Cosmic structures and gravitational waves in ghost-free scalar-tensor theories of gravity

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with Nicola Bartolo, Sabino Matarrese and Mattia Scomparin
(arXiv:1712.04002 [gr-qc])

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Screening in Modified Gravity

Modified gravity

Introduce additional degrees of freedom (often scalar): fifth force

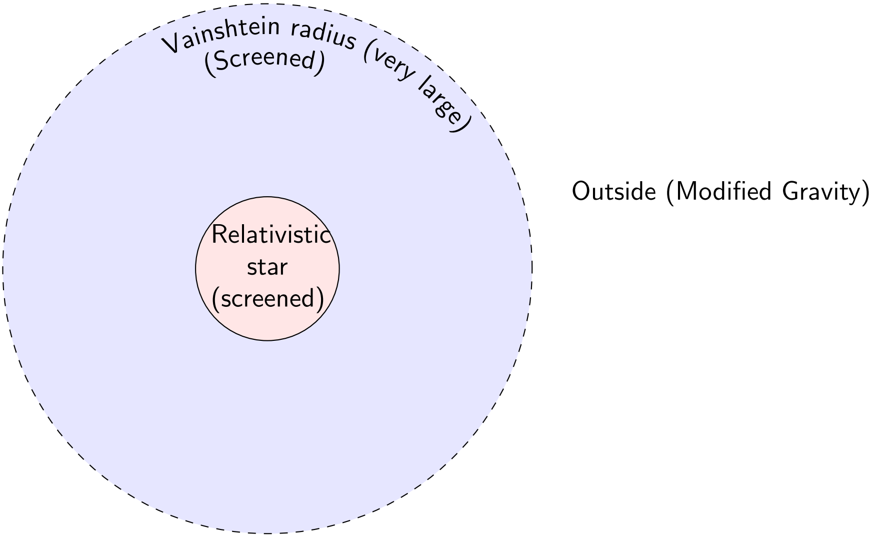
Gravity is well tested in the **solar system**.

Screening

Screening the fifth force in the solar system, and GR is recovered.
e.g.: Vainshtein, Chameleon, Symmetron, disformal screening etc.

•P. Brax, C. vd. Bruck, AC. Davis, J. Khoury, A. Weltman(astro-ph/0408415)
•C. de Rham (1401.4173[hep-th])
•T. S. Koivisto, D. F. Mota, M. Zumalacarregui (1205.3167 [astro-ph.CO])

Vainshtein Screening



Quadratic DHOST model

$$\mathcal{L} = \mathcal{L}_g + \mathcal{L}_\varphi + \mathcal{L}_{oth} + \mathcal{L}_m \,,$$

$$\mathcal{L}_g \equiv f R \,, \qquad \mathcal{L}_\varphi \equiv \sum_{I=1}^{5} \zeta_I(X) \mathcal{L}_I \,,$$

$$\mathcal{L}_{oth} \equiv (A X - B\Lambda) \,, \qquad \text{(shift symmetry)}$$

where

$$\mathcal{L}_1 \equiv \nabla^\mu \nabla^\nu \varphi \nabla_\mu \nabla_\nu \varphi \,, \qquad \mathcal{L}_2 \equiv (\Box\varphi)^2 \,,$$

$$\mathcal{L}_3 \equiv (\Box\varphi) \nabla^\mu \varphi \nabla^\nu \varphi \nabla_\mu \nabla_\nu \varphi \,, \qquad \mathcal{L}_4 \equiv \nabla^\mu \varphi \nabla^\nu \varphi \nabla_\mu \nabla^\rho \varphi \nabla_\nu \nabla_\rho \varphi \,,$$

$$\mathcal{L}_5 \equiv (\nabla^\mu \varphi \nabla_\mu \nabla_\nu \varphi \nabla^\nu \varphi)^2 .$$

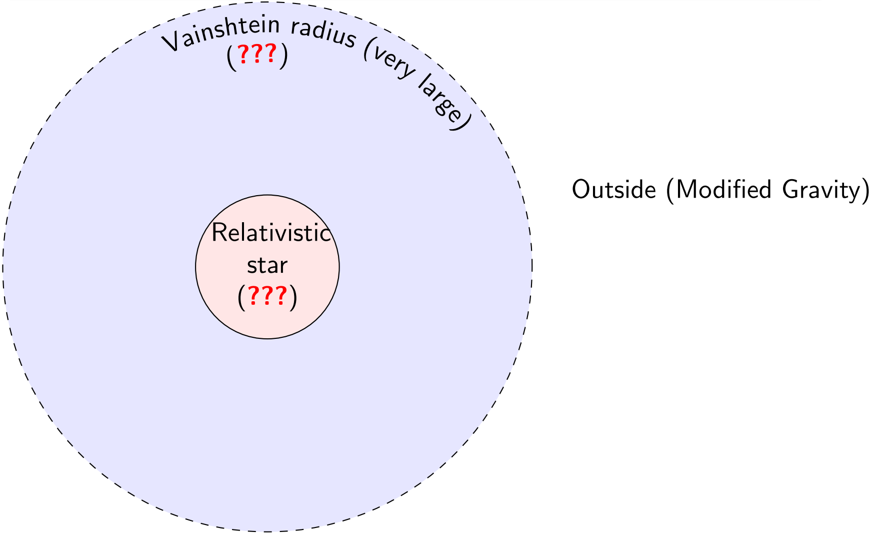
DHOST Class Ia* (scalar sector alone): Ghost free

$$\zeta_2(X) = -\zeta_1(X) \,, \quad \zeta_3(X) = -\zeta_4(X) = 2X^{-1}\zeta_1(X), \quad \zeta_5(X) = 0$$

- JB. Achour, D. Langlois, K. Noui (1602.08398 [gr-qc])
- JB. Achour, M. Crisostomi, K. Koyama, D. Langlois, K. Noui, G. Tasinato (1608.08135)

Objective

Testing Vainshtein screening mechanism in the qDHOST theory.



Method

We study a static and spherically symmetric object embedded in de Sitter space-time for the qDHOST model.

Assuming the background is spatially flat de Sitter universe.
$ds^2_{(0)} = -d\tau^2 + e^{2H\tau}\left(d\rho^2 + \rho^2 d\Omega_2^2\right)$

Introducing a static and spherically symmetric cosmic structure,
$ds^2 = -e^{\nu(r)}dt^2 + e^{\lambda(r)}dr^2 + r^2 d\Omega_2^2$

Sub-Horizon, Weak-Field Limit $(Hr << 1)$

$\nu(r) \sim \ln\left(1 - H^2 r^2\right) + \delta\nu(r) \qquad \lambda(r) \sim -\ln\left(1 - H^2 r^2\right) + \delta\lambda(r)$
$\varphi(r,t) \sim v_0 t + \frac{v_0}{2H}\ln\left(1 - H^2 r^2\right) + \delta\varphi(r)$

At $r \to \infty$, we have $\delta\nu \to 0$, $\delta\lambda \to 0$ and $\delta\varphi \to 0$ (de Sitter)

Result - 1: Covariant field Equation of HOST and qDHOST

- Covariant field EOM of **full** quadratic Higher Order Scalar-Tensor Theory (qHOST).
- It will allow you to do other cosmology analysis of **all** qDHOST model by setting the conditions over $\zeta_I(X)$.

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$$
\begin{aligned}
\mathcal{H}_{\mu\nu} \equiv & \Big\{2fG_{\mu\nu}\Big\}_{(g)} - \Big\{T_{\mu\nu}\Big\}_{(m)} + \Big\{A\big(2\nabla_\mu\varphi\nabla_\nu\varphi - g_{\mu\nu}X\big) + B\Lambda g_{\mu\nu}\Big\}_{(oth)} \\
& + \Big\{\zeta_{1X}\big(2\nabla_\mu\varphi\nabla_\nu\varphi\nabla^\rho\nabla^\sigma\varphi\nabla_\rho\nabla_\sigma\varphi + 4\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\mu\nabla_\nu\varphi\nabla_\rho\nabla_\sigma\varphi - 8\nabla_\mu\varphi\nabla^\rho\varphi\nabla_\nu\nabla^\sigma\varphi\nabla_\rho\nabla_\sigma\varphi \\
& \quad + \zeta_1\big(2\nabla_\mu\nabla_\nu\varphi\nabla^\rho\nabla_\rho\varphi + 2\nabla^\rho\varphi\nabla_\rho\nabla_\mu\nabla_\nu\varphi - 4\nabla_\mu\varphi\nabla^\rho\nabla_\rho\nabla_\nu\varphi - g_{\mu\nu}\nabla^\rho\nabla^\sigma\varphi\nabla_\rho\nabla_\sigma\varphi\big)\Big\}_{(1)} \\
& + \Big\{\zeta_{2X}\big(2\nabla_\mu\varphi\nabla_\nu\varphi\nabla^\rho\nabla_\rho\varphi\nabla^\sigma\nabla_\sigma\varphi + 4g_{\mu\nu}\nabla^\alpha\varphi\nabla^\rho\varphi\nabla_\alpha\nabla_\rho\varphi\nabla^\sigma\nabla_\sigma\varphi \\
& \quad - 8\nabla_\mu\varphi\nabla^\rho\varphi\nabla_\nu\nabla_\rho\varphi\nabla^\sigma\nabla_\sigma\varphi\big) + \zeta_2\big(g_{\mu\nu}\nabla^\rho\nabla_\rho\varphi\nabla^\sigma\nabla_\sigma\varphi + 2g_{\mu\nu}\nabla^\rho\varphi\nabla_\rho\nabla^\sigma\nabla_\sigma\varphi \\
& \quad - 4\nabla_\mu\varphi\nabla^\nu\nabla^\rho\nabla_\rho\varphi\big)\Big\}_{(2)} \\
& + \Big\{\zeta_{3X}\big(2g_{\mu\nu}\nabla^\alpha\varphi\nabla^\beta\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\alpha\nabla_\beta\varphi\nabla_\rho\nabla_\sigma\varphi - 4\nabla_\mu\varphi\nabla^\alpha\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\nu\nabla_\alpha\varphi\nabla_\rho\nabla_\sigma\varphi\big) \\
& \quad + \zeta_3\big(2g_{\mu\nu}\nabla^\alpha\varphi\nabla^\rho\varphi\nabla_\alpha\nabla^\sigma\varphi\nabla_\rho\nabla_\sigma\varphi + g_{\mu\nu}\nabla^\alpha\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\alpha\nabla_\rho\nabla_\sigma\varphi \\
& \quad + 2\nabla_\nu\varphi\nabla^\rho\varphi\nabla_\mu\nabla_\rho\varphi\nabla^\sigma\nabla_\sigma\varphi - 4\nabla_\mu\varphi\nabla^\rho\varphi\nabla_\nu\nabla^\sigma\varphi\nabla_\rho\nabla_\sigma\varphi - 2\nabla_\mu\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\nu\nabla_\rho\nabla_\sigma\varphi \\
& \quad - \nabla_\nu\varphi\nabla_\mu\varphi\nabla^\rho\nabla_\rho\varphi\nabla^\sigma\nabla_\sigma\varphi - \nabla_\nu\varphi\nabla_\mu\varphi\nabla^\rho\varphi\nabla_\rho\nabla^\sigma\nabla_\sigma\varphi\big)\Big\}_{(3)} \\
& + \Big\{\zeta_{4X}\big(-2\nabla_\nu\varphi\nabla_\mu\varphi\nabla^\alpha\varphi\nabla^\rho\varphi\nabla_\alpha\nabla^\sigma\varphi\nabla_\rho\nabla_\sigma\varphi\big) + \zeta_4\big(2\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\mu\nabla_\rho\varphi\nabla_\nu\nabla_\sigma\varphi \\
& \quad - 2\nabla_\mu\varphi\nabla_\nu\varphi\nabla^\rho\nabla^\sigma\varphi\nabla_\rho\nabla_\sigma\varphi - 2\nabla_\nu\varphi\nabla_\mu\varphi\nabla^\rho\varphi\nabla^\sigma\nabla_\sigma\nabla_\rho\varphi \\
& \quad - g_{\mu\nu}\nabla^\alpha\varphi\nabla^\rho\varphi\nabla_\alpha\nabla^\sigma\varphi\nabla_\rho\nabla_\sigma\varphi\big)\Big\}_{(4)} \\
& + \Big\{\zeta_{5X}\big(-2\nabla_\mu\varphi\nabla_\nu\varphi\nabla^\alpha\varphi\nabla^\beta\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\alpha\nabla_\beta\varphi\nabla_\rho\nabla_\sigma\varphi \\
& \quad + \zeta_5\big(4\nabla_\nu\varphi\nabla^\alpha\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\mu\nabla_\alpha\varphi\nabla_\rho\nabla_\sigma\varphi - 2\nabla_\nu\varphi\nabla_\mu\varphi\nabla^\alpha\varphi\nabla^\rho\varphi\nabla_\alpha\nabla_\rho\varphi\nabla^\sigma\nabla_\sigma\varphi \\
& \quad - 4\nabla_\nu\varphi\nabla_\mu\varphi\nabla^\alpha\varphi\nabla^\rho\varphi\nabla_\alpha\nabla^\sigma\varphi\nabla_\rho\nabla_\sigma\varphi - 2\nabla_\nu\varphi\nabla_\mu\varphi\nabla^\alpha\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\alpha\nabla_\rho\nabla_\sigma\varphi \\
& \quad - g_{\mu\nu}\nabla^\alpha\varphi\nabla^\beta\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\alpha\nabla_\beta\varphi\nabla_\rho\nabla_\sigma\varphi\big)\Big\}_{(5)},
\end{aligned}
\tag{3.4}
$$

$$
\begin{aligned}
\mathcal{J}^\mu \equiv & \Big\{-2A\nabla^\mu\varphi\Big\}_{(oth)} \\
& + \Big\{\zeta_{1X}\big(4\nabla^\nu\varphi\nabla^\mu\nabla^\rho\varphi\nabla_\nu\nabla_\rho\varphi - 2\nabla^\mu\varphi\nabla^\nu\nabla^\rho\varphi\nabla_\nu\nabla_\rho \\
& + \Big\{\zeta_{2X}\big(4\nabla^\nu\varphi\nabla^\mu\nabla_\nu\varphi\nabla^\rho\nabla_\rho\varphi - 2\nabla^\mu\varphi\nabla^\nu\nabla_\nu\varphi\nabla^\rho\nabla_\rho \\
& + \Big\{\zeta_{3X}\big(2\nabla^\nu\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla^\mu\nabla_\nu\varphi\nabla_\rho\nabla_\sigma\varphi\big) + \zeta_3\big(2\nabla^\nu\varphi \\
& \quad + \nabla^\mu\varphi\nabla^\nu\nabla_\nu\varphi\nabla^\rho\nabla_\rho\varphi - \nabla^\nu\varphi\nabla^\mu\nabla_\nu\varphi\nabla^\rho\nabla_\rho\varphi + \nabla^\mu \\
& + \Big\{\zeta_{4X}\big(2\nabla^\nu\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla^\mu\nabla_\nu\varphi\nabla_\rho\nabla_\sigma\varphi\big) + \zeta_4\big(\nabla^\nu\varphi \\
& \quad + \nabla^\mu\varphi\nabla^\nu\nabla^\rho\varphi\nabla_\nu\nabla_\rho\varphi + \nabla^\mu\varphi\nabla^\nu\varphi\nabla^\rho\nabla_\rho\nabla_\nu\varphi\big)\Big\}_{(4)} \\
& + \Big\{\zeta_{5X}\big(2\nabla^\mu\varphi\nabla^\alpha\varphi\nabla^\nu\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\alpha\nabla_\nu\varphi\nabla_\rho\nabla_\sigma\varphi\big) + \\
& \quad - 2\nabla^\nu\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla^\mu\nabla_\nu\varphi\nabla_\rho\nabla_\sigma\varphi + 4\nabla^\mu\varphi\nabla^\nu\varphi\nabla^\rho\varphi \\
& \quad + 2\nabla^\mu\varphi\nabla^\nu\varphi\nabla^\rho\varphi\nabla^\sigma\varphi\nabla_\nu\nabla_\rho\nabla_\sigma\varphi\big)\Big\}_{(5)},
\end{aligned}
$$

Result - 2: Vainshtein screening breaks down

Grav. force:

$$\frac{d\Phi(r)}{dr} = \frac{G_N M(r)}{r^2} + \frac{\Upsilon_1 G_N M''(r)}{4}$$

$$\frac{d\Psi(r)}{dr} = \frac{G_N M(r)}{r^2} - \frac{5\Upsilon_2 G_N M'(r)}{4r^2}$$

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where G_N, $\Upsilon_{1,2}$ parameters defined as

$$G_N = \frac{1}{2\bar{f}\left[\frac{3\zeta_1^{(0)} - 2v_0^2\zeta_{1,X}^{(0)}}{2\zeta_1^{(0)} - v_0^2\zeta_{1,X}^{(0)}}(B\sigma^2 - 1) + 1\right]}\mathcal{G}\,, \qquad \sigma^2 = \frac{\Lambda}{6H^2 f}$$

$$\Upsilon_1 = \frac{2\zeta_1^{(0)^2}}{\left(\zeta_{1,X}^{(0)}v_0^2 - \zeta_1^{(0)}\right)\left(\zeta_{1,X}^{(0)}v_0^2 - 2\zeta_1^{(0)}\right)}(B\sigma^2 - 1)$$

$$\Upsilon_2 = -\frac{2\zeta_1^{(0)}\left(2\zeta_{1,X}^{(0)}v_0^2 - 3\zeta_1^{(0)}\right)}{5\left(\zeta_{1,X}^{(0)}v_0^2 - \zeta_1^{(0)}\right)\left(\zeta_{1,X}^{(0)}v_0^2 - 2\zeta_1^{(0)}\right)}(B\sigma^2 - 1)$$

$$\frac{d\Phi(r)}{dr} = \frac{G_N M(r)}{r^2} + \frac{\Upsilon_1 G_N \boxed{M''(r)}}{4}$$

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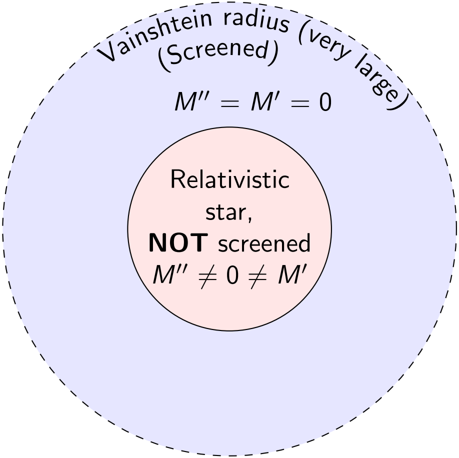


Outside (Modified Gravity)

Result-3: Condition to recover Vainstein Screening

$$\Upsilon_1 = \frac{2\,\boxed{\zeta_1^{(0)^2}}}{\left(\zeta_{1,X}^{(0)} v_0^2 - \zeta_1^{(0)}\right)\left(\zeta_{1,X}^{(0)} v_0^2 - 2\zeta_1^{(0)}\right)}(B\sigma^2 - 1)$$

$$\Upsilon_2 = -\frac{2\,\boxed{\zeta_1^{(0)}}\left(2\zeta_{1,X}^{(0)} v_0^2 - 3\zeta_1^{(0)}\right)}{5\left(\zeta_{1,X}^{(0)} v_0^2 - \zeta_1^{(0)}\right)\left(\zeta_{1,X}^{(0)} v_0^2 - 2\zeta_1^{(0)}\right)}(B\sigma^2 - 1)$$

Fully Vainshtein screening, $\Upsilon_1 = \Upsilon_2 = 0$

Condition on the free functions of the qDHOST, $\zeta_1^{(0)} = 0$

$$G_N = \frac{1}{2\bar{f}\left(2B\sigma^2 - 1\right)}\mathcal{G}$$

May help in imposing the constraints on the qDHOST functions.

GLPV Beyond Horndeski ($\mathcal{L}_{4,bH}$)

$$\Upsilon_1 = \Upsilon_2 = -\frac{1}{3}\left(1 - B\sigma^2\right).$$

Condition: $\zeta_1^{(0)} + v_0^2 \zeta_{1,X}^{(0)} = 0.$

$$G_N = \frac{3}{2\bar{f}\left(5B\sigma^2 - 2\right)}\,\mathcal{G}$$

- E. Babichev, K. Koyama, D. Langlois, R. Saito, J. Sakstein (1606.06627)
- T. Kobayashi, Y. Watanabe, D. Yamauchi (1411.4130 [gr-qc])

Propagation of Gravitational Waves

GW170817/GRB170817A constraint: $|c_T^2/c^2 - 1| \leq 5 \times 10^{-16}$

$$\frac{c_T^2}{c^2} = 1 - \frac{\zeta_1^{(0)} \dot{\varphi}_{(0)}^2}{f + \zeta_1^{(0)} \dot{\varphi}_{(0)}^2}, \\ = 1 + \alpha_T ,$$

$c_T^2/c^2 = 1$ can be obtained in principle by setting $\zeta_1^{(0)} = 0$, without setting $\zeta_1(X) = 0$.

$$\text{However,} \quad \frac{\zeta_1^{(0)} {\varphi'_{(0)}}^2}{f} = \frac{A + \Lambda B \frac{\zeta_1^{(0)}}{f}}{2A - \Lambda B \frac{\zeta_{1,X}^{(0)}}{\zeta_1^{(0)}}} .$$

A small deviation of $\zeta_1^{(0)}$ from 0 $\Rightarrow$ a large amount to α_T (huge fine-tuning of the parameters)

$$\boxed{\zeta_1(X) = 0}$$

Status after GW170817 constraint and screening test

Horndeski

Screening

Horndeski

GW

Ezquiaga, Zumalacrregui, 1710.05901.
Creminelli, Vernizzi 1710.05877.
Baker et. al. 1710.06394
Arai, Nishizawa, 1711.03776

DHOST:

$$\mathcal{L} = f(\varphi, X)R + \sum_{I=1}^{5} \zeta_I(\varphi, X)\mathcal{L}_I$$

$$+A(\varphi, X) + B(\varphi, X)\Box\varphi + \text{cubic}\ldots$$

GW (same ref.)

Independent of background:
qDHOST: $\zeta_1 = \zeta_2 = 0$,
All cubic & higher: ruled out

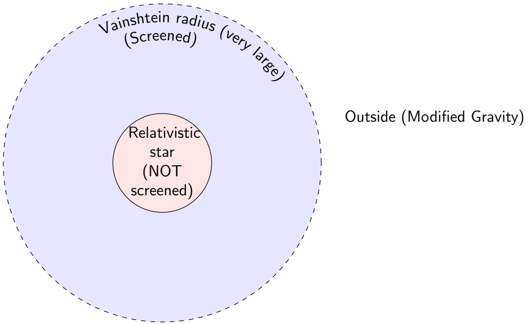
screening

Langlois, Saito, Yamauchi, K. Noui, 1711.07403.
Crisostomi, Koyama, 1711.06661. Bartolo, makar, Matarrese, Scomparin 1712.04002

$G_5 = 0, G_4 = G_4(\varphi)$; All $\zeta_I(\varphi, X) = 0$,

$$\mathcal{L} = f(\varphi)R + A(\varphi, X) + B(\varphi, X)\Box\varphi$$

Take Home Message



- Studied a static, spherically symmetric object embedded in de Sitter space-time for the qDHOST model.
- The Vainshtein mechanism breaks down inside matter.
- Found the possible conditions of healthy Vainshtein screening within the qDHOST scenario.
- Remaining DHOST after GW170817 and screening.

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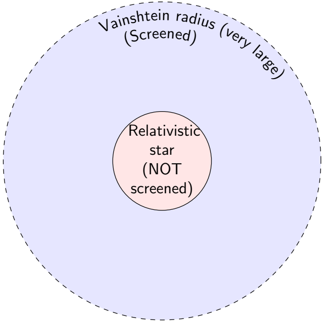

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Thank You