Probing Extreme Gravity through Gravitational-wave Observations

Kent Yagi
University of Virginia

TeVPA, Sydney
Dec. 5th 2019
Weak-field Tests? Strong-field Tests?

[Yunes, KY & Pretorius PRD (2016)]
Weak-field Tests? Strong-field Tests?

[Yunes, KY & Pretorius PRD (2016)]
Weak-field Tests? Strong-field Tests?

[Yunes, KY & Pretorius PRD (2016)]
Weak-field Tests? Strong-field Tests?

[Yunes, KY & Pretorius PRD (2016)]
Weak-field Tests? Strong-field Tests?

Solar System Exp.
- LAGEOS
- Double Binary Pulsar
- Cassini
- Perihelion Precession of Mercury

large
neutron star
- Sgr A*
- M87

Strong & Dynamical Gravity

[Yunes, KY & Pretorius PRD (2016)]
Tests of GR with GWs (based on LVC’s work)

[PRL 116, 221101 (2016); PRX 6, 041015 (2016); PRL 118, 221101 (2017); PRL 119, 141101 (2017); ApJL 848, L13 (2017); arXiv:1811.00364; arXiv:1903.04467; … ]

✓ residual signal-to-noise ratio (SNR) from best-fit template
  GR prediction for GW150914 verified within 4% error

✓ Non-GR polarization

GW170817

Bayesian Model Selection:
(tensor only) vs (scalar only) = $10^{21} : 1$
(tensor only) vs (vector only) = $10^{23} : 1$

[Will (2014)]
Tests of GR with GWs (based on LVC’s work)

[PRL 116, 221101 (2016); PRX 6, 041015 (2016); PRL 118, 221101 (2017); PRL 119, 141101 (2017); ApJL 848, L13 (2017); arXiv:1811.00364; arXiv:1903.04467; …]

✓ residual signal-to-noise ratio (SNR) from best-fit template

GR prediction for GW150914 verified within 4% error

✓ Non-GR polarization

✓ Propagation speed of GWs

dispersion relation of gravitons

graviton mass bounds

<table>
<thead>
<tr>
<th>Event</th>
<th>$m_g$ [$10^{-23}$ eV/c²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>10</td>
</tr>
<tr>
<td>GW151012</td>
<td>17</td>
</tr>
<tr>
<td>GW151226</td>
<td>29</td>
</tr>
<tr>
<td>GW170104</td>
<td>9.4</td>
</tr>
<tr>
<td>GW170608</td>
<td>30</td>
</tr>
<tr>
<td>GW170729</td>
<td>7.6</td>
</tr>
<tr>
<td>GW170809</td>
<td>9.6</td>
</tr>
<tr>
<td>GW170814</td>
<td>8.8</td>
</tr>
<tr>
<td>GW170818</td>
<td>7.4</td>
</tr>
<tr>
<td>GW170823</td>
<td>6.4</td>
</tr>
<tr>
<td>Combined</td>
<td>5.0</td>
</tr>
</tbody>
</table>

scalar-tensor theories after GW170817

[Ezquiaga & Zumalacarregui (2017)]

Kent Yagi
Tests of GR with GWs (based on LVC’s work)

[PRL 116, 221101 (2016); PRX 6, 041015 (2016); PRL 118, 221101 (2017); PRL 119, 141101 (2017); ApJL 848, L13 (2017); arXiv:1811.00364; arXiv:1903.04467; … ]

- Residual signal-to-noise ratio (SNR) from best-fit template
- GR prediction for GW150914 verified within 4% error
- Non-GR polarization
- Propagation speed of GWs
  Dispersion relation of gravitons
- Number of spacetime dimension
- Lorentz violation
- Equivalence principle
- Parameterized deviation from GR
parameterized post-Einsteinian (ppE) Formalism

waveform phase:

$\Psi^{(\text{insp})} = \Psi^{(\text{insp})}_{GR} + \beta \frac{v}{c}^{2n-5}$

relative velocity

$n$th post-Newton (PN) correction

PN approximation:

