rodriguez (16)
 Beltran Jimenez and Heisenberg (16)

$$S = \int d^4x \sqrt{-g} \sum_{i=2}^6 \mathcal{L}_i$$

$$\begin{aligned} X &:= -\frac{1}{2} g^{\mu\nu} A_\mu A_\nu \\ Y &:= A^\mu A^\nu F_{\mu\alpha} F_\nu^\alpha \end{aligned}$$

$$\begin{aligned} F &:= -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} \\ L^{\mu\nu\alpha\beta} &:= \frac{1}{4} \varepsilon^{\mu\nu\rho\sigma} \varepsilon^{\alpha\beta\gamma\delta} R_{\rho\sigma\gamma\delta} \end{aligned}$$

$$\mathcal{L}_2 = G_2 (X, F, Y)$$

$$\mathcal{L}_3 = -G_3 (X) \nabla_\mu A^\mu$$

$$\mathcal{L}_4 = G_4 (X) R + G_{4X}(X) \left[(\nabla_\mu A^\mu)^2 - \nabla_\mu A_\nu \nabla^\nu A^\mu \right]$$

$$\mathcal{L}_5 = G_5 (X) G_{\mu\nu} \nabla^\mu A^\nu - \frac{G_{5X}(X)}{6} \left[(\nabla_\mu A^\mu)^3 - 3 \nabla_\mu A^\mu \nabla_\rho A_\sigma \nabla^\sigma A^\rho + 2 \nabla_\rho A_\sigma \nabla^\gamma A^\rho \nabla^\sigma A_\gamma \right]$$

$$-g_5(X) \tilde{F}^{\alpha\mu} \tilde{F}_\mu^\beta \nabla_\alpha A_\beta$$

$$\mathcal{L}_6 = \frac{1}{4} G_6 (X) L^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} + \frac{1}{2} G_{6X}(X) \tilde{F}^{\alpha\beta} \tilde{F}^{\mu\nu} \nabla_\alpha A_\mu \nabla_\beta A_\nu$$

シフト対称な Horndeski 理論 : $\varphi \rightarrow \varphi + c$

$$A_\mu \rightarrow \nabla_\mu \varphi$$

$$S = \sum_{i=2}^5 \int d^4x \sqrt{-g} \mathcal{L}_i \quad X = -\frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi$$

$$\mathcal{L}_2 = G_2(X)$$

$$\mathcal{L}_3 = -G_3(X) \square \varphi$$

$$\mathcal{L}_4 = G_4(X)R + G_{4X}(X)[(\square \varphi)^2 - \varphi_{\mu\nu}^2]$$

$$\mathcal{L}_5 = -G_5(X)G_{\mu\nu}\varphi^{\mu\nu} - \frac{G_{5X}(X)}{6}[(\square \varphi)^3 + 2\varphi_{\mu\nu}^3 - 3\varphi_{\mu\nu}^2 \square \varphi]$$

非最小結合 $G_{\mu\nu} A^\mu A^\nu$

$$S = \int d^4x \sqrt{-g} \left[\frac{m_p^2}{2} (R - 2\Lambda) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - m^2 g_{\mu\nu} A^\mu A^\nu + \beta G_{\mu\nu} A^\mu A^\nu \right]$$

$$\Downarrow \quad A_\mu \rightarrow \nabla_\mu \varphi$$

$$S = \int d^4x \sqrt{-g} \left[\frac{m_p^2}{2} (R - 2\Lambda) - m^2 g_{\mu\nu} \nabla^\mu \varphi \nabla^\nu \varphi + \beta G_{\mu\nu} \nabla^\mu \varphi \nabla^\nu \varphi \right]$$

静的球対称時空

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

$$A_\mu dx^\mu = A_0(r)dt + A_1(r)dr$$

- スカラー・テンソル理論の解 \Rightarrow 一般化されたProca 理論の解

Babichev and Charmousis (14)

Rinaldi (12) Minamitsuji (14)

