Modifying gravity through instabilities

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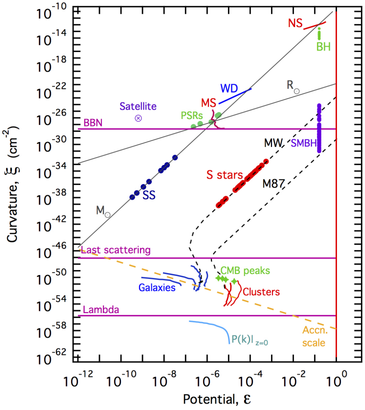
“GWverse: black holes, gravitational waves and fundamental physics”
Supported under CA 16104

University of Malta
January 24, 2018

Takeaway Message

- 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.

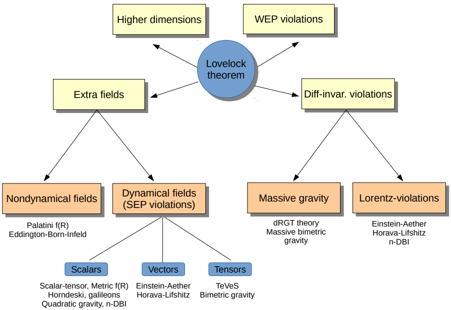
Testing general relativity



Baker et al. 2014

- 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.

Modifying general relativity



Berti et al. 2015

- 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

Scalar-Tensor theories & Spontaneous Scalarization

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R + S_M(g_{ab}, \psi)$$

Scalar-Tensor theories & Spontaneous Scalarization

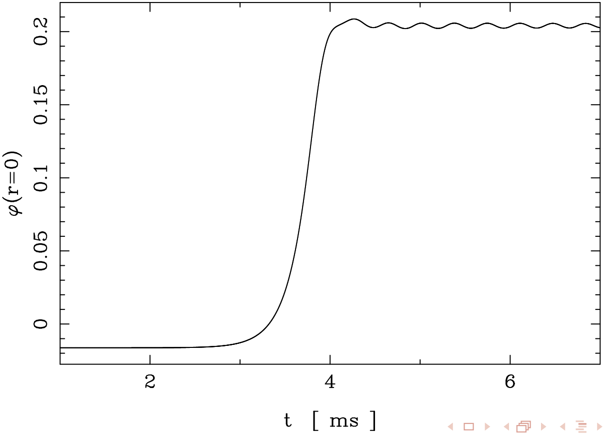
$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}R - \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left(2(\partial\phi)^2 + 2m_\phi\phi^2\right)$$
$$+ S_M(A^2(\phi)g_{ab}, \psi)$$

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

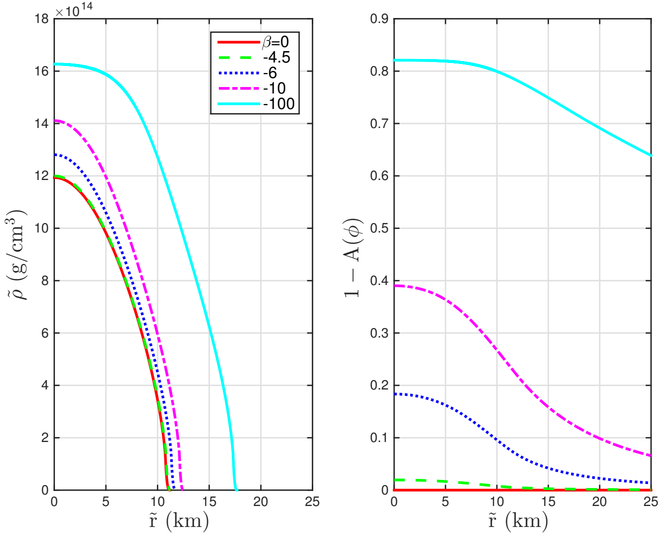
- Possibly most famous alternative to GR.
- Less popular after solar system observations
- Many $f(R)$ theories can be recast as scalar-tensor theories.
- Spontaneous scalarization when $A(\phi) = e^{\beta/2\ \phi^2}$ (Damour, Esposito-Farese, 1993)

Why Spontaneous?

Novak, 1998



How does this modification effect neutron stars?



