Fundamental physics with gravitational waves

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Fundamental physics with gravitational waves (from coalescing binaries)

1. The nature of gravity

2. The nature of compact objects

3. The nature of dark matter

[In part based on work by the GWIC 3G Science Case Team]

1. The nature of gravity

10_{-1} 10_{-2} 10_{-3}] 10_{-4} mk[10_{-5} 10_{-6}) L/M(= $_R$ 1010101010 $_{-10\ -11\ -9\ -7\ -8}$ **Lunar Laser Ranging**

Double Binary Pulsar

10_{-12} 10_{-13} 10^{-14} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} Φ=M/L

10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}

2G/3G
(Orbital Decay)
LISA

Double Binary Pulsar (Shapiro Delay)EHT

LAGEOS
Cassini

GRAVITY Perihelion Precession of Mercury

Pulsar Timing Arrays

Courtesy N. Yunes

➢ *M*, *L* characteristic mass and size of a system ➢ In the case of binaries: $M/L \propto v^2/c^2$ ➢ **Accessing strong-curvature *and* highly dynamical regime**

1. The nature of gravity

➢ Lovelock's theorem:

"In four spacetime dimensions the only divergence-free symmetric rank-2 tensor constructed solely from the metric $g_{\mu\nu}$ and its derivatives up to second differential order, and preserving diffeomorphism invariance, is the Einstein tensor plus a cosmological term."

➢ Relaxing one or more of the assumptions allows for a plethora of alternative theories:

➢ Most alternative theories: no full inspiral-merger-ringdown waveforms known

▪ Most current tests are **model-independent**
Berti et al., CQG **32**, 243001 (2015)

➢ Inspiral-merger-ringdown process

- Post-Newtonian description of inspiral phase

- Merger-ringdown governed by additional parameters β_n, α_n

➢ Place bounds on deviations in these parameters with Advanced LIGO/Virgo:

➢ **3G detectors will improve on this because of higher SNR and many more sources**

1. The nature of gravity: *binary dynamics*

LIGO + Virgo, arXiv:1903.04467

1. The nature of gravity: *GW propagation*

➢ Allow for anomalous GW dispersion:

$E^2 = p^2c^2 + Ap^\alpha c^\alpha$

Lorentz invariance

▪ Case α = 0

corresponds A = m c to

massive graviton α = 0 (

$A = m^2_g c^4$

):

m_g □ 5.0 → 10^{-23} eV/c^2

▪ For α = 0

one has violation of local

LIGO + Virgo, arXiv:1903.04467

➢ **3G detectors will improve on this because of higher reds**

reach

2. The nature of compact objects

How certain are we that the massive compact objects we are observing are the "standard" black holes of general relativity?

Alternatives (“black hole mimickers”):

➢ Boson stars

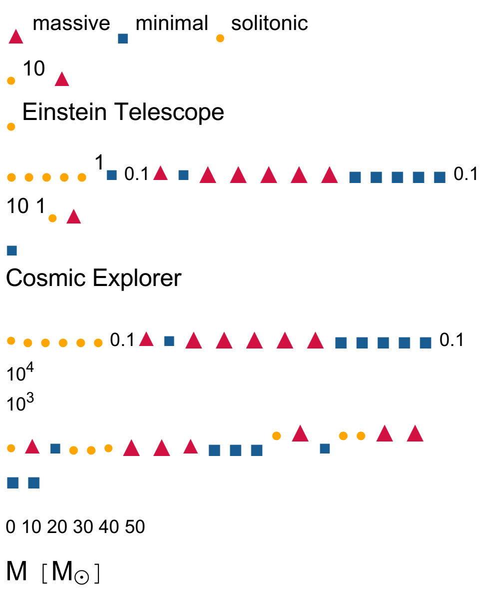
➢ Dark matter stars

➢ Gravastars

➢ Wormholes

➢ Firewalls, fuzzballs

➢ *The unknown*



LIGO
10^2
10
Cardoso et al., PRD **95**, 084014 (2017)
Krishnendu et al., PRL **119**, 091101 (2017) Krishnendu et al., PRD **99**, 064008

2. The nature of compact objects: *inspiral*

➢ Tidal deformability during inspiral

- Finite size effects cause tidal deformations in the phase starting at
- **3G will distinguish neutron stars from boson stars even for th compact models**

➢ Spin-induced quadrupole moment

during inspiral

- 2PN effect, quadratic in spins
- $\kappa_S = 1$ for ordinary black holes, but not for black hole mimickers
- **Hard to access with 2G, while 3G measurements to few percer**

➢ Tidal heating

- Absorption of radiation
- $2.5^{(l)}$PN but linear in spin

2. The nature of compact objects: *no hair conjecture*

➢ Black hole “no hair” conjecture:

Stationary, vacuum black hole completely determined by mass spin

➢ Black hole ringdown: quasi-normal mode frequencies and da

times sall determined by mass and spin s-es

▪ Linearized Einstein equations around Kerr background force s

dependences:

▪ However, amplitudes depend on how the black hole came int

(masses and spins of the progenitor binary)

• Modeling with input from NR simulations form

$$h(t) = \Sigma_{nlm} A_{nlm} e^{t/\tau_{nlm}} \cos(\omega_{nlm} t + \varphi_{nlm}). \quad (1)$$

For black holes in GR, all frequencies ! ☒

ω and damp- ! ☒ $!_{nlm} = !_{nlm}(M_f, a_f)$ ☒$_{nlm}$ = ☒ $(M\ , a_f)$ ☒$_{nlm}$ = ☒

A_{nlm}

2. The nature of compact objects: *no hair conjecture*

➢ Indirect test of the no-hair conjecture:

▪ Allow for deviations in dependences of frequencies, damping

on mass, spin:

! ☒$_{lmn}$(M$_{lmn}$(M= 16M

f,af,af) f) → → ˆ! (1 (1 + + ˆ!lmn)!lmn(Mf,af) ˆ⊠lmn)⊠lmn(Mf,af) ▪ Let the

and the other parameters ˆ⊠lmn

in the vary problem

in turn, and measure them together with all

▪ Advanced LIGO/Virgo at design sensitivity, and 6 sources ˆ!

similar to GW150914

• • ˆ!220 measurable measurable ˆ⊠220

to O(2%) to O(10%)

➢ Going beyond the linearized regime

0.15

probability density

E.g. Del Pozzo & Nagar, PRD **95**, 12034 (2017)

0.10

0.05 ˆ!

0.00

−0.05 ˆ!220 ˆ⊠220

−0.10

−0.15

1 2 3 4 5 6 N_{events}

Carulllo et al., PRD **98**, 104020 (2018) Brito et al., PRD **98**, 084038 (2018)

2. The nature of compact objects: *no*

hair conjecture

➢ **Advantage of 3G: ability to separate the modes ➢ (**

two of the $!_{lmn}$, ☒lmn

are independent; check for consistency between any thre
them

Adapted from Brito et al., PRD **98**, 084038 (2018)

2. The nature of compact objects: *echoes*

- 0.15servable

Eq. (6), a

Exotic objects with corrections near horizon: inner potential b

where M The pi

- After formation/ringdown: continuing barrier is in Fig. 2

bursts of radiation called *echoes* the echo slow leak ergy than effect is s to the “o peak of t

- If horizon modification

-50 -40 -30 -20 -10 0 10 20 30 40 50 r*/M

is model- mildly on rier, whic

then time between successive echo

where *n* set by nature of object:

- *n* = 8 for wormholes
- *n* = 6 for thin-shell gravastars
- *n* = 4 for empty shell

-200 0 200 400 600 800 t/M

- For GW150914 (M = 65 M_{sun}), taking $l = l_{Planck}$, and n = 4:

0.10
0.05
outgoing at infinity ingoing at horizon

0.15 0.00

M) r(V outgoing at infinity

trapped outgoing at infinity **star-like ECO**
trapped
wormhole
0.10
0.05

0.00 0.15

centrifugal barrier

is the location of the minimum

0.10
0.05
regular at the center

Fig. 1. If we consider a micro

0.00

outgoing at infinity rizon scale Δt (` = ⊠ Δt M), Γ then 1 e delay comes near t

radius the c m

' 2Γ

, Δt ' nM log Cardoso et al., PRL **116**, 171101 (2016) Cardoso et al., PRD **94**, 084031 (

(Ml

)

Scattering 0.2
0.0

$\tau \,!\, \tau/\Gamma^{2+2\alpha}$

0.1

-0.2

0.0-0.4 -0.1

200 400 600 800

3. The nature of dark matter

➢ Can black holes themselves contribute to dark matter?

▪ Primordial black holes with masses 0.1 – 100 M_{sun} ▪ Excess in the mass dis

in certain ranges?

(benefit from 3G accuracy)

▪ Black holes at very high redshift would almost have to be primordial **(benefit f distance reach)**

➢ Can dark matter particles be detected with binary compact o

▪ Accumulation of dark matter particles around compact objects: gravitational dr cumulative effect over many orbits

▪ **Joint LISA-ET observations of the same sources**

▪ Accumulation of dark matter particles in the centers of neutron stars

▪ Collapse to a black hole: abundance of light black holes could be indicative of process

➢ New light particles

▪ Bosons with mass 10^{-21} – 10^{-10} eV may extract rotational energy from BH to fo condensates

▪ Impact on binary dynamics, continuous waves from annihilation, stochastic ba

[See e.g. references in Sathyaprakash et al., arXiv:1903.09221]

Summary

Questions that can be addressed by studying compact binary coalescences:

1. What is the nature of gravity? 2. What is the nature of compact objects? 3. What is the nature of dark matter?

Future detectors can probe qualitatively new aspects:

- Similar sources as seen with 2G will appear louder and better resolved
- Information from many more sources can be combined
- Access to much larger redshifts/distances