Dynamics of Screening in Modified Gravity

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GWMESS2021
April 2021
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Based on Phys.Rev.Lett. 126 (2021) 091102, in collaboration with Miguel Bezares, Marco Crisostomi, Enrico Barausse, and Carlos Palenzuela

(Picture by Eric Nyquist for Quanta Magazine)
Compact Objects in Modified Gravity

Neutron stars

Precision tests?
Known solutions?

Stability?
IVP well-posed?

Astrophysical scales

$g_{\mu\nu}, \phi \rightarrow k$-essence

Dark Energy$^1,2$
No Ostrogradski ghosts
Unconstrained by GW170817$^3$

$^1$T. Chiba, T. Okabe, and M. Yamaguchi, astro-ph/9912463
$^2$C. Armendariz-Picon, V. Mukhanov, and P.J. Steinhardt, PRL 85 (2000), 4438
$^3$P. Creminelli, G. Tambalo, F. Vernizzi, and V. Yingcharoenrat, 1910.14035
Neutron Stars in $k$-essence

$$S = \int d^4x \sqrt{-\tilde{g}} \left( \frac{M_{\text{Pl}}^2}{2} \tilde{R} + K(\tilde{X}) + \mathcal{L}_m (A(\phi) \tilde{g}_{\mu\nu}, \psi) \right)$$

$$K(\tilde{X}) = -\frac{1}{2} \tilde{X} + \frac{\beta}{4\Lambda^4} \tilde{X}^2 - \frac{\gamma}{8\Lambda^8} \tilde{X}^3$$

$$\tilde{X} \equiv \nabla_\mu \phi \nabla^\mu \phi$$

$$A(\phi) = e^{\alpha \phi / M_{\text{Pl}}}$$

$\alpha, \beta, \gamma \sim \mathcal{O}(1)$

**Screening:** Scalar modes are damped by non-linearities within the screening radius.

$k$-mouflage $^1$

\[ \tilde{X}^2 / \Lambda^4, \tilde{X}^4 / \Lambda^8 \gg \tilde{X} \]

\[ \tilde{X} / \Lambda^4 \sim 1 \]

\[ \tilde{X} \gg \tilde{X}^2 / \Lambda^4, \tilde{X}^4 / \Lambda^8 \]

$\text{GR-like}$

$r_k$

deviations w.r.t. GR

$^1$E. Babichev, C. Deffayet, and R. Ziour, 0905.2943
What questions did we have?

Do we still see screening if we solve the **full non-linear system** numerically?

Does $k$-mouflage survive in the **strong-field regime**?

Are the obtained screened solutions **stable**?
What questions did we have?

- Do we still see screening if we solve the full non-linear system numerically? **YES**
- Does $k$-mouflage survive in the strong-field regime? **YES**
- Are the obtained screened solutions stable?
Screening for Neutron Stars

\[ \rho(r) = \frac{P(r)}{\Gamma - 1} + \left( \frac{P(r)}{\kappa} \right)^{1/\Gamma} \]

\[ \Gamma = 2 \quad \kappa = 123 \]

\[ G = c = M_\odot = 1 \]

results hold for any \( \beta < 0 \) and \( \gamma > 0 \)

LtH, M. Bezares, M. Crisostomi, E. Barausse, and C. Palenzuela, 2009.03354
Newtonian Fifth Force

\[ U = - \frac{(g_{tt} + 1)}{2} \]

**FJBD constraint:**
\[ \alpha \sim 5 \times 10^{-3} \]

LtH, M. Bezares, M. Crisostomi, E. Barausse, and C. Palenzuela, 2009.03354
What questions did we have?

Do we still see screening if we solve the full non-linear system numerically? [YES]

Does $k$-mouflage survive in the strong-field regime? [YES]

Are the obtained screened solutions stable?
Evolution of K-mouflage

\[ \frac{\rho_c(t)}{\rho_c(0)} \]

A: static  
B: small perturbation  
C: large perturbation  
D: perturbation that triggers gravitational collapse
Evolution of K-mouflage

We define an effective metric

\[ \gamma^{\mu\nu} \equiv \tilde{g}^{\mu\nu} + \frac{2K''(\tilde{X})}{K'(\tilde{X})} \tilde{\nabla}^\mu \phi \tilde{\nabla}^\nu \phi \]

The characteristic matrix of the principal part is...

\[ M = \begin{pmatrix} 0 & \frac{\sqrt{-\tilde{g}_{tt}}}{\sqrt{\tilde{g}_{rr}}} \\ \frac{\sqrt{\tilde{g}_{rr}}}{\sqrt{-\tilde{g}_{tt}}} \gamma^{rr} & -2\frac{\gamma^{tr}}{\gamma^{tt}} \end{pmatrix} \]

characteristic speeds

\[ V_{\pm} = -\frac{\gamma^{tr}}{\gamma^{tt}} \pm \sqrt{-\text{det}(\gamma^{\mu\nu})} \frac{1}{(\gamma^{tt})^2} \]

Keldysh problem: The necessary time-step goes to zero when the speeds diverge.
References

Dynamics of Screening in Modified Gravity
LtH, M. Bezares, M. Crisostomi, E. Barausse, and C. Palenzuela,
Phys. Rev. Lett. 126 (2021) 091102, arXiv:2009.03354 [gr-qc]

k-dynamics: well-posed initial value 1+1 evolutions in \( k \)-essence
M. Bezares, M. Crisostomi, C. Palenzuela, E. Barausse, JCAP 03
(2021) 072, arXiv:2008.07546 [gr-qc]
Conclusions

We have shown by solving numerically the full field equations that screened solutions in $k$-essence do not only exist for Sun-like stars, but also for neutron stars.

These $k$-mouflage solutions are stable to small perturbations, and also to large ones as long as they do not cause gravitational collapse.

However, in some cases we run into a so-called Keldysh problem, and we cannot evolve the $k$-essence field equations starting from a $k$-mouflage configuration.

Outlook: solve Keldysh problem, evolve in 3+1.
Thank you for your attention!