Testing Dark Energy with Gravitational Waves

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GW astronomy can probe the Dark Universe

**Black Holes of Known Mass**

**Neutron Star Binaries**

**Dark Matter**

**Dark Energy**

*E.g.* PBH in Critical Higgs Inflation

[JME+García-Bellido+Ruiz-Morales’17]

[Wednesday session about PBH]

[This talk]

Quest for fundamental nature of DE

[Bettoni *et al.*’16, JME+Zumalacáregui’17]
- GW propagation in GR+FRW and how to do cosmology

\[ h''_{ij} + 2\mathcal{H}h'_{ij} + c^2k^2h_{ij} = 0 \]
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\[ h_{GW} = \frac{M_5^{5/3} f^{2/3}}{d_L^{gw}} F(\text{angles}) \cos \Phi(\eta) \]

\[ d_L^{gw} = (1 + z) \int_0^z \frac{c}{H(z)} dz \]
• GW propagation in GR+FRW and how to do cosmology

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\[ d_{L}^{gw} = (1 + z) \int_0^z \frac{c}{H(z)} dz \]

• A redshift measurement breaks the degeneracy

\[ z \ll 1 \Rightarrow d_{L}^{gw} = \frac{cz}{H_0} + \cdots \]

\[ H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1} \]

[Nature 551, 85–88 (2017)]
• Modified propagation and how to test DE

\[ h''_{ij} + (2 + \nu) \mathcal{H} h'_{ij} + (c_g^2 k^2 + a^2 m^2) h_{ij} = 0 \]
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\[ h_{GW} \sim h_{GR} \quad e^{-\frac{1}{2} \int \nu \mathcal{H} d\eta} \quad e^{i k \int (\alpha_T + a^2 m^2 / k^2)^{1/2} d\eta} \quad \alpha_T = c_g^2 - 1 \]

Effect amplitude \quad Effect phase
• Modified propagation and how to test DE

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Effect amplitude

Effect phase

• Propagation effects are **accumulative** and thus can dominate

• I will focus on **phase effects**, in particular, the **anomalous GW speed**

[\textit{LIGO Living Rev.Rel. 19 (2017)}]

\text{\texttt{jose.ezquiaga@uam.es}}
• Modified propagation and how to test DE

\[ h''_{ij} + (2 + \nu) \mathcal{H} h'_{ij} + (c^2 g k^2 + a^2 m^2) h_{ij} = 0 \]

\[ h_{GW} \sim h_{GR} \left( e^{-\frac{1}{2} \int \nu \mathcal{H} d\eta} \right)^{\frac{1}{2}} \left( e^{ik \int (\alpha_T + a^2 m^2 / k^2)^{1/2} d\eta} \right)^{1/2} \]

\[ \alpha_T = c_g^2 - 1 \]

• Propagation effects are accumulative and thus can dominate

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What DE models modify GW propagation? [LIGO Living Rev.Rel. 19 (2017)]
Dark energy with a scalar field

• Simplest modification of GR: $\phi$ scalar
Dark energy with a scalar field

- Simplest modification of GR: + \( \phi \) scalar
- Archetypical examples are Brans-Dicke and quintessence

\[ \mathcal{L} = \frac{1}{16\pi G(\phi)} R - \frac{1}{2} (\partial \phi)^2 - V(\phi) \]
Dark energy: scalar field

- Simplest modification of GR: $\ + \phi$

- Archetypical examples are

$$\mathcal{L} = \frac{1}{16\pi G(\phi)} R - \frac{1}{2} (\partial \phi)^2 - V(\phi)$$

- Modern theories described by Horndeski theory (2nd order EoM)

$$\mathcal{L}_H = G_2 + G_3 \Box \phi + G_4 R - G_{4,X} \{\nabla \nabla \phi\}^2 + G_5 G_{\mu\nu} \phi^{\mu\nu} - G_{5,X} \{\nabla \nabla \phi\}^3$$

contains k-essence, $f(R)$, KGB, covariant Galileon, Gauss-Bonnet...
Dark energy: scalar field

- Simplest modification of GR: \[
\begin{array}{c}
\includegraphics[width=1cm]{Einstein}\quad + \quad \phi_{\text{scalar}}
\end{array}
\]
- Archetypical examples are
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  contains k-essence, \(f(R)\), KGB, covariant Galileon, Gauss-Bonnet...
- At the linear level and over FRW backgrounds [Bellini and Sawicki 2014]
  \[
  \dddot{h}_{ij} + (3 + \alpha_M)H \dot{h}_{ij} + (1 + \alpha_T)k^2 h_{ij} = 0
  \]
  \[\alpha_K \delta \dddot{\phi} + 3H \alpha_B \dddot{\Phi} + \cdots = 0\]
• **Example of interesting cosmology:** Covariant Galileons

\[
G_2 = c_2 X , \quad G_3 = 2 \frac{c_3}{M^3} X \\
G_4 = \frac{M_P^2}{2} + \frac{c_4}{M^6} X^2 , \quad G_5 = \frac{c_5}{M^9} X^2
\]

1) DE without \( \Lambda \)

2) Requires massive neutrinos

3) Better fit to local \( H_0 \)
• Example of interesting cosmology: Covariant Galileons

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1) DE without \( \Lambda \)
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3) Better fit to local \( H_0 \)

\[ \sum_m m_\nu [eV] \]

\[ c_g^2 - 1 \]

[Renk et al. 2017]

[JME+ Zumalacárregui PRL’17]

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Rencontres de Moriond Cosmo18
GW170817: first binary neutron star merger detected!

