Consistent models of Dark Energy after GW170817 and GRB170817A

Leonardo G. Trombetta
Scuola Normale Superiore - Pisa and INFN - Sezione di Pisa

1806.XXXX

In collaboration with:

Luca Santoni (Utrecht University) and Enrico Trincherini (SNS and INFN)

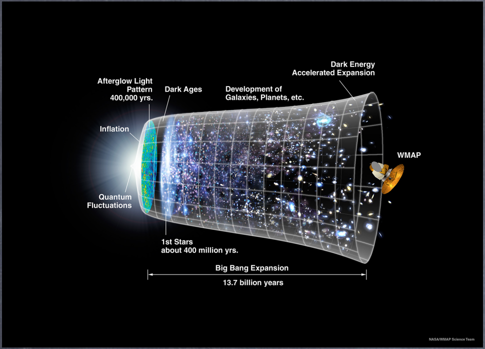
New Frontiers in Theoretical Physics XXXVI
Convegno Nazionale di Fisica Teorica 2018

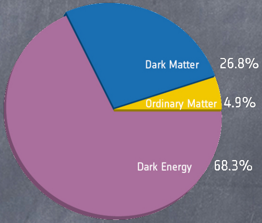
Cortona, May 24th, 2018

Outline

- Dark Energy models
- Absence of Instabilities
- Measurement of the speed of GWs
  - Constrains
- Consistency
  - Stability under quantum corrections (WBG)
- Summary

Current Acceleration of the Universe





Planck (2013)

Riess et al. (1998) and Perlmutter et al. (1999)

Possible explanations

- Cosmological constant (ΛCDM)
- Dark Energy
- Modified gravity
- ...

Dark Energy models

Scalar-Tensor theories

- Scalar condensate $\phi_0 \Longrightarrow$ Accelerated expansion
- Shift-symmetry and Higher derivative operators
- Propagates a single "new" degree of freedom

Scalings

- Single scale Λ: Higher derivative operators are suppressed at low energies $E \ll \Lambda$

$$\mathcal{L} = \Lambda^4 L\left(\frac{\partial}{\Lambda}, \frac{\phi}{\Lambda}\right)$$

- Two scales Λ_2 and Λ_3:

$$\mathcal{L} \quad \supset \quad \frac{(\nabla\phi)^4}{\Lambda_2^4} \qquad (\nabla\phi)^2\frac{(\nabla\nabla\phi)^2}{\Lambda_3^3}$$

Both kinds of operators contribute equally if:

$$\Lambda_2^4 \sim M_{Pl}\Lambda_3^3$$

Λ_3: Cutoff

Absence of Instabilities

Single "new" degree of freedom

Higher derivative theories could lead to instabilities, unless:

- The EOMs are of second order
- The EOMs are degenerate

Horndeski (G) + Beyond Horndeski (F)

$$X \equiv (\nabla\phi)^2/\Lambda_2^4$$

$$\begin{aligned}
\mathcal{L}_2 &= \Lambda_2^4\, G_2(X) \\
\mathcal{L}_3 &= \frac{\Lambda_2^4}{\Lambda_3^3}\, G_3(X)\Box\phi \\
\mathcal{L}_4 &= \frac{\Lambda_2^8}{\Lambda_3^6}\, G_4(X)R - 2\frac{\Lambda_2^4}{\Lambda_3^6}\, G_{4,X}(X)\left(\Box\phi^2 - \phi^{\mu\nu}\phi_{\mu\nu}\right) \\
&\quad + \frac{\Lambda_2^4}{\Lambda_3^6}\, F_4(X)\varepsilon^{\mu\nu\rho}_{\sigma}\varepsilon^{\mu'\nu'\rho'\sigma}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'} \\
\mathcal{L}_5 &= \frac{\Lambda_2^8}{\Lambda_3^9}\, G_5(X)G_{\mu\nu}\phi^{\mu\nu} + \frac{1}{3}\frac{\Lambda_2^4}{\Lambda_3^9}\, G_{5,X}(X)\left(\Box\phi^3 - 3\Box\phi\,\phi_{\mu\nu}\phi^{\mu\nu} + 2\phi_{\mu\nu}\phi^{\mu\sigma}\phi^{\nu}_{\sigma}\right) \\
&\quad + \frac{\Lambda_2^4}{\Lambda_3^9}\, F_5(X)\varepsilon^{\mu\nu\rho\sigma}\varepsilon^{\mu'\nu'\rho'\sigma'}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\phi_{\sigma\sigma'}
\end{aligned}$$

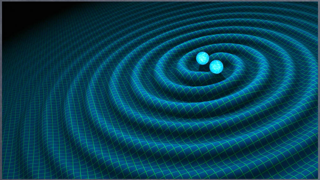
DHOST theories

Most general degenerate theories with $(\nabla\nabla\phi)^2$ and/or $(\nabla\nabla\phi)^3$

Measurement of the speed of GWs

Simultaneous observations of GWs and Gamma Rays origining from a Neutron Star merger

GW170817 (LIGO/VIRGO)



GRB170817A (Fermi)