Why Spontaneous?: Tachyon Instability

$$\Box_g \phi = \left(m_\phi^2 - 8\pi A^4 \frac{d \ln A}{d(\phi^2)} \right) \phi$$
$$\approx \left(m_\phi^2 - 4\pi\beta \tilde{T} \right) \phi$$
$$\approx m_{eff}^2 \phi$$

- Non-relativistic Matter: $T = -\rho + 3P \approx -\rho < 0$.
- $m_{eff}^2 < 0$, tachyon instability!
- Alternatively, V_{eff} is not bounded from below.
- Not tachyonic for larger ϕ: regularization.

Generalizing to other fields

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

Recipe: Replace ϕ with any other field and choose A as an "inverse parabola". The new field will have a tachyonic EOM.

Example: Spontaneous vectorization

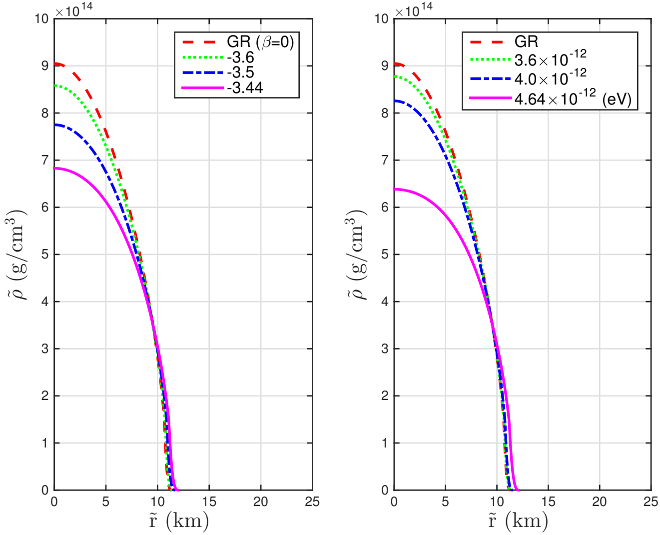
$$S = \overbrace{\frac{1}{16\pi G}\int d^4x\sqrt{-g}R}^{S_{GR}} - \overbrace{\frac{1}{16\pi G}\int d^4x\sqrt{-g}\left(F^{\mu\nu}F_{\mu\nu} + 2m_X^2 X_\mu X^\mu\right)}^{S_{X^\mu}}$$

$$+ \overbrace{S_M(A^2(X_\mu X^\mu)g_{ab}, \psi)}^{S_{matter}} \qquad F_{\mu\nu} \equiv \partial_\mu X_\nu - \partial_\nu X_\mu$$

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

$A = e^{\beta X_\mu X^\mu}$ again gives negative mass square!

How does this modification effect neutron stars?



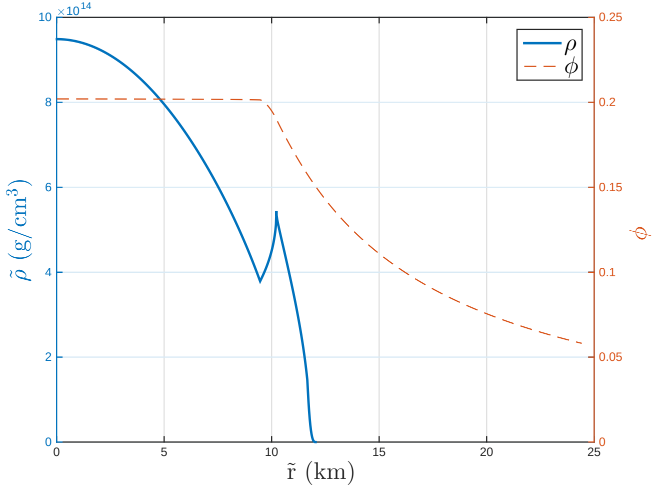
Generalizing to other instabilities: Ghost-based scalarization

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

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

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



Regularization of instabilities in Gravity

- 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
  $\rightarrow$ Take a field and incite an instability
  $\rightarrow$ leave it to nonlinearity to regularize it
  $\rightarrow$ alternative theory with large deviations in strong field
  $\rightarrow$???
  $\rightarrow$ profit

Relevance to CO mergers

- 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
  - . . .

Summary – Future

- 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?