What Theoretical Physics can we learn from LISA Gravitational Wave Observations?

Nicolas Yunes
eXtreme Gravity Institute
Montana State University

LISA Telecon
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eXtreme Matter meets eXtreme Gravity Workshop, Bozeman, Montana, USA

XG1 Workshop First Announcement

"eXtreme Matter meets eXtreme Gravity"
August 17-19, Bozeman Montana

The eXtreme Gravity Initiative at Montana State University will hold a workshop to discuss methods for constraining the properties of Neutron Stars and the dense-matter equation of state. Like previous XGI workshops, the format will emphasize discussion and exchange of ideas over formal presentations. Each session will be organized around a science question, with a moderator and two discussion leaders. Topics to be covered include gravitational-wave observations of Neutron Star – Neutron Star and Neutron Star – Black Hole binaries, X-ray observations by the NICER mission (set to launch very soon), theoretical calculations of the dense-matter equation of state, and numerical simulations of NS-NS and NS-BH mergers.

The meeting is being held immediately prior to the HEAD meeting in Sun Valley, and participants may choose to drive between the meetings, or simply head a little south of Bozeman to view the total eclipse on the 21st of August. Bozeman is a beautiful mountain town a one-hour drive from the North entrance of Yellowstone National Park. The surrounding area offers great opportunities for hiking, fishing, white water rafting, and mountain biking.
Plan of Attack

What are we testing?

How well will we do?

What are the open problems?
What are we testing?

Gravitational Wave Generation
- Scalar/Vector Field Activation
- Gravitational Parity Violation
- Gravitational Lorentz Violation
- Extra-Dimensional Leakage
- Time-Variation of $G$
  - Spacetime Dimensionality
    - Parity Violation
    - Lorentz Violation
    - SEP Violation

Gravitational Wave Propagation
- Modified Dispersion Relations
- Modified Kinematics
- Gravitational Lorentz Violation
- Cosmological Screening
- Time-Variation of $G$
  - Speed of Gravity
  - Mass of Graviton
  - Lorentz Violation
  - SEP Violation

Constrain Deviations of GR Pillars
What well will we do?

[Barausse, Yunes, Chamberlain, PRL '16]

[Chamberlain & Yunes, submitted]
What are the open problems?

Theory

**Modified Gravity**
- New & Interesting Physical Mechanisms?
- Cosmological Modified Theories?

**GR Modeling**
- Spin Precession in Modified Gravity?
- Mergers in Modified Gravity?
- EMRIs and resonances in Modified Gravity?

Data Analysis

- Efficient data analysis w/high D parameter space?
- Reduced order methods for Modified gravity?
- Pipelines for combined GW+EM studies of modified gravity?
- Pipelines for stacking tests of gravity? (including e.g. coherent stacking and ringdown tests)

Community

- Collaborative structure for theorists and data analysts?
- Just releasing analysis “code” will not work
- Support for both data analysis development and theory development is needed.
Back Up Slides
Intro Stuff
What Physics Regime do GWs Probe?

GWs probe Extreme Gravity

Field Strength

Curvature Strength

Weak Field Tests

Extreme Gravity Tests

LAGEOS

Lunar Laser Ranging

Perihelion Precession of Mercury

Cassini

Double Binary Pulsar (Orbital Decay)

Double Binary Pulsar (Shapiro Delay)

Pulsar Timing Arrays

GW150914

GW151226

$R^{1/2} = (M/L)^{3/2}$ [km$^{-1}$]

