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Exploring fundamental physics with gravitational waves

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based on 1605.01209 with M. McCullough & A. Urbano
GW: science fiction come true!

Merging of two BH (36 and 29 $M_\odot$) 410 Mpc away, emitting $3 M_\odot$ in GW
BH radius:

\[ R_{BH} = \frac{2M_{BH}G_N}{c^2} = 106 \text{ km} \]

\[ \frac{M_{BH}}{36M_\oplus} \]
BH radius:

\[ R_{BH} = \frac{2 M_{BH} G_N}{c^2} = 106 \text{ km} \frac{M_{BH}}{36 M_\odot} \]

relativistic velocities!
Energetic output
≈ 3 M☉ in 0.1 s

3 M☉ = 2×10^{41} \text{ kWh} ≈ 10^{34} \text{ Hiroshima}

Power: 3 M☉ / 0.1 s = 10^{46} \text{ kW} = 3×10^{22} L☉

Stars in the universe: 10^{22}-10^{24}
Flux: $5 \times 10^{-3} \text{ W/m}^2 = 4 \times 10^{-6} F_\odot$

Strain: $10^{-21}-10^{-22}$ of 4 km arms

⇒ $10^{-18} \text{ m} \approx 10^{-3}$ proton radius
Not only a fantastic tool for astronomy, but a new testing ground for fundamental physics

Testing gravity under extreme conditions

- gravitational field is strong and rapidly changing
- curvature of spacetime in large
- dynamics of event horizons
- velocities are relativistic

GW150914 can be used to test:
- equivalence principle, modifications of gravity,
- quantum structure of BH, propagation of GW, ...
Search for new physics in the form of Exotic Compact Objects (ECO)

- DM primary motivation
- New light elusive particles that can coalesce into ECOs
- GW offer unique tool for probing the existence of ECOs
Boson stars

- Supported by Heisenberg’s principle

\[ R \sim \frac{\hbar}{m_B c} \quad \text{no gravitational collapse if } R > R_{BH} = \frac{2G_N M}{c^2} \quad \Rightarrow \]

\[ M_{\text{max}} = 0.633 \frac{M_P^2}{m_B} \approx \left( \frac{10^{-10} \text{ eV}}{m_B} \right) M_\odot \]

- Supported by repulsive self-interaction

\[ V(\phi) = m_B^2 |\phi|^2 + \frac{\lambda}{2} |\phi|^4 \]

\[ M_{\text{max}} = 0.06 \sqrt{\lambda} \frac{M_P^3}{m_B^2} \approx \sqrt{\lambda} \left( \frac{100 \text{ MeV}}{m_B} \right)^2 10 M_\odot \]

- Non-topological solitons (localized solutions of EoM in presence of a conserved charge Q and with trivial asymptotic behaviour)
Fermion stars
Supported by Fermi pressure
Chandrasekhar limit \( M \lesssim \frac{M_P^3}{m_F^2} \)
Multi-component stars
Mixtures of exotic or ordinary/exotic matter components

Dark-matter stars
- Strongest motivation for exotic matter
- Is DM collisionless?

Problems of simulations with collisionless DM:
- Profiles of dwarf galactic haloes too cuspy
- Too many satellite galaxies
- Dwarf galaxies too massive
  + Indications from gravitational lensing of elliptical galaxies falling into Abell 3827 cluster

\[
\frac{\sigma}{m_{DM}} \approx 0.1 - 1 \, \text{cm}^2\text{g}^{-1}
\]

ECO formation?
Dark-energy stars (gravastars)

- Relativistic fluid: $p = \rho$
- Vacuum energy: $p = -\rho_0$
Limits from microlensing in the LMC

For $M \sim 1$ to tens of $M_\odot$, 20-40% of halo DM is allowed:

- ECO can be as numerous as ordinary stars
- ECO could be made of DM, if DM is both in dust and compact objects
LIGO sensitivity to ECO binary mergers

In terms of the astrophysical parameters only:

• mass $M$ (for $M_1=M_2$)
• compactness $C = M/R \ (C_{BH}=1/2)$

GW frequency grows as the two objects approach $\Rightarrow$ sensitivity to size

At innermost stable orbit: $f = \frac{\sqrt{2} C^{3/2}}{3 \sqrt{3} \pi M}$ $f_{\text{LIGO}} \sim 50 - 1000 \text{ Hz}$

Signal/noise must be sufficiently large (depends on $D_L$)
Interesting for axion-like DM:

$$m_a = \left( \frac{10^{17} \text{ GeV}}{f_a} \right) 0.6 \times 10^{-10} \text{ eV}$$

Interesting for asymmetric DM:

$$m_{DM} = \frac{\eta_b}{\eta_{DM}} \ 5 \text{ GeV}$$
How to detect ECO in a single GW event

**Inspiral**
- post-Newtonian expansion
- chirp mass $M_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}}$
- redshift (from the way frequency and amplitude change)

**Ringdown**
- QNM as perturbations of Kerr BH solution

**Merger**
- numerical relativity (progress in the last 10 yrs)
- need to develop ECO simulations
Extraordinary sensitivity

\[
\begin{align*}
\{ & m_1 = 39.4 \, M_\odot \\
& m_2 = 30.9 \, M_\odot \} \quad \text{vs} \quad \{ & m_1 = 43.4 \, M_\odot \\
& m_2 = 28.0 \, M_\odot \} \\
\end{align*}
\]

Black: LIGO best fit
Red: same chirp mass, but mass ratio excluded @ 90% CL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary black hole mass</td>
<td>$36^{+5}<em>{-4} M</em>\odot$</td>
</tr>
<tr>
<td>Secondary black hole mass</td>
<td>$29^{+4}<em>{-4} M</em>\odot$</td>
</tr>
<tr>
<td>Final black hole mass</td>
<td>$62^{+4}<em>{-4} M</em>\odot$</td>
</tr>
<tr>
<td>Final black hole spin</td>
<td>$0.67^{+0.05}_{-0.07}$</td>
</tr>
<tr>
<td>Luminosity distance</td>
<td>$410^{+160}_{-180}$ Mpc</td>
</tr>
<tr>
<td>Source redshift z</td>
<td>$0.09^{+0.03}_{-0.04}$</td>
</tr>
</tbody>
</table>
From inspiral, we could learn about $C$
(GW150914 must come from BH merger as objects come very close)

At innermost stable orbit

$$\frac{f_{BH}}{f_{ECO}} = 5.5 \left( \frac{0.16}{C} \right)^{3/2}$$

$M_{BH} = M_{ECO} = 35 \, M_{\odot}$
$C_{BH} = 0.5$
$C_{ECO} = 0.16$
Ringdown is sensitive to EoS and absence of horizon

For a gravastar with $M_{BH} = M_{ECO} = 35 \, M_{\odot}$, $C_{ECO} = 0.44$
What can be learned from GW event distributions?

Conventional heavy objects:
- **NS**: most massive observed $M=2.01\pm0.04\,M_\odot$ and most models hardly exceed $2\,M_\odot$ ($0.13\leq C\leq0.23$)
- **Stellar BH**: mass distribution expected to start at $5\,M_\odot$ ($C=0.5$)

Mass gap can be explained in stellar evolution models
Filling the gap is evidence of a new population of exotic objects.

Distribution is an essential tool to understand ECO mass function and formation process.
Test of Area Theorem

Hawking’s Area Theorem: the sum of the horizon areas of a system of BHs never decreases.
It follows from GR + null energy condition.

Hawking’s radiation: $M$ decreases $\Rightarrow R$ decreases $\Rightarrow A$ decreases.
Violation of the theorem?

Thermodynamics interpretation: BH temperature $T = M_p^2/M$
BH entropy $S = A/4$.
Second law of thermodynamics $\Rightarrow$ Area Theorem.
Once the entropy of the emitted radiation is taken into account, no violation of the “generalized” second law of thermodynamics.
Test of Area Theorem in BH mergers

For a Kerr BH: \[ A = 8\pi M^2 \left( 1 + \sqrt{1 - a^2} \right) \quad a \equiv \frac{J}{M^2} \]

Hawking’s Area Theorem: \[ A_f > A_1 + A_2 \]

\[ M_f > \sqrt{M_1^2 s_1 + M_2^2 s_2} \quad s_{1,2} \equiv \frac{1 + \sqrt{1 - a_{1,2}^2}}{1 + \sqrt{1 - a_f^2}} \]

Hawking’s Area Theorem:
lower bound on \( M_f \) \( \Rightarrow \) upper bound on efficiency of GW emission
What if the Area Theorem is observed to be violated? A BH-mimicker ECO can violate it by emitting dark radiation

- Test of fundamental principles
- Test of undetected radiation
Conclusions

- GW observations have opened a new avenue in astronomy
- A unique tool to test gravity in the regime of strong and rapidly-changing field, and relativistic velocities
- Search for new forms of matter in compact objects
- Probing DM clumping in astronomical bodies
- Probing a variety of new-physics ideas
- Information in single GW events and event distribution
- Testing Hawking’s Area Theorem can probe dark radiation