Gravitational Waves as Probes of Extreme Gravity

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Yunes & Siemens, Living Reviews in Relativity 2014,
http://arxiv.org/abs/1304.3473
Standing on the Shoulders of...

Clifford Will, Jim Gates, Stephon Alexander, Abhay Ashtekar, Sam Finn, Ben Owen, Pablo Laguna, Emanuele Berti, Uli Sperhake, Dimitrios Psaltis, Avi Loeb, Vitor Cardoso, Leonardo Gualtieri, Daniel Grumiller, David Spergel, Frans Pretorius, Neil Cornish, Scott Hughes, Carlos Sopuerta, Takahiro Tanaka, Jon Gair, Paolo Pani, Antoine Klein, Kent Yagi, Laura Sampson, Luis Lehner, Masaru Shibata, Curt Cutler, Haris Apostolatos,

**An incomplete summary of what GWs will tell us about gravity**

Leo Stein, Sarah Vigeland, Katerina Chatziioannou, Philippe Jetzer, Leor Barack, Kostas Glampedakis, Stanislav Babak, Ilya Mandel, Chao Li, Eliu Huerta, Chris Berry, Alberto Sesana, Carl Rodriguez, Georgios Lukes-Gerakopoulos, George Contopoulos, Chris van den Broeck, Walter del Pozzo, Jon Veitch, Nathan Collins, Deirdre Shoemaker, Sathyaprakash, Devin Hansen, Enrico Barausse, Carlos Palenzuela, Marcelo Ponce, etc.
Roadmap

How do GW tests differ from other tests?

How do we use GWs to test GR?

What will we learn from GW tests of GR?
How do GW tests Differ from Other Tests?

1. **Extreme Gravity:**

   **Sources:** Compact Object Coalescence
   Supernova, deformed NSs, etc.
   (excluding pulsar timing in this talk)

   **Phases:** Late Inspiral, Merger, Ringdown.

   **Processes:** Generation and Propagation of metric perturbation.

2. **Clean:** Absorption is negligible, lensing unimportant at low z, accretion disk and magnetic fields unimportant during inspiral.

   [Baker, et al, Psaltis LRR]
3. **Localized:** Distinct point sources in spacetime (not a background)

4. **Constraint Maps:**
   
   If large # of sources detected. eg. preferred position tests.

5. **Very Local Universe:** \( z < 0.07 \) or \( D < 300 \) Mpc for NS/NS inspiral.
How do use GWs to test GR? Matched Filtering

**Matched Filtering:**

- Create template “filters”
- Cross-correlate filters & data
- Find filter that maximizes the cross-correlation.

signal-to-noise ratio (SNR)

detector noise (spectral noise density)

\[ \rho^2 \sim \int \frac{\tilde{s}(f)\tilde{h}(f, \chi^\mu)}{S_n(f)} \, df \]

\[ \tilde{s}(f) \sim \text{data} \]

\[ \tilde{h}(f, \chi^\mu) \sim \text{template (projection of GW metric perturbation)} \]

\[ S_n(f) \sim \text{template param that characterize system} \]
How do use GWs to test GR? Source Modeling

**Inspiral:** thousands of cycles, most SNR at low masses.

**Approximations:** PN + PM

**Accuracy:** 3.5 PN (“3 loop” order)

**Template:** $h_x(t) \sim \frac{\eta M}{D_L} \cos \iota (M \omega)^{2/3} \cos 2\Phi + \ldots$

- gravitational wave
- symmetric mass ratio
- distance to the source
- inclination angle
- total mass
- orbital freq.
- orbital phase
How do use GWs to test GR?

Top-Down (test specific theory) vs. Bottom-Up (search for deviations).
Current Constraints

GW Constraints

### Search for Generic Deviations: Parameterize post-Einsteinian (ppE)

<table>
<thead>
<tr>
<th>Templates/Theories</th>
<th>GR</th>
<th>ppE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR</td>
<td>Business as usual</td>
<td>Quantify the statistical significance that the detected event is within GR. Anomalies?</td>
</tr>
<tr>
<td>Not GR</td>
<td>Quantify <strong>fundamental bias</strong> introduced by filtering non-GR events with GR templates</td>
<td>Can we measure deviations from GR characterized by non-GR signals? Model Evidence.</td>
</tr>
</tbody>
</table>

What will we learn from GW tests of GR?