- Delay between signals: $\Delta t \simeq 2sec$
- Distance to the source: $d \sim 130Mly$
- Main implication:

$$\left|\frac{c_T}{c} - 1\right| \lesssim 10^{-15}$$

Measurement of the speed of GWs

Constrains on ST theories

- In general $c_T \neq c$
- $\mathcal{L}_2$ and $\mathcal{L}_3$ do not affect c_T
- Imposing $\underline{c_T = c}$ for any background:

$$G_{5,X} = 0 \qquad F_5 = 0 \qquad 2G_{4,X} - XF_4 + G_{5,\phi} = 0$$

Creminelli & Vernizzi (2017)
Ezquiaga & Zumalacárregui (2017)
Sakstein & Jain (2017)

Remarks:

- Asuming shift-symmetry: $G_5 = 0 \Longrightarrow \mathcal{L}_5 = 0$
- If also $F_4 = 0$, then $G_4 = const \Longrightarrow \mathcal{L}_4 \sim R$

Consistency

Effective Field Theories

- All operators compatible with the symmetries are generated at $\mathcal{O}(1)$ by quantum corrections
- Stability under Quantum Corrections: The structure of the theory (i.e. relative scaling of the operators) is not spoiled

DE models

- Naive power counting:

$$\frac{(\nabla\phi)^{2n}}{\Lambda_2^{4(n-1)}}\frac{(\nabla\nabla\phi)^m}{\Lambda_3^{3m}} \qquad \Longrightarrow \qquad \frac{\delta c_n}{c_n} \sim 1$$

- Taking into account the structure of Horndeski theories:
  Weakly Broken Galilean (WBG) invariance

$$\frac{(\nabla\phi)^{2n}}{\Lambda_2^{4n}}\frac{(\nabla\nabla\phi)^m}{\Lambda_3^{3m-4}} \qquad \Longrightarrow \qquad \frac{\delta c_n}{c_n} \sim \frac{\Lambda_3}{M_{Pl}} \sim \left(\frac{H_0}{M_{Pl}}\right)^{2/3} \sim 10^{-40}$$

Pirtskhalava, Santoni, Trincherini & Vernizzi (2015)

Consistency

Generic shift-symmetric ST theory quadratic in $(\nabla\nabla\phi)$

$$\mathcal{L}_4 = \frac{\Lambda_2^8}{\Lambda_3^6} f(X) R + \frac{\Lambda_2^4}{\Lambda_3^6} C^{\mu\nu\rho\sigma} \nabla_\mu \nabla_\nu \phi \nabla_\rho \nabla_\sigma \phi$$

$$C^{\mu\nu,\rho\sigma} = \frac{\alpha_1(X)}{2} \frac{(\nabla\phi)^2}{\Lambda_2^4} (g^{\mu\rho} g^{\nu\sigma} + g^{\mu\sigma} g^{\nu\rho}) + \alpha_2(X) \frac{(\nabla\phi)^2}{\Lambda_2^4} g^{\mu\nu} g^{\rho\sigma} + \frac{\alpha_3(X)}{2\Lambda_2^4} (g^{\rho\sigma} \nabla^\mu \phi \nabla^\nu \phi + g^{\mu\nu} \nabla^\rho \phi \nabla^\sigma \phi) + \frac{\alpha_4(X)}{4\Lambda_2^4} (g^{\nu\sigma} \nabla^\mu \phi \nabla^\rho \phi + g^{\mu\sigma} \nabla^\nu \phi \nabla^\rho \phi + g^{\nu\rho} \nabla^\mu \phi \nabla^\sigma \phi + g^{\mu\rho} \nabla^\nu \phi \nabla^\sigma \phi) + \frac{\alpha_5(X)}{\Lambda_2^8} \nabla^\mu \phi \nabla^\nu \phi \nabla^\rho \phi \nabla^\sigma \phi$$

Special case

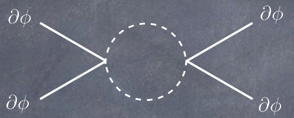
- Quartic Horndeski+Beyond-Horndeski:

$$f = G_4\,, \qquad X\alpha_1 = -X\alpha_2 = 2G_{4X} + XF_4\,, \qquad \alpha_3 = -\alpha_4 = 2F_4$$

Consistency

Nonrenormalization theorem

- Explicit loop calculations:



$$\sim \qquad I_0[f,\alpha_i] \int d^4q \, \ldots$$

$$\sim \qquad I_1[f,\alpha_i] \int d^4q \, \ldots$$

- Vanishing for any external momenta and number of vertices:

$$I_0[f,\alpha_i] = 0 \qquad \qquad \alpha_1 = -\alpha_2\,, \qquad \alpha_3 = -\alpha_4\,, \qquad \alpha_5 = 0$$

$$I_1[f,\alpha_i] = 0 \qquad \qquad 4f_X + 2X\alpha_2 + X\alpha_3 = 0$$

- Most general WBG theories: $H_4 + BH_4$

$$\frac{\delta c_n}{c_n} \sim \frac{\Lambda_3}{M_{Pl}} \ll 1$$

Summary

DHOST	$\supset$	WBG	$\supset$	$c_T = c$
No instabilities		Nonrenormalization		Speed of GWs

Remarks

- The measurement of the speed of GWs does not impose fine tuning on the DE models with WBG due to their Nonrenormalization properties
- The most general WBG theories are those formed by the combination of quartic Horndeski and Beyond-Horndeski lagrangians (previously only known for the former)
- No assumption on the existence of a decoupling limit is necessary

Outlook

- Further constrains from theoretical considerations? (ex. positivity bounds from analiticity of the S-matrix, etc)