$\frac{v}{c} \ll 1$

[Yunes & Pretorius (2009)]
[LVC, PRL 116, 221101 (2016)]
# PPE Dictionary

<table>
<thead>
<tr>
<th>Theories</th>
<th>PPE Phase Parameters</th>
<th>Exponent $(2n - 5)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar-Tensor [95, 96]</td>
<td>$-\frac{5}{7168}\eta^{2/5}(\alpha_1 - \alpha_2)^2$</td>
<td>-7</td>
</tr>
<tr>
<td>Einstein-dilaton Gauss-Bonnet</td>
<td>$-\frac{5}{7168}\zeta_{EdGB}\frac{(m_1^2s_2^2EdGB - m_2s_1^2EdGB)^2}{m^4\eta^{18/5}}$</td>
<td>-7</td>
</tr>
<tr>
<td>dynamical Chern-Simons</td>
<td>$\frac{1549225}{11812864}\eta^{-14/5}\zeta_{dCS}\left[-2\delta_0\chi_0\chi_s + \left(1 - \frac{16068\eta}{61969}\right)\chi_a^2 + \left(1 - \frac{231808\eta}{61969}\right)\chi_s^2\right]$</td>
<td>-1</td>
</tr>
<tr>
<td>Einstein-Æther [99]</td>
<td>$-\frac{5}{3584}\eta^{2/5}\frac{(s_1^{EA} - s_2^{EA})^2}{(1 - s_1^{EA})(1 - s_2^{EA})^{4/3}}\left[\frac{(c_{14} - 2)w_0^3 - w_1^3}{c_{14}w_0^3w_1^3}\right]$</td>
<td>-7</td>
</tr>
<tr>
<td>Khronometric [99]</td>
<td>$-\frac{5}{3584}\eta^{2/5}\frac{(s_1^{kh} - s_2^{kh})^2}{(1 - s_1^{kh})(1 - s_2^{kh})^{4/3}}\sqrt{\alpha_{kh}}\left[\frac{(\beta_{kh} - 1)(2 + \beta_{kh} + 3\lambda_{kh})}{(\alpha_{kh} - 2)(\beta_{kh} + \lambda_{kh})}\right]^{3/2}$</td>
<td>-7</td>
</tr>
<tr>
<td>Noncommutative [100]</td>
<td>$-\frac{75}{256}\eta^{-4/5}(2\eta - 1)\Lambda^2$</td>
<td>-1</td>
</tr>
<tr>
<td>Varying-$G$ [92]</td>
<td>$-\frac{25}{851968}\eta_0^{3/5}\dot{G}<em>{C,0}\left[11m_0 + 3(s</em>{1,0} + s_{2,0} - \delta_G)m_0 - 41(m_{1,0}s_{1,0} + m_{2,0}s_{2,0})\right]$</td>
<td>-13</td>
</tr>
</tbody>
</table>

[Tahura & KY (2018)]
Constraining GR Fundamental Pillars

[Yunes & Hughes (2010)]
[LIGO-Virgo Collaboration (2016)]
[Yunes, KY & Pretorius (2016)]

\[ \delta \Psi = \beta v^{2n-5} \]

\( \text{ppE} | \beta | \) vs. \( n_{\text{PN}} \)

- PSR J0737-3039
- GW150914, Bayesian
- GW150914, Fisher

Kent Yagi
Constraining GR Fundamental Pillars

[Yunes & Hughes (2010)]
[LIGO-Virgo Collaboration (2016)]
[Yunes, KY & Pretorius (2016)]

\[ \delta \Psi = \beta \nu^{2n-5} \]

- extra dimension
- time varying $G$
- scalar monopole activation
- vector field activation
- scalar dipole activation

4D equivalence principle
4D equivalence principle
Lorentz invariance
parity invariance
PPE for Modified GW Propagation

\[ c = 1 \]

- graviton dispersion relation

\[ E^2 = p^2 + A p^\gamma \quad \Rightarrow \quad v_g^2 \approx 1 + (\gamma - 1) A E^{\gamma - 2} \]

\[ \Psi \sim 2\pi f \frac{D}{v_g} \quad \Rightarrow \quad \Psi = \Psi_{GR} + \beta \left(\frac{v}{c}\right)^{2n-5} \]

\[ \beta \sim A D M^{1-\gamma} \quad n = \frac{(3\gamma + 2)}{2} \]

Kent Yagi
Constraints on GW Propagation

\[ E^2 = p^2 + A p^\gamma \]

\[ v_g^2 \approx 1 + (\gamma - 1) A E^{\gamma - 2} \]
Constraints on GW Propagation

\[ E^2 = p^2 + A p^\gamma \]

superluminal

subluminal

[Kiyota & Yamamoto (2015)]
Constraints on GW Propagation

\[ E^2 = p^2 + A p^\gamma \]

superluminal

subluminal
Constraints on GW Propagation

-Kiyota & Yamamoto (2015)
-Yunes, KY & Pretorius (2016)
-LIGO/Virgo Collaboration (2017)

\[ E^2 = p^2 + A p^\gamma \]

superluminal

subluminal

-massive gravity
-Lorentz violation
-multifractional spacetime
-Lorentz violation
-mod. special relativity
-extra dimension

Kent Yagi
Tests of GR with GWs (based on LVC’s work)

[PRL 116, 221101 (2016); PRX 6, 041015 (2016); PRL 118, 221101 (2017);

- residual signal-to-noise ratio (SNR) from best-fit template
- GR prediction for GW150914 verified within 4% error
- Non-GR polarization
- Propagation speed of GWs
- dispersion relation of gravitons
- Number of spacetime dimension
- Lorentz violation
- Equivalence principle
- Parameterized deviation from GR
- Consistency test of GR Kerr with inspiral and post-inspiral
IMR Consistency Test of GR with GW150914

\[ (m_1, m_2, \chi_1, \chi_2) \rightarrow (M_f, \chi_f) \]

numerical relativity
assuming GR

Kent Yagi
IMR Consistency Test of GR with GW150914

initial masses & spins

\((m_1, m_2, \chi_1, \chi_2)\) \quad \rightarrow \quad (M_f, \chi_f)

numerical relativity
assuming GR

Fisher analysis
[credit: Zack Carson]
IMR Consistency Test of GR with GW150914

initial masses & spins

\((m_1, m_2, \chi_1, \chi_2)\)

→

final mass & spin

\((M_f, \chi_f)\)

numerical relativity assuming GR

Fisher analysis

[credit: Zack Carson]
IMR Consistency Test of GR with GW150914

Initial masses & spins

\((m_1, m_2, \chi_1, \chi_2)\)  

Final mass & spin

\((M_f, \chi_f)\)

Numerical relativity assuming GR

Fisher analysis

[credit: Zack Carson]
IMR Consistency Test of GR with GW150914

initial masses & spins

\[(m_1, m_2, \chi_1, \chi_2)\]

\[\rightarrow\]

final mass & spin

\[(M_f, \chi_f)\]

numerical relativity

assuming GR

GW150914

Fisher analysis

[credit: Zack Carson]
IMR Consistency Test of GR with GW150914

Bayesian, actual data

\[ \Delta \chi_f = \chi_f^I - \chi_f^{MR} \]

\[ \Delta M_f = M_f^I - M_f^{MR} \]
Future Improvement on IMR Consistency Tests

[Carson & KY arXiv:1908.07103]

Kent Yagi
Future Improvement on IMR Consistency Tests

\[ \Delta \chi_f / \bar{\chi}_f \]

GW150914

Cosmic Explorer

aLIGO (O1, Bayesian)

[Carson & KY arXiv:1908.07103]
Future Improvement on IMR Consistency Tests

An order of magnitude improvement!

[Carson & KY arXiv:1908.07103]
Black Hole / Neutron Star
Black Hole / Neutron Star

NS/BH

S190814

<table>
<thead>
<tr>
<th>NSBH</th>
<th>&gt;99%</th>
</tr>
</thead>
<tbody>
<tr>
<td>MassGap</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>0%</td>
</tr>
<tr>
<td>BNS</td>
<td>0%</td>
</tr>
<tr>
<td>BBH</td>
<td>0%</td>
</tr>
</tbody>
</table>

\[ D_L = 267 \pm 52 \text{ Mpc} \]

Einstein-dilaton Gauss-Bonnet (EdGB) gravity

\[ \mathcal{L} \sim R + \alpha e^\phi R_{GB}^2 \]
Black Hole / Neutron Star

<table>
<thead>
<tr>
<th>NS/BH</th>
<th>S190814</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSBH</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>MassGap</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>0%</td>
</tr>
<tr>
<td>BNS</td>
<td>0%</td>
</tr>
<tr>
<td>BBH</td>
<td>0%</td>
</tr>
</tbody>
</table>

\[ D_L = 267 \pm 52 \text{ Mpc} \]

\[ \sqrt{\alpha} \text{ [km]} \]

Einstein-dilaton Gauss-Bonnet (EdGB) gravity

\[ \mathcal{L} \sim R + \alpha e^\phi R_{GB}^2 \]

SNR = 8

SNR = 20

current bound

[Carson, Seymour & KY arXiv:1907.03897]

