Gravitational wave echoes in multimetric gravity

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Centre of Excellence “The Dark Side of the Universe”

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First observation of gravitational waves

Hanford, Washington (H1)   Livingston, Louisiana (L1)

Strain ($10^{-21}$)

Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)

Residual

Frequency (Hz)

32 64 128 256 512

Time (s)

0.30 0.35 0.40 0.45

Normalized amplitude

0 2 4 6 8

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Black hole merger:
- Before merger: $36M_\odot$ and $29M_\odot$ black holes.
- After merger: $62M_\odot$ black hole.
  $\Rightarrow$ $3M_\odot$ radiated into gravitational waves.
Black hole merger:
- Before merger: $36M_\odot$ and $29M_\odot$ black holes.
- After merger: $62M_\odot$ black hole.
  $\Rightarrow$ $3M_\odot$ radiated into gravitational waves.
$\Rightarrow$ Distance reconstructed from observed amplitude: 410Mpc.
$\Rightarrow$ Signal travel time to Earth: 1.3Ga.
Idea of wave echoes

- Binary black hole emits different wave components.
Idea of wave echoes

- Binary black hole emits different wave components.
- Different components get deflected differently on their way.
Idea of wave echoes

- Binary black hole emits different wave components.
- Different components get deflected differently on their way.
- Different signal travel times - echo.
Simple bimetric model

Field content:
- Two metric tensors $g^1_{\mu\nu}$, $g^2_{\mu\nu}$.
- Two matter sectors $\phi^1$, $\phi^2$.

$S = S_G[\ g^1_{\mu\nu}, \ g^2_{\mu\nu}] + S_M[\ g^1_{\mu\nu}, \ \phi^1] + S_M[\ g^2_{\mu\nu}, \ \phi^2]$. 

⇒ Both types of matter appear mutually dark.
⇒ Both metrics may carry gravitational waves.
⇒ Trajectories of gravitational waves depend on background metrics.
Simple bimetric model

- Field content:
  - Two metric tensors $g_{\mu\nu}^1, g_{\mu\nu}^2$.
  - Two matter sectors $\phi^1, \phi^2$.
- Structure of the action:

$$S = S_G[g^1, g^2] + S_M[g^1, \phi^1] + S_M[g^2, \phi^2].$$
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⇒ Both types of matter appear mutually dark.
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⇒ Trajectories of gravitational waves depend on background metrics.
Metric $g^I_{\mu\nu}$ near point mass $M$ of type $J$:

\[ g_{00}^I = -1 + 2G^{IJ} \frac{M}{r} + O\left(\frac{M^2}{r^2}\right), \]

\[ g_{0i}^I = 0, \]

\[ g_{ij}^I = \left(1 + 2G^{IJ} \gamma_{IJ} \frac{M}{r}\right) \delta_{ij} + O\left(\frac{M^2}{r^2}\right). \]
Weak field limit

- Metric $g^I_{\mu\nu}$ near point mass $M$ of type $J$:

$$
\begin{align*}
g^I_{00} &= -1 + 2G^{IJ} \frac{M}{r} + \mathcal{O} \left( \frac{M^2}{r^2} \right), \\
g^I_{0i} &= 0, \\
g^I_{ij} &= \left( 1 + 2G^{IJ} \gamma^{IJ} \frac{M}{r} \right) \delta_{ij} + \mathcal{O} \left( \frac{M^2}{r^2} \right).
\end{align*}
$$

- Constants determined by the action:
  - Effective gravitational constants $G^{IJ}$.
  - Spatial curvature parameters $\gamma^{IJ}$. 
Weak field limit

- Metric $g_{\mu\nu}$ near point mass $M$ of type $J$:

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$$

- Constants determined by the action:
  - Effective gravitational constants $G^{IJ}$.
  - Spatial curvature parameters $\gamma_{IJ}$.
- Different spacetime geometries seen by different sectors.
Wave propagation and Shapiro delay

- Assume massless gravitons (lightlike trajectories).
  \[ \delta t = G (1 + \gamma) M \ln \left( \frac{(|\vec{x}_s| - \vec{x}_s \cdot \vec{n})(|\vec{x}_d| + \vec{x}_d \cdot \vec{n})}{d^2} \right). \]

  - Effective gravitational constant $G$.
  - Spatial curvature parameter $\gamma$.
  - Source location $\vec{x}_s$.
  - Detector location $\vec{x}_d$.
  - Unit vector $\vec{n}$ from source to detector.
  - Shortest distance $d$ between wave and deflecting mass.

\[ \Rightarrow \text{Shapiro delay from single deflecting point mass:} \]
Wave propagation and Shapiro delay

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- In general: many deflecting masses along the way.
  \[ \Rightarrow \text{Cumulative effect on propagating gravitational wave.} \]
Wave propagation and Shapiro delay

- Assume massless gravitons (lightlike trajectories).

\[ \delta t = G \left(1 + \gamma\right) M \ln \left( \frac{\left(\|\vec{x}_s\| - \vec{x}_s \cdot \vec{n}\right)\left(\|\vec{x}_d\| + \vec{x}_d \cdot \vec{n}\right)}{d^2} \right) . \]

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- Unit vector \( \vec{n} \) from source to detector.
- Shortest distance \( d \) between wave and deflecting mass.

- In general: many deflecting masses along the way.

\[ \Rightarrow \quad \text{Cumulative effect on propagating gravitational wave.} \]
- Different parameters \( G \) and \( \gamma \) in different sectors.
- Different matter distributions in different sectors.

\[ \Rightarrow \quad \text{Waves will undergo different Shapiro delays.} \]
**Conclusion**

- **Gravitational wave echo:**
  - Assume different gravitational wave components.
  - Gravitational waves get deflected by matter.
  - Different deflection of different components.
  - Different Shapiro delay causes echo.
  - Realization possible via multimetric model.
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- Calculation of echo parameters:
  - Multimetric action and field equations.
  - Theory parameters $G$ and $\gamma$.
  - Matter distribution along wave trajectory.

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I have heard the echoes in the dark
Dim and distant voices of the past
And I've seen so far into the night
And lingered in the land of no light.

(Uriah Heep, 1991)
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