Both the GWs and the sGRB arrived almost simultaneously

\[ \Delta t = 1.74 \pm 0.05 \text{s} \]

after traveling approx. 100 million light years \((40^{+8}_{-14} \text{ Mpc})\).

\[ -3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16} \]
Anomalous GW speed

- At small scales for *arbitrary backgrounds*

\[ \mathcal{L} \propto h_{\mu\nu} G^{\alpha\beta} \partial_\alpha \partial_\beta h^{\mu\nu} = h_{\mu\nu} (C \Box + W^{\alpha\beta} \partial_\alpha \partial_\beta) h^{\mu\nu} \]
Anomalous GW speed

- At small scales for arbitrary backgrounds

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**Conditions anomalous GW speed**

i) Non-trivial scalar field configuration
   \[
   \text{Dark energy} \quad \dot{\phi} \sim H_0
   \]

ii) Derivative coupling to the curvature
    \[
    \text{Modified gravity} \quad \mathcal{W}^{\alpha\beta} \sim \partial^\alpha \phi \partial^\beta \phi
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- If \( c_g \neq c \) no possible multi-messenger events

\[ c_g/c - 1 \sim 0.01 \text{ and } D \sim 100 \text{ Mpc } \Rightarrow \Delta t \sim 10^7 \text{ years} \]
Dead Ends after GW170817

- Constraint from GW170817
  \[ \alpha_T = c_g^2 - 1 \]

\[ |\alpha_T| < 9 \cdot 10^{-16} \left( \frac{40 \text{ Mpc}}{d} \right) \left( \frac{\Delta t}{1.7 \text{s}} \right) \]
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Covariant Galileons are now ruled out

Ruled out by ISW
The road ahead

*Conditions anomalous GW speed*

1. Non-trivial scalar field configuration
   
   **Dark energy** \( \dot{\phi} \sim H_0 \)

2. Derivative coupling to the curvature
   
   **Modified gravity** \( \mathcal{W}^{\alpha\beta} \sim \partial^\alpha \phi \partial^\beta \phi \)

- Avoiding GW170817 requires \( c_g=1 \) on arbitrary backgrounds
The road ahead

Conditions anomalous GW speed

i) Non-trivial scalar field configuration

Dark energy $\dot{\phi} \sim H_0$

ii) Derivative coupling to the curvature

Modified gravity $\mathcal{W}^{\alpha\beta} \sim \partial^\alpha \phi \partial^\beta \phi$

- Avoiding GW170817 requires $c_g = 1$ on arbitrary backgrounds

- Viable Horndeski models are those with

$$G_{4,X} \approx 0, \quad G_5 \approx \text{constant}$$

This includes (simplest models)

E.g. quintessence/k-essence, Brans-Dicke/f(R) and Kinetic Gravity Braiding

[see also Creminelli-Vernizzi, Baker et al., Sakstein-Jain’17]
Dark Energy after GW170817

[modified from original diagram by M. Zumalacárregui]
Dark Energy after GW170817

[modified from original diagram by M. Zumalacárregui]
Dark Energy after GW170817

General Relativity
Unique theory of massless $g_{\mu\nu}$

Massive Gravity $m_g > 0$

Additional Field

Tensor $f_{\mu\nu}$

Vector $V_{\mu}$

Scalar $\phi$

Horndeski

Beyond Horndeski

Galileon

KGB

f(R)

Brans-Dicke

Quintessence

Lorentz Violating

Break Assumptions

Extra dimensions

Non-Local

Horava

Einstein Aether

[modified from original diagram by M. Zumalacárregui]
Dark Energy after GW170817

General Relativity
Unique theory of massless $g_{\mu\nu}$

Massive Gravity
$m_g > 0$

Bigravity

Multi-gravity

Tensor $f_{\mu\nu}$

Additional Field

Vector $V_\mu$

Scalar $\phi$

Horndeski

Brans-Dicke $f(R)$

Quintessence

Beyond Horndeski $C(X)$

Galileon $D(X)$

KGB

General Proca

Proca $m_V > 0$

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Einstein Aether

Non-Local

[modified from original diagram by M. Zumalacárregui]

Constrained by

GW speed

[Ezquiaga+Zumalacárregui’17]
Dark Energy after GW170817

- **General Relativity**
  - Unique theory of massless $g_{\mu\nu}$

- **Massive Gravity**
  - $m_g > 0$

- **Additional Field**
  - Tensor $f_{\mu\nu}$

- **Vector** $V_\mu$

- **Scalar** $\phi$

- **Break Assumptions**
  - Non-Local
  - Lorentz Violating

- **Extra Dimensions**

- **Constrained by**
  - GW speed
  - Damping
  - Dispersion
  - Oscillations

[modified from original diagram by M. Zumalacárregui]
Conclusions

- GWs can probe Dark Universe
- **GW170817** sets a new landmark for DE
  - Only models with $c_g=1$ survive
  - Interesting models (e.g. Galileons) are now ruled out
- GW propagation is a powerful test of gravity. Other effects could be constrained
- Searches for additional polarization are crucial
- Looking forward for O3!
Conclusions

- GWs can probe Dark Universe

- \textbf{GW170817} sets a new landmark for DE
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- Looking forward for O3!

\[ g^{\mu\nu} q_\mu q_\nu = 0 \]

\[ G^{\mu\nu} k_\mu k_\nu = 0 \]
- Summary table for **scalar-tensor** dark energy models

<table>
<thead>
<tr>
<th>$c_g = c$</th>
<th>$c_g \neq c$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horndeski</strong></td>
<td></td>
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<tr>
<td>General Relativity</td>
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<tr>
<td>quintessence/k-essence</td>
<td></td>
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<tr>
<td>Kinetic Gravity Braiding</td>
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<td><strong>beyond H.</strong></td>
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<td>Derivative Conformal</td>
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<td>Disformal Tuning</td>
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<tr>
<td>quadratic DHOST with $A_1 = 0$</td>
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<tr>
<td>Viable after GW170817</td>
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<tr>
<td>quartic/quintic Galileons</td>
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<tr>
<td>Fab Four</td>
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<td>de Sitter Horndeski</td>
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<tr>
<td>$G_{\mu\nu} \phi^\mu \phi^\nu$, $f(\phi) \cdot$ Gauss-Bonnet</td>
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<tr>
<td><strong>quartic/quintic GLPV</strong></td>
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<tr>
<td>quadratic DHOST with $A_1 \neq 0$</td>
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</tr>
<tr>
<td>cubic DHOST</td>
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<tr>
<td>Non-viable after GW170817</td>
<td></td>
</tr>
</tbody>
</table>
• Going **beyond Horndeski**, we can modify the causal structure

\[
\tilde{g}_{\mu\nu} = \Omega^2(\phi, X)g_{\mu\nu} + D(\phi, X)\phi,_{\mu}\phi,_{\nu}
\]

leading to

\[
\tilde{c}_g^2 = \frac{c^2_g(\tilde{X})}{1 + 2\tilde{X}D}
\]

A) Apply a conformal transformation to a theory with \(c_g=1\)

\[
\mathcal{L}_C = \frac{1}{16\pi G} \left( \Omega^2 R + 6\Omega,_{\alpha}\Omega^{\cdot\alpha} \right) + \tilde{\mathcal{L}}_2 + \tilde{\mathcal{L}}_3
\]

B) Compensate the anomalous speed with a disformal transformation

\[
D = (c_g^2 - 1)/2\tilde{X}
\]
• Avoiding GW170817 constraint: $D, E \approx 0$

\[ G^{\mu \nu} = C g^{\mu \nu} \left[ D \phi^{,\mu} \phi^{,\nu} \right] + E \phi^{,\mu \nu} \]  

**Quintic models**

**Quartic models**

• A cancellation between *quartic* (D) and *quintic* (E) terms at the cosmological level is broken by perturbations

• Assuming such cancellation exists (at the level of $10^{-15}$)

\[ \phi = \phi(t) + \varphi(x) \rightarrow c_g^2 = 1 + 2 \frac{E}{C} \hat{k} \cdot \vec{\partial} \phi \pm \cdots \]

Avoiding GW170817 constraint requires $c_g=1$

on arbitrary backgrounds
- Test speed of gravity with periodic sources

- *Phase Lag Test*: measure difference in phase of GWs and EM radiation

  [for graviton mass test see Cooray and Seto 2004]

- There are sources already identified: *eLISA verification binaries*

  *E.g.* WDS J0651+2844  [Brown *et al.* 2011]

  - Distance to Sun: $1.0 \pm 0.1$ kpc
  - Inclination: $i = 86.9^{+1.6}_{-1.0}$ degrees
  - Period: $T = 765.206543(55)$ s
    \[
    \dot{T} = (-8.2 \pm 1.7) \cdot 10^{-12}
    \]
    [Hermes *et al.* 2012]
- Eclipsing WD emit mostly + polarization

- There will be a delay between the GWs and EM radiation

\[ \Delta t = \frac{r(t)}{c} \left( \frac{c}{c_g} - 1 \right) \]

\[ \Delta \Phi(t) = 2\omega \frac{r(t)}{c} \left( \frac{c}{c_g} - 1 \right) \]