Kent Yagi
Black Hole / Neutron Star

**NS/BH**

**S190814**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NSBH</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>MassGap</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>0%</td>
</tr>
<tr>
<td>BNS</td>
<td>0%</td>
</tr>
<tr>
<td>BBH</td>
<td>0%</td>
</tr>
</tbody>
</table>

\[ D_L = 267 \pm 52 \text{ Mpc} \]

**Einstein-dilaton Gauss-Bonnet (EdGB) gravity**

- **SNR = 8**
- **SNR = 20**

**current bound**

**stronger bound when**

\[ m_{BH} \lesssim 16M_\odot \]

[Carson, Seymour & KY arXiv:1907.03897]
Black Hole / Neutron Star (Future Prospect)

neutron star / black hole

$(1.4, 10) M_\odot$

$1 \text{Gpc}$

Einstein-dilaton Gauss-Bonnet gravity

$10^1$

$10^0$

$10^{-1}$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$\sqrt{\alpha} [\text{km}]$

ground-based

space-based

[A+ Voyager CE ET]

[B-DECIGO DECIGO]

[Carson, Seymour & KY arXiv:1907.03897]
Black Hole / Neutron Star (Future Prospect)

Einstein-dilaton Gauss-Bonnet gravity

neutron star / black hole
$(1.4, 10) M_\odot \quad 1 \text{Gpc}$

current bound

single event

ground-based

space-based

[Carson, Seymour & KY arXiv:1907.03897]
Black Hole / Neutron Star (Future Prospect)

neutron star / black hole

$(1.4, 10)M_\odot$

1 Gpc

ground-based

space-based

[Carson, Seymour & KY arXiv:1907.03897]
Conclusions
Takeaway

- can be applied to specific theories such as string-inspired ones
- black hole / neutron star binaries will improve the bounds significantly

- various tests of GR with GWs being carried out
- no evidence for beyond-GR effects so far
- model-independent analyses include parameterized tests & inspiral-merger-ringdown consistency tests

Kent Yagi
Takeaway

- various tests of GR with GWs being carried out
- no evidence for beyond-GR effects so far
- model-independent analyses include parameterized tests & inspiral-merger-ringdown consistency tests

- can be applied to specific theories such as string-inspired ones
- black hole / neutron star binaries will improve the bounds significantly

Thank You!
Back Up
Future Detectors

- LISA
- TianQin
- B-DECIGO
- DECIGO
- CE
- aLIGO (O2)

[Carson & KY arXiv:1905.13155]
### Theoretical Constraints

[器具, KY & Pretorius PRD (2016)]

<table>
<thead>
<tr>
<th>Example Theories (Theoretical Parameters)</th>
<th>GR Pillar</th>
<th>Example Theory Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Einstein-dilaton Gauss-Bonnet ( \sqrt{\alpha_{\text{EdGB}}} ) [km]</td>
<td>Equiv. Princ.</td>
<td>—</td>
</tr>
<tr>
<td>scalar-tensor (</td>
<td>\dot{\phi}</td>
<td>) [1/sec]</td>
</tr>
<tr>
<td>dynamical Chern-Simons ( \sqrt{\alpha_{\text{dCS}}} ) [km]</td>
<td>Parity Inv.</td>
<td>—</td>
</tr>
<tr>
<td>Einstein-Æther ( (c_+, c_-) )</td>
<td>Lorentz Inv.</td>
<td>( 0.9, 2.1 )</td>
</tr>
<tr>
<td>RS-II Braneworld ( (\ell ) [( \mu \text{m} )]</td>
<td>4D</td>
<td>( 5.4 \times 10^{10} )</td>
</tr>
<tr>
<td>time-varying ( G ) ( (</td>
<td>\dot{G}</td>
<td>/G ) [( 10^{-12} / \text{yr} )]</td>
</tr>
<tr>
<td>Massive Gravity ( (m_g ) [eV])</td>
<td>( m_g = 0 )</td>
<td>( 10^{-22} )</td>
</tr>
<tr>
<td>Modified Special Rel.</td>
<td>Lorentz Inv.</td>
<td>( 1.3 \times 10^{22} )</td>
</tr>
<tr>
<td>( (\eta_{\text{dsrt}} / L_{\text{Pl}} &gt; 0) )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Graviton Dispersion Relation:**

\[
E^2 = (pc)^2 + A (pc)^\alpha
\]

[Mirshekari, Yunes & Will (2011)]

Kent Yagi