Detecting new forces in the gravitational wave background

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The era of gravitational waves

Moore et al. [2015]

\[ \sim 10^9 M_\odot \]

This talk

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1. SMBH GW background is a guaranteed discovery

2. Long range forces can *detectably* modify spectrum

3. SMBH GWs potentially probe many BSM scenarios
The stochastic GW background

NGC 6240

SGWB: incoherent superposition of many binaries

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Stochastic background spectrum

Amplitude is uncertain, but shape is robust

\[ h_c^2(f) \propto \frac{1}{f} \sum_{\text{sources}} \frac{dE_{GW}}{df} \]

\[ h_c \propto f^{-2/3} \]
Gravitational waves drive the evolution of the binary

\[
\frac{dE_{GW}}{df_{GW}} = -\pi^2 \mu r^2 f_{GW} \left( \frac{2f_{GW}}{r} \frac{dr}{df_{GW}} + 1 \right)
\]

\[
f_{\text{orbit}}(r) = \left( \frac{G(M_1 + M_2)}{4\pi^2 r^3} \right)^{1/2}
\]

(Kepler’s third law)

\[
\frac{dE_{GW}}{df_{GW}} \propto f^{-1/3} \quad \Rightarrow \quad \frac{dh_c}{df_{GW}} \propto f^{-2/3}
\]

[Phinney, 2001]

New physics can break this prediction
Assumptions are made to be broken

1. $f \leftrightarrow r$ relation
   Kepler’s law

2. All energy loss is gravitational

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Additional dynamics spoil the $-\frac{2}{3}$
Toy model: charge BHs under dark U(1)

1. New force changes Kepler’s law
2. New radiation takes energy

**Charge parameters**

\[
\alpha = \frac{Q_1 Q_2}{GM_1 M_2} \\
\gamma = \frac{1}{G} \left( \frac{Q_1}{M_1} - \frac{Q_2}{M_2} \right)^2
\]

Force

Radiation
Modifying the force law ($|\alpha| > 0$)

\[ \frac{dE_{gw}}{df_{gw}} / \text{(gravity-only)} \]

- $\alpha = 0.33$
- $\alpha = 0.66$
- $\alpha = 0.99$

$m = 10^{-7} \text{ Hz}$

Extremal range

Effective range

Large $r$

Small $r$
New dipole radiation ($|\gamma| > 0$)

\[
\frac{dE_{\text{GW}}}{df_{\text{GW}}}/(\text{gravity-only})
\]

\begin{align*}
\gamma &= 0.2 \\
\gamma &= 0.4 \\
\gamma &= 0.2 \\
\gamma &= 0.4
\end{align*}

Mediator mass $m = 10^{-9}$ Hz

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The observable spectrum

**Force law ($|\alpha| > 0$)**

- $f$ [eV]
- $h_c(f)$
- $m = 10^{-22}$ eV
- $\alpha = 0$
- $\alpha = 0.33$
- $\alpha = 0.66$
- $\alpha = 0.99$
- PTA sensitivities
- no new radiation ($\gamma = 0$)

**Dipole radiation ($|\gamma| > 0$)**

- $f$ [eV]
- $f$ [Hz]
- $m = 0$
- $m = 10^{-24}$ eV
- $\gamma = 0$
- $\gamma = 0.2$
- $\gamma = 0.4$
- Gravity-only
- no new force ($\alpha = 0$)

**Key Points**

1. Single-source features are intact
2. Both modified slope and novel features observable
3. Sensitivity curves: this is happening **NOW**
NANOGrav sees evidence for a GW background now!
Supermassive black holes are our new laboratories

SGWB discovery is imminent

Long-range forces are detectable

SMBHs can probe many NP scenarios

Data is on the way!

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HIDDEN SECTOR
Distribution of sources

\[ \frac{\partial^2 A_{GW}^2}{\partial z \partial \log M_1} \]
New force and radiation modify the spectrum

\[
\frac{dE_{GW}}{df_{GW}} = -\pi^2 \mu r^2 f_{GW} \left( \frac{2f_{GW}}{r} \frac{dr}{df_{GW}} + 1 \right) \frac{P_{GW}}{P_{GW} + P_{\text{new}}}
\]

\[
F = \frac{GM_1 M_2}{r^2} \left( 1 - \alpha e^{-mr} (1 + mr) \right)
\]

\[
P_{\text{new}} = \frac{1}{3} G \gamma^2 \mu^2 r^2 \omega^4 \text{Re} \left[ \sqrt{1 - \frac{m^2}{\omega^2}} \right] \left\{ \begin{array}{ll}
\left( 1 - \frac{m^2}{2\omega^2} \right) & \text{(scalar)} \\
2 \left( 1 + \frac{m^2}{2\omega^2} \right) & \text{(vector)}
\end{array} \right.
\]