Anabalón, Cisterna and Oliva (14)

$$\varphi(t, r) = P t + \psi(r)$$

$$\Rightarrow A_0(r) = P \quad A_1(r) = \psi'(r)$$

$$\nabla_\mu \varphi \rightarrow A_\mu$$

$$A_0(r) = P \Rightarrow F_{rt} = A'_0(r) = 0$$

1) Stealth Schwarzschild 解: $m = \Lambda = 0$

$$S = \int d^4x \sqrt{-g} \left[\frac{m_p^2}{2} R - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \beta G_{\mu\nu} A^\mu A^\nu \right]$$

$$f(r) = 1 - \frac{2M}{r} \Rightarrow \text{Schwarzschild 時空}$$

$$A_1(r) = \pm \sqrt{\frac{2M}{r}} \frac{P}{f(r)}$$

ベクトル場が時空幾何に寄与しない。

2) Schwarzschild-(A)dS 解

$$P = \pm \frac{m_p}{\sqrt{2}m} \sqrt{\Lambda + \frac{m^2}{\beta}} \Rightarrow \Lambda \geq -\frac{m^2}{\beta}$$

$$f(r) = 1 - \frac{2M}{r} + \frac{m^2}{3\beta} r^2$$

$$A_1(r) = \pm \frac{m_p}{m} \sqrt{\frac{(m^2 + \beta\Lambda)(1 - f(r))}{2\beta}} \frac{1}{f(r)}$$

$$\Lambda_{\text{eff}} = -\frac{m^2}{\beta} \quad \Rightarrow \begin{cases} \beta > 0 & AdS \\ \beta < 0 & dS \end{cases}$$

宇宙項 Λ は時空幾何に寄与しない。

3) 漸近 AdS 解 $P = 0$

$$f(r) = \frac{1}{3mr\beta(m^2 - \beta\Lambda)^2} \left[m^7r^3 - 3mr\beta^3\Lambda^2 + m^3r\beta^2\Lambda(-6 + r^2\Lambda) \right. \\ \left. + m^5\beta(9r - 2r^3\Lambda - 24M) + 3\beta^{3/2}(m^2 + \beta\Lambda)^2 \arctan\left(\frac{mr}{\sqrt{\beta}}\right) \right]$$

$$h(r) = \frac{(m^2 - \beta\Lambda)^2(m^2r^2 + \beta)^2}{m^4(m^2r^2 + \beta(2 - r^2\Lambda))^2} f(r)$$

$$A_1(r) = \pm \sqrt{-\frac{m^2 + \beta\Lambda}{2\beta(m^2r^2 + \beta)h(r)}} m_p r$$

- $r \gg \frac{\sqrt{\beta}}{m} \Rightarrow f(r) \approx h(r) \approx \frac{m^2r^2}{3\beta} \Rightarrow \Lambda_{\text{eff}} = -\frac{m^2}{\beta} < 0 \quad \text{AdS}$

$$A_0(r) = P + \frac{Q}{r} \Rightarrow F_{rt} = A'_0(r) = -\frac{Q}{r^2}$$

0) Reissner–Nordström 解: $m = \beta = 0$

$$f(r) = h(r) = 1 - \frac{\Lambda}{3}r^2 - \frac{2M}{r} + \frac{Q^2}{2m_p^2 r^2} \quad A_1(r) = 0$$

1) Stealth Schwarzschild 解: $\beta = \frac{1}{4}$ $m = \Lambda = 0$ Chagoya, Niz and Tasinato (16)

$$f(r) = h(r) = 1 - \frac{2M}{r} \Rightarrow \text{Schwarzschild 時空}$$

$$A_1(r) = \pm \frac{\sqrt{Q^2 + 2PQr + 2MP^2r}}{r} \frac{1}{f(r)}$$

電荷は時空幾何に寄与しない.

2) Schwarzschild-AdS 解: $\beta = \frac{1}{4}$

$$P = \pm \frac{m_p}{\sqrt{2}m} \sqrt{4m^2 + \Lambda} \quad \left(m^2 > -\frac{\Lambda}{4} \right)$$

$$f(r) = h(r) = 1 - \frac{2M}{r} + \frac{4m^2}{3} r^2$$

$$\begin{aligned} A_1(r) = \pm \frac{1}{\sqrt{3}mr f(r)} & [m_p^2 r (3M - 2m^2 r^3)(4m^2 + \Lambda) \\ & \pm 3mm_p r \sqrt{8m^2 + 2\Lambda} Q + 3m^2 Q^2]^{1/2} \end{aligned}$$

$$\Rightarrow \Lambda_{\text{eff}} = -4m^2 < 0$$

宇宙項と電荷は時空幾何に寄与しない。

3) 漸近AdS 解: $\beta = \frac{1}{4}$ $P = 0$

$$f(r) = \frac{1}{6mr(\Lambda - 4m^2)^2} [-6\Lambda^2 mr + 128m^7 r^3 - 32m^5(24M + 2\Lambda r^3 - 9r) \\ + 8\Lambda m^3 r(\Lambda r^2 - 6) + 3(4m^2 + \Lambda)^2 \arctan(2mr)]$$

$$h(r) = \frac{(\Lambda - 4m^2)^2 (4m^2 r^2 + 1)^2}{16m^4 (4m^2 r^2 + 2 - r^2 \Lambda)^2} f(r)$$

$$A_1(r) = \pm \sqrt{\frac{Q^2(1 + 4m^2 r^2) - 2m_p^2(\Lambda + 4m^2)r^4 f(r)}{r \sqrt{f(r)h(r)(1 + 4m^2 r^2)}}}$$

電荷 Q が時空幾何に寄与しない

$$A_0(r) = P + \frac{Q}{r} + Q_p r^p \quad (p \neq -1)$$

漸近的に最大対称時空ではない

$$1) \quad \beta = \frac{1}{4} \quad m = 0 \quad p = 2 \quad \forall P \quad Q_2 = \frac{2m_p^2 P \Lambda}{3(P^2 - 4m_p^2)} \quad \text{Chagoya, Niz and Tasinato (16)}$$

$$f(r) = 1 - \frac{2M}{r} + \frac{4m_p^2 r^2 \Lambda (5P^2 + m_p^2 (-20 + 3r^2 \Lambda))}{15 (P^2 - 4m_p^2)^2}$$

$$h(r) = \frac{(P^2 - 4m_p^2)^2}{(P^2 + 2m_p^2 (-2 + r^2 \Lambda))^2} f(r)$$

$$A_1(r) = \pm \sqrt{\frac{A_0(r)^2}{f(r)h(r)} - \frac{P^2 + 2m_p^2 r^2 \Lambda}{h(r)}}$$

$$2. \quad \beta = \frac{1}{4} \quad P = \pm 2m_p \quad m = \pm \frac{\sqrt{\Lambda}}{2} \quad \forall p$$

$$f(r) = \frac{1}{4m_p^2 r} \left[-8Mm_p^2 + \frac{4}{3}\Lambda m_p^2 r^3 + 4m_p^2 r \pm 4m_p Q_p r^{p+1} \left(\frac{\Lambda(p+1)r^2}{p+3} + 1 \right) + (p+1)^2 Q_p^2 r^{2p+1} \left(\frac{\Lambda r^2}{2p+3} + \frac{1}{2p+1} \right) \right]$$

$$h(r) = \frac{1}{\left(1 \pm \frac{(p+1)Q_p r^p}{2m_p} \right)^2} f(r)$$

$$\begin{aligned} A_1(r) &= \pm 2\sqrt{3}m_p \sqrt{(2p+1)(2p+3)(p+3)} (\pm 2m_p + (p+1)Q_p r^p) \\ &\times \left\{ -r \left[r \left(p^3 (16\Lambda m_p^2 r^2 \pm 48\Lambda m_p Q_p r^{p+2} + 3Q_p^2 r^{2p} (11\Lambda r^2 + 9)) \right. \right. \right. \\ &+ p^2 (80\Lambda m_p^2 r^2 \pm 144\Lambda m_p Q_p r^{p+2} + 3Q_p^2 r^{2p} (19\Lambda r^2 + 9)) + 3\Lambda p r^2 (36m_p^2 \pm 44m_p Q_p r^p + 13Q_p^2 r^{2p}) \\ &+ 9\Lambda r^2 (\pm 2m_p + Q_p r^p)^2 + 6p^4 Q_p^2 r^{2p} (\Lambda r^2 + 1) \left. \left. \left. \right) - 24Mm_p^2 (2p+1)(2p+3)(p+3) \right] \right. \\ &+ 6(2p+1)(2p+3)(p+3)Qr(\pm 2m_p + Q_p r^p) + 3(2p+1)(2p+3)(p+3)Q^2 \}^{\frac{1}{2}} \\ &\times \left\{ r \left[4m_p^2 (2p+1)(2p+3)(p+3)(\Lambda r^2 + 3) \pm 12m_p (2p+1)(2p+3)Q_p r^p (\Lambda p r^2 + p + \Lambda r^2 + 3) \right. \right. \\ &+ 3(p+1)^2 (p+3)Q_p^2 r^{2p} (2p(\Lambda r^2 + 1) + \Lambda r^2 + 3) \left. \left. \right] - 24Mm_p^2 (2p+1)(2p+3)(p+3) \right\}^{-1}, \end{aligned}$$

$$A_1(r) = 0$$

- Geng-Lu 解: $\beta = \frac{1}{4}$ $m = 0$ $\Lambda = 0$ Geng and Lu (15)

$$f(r) = h(r) = 1 \pm \sqrt{\frac{r_0}{r}}$$

$$A_0(r) = 2m_p f(r)$$

Newton 重力を再現しない

低速回転ブラックホール解

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

Frame dragging

$$A_\mu = (A_0(r), A_1(r), 0, a_3(r)\sin\theta^2) + O(\Omega^2)$$

誘導磁場

$O(\Omega)$: Hartle and Thorne (67)

$$E_{t\phi}^{(g)} = 0, \quad E_\phi^{(A)} = 0 \quad \Rightarrow (\omega(r), a_3(r))$$

1. $m = \beta = 0$: RN ブラックホールに対する低速回転補正

$$\omega(r) = \omega_0 + \frac{2J}{r^3} - \frac{JQ^2}{2m_p^2 Mr^4}$$

Kerr-Newman-(A)dS解に一致

$$a_3(r) = -\frac{JQ}{Mr}$$

2. $A_0(r) = P + \frac{Q}{r}$: 球対称解への低速回転補正 ($\beta = \frac{1}{4}$)

$$\omega(r) = \omega_0 + \frac{2J}{r^3}$$

Kerr- (A)dS 解に一致

$$a_3(r) = -\frac{JQ}{Mr}$$

Kerr-Newman-(A)dS 解に一致

電荷 Q が frame-dragging に寄与しない

結論

要約

- シフト対称なHorndeski 理論におけるブラックホール
⇒ 一般化された Proca 理論におけるブラックホール
 $\partial_\mu \phi \rightarrow A_\mu \Rightarrow F_{\mu\nu} = 0$

- $F_{\mu\nu} \neq 0$ の場合

特定の場合、電荷の時空幾何への影響をゼロにできる

今後

- 2次の低速回転補正 \Rightarrow 一般相対論との差異？
 - 安定性 スカラーテンソルの場合 Ogawa, Kobayashi and Suyama (16)
 - “無毛性”に関する一般的な議論
 - 静的解への時間発展 \Rightarrow 解のアトラクター性の検証
 - 観測的示唆 \Rightarrow 一般相対論の検証実験、重力波…



Obrigado.

ご清聴ありがとうございました。