$\Phi = M/L$

### The Parameterized post-Einsteinian Framework

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

<table>
<thead>
<tr>
<th>Theoretical Effect</th>
<th>Theoretical Mechanism</th>
<th>Theories</th>
<th>ppE b</th>
<th>Order</th>
<th>Mapping</th>
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<tbody>
<tr>
<td>Scalar Dipolar Radiation</td>
<td>BH Hair Growth                                                                 schöneke [140, 142, 149, 150]</td>
<td>Scalar-Monopole Field Theory</td>
<td>-7</td>
<td>-1PN</td>
<td>( \beta_{EBGB} ) [140]</td>
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<td></td>
<td><strong>Scalar Monopole Field Activation</strong></td>
<td>Scalar-Tensor Field Theory</td>
<td>-7</td>
<td>-1PN</td>
<td>( \beta_{ET} ) [59, 151]</td>
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<tr>
<td>Anomalous Acceleration</td>
<td>Extra Dimension Mass Leakage</td>
<td>RS-II Braneworld [152, 153]</td>
<td>-13</td>
<td>-4PN</td>
<td>( \beta_{ED} ) [141]</td>
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<td>Time-Variation of G</td>
<td>Phenomenological [137, 154]</td>
<td>-13</td>
<td>-4PN</td>
<td>( \beta_{Q} ) [137]</td>
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<tr>
<td>Scalar Quadrupolar Radiation</td>
<td>Scalar Dipole Field Activation due to Gravitational Parity Violation</td>
<td>dCS [140, 155]</td>
<td>-1</td>
<td>+2PN</td>
<td>( \beta_{dCS} ) [146]</td>
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<tr>
<td>Quadrupole Moment Deformation</td>
<td><strong>Scalar Dipolar Force</strong></td>
<td>( \tilde{h}_{GR}(f) )</td>
<td>-7</td>
<td>-1PN</td>
<td>( \beta_{E}^{(-1)} ) [113]</td>
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<td><strong>Vector Field Activation due to Lorentz Violation</strong></td>
<td>EA [109, 110], Khronometric [111, 112]</td>
<td>-5</td>
<td>0PN</td>
<td>( \beta_{E}^{(0)} ) [113]</td>
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<tr>
<td>Modified Quadrupolar Radiation</td>
<td><strong>GW Propagation/Kinematics</strong></td>
<td>Massive Gravity [156–159]</td>
<td>-3</td>
<td>+1PN</td>
<td>( \beta_{MDR} ) [146, 156]</td>
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<tr>
<td>Modified Dispersion Relation</td>
<td></td>
<td>Double Special Relativity [160–163]</td>
<td>+6</td>
<td>+5.5PN</td>
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<td>Horava-Lifshitz [165–167], gravitational SME ((d = 4)) [179]</td>
<td>+9</td>
<td>+7PN</td>
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<tr>
<td></td>
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<td>gravitational SME ((d = 5)) [179]</td>
<td>+3</td>
<td>+4PN</td>
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<td>+5.5PN</td>
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<td>Multifractional Spacetime [168–170]</td>
<td>+9</td>
<td>+7PN</td>
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</table>

[MSU: Cornish et al PRD 84 (’11), Sampson et al PRD 87 (’13), Sampson, et al PRD 88 (’13), Sampson et al PRD 89 (’14), Nikhef: Del Pozzo et al PRD 83 (’11), Li et al PRD 85 (’12), Agathos et al PRD 89 (’14), Del Pozzo et al CQG (’14).]
Current Ligo Bounds
GR Consistency Implies Constraints on Modified

- Scalar Dipole Radiation
- Lorentz Violation
- Parity Violation
- Anomalous Acceleration

Sources:
- Solar System
- PSR J0737-3039
- 2011 Projection, Bayesian
- GW150914, Bayesian
- GW150914, Fisher
- GW151226, Fisher

[Yunes, Yagi, Pretorius, PRD '16]
| Theoretical Mechanism | GR Pillar | PN | | | | Repr. Parameters | Example Theory Constraints |
|------------------------|-----------|----|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| Scalar Field Activation | SEP | −1 | $1.6 \times 10^{-4}$ | $4.4 \times 10^{-5}$ | | $\sqrt{\alpha_{\text{GB}}}$ | $[\phi]$ | 1/sec | | | 10$^{-6}$ | [56], 2 [57–59] | 10$^{-6}$ [60] |
| Scalar Field Activation | SEP, PI | +2 | $1.3 \times 10^{1}$ | 4.1 | | $\sqrt{\alpha_{\text{CS}}}$ | km | | | | | 10$^{8}$ [61, 62] |
| Vector Field Activation | SEP, LI | 0 | $7.2 \times 10^{-3}$ | $3.4 \times 10^{-3}$ | | $\beta_{+}$ | $\lambda_{\text{GC}}$ | | (0.9, 2.1) | (0.42, −) | (0.8, 1.1) | (0.40, −) | (0.03, 0.003) [63, 64] | (0.005, 0.1) [63, 64] |
| Extra Dimensions | 4D | −4 | $9.1 \times 10^{-9}$ | $9.1 \times 10^{-11}$ | | $\nu$ | [μm] | | | | 10$^{-10}$ | [65–69] |
| Time-Varying G | SEP | −4 | $9.1 \times 10^{-9}$ | $9.1 \times 10^{-11}$ | | $\alpha$ | [10$^{-12}$/yr] | | | | | 0.1–1 [70–74] |
| Massive graviton | m$_g$ = 0 | +1 | $1.3 \times 10^{-1}$ | $8.9 \times 10^{-2}$ | | $m_g$ | [eV] | | | | | 10$^{-22}$ [19] | 10$^{-22}$ [5] | 10$^{-20}$–10$^{-18}$ [75–79] |
| Mod. Disp. Rel. | Li | +4.75 | $1.1 \times 10^{2}$ | $2.6 \times 10^{2}$ | | $E_{-1}$ | [eV$^{-1}$] | (time) | | | | | 3.3 \times 10$^{-26}$ | — |
| (Multifractional) | | | | | | $E_{-1}$ | [eV$^{-1}$] | (space) | | | | | 5.7 \times 10$^{-26}$ | 3.9 \times 10$^{-53}$ [80] |
| Mod. Disp. Rel. | Li | +5.5 | $1.4 \times 10^{2}$ | $4.3 \times 10^{2}$ | | $\eta_{\text{Pert}}/L_{\text{P}}$ | $> 0$ | | | | | 1.3 \times 10$^{22}$ | 3.8 \times 10$^{22}$ | 2.1 \times 10$^{-7}$ [80] |
| (Modified Special Rel.) | | | | | | $\eta_{\text{Pert}}/L_{\text{P}}$ | $< 0$ | | | | | — | — | — |
| Mod. Disp. Rel. | 4D | +7 | $3.3 \times 10^{2}$ | $2.4 \times 10^{3}$ | | $\alpha_{\text{undef}}/L_{\text{P}}^2$ | $> 0$ | | | | | 5.5 \times 10$^{62}$ | 2.5 \times 10$^{63}$ | 2.7 \times 10$^{2}$ [80] |
| (Extra Dim.) | | | | | | $\alpha_{\text{undef}}/L_{\text{P}}^2$ | $< 0$ | | | | | — | — | — |
| Mod. Disp. Rel. | Li | +5.5 | $1.4 \times 10^{2}$ | $4.3 \times 10^{2}$ | | $k_{(1)}^{(4)}$ | > 0 | | | | | 1.7 \times 10$^{-12}$ [82] | 3.1 \times 10$^{-11}$ | 1.7 \times 10$^{-40}$ [80, 81] |
| (Standard Model Ext.) | | | | | | $k_{(1)}^{(4)}$ | < 0 | | | | | 0.64 | 19 | — |
| | | +7 | $5.3 \times 10^{2}$ | $2.4 \times 10^{3}$ | | $k_{(1)}^{(4)}$ | > 0 | [cm] | | | | 7.2 \times 10$^{-4}$ | 3.3 \times 10$^{-3}$ | 3.5 \times 10$^{-64}$ [80, 81] |
| | | | | | | $k_{(1)}^{(4)}$ | < 0 | [cm$^2$] | | | | — | — | — |
| Mod. Disp. Rel. | Li | +7 | $5.3 \times 10^{2}$ | $2.4 \times 10^{3}$ | | $\kappa_{M_{BL}}^{2}$ | [1/eV$^2$] | | | | | 1.5 \times 10$^{6}$ | 6.9 \times 10$^{6}$ | — |
| (Hořava-Lifshitz) | | | | | | $\kappa_{M_{BL}}^{2}$ | [1/eV$^2$] | | | | | — | — | — |
| Mod. Disp. Rel. | Li | +4 | — | — | | $c_+$ | | | | | | | 0.7 [83] | 0.998 | 0.03 [63, 64] |

[Yunes, Yagi, Pretorius, PRD ‘16]
Virtual Text:
More on Robustness of Constraints

Constraint on ppE amplitude as a function of PN order at which the modification first enters (assuming BD functional structure)

**Constraints are always robust, provided the modifications to the GW generation enter below 2.5PN order (ie. provided there is enough “information” in the inspiral part of the waveform)**
But what about the higher PN order terms?

Case Study: Scalar-Tensor (Brans Dicke) theory

\[ \Phi_{I}^{BD}(f) = \Phi_{I}^{GR}(f) + \beta_{BD} \left( \pi \mathcal{M} f \right)^{b_{BD}} \]

\[ 1 + \sum_{i=2}^{5} \delta \phi_{i}^{BD}(\eta) \left( \pi \mathcal{M} f \right)^{i/3} \]

Caveat: These constraints are “conservative.” We could do better if we knew how the merger was modified and we included this in the analysis.
Some Future Bounds (Including With Lisa)
Future ppE Constraints on GR

[Diagram: Space-based and Ground-based Constraints on p-n Order]

[Chamberlain & Yunes, to appear soon]
Future Constraints on Violations of SEP

Extractable Physics:
Non-Schw BHs (yes-hair theorem in EdGB)
NSs have scalar charge (scalar-tensor)
Compact Object binaries inspiral faster due to dipole radiation

Maximize Extraction:
Low-mass BH or NS (long-inspiral) GWs
Binary with tiny mass ratio

Open Questions:
Merger?
Hybrid IMR waveforms?

\[ \beta = -\frac{3}{224} \eta^{2/5} \delta \dot{E} \]
Future Constraints on Gravitational Lorentz

Extractable Physics:

Non-Spinning BH is not Schwarzschild
NSs have sensitivity-dependent GR deviations
Compact Object binaries inspiral faster due to dipole radiation

Maximize Extraction:

SMBHs or EMRIs do best

Open Questions:

BH sensitivities and Inspiral BH waveforms
Merger? Hybrid IMR waveforms?

\[ \beta = \frac{3}{128} \text{nasty}(c_+, c_-) \]

[Chamberlain & Yunes, to appear soon]
Maximize Extraction:
- Binary system at widest separation possible (lowest frequency)
- Binary with largest chirp mass

Open Questions:
- Generation of GWs?
- Merger? Hybrid IMR waveforms?

\[ \beta = -\frac{25}{65526} \frac{\dot{G}}{G} \mathcal{M}_z \]  

[Chamberlain & Yunes, to appear soon]