Modifying gravity through instabilities

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Spontaneous scalarization is a member of a family of theories common in their underlying mechanism and observable signatures: spontaneous tensorization.

They all arise from a spontaneously growing instabilities which are eventually regularized: regularized instabilities.

They all (likely) have order-of-unity deviations from GR in strong field: relevant for near-future observations.
Many since Eddington’s observation of light deflection in 1919

GR is victorious, including the “bizarre” predictions

So far mainly for weak fields.

Field theories most likely break at strong-fields.

Now we have the means to probe dynamical strong fields, even dynamical ones: gravitational waves.

Baker et al. 2014
Many motivations from unification, high energy ...

Weak field well tested: cannot modify much (killed many early ideas)

Strong field experimental accuracy low: large modifications preferred

Make sure there is no fundamental physical or mathematical problem

Still left with many options
Beyond general relativity
Spontaneous Scalarization
Spontaneous tensorization – Instability regularization

Scalar-Tensor theories & Spontaneous Scalarization

\[
S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} R + S_M(g_{ab}, \psi)
\]
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Scalar-Tensor theories & Spontaneous Scalarization

$$S = \frac{1}{16\pi G} \int d^4 x \sqrt{-g} R - \frac{1}{16\pi G} \int d^4 x \sqrt{-g} \left( 2(\partial \phi)^2 + 2m_\phi \phi^2 \right)$$

$$+ S_M(A^2(\phi)g_{ab}, \psi)$$

$$\tilde{g}_{ab} \equiv A^2(\phi)g_{ab}$$

- Possibly most famous alternative to GR.
- Less popular after solar system observations
- Many $f(R)$ theories can be recast as scalar-tensor theories.
- Spontaneous scalarization when $A(\phi) = e^{\beta/2} \phi^2$ (Damour, Esposito-Farese, 1993)

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Modifying gravity through instabilities
Why Spontaneous?

*Novak*, 1998
Beyond general relativity
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How does this modification effect neutron stars?

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Modifying gravity through instabilities
Why Spontaneous?: Tachyon Instability

\[ \Box_g \phi = \left( m_{\phi}^2 - 8\pi A^4 \frac{d \ln A}{d(\phi^2)} \right) \phi \]

\[ \approx \left( m_{\phi}^2 - 4\pi \beta \tilde{T} \right) \phi \]

\[ \approx m_{\text{eff}}^2 \phi \]

- Non-relativistic Matter: \( T = -\rho + 3P \approx -\rho < 0 \).
- \( m_{\text{eff}}^2 < 0 \), tachyon instability!
- Alternatively, \( V_{\text{eff}} \) is not bounded from below.
- Not tachyonic for larger \( \phi \): regularization.
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Generalizing to other fields

\[
S = \underbrace{\frac{1}{16\pi G} \int d^4x \sqrt{-g} R}_{S_{GR}} - \underbrace{\frac{1}{16\pi G} \int d^4x \sqrt{-g} \left( 2(\partial \phi)^2 + 2m_\phi \phi^2 \right)}_{S_\phi} + \underbrace{S_{\text{matter}}}_{S_M(A^2(\phi)g_{ab}, \psi)}
\]

Recipe: Replace \( \phi \) with any other field and choose \( A \) as an “inverse parabola”. The new field will have a tachyonic EOM.
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Example: Spontaneous vectorization

\[
S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} R - \frac{1}{16\pi G} \int d^4x \sqrt{-g} \left( F_{\mu\nu} F^{\mu\nu} + 2m_X^2 X_\mu X^\mu \right)
\]

\[
S_{matter} + S_M \left( A^2 (X_\mu X^\mu) g_{ab}, \psi \right)
\]

\[
F_{\mu\nu} \equiv \partial_\mu X_\nu - \partial_\nu X_\mu
\]

\[
\Rightarrow \nabla_\rho F^{\rho\mu} = \left( -8\pi A_X^4 \frac{d \ln A_X}{d(X_\mu X^\mu)} \tilde{T} + m_X^2 \right) X^\mu
\]

\[
A = e^{\beta X_\mu X^\mu} \text{ again gives negative mass square!}
\]
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Generalizing to other instabilities: Ghost-based scalarization

\[
S = \frac{1}{16\pi G} \int d^4 x \sqrt{-g} R - \frac{1}{16\pi G} \int d^4 x \sqrt{-g} \left(2(\partial \phi)^2 + 2m_\phi \phi^2\right) + S_{\text{matter}}(A^2(K) g_{ab}, \psi), \quad K = (\partial_\mu \phi \partial^\mu \phi)
\]

\[
\Rightarrow \left(-8\pi A^4 \frac{dA}{dK} \tilde{T} + 1\right) \Box \phi = m_\phi^2 \phi
\]

Recipe: Replace the potential-like conformal scaling with kinetic-like conformal scaling. The scalar will be a ghost!
Generalizing to other instabilities: Ghost-based scalarization
Can combine the two ideas: ghost-based spontaneous vectorization

Beyond vectors, spin-2 fields? Major obstacles due to “other” ghosts.

The essence is not scalars vs vectors, or tachyon vs ghost: instability regularization in GR
→ Take a field and incite an instability
→ leave it to nonlinearity to regularize it
→ alternative theory with large deviations in strong field
→ ???
→ profit
Due to large deviations, any mergers with NSs are significant

Events with mass change are even better
- NSNS mergers with long-lived HMNS
- Eccentric mergers with partial disruptions
- . . .
Still quite a bit to do with (massive) scalarization.

Well-posedness of the family.

Perturbative signatures: monopole, dipole emissions, ...

Numerical relativity

Spin-2?

Regularized instabilities to any other modifications to GR?