Dilatonic couplings
and
the late time universe

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Late time universe

- Dark energy (looks like $\Lambda$ very much)
- (To be sure it’s $\Lambda$) Test against other models
- Strong local constraints (Screenings?)
- What do we do?
  - Fundamental model?
  - Study most general set up?
Propagation of GWs

- Interesting signatures: modification of $c_{gw}$!
  \[ G_4 R + G_{4,X} \left( (\Box \phi)^2 - (\nabla \nabla \phi)^2 \right) \]

- In ADM…
  \[ G_4 R^{(3)} + \left( G_4 - 2XG_{4,X} \right) \left( K_{ij}K^{ij} - K^2 \right) \]
  \[ x = -\frac{1}{2}(\partial \phi)^2 \]

- Late Universe (up to $z \approx 0.08$): $c_{gw} \approx 1 \pm 10^{-15}$!
  Ezquiaga+17, Creminelli +17, Sakstein +17, ...
  (no $X$ dependence in $G_4$)

- Early Universe: $c_{gw} \neq 1$? (B-modes)

Horndeski ‘74
Deffayet +11
LIGO ‘17
GW170817
Higher-derivatives out?

- More precisely
  \[ c^2_{gw} = \frac{G_4 - \phi X G_{5,X}}{G_4 - 2X G_{4,X} - 2X \phi H G_{5,X}} \]

- Fine tuning? Easily spoiled! \( (\Omega_{DM} \sim 27\%!) \)

- Ways out?
  
  - Bg independent tuning (in DHOST)
    
    - Interacting dark sector?

References:
- Kobayashi +11
- Langlois +17
- Amendola +99
- Miranda +17
Interacting dark sector

• (Not to mess with SM) Non-universal coupling
  \[ \mathcal{L} \sim \mathcal{L}_{\text{Horn}}(\phi, g) + \mathcal{L}_{\text{DM}}(\bar{g}(\phi)) + \mathcal{L}_{\text{SM}}(g) \]
  \[ \bar{g}_{\mu\nu} = e^{\beta \phi} g_{\mu\nu} \]

• Non-conservation of DM energy density
  \[ \dot{\rho}_{\text{DM}} + 3H\rho_{\text{DM}} = -Q(\phi)\rho_{\text{DM}} \]
  \[ \dot{\rho}_{\text{DE}} + 3H(1 + w_{\text{DE}})\rho_{\text{DE}} = Q(\phi)\rho_{\text{DE}} \]

• Interesting cosmology? \[ \Omega_b/\Omega_{\text{DM}} \neq \text{constant} \]

  • Alleviate \( H_0 \) or \( f\sigma_8 \) tensions (CMB and local exp).
  
  • Baryogenesis \ Sakstein +17

  • Effects to 21 cm line (\( z \sim 17 \); dark ages). \ Costa +17

  • At \( z < 0.3 \) \[ \Omega_{\text{DM}}/\Omega_{\text{DE}} = \text{constant?} \] \ Amendola + 99
Doppelgänger DE

• Quite messy in general but:
  - Like Jordan $\leftrightarrow$ Einstein frame
    \[ d\bar{\rho}_{DM}/d\bar{t} + 3\bar{H}\bar{\rho}_{DM} = 0 \]
    \[ \bar{g}_{\mu\nu} = e^{\beta\phi}g_{\mu\nu} \]
  - We have Matter $\leftrightarrow$ Dark Matter frame
    \[ 1 + \bar{w}_{eff} = \frac{1}{1 - \alpha} \left( 1 + w_{eff} - \frac{2}{3} \alpha - \frac{2}{3} \frac{d \ln(1 - \alpha)}{Hdt} \right) \]
    \[ \alpha \equiv \frac{d(\beta\phi)}{Hdt} = \frac{Q}{H} \]
  - Now they are decoupled
    \[ 3H^2G_4 = \rho_\phi + \rho_{DM} \]
  - E.g. Canonical: $V \propto e^{-\lambda\phi}$
    \[ G_4 = 1 \]
    \[ \rho_\phi \propto a^{-\lambda^2} \]
    \[ \lambda = \sqrt{3} \rightarrow \rho_\phi \propto \rho_{DM} \]
  - In general: $Y = Xe^{-\lambda\phi} = \text{constant} \rightarrow G_i = e^{p_i\phi}a_i(Y)$
Tuning $c_{gw}=1$

- **Fix point, attractor** with accelerated expansion

$$c_{gw}^{-2} = \frac{a_4 - 2Ya_4,Y}{a_4}$$

$$a_4, Y \bigg|_{Y=Y_*} = 0$$

- A simple non-trivial choice is

$$a_4 = 1 + c_4 (1 - Y/Y_*)^n$$

- The background dependence is now hidden in $Y_*$

- Is this choice still okay? What effects do we have?
Effect of baryons

• We should not forget that: \(3H^2G_4 = \rho_\phi + \rho_{DM} + \rho_b(\phi)\)

• Take us out of fix point by: \(\Omega_b/\Omega_{DM} \approx 4\%\)

• You can see how sensitive it is:

\[
\delta c_{gw}^2 \propto \frac{2Y^2a_4,YY}{a_4} \left| \frac{\Omega_b}{\Omega_{DM}} \right| < 10^{-15}
\]

• The Lagrangian is highly constrained: \(n>16!\)

\[
\delta c_{gw}^2 \propto \sim 10^{-n} \frac{Y^n a_4,Y^n}{a_4} \left| \right. < 10^{-15}
\]

Note: This value is only at the fix point nowadays. In the past

\[
a_4 = 1 + c_4 (1 - Y/Y_*)^n \neq 1
\]
Summary

• Modified gravity may need a more fundamental approach

• Modifications to $c_{gw} = 1$ seem unlikely (or at least hard to conceive) if due to DE field

• Interacting dark sector might provide ways out but Lagrangian very much constrained

• Possible effects in the early universe

• Origin of non-universal coupling?