1. **Gravitational Lorentz Violation**: Primarily from propagation speed w/coincident EM

   \[ \frac{v_g}{c} - 1 \lesssim 10^{-14} \]


2. **Graviton Mass**: Primarily from modification of dispersion relation.

   \[ \lambda_g^{\text{Pul.Tim.}} \gtrsim 10^{13} \text{ km} \quad \lambda_g^{\text{GW}} \gtrsim 10^{14} - 10^{16} \text{ km} \]


3. **Dipolar Emission**: From activation of scalar or vectorial modes.

What will we learn from GW tests of GR?

4. **Higher Curvature Action**: Effective theories (EDGB, CS)

\[ \xi_{LAGEOS} \lesssim 10^7 \text{ km} \quad \xi_{GW} \lesssim 10 \text{ km} \]

Yagi, PRD 2012,
Yagi, et al, PRD 2012]

5. **Screening Strong-Field Mechanism**: Scalarization

\[ \beta_{\text{Bin.Pul.}} \gtrsim (-4.75, -4.5) \quad \beta_{\text{ST}}^{\text{GW}} \gtrsim -4.5 \]

[Damour & Esposito-Farese, CQG, 1992,
Freire et al, MNRAS 2012,
Sampson et al, PRD 2014]

6. **No-Hair Theorem**: From binary black hole ringdown.
   (more difficult, requires high SNR)

[Meier, et al, CQG, 2004,
Berti et al, PRD 2006,
Gossan et al, PRD 2012]
What does it all mean?

GW tests of GR differ from other tests in a variety of ways: probe extreme gravity, clean, localized, constraint maps, present day.

GW tests will constrain a variety of phenomena: Lorentz violation, graviton mass, dipole emission, higher curvature action, screening mechanisms, no-hair theorem.

*Doveryai, no proveryai*
What will we learn from GW tests of GR?

**Nico’s (GW-Biased) GW Modified Theory Classification:**

- **“Weak Field”**
  - Well-constrained by binary pulsars, so need screening
  - Eg, Scalar-Tensor theories

- **Strong-Field**
  - Constrainable with GW observations, natural suppression without screening
  - Eg, Chern-Simons, Gauss-Bonnet, etc.

**Nico’s (GW-Biased) Cosmological Modified Theory Classification:**

- **Screened**
  - Late-time expansion, DE
  - Eg, chameleon, Vainshtein, etc.

- **Unscreened**
  - Early-time cosmology, inflation
  - Eg, Chern-Simons, Gauss-Bonnet, etc.
Screening in Cosmology ≠ Screening in GWs

In Cosmology

Weak Field, Low Energy

Galactic Dynamics

Not GR

GR

Strong Field, High Energy

Solar System

Binary Black Hole Mergers

In Gravitational Wave Physics

Solar System

Binary Black Hole Mergers

GR

Not GR
Weak Field Theories
Example: Scalar Tensor Theories

Definition:
\[
S_{Jordan} \sim \int d^4x \sqrt{-g} \left[ \phi R - \frac{\omega(\phi)}{\phi} (\partial^\mu \phi) (\partial_\mu \phi) + \mathcal{L}_{\text{matter}} \right]
\]

\[
\phi \rightarrow g_{\mu\nu} \rightarrow T_{\mu\nu}
\]

Effective Coupling to Matter:
\[
\alpha \sim \frac{1}{\sqrt{3 + 2\omega_{BD}}} \beta(\phi - \phi_0)
\]

Main Effect: Stars acquire scalar charge + Spontaneous Scalarization

Dominant Observables: Grav. and Inertial center of mass do not coincide → Screened Dipole Gravitational Wave Emission → Faster Orbital Decay

Damour+Esposito-Farese, PRD 54 (’96)
Constraints on Weak Field Theories

Scalarizable Scalar-Tensor:

(similar constraints for TeVeS and for massive Brans-Dicke)

Strong Field Theories
Example: Quadratic Gravity

Definition:

\[ S_{\text{Quad}} \sim \int d^4x \sqrt{-g} \left[ R - \frac{1}{2} (\partial_\mu \vartheta) (\partial^\mu \vartheta) + \alpha_1 \vartheta R^2 + \alpha_2 \vartheta R_{\mu\nu} R^{\mu\nu} + \alpha_3 \vartheta R_{\mu\nu\delta\sigma} R^{\mu\nu\delta\sigma} + \alpha_4 \vartheta R_{\mu\nu\delta\sigma} * R^{\mu\nu\delta\sigma} \right] \]

certain choices of couplings lead to Einstein-Dilaton-Gauss-Bonnet theory or dynamical Chern-Simons gravity.

Main Effects: dCS. Gravitational Parity Violation, inverse no-hair theorem.

Dominant Observables: Chirping of Gravitational Wave Phase

Requires observation of late inspiral & merger

Alexander & Yunes, Phys. Rept 480 ('09)
Yunes & Stein, PRD 83 ('11)
Constraints on Strong Field Theories

Current constraints
Extremely weak from Solar System (GPB)

Projected GW constraints

\[ \alpha_4^{1/2} < \mathcal{O}(10^8 \text{ km}) \]

Yagi, Yunes & Tanaka, PRL 109 (’12)
Parametrized Post-Einsteinian
Projected Gravitational Wave Constraints

GR Signal/ppE Templates, 3-sigma constraints, SNR = 20

\[ \tilde{h}(f) = \tilde{h}_{GR}(f) (1 + \alpha f^a) e^{i\beta f^b} \]

Yunes & Hughes, 2010,
Cornish, Sampson, Yunes & Pretorius, 2011
Sampson, Cornish, Yunes 2013.
GW Probes of Extreme Gravity

Yunes

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At our doorstep...

- is the Pontryagin density.
- is either a dynamical field that evolves.

First Lock

LIGO India?

Strain Noise

\(|\text{Hz}^{1/2}\)|

<table>
<thead>
<tr>
<th>Year</th>
<th>S5</th>
<th>S6</th>
<th>Now</th>
<th>Early runs: LIGO Only?</th>
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<tbody>
<tr>
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<tr>
<td>2020</td>
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</tbody>
</table>
Non-GR Signal/GR Templates, SNR = 20

Non GR injection, extracted with GR templates (blue) and ppE templates (red). GR template extraction is “wrong” by much more than the systematic (statistical) error. “Fundamental Bias”

Cornish, Sampson, Yunes & Pretorius, 2011
Ignoring Fundamental Bias...

Physical Parameters Completely Biased

Fitting Factor Deteriorates

injection=(not-ruled out) ppE

template=GR

GW Probes of Extreme Gravity

Yunes
Stealth Bias

Fundamental Bias that we can’t detect!

SNR needed for fundamental bias error to be larger than systematic error

SNR needed to detect a GR deviation

Negligible Bias
Stealth Bias
Overt Bias
Bayes Factor between a 1-parameter ppE template and a GR template (red) and between a 2-parameter ppE template and a GR template (blue), given a non-GR injection with 3 phase deformations, as a function of the magnitude of the leading-order phase deformation.

Sampson, Cornish & Yunes, 2013
The Need for Accuracy

Quantum Noise (Amelino-Camelia)
is either a dynamical field.

Bounce light off mirrors and look for interference pattern when the light recombines.
I. Parametrically deform the Hamiltonian.

\[ A = A_{GR} + \delta A \]
\[ \delta A_{H,RR} = \bar{\alpha}_{H,RR} \nu^\alpha_{H,RR} \]

II. Parametrically deform the RR force.

\[ h = F_+ h_+ + F_\times h_\times + F_s h_s + \ldots \]

III. Deform waveform generation.

IV. Parametrically deform g propagation.

\[ E_g^2 = p_g^2 c^4 + \bar{\alpha} p_g \]

Result: To leading PN order and leading GR deformation

\[ \tilde{h}(f) = \tilde{h}_{GR}(f) (1 + \alpha f^a) e^{i\beta f^b} \]

Yunes & Pretorius, PRD 2009
Mirshekari, Yunes & Will, PRD 2012
Chatziioannou, Yunes & Cornish, PRD 2012