Learning about dark matter from binary black hole mergers

Philippa (Pippa) Cole, University of Amsterdam

with Gianfranco Bertone, Adam Coogan, Daniele Gaggero, Bradley Kavanagh, Theophanes Karydas, Thomas Spieksma and Giovanni Maria Tomaselli

Vacuum or non-vacuum
that is the question

• So far, all LIGO/Virgo/KAGRA binary black hole mergers have been detected and measured assuming that they occurred in vacuum

• OK for short duration signals, but looking towards future interferometers, long duration signals may be affected by their environment
• Environmental effects can cause inspiral to either speed up or slow down with respect to vacuum case

• A dephasing to accumulate, which alters the gravitational waveform from the binary’s inspiral

\[
\dot{r} = \dot{r}_{GW} + \dot{r}_{\text{env}}
\]

\[
f(t) = \frac{1}{\pi} \sqrt{\frac{GM}{r(t)^3}}
\]

\[
\Phi(f) = \int_{f}^{f_{\text{ISCO}}} \frac{dt}{df'} f' \, df'
\]

\[
h_0(f) = \frac{1}{2} \frac{4\pi^{2/3} G_N^{5/3} M^{5/3} f^{2/3}}{c^4} \sqrt{\frac{2\pi}{\ddot{r}}} \]
Need to observe many cycles

- dephasing accumulates over thousands or millions of cycles
- small mass ratio
  \[ q = \frac{m_2}{m_1} < 10^{-2.5} \]
  so that environment survives
- systems possible sources for LISA and Einstein Telescope/Cosmic Explorer

\[ m_1 = 10^5 M_\odot, \quad m_2 = 10 M_\odot \]
Why should we care about environmental effects?

- If we can measure the parameters of the environment via the dephasing in the waveform, chance to learn about the environment
- If we search the data with the wrong ‘template’ we might miss the signal
- If we do parameter estimation with the ‘wrong’ parameters, we might come up with biased results

See also Barausse, Cardoso, Pani 2011
Dark dress

Accretion disc

Gravitational atom

Cold, collisionless dark matter

Baryonic matter

Ultra-light bosons

Eda et al. 2013, 2014
Gondolo, Silk 1999
Kavanagh et al. 2020
Coogan et al. 2021

Goldreich & Tremaine 1980
Tanaka 2002
Derdzinski et al. 2020

Baumann et al. 2019
Nielsen 2019
Bauman et al. 2021, 2022

Credit: Sophia Dagnello, NRAO/AUI/NSF
Dark dress

\[ \rho(r) = \rho_6 \left( \frac{r_6}{r} \right)^{\gamma_s} \]

Spike density normalisation
Spike power law slope

Accretion disc

\[ \Sigma(r) = \Sigma_0 \left( \frac{r}{r_0} \right)^{-1/2} \]

Surface density normalisation
Mach number

Gravitational atom

\[ \rho(\vec{r}) = M_c |\psi(\vec{r})|^2 \]

\[ \alpha \equiv Gm_1\mu \ll 1 \]

Mass of cloud
Mass of light scalar field
\((10^{-10} - 10^{-20} \text{ eV})\)
What kind of densities?
Form of energy losses

\[ \dot{r} = \dot{r}_{GW} + \dot{r}_{env} \]

<table>
<thead>
<tr>
<th>Dark dress</th>
<th>Accretion disk</th>
<th>Gravitational atom</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{r}<em>{env} = \dot{r}</em>{DF} )</td>
<td>( \dot{r}<em>{env} = \dot{r}</em>{gas} )</td>
<td>( \dot{r}<em>{env} = \dot{r}</em>{ion} + \dot{r}_{acc} )</td>
</tr>
<tr>
<td>Dynamical friction according to Chandrasekhar formula plus feedback on spike with HaloFeedback (Kavanagh et al. 2020)</td>
<td>Gas torques according to Type I migration, analytic prescription including Lindblad and corotation torques</td>
<td>Ionization (dynamical friction-like) and accretion of scalar field onto companion object</td>
</tr>
</tbody>
</table>
Dynamical friction

\[ \dot{r}_{DF} = - \frac{8\pi G_N^{1/2}}{m_2} \log \Lambda r_2^{5/2} \rho_{DM}(r_2, t) \xi(r_2, t) }{\sqrt{M m_1}} \]

Kavanagh, Nichols, Bertone, Gaggero 2020

HaloFeedback

![Diagram showing dynamical friction process with a compact object, an intermediate mass black hole, and a dark matter spike.](image-url)
**Gas torques**

\[ \dot{r}_{\text{gas}} = \frac{\dot{L}_{\text{gas}} r^{1/2}}{2\sqrt{G(m_1 + m_2)m_2}} \]

\[ \dot{L}_{\text{gas}} = T_{\text{gas}} = \pm \sum (r) r^4 \Omega^2 q^2 M^2 \]

Assume gas in the disc is corotating with the companion object, which is orbiting in the plane of the disc.

Assume Mach number is locally constant, independent of r, i.e. locally isothermal.

See e.g. Goldreich & Tremaine 1980, Tanaka 2002, Derdzinski et al. 2020
Ionization

Perturber excites resonances in the cloud and it transitions from bound states to unbound states as the orbital frequency of the perturber hits the frequency of the energy difference between states.
Energy losses

![Graph showing energy losses as a function of $r/r_s$]
Dephasing

\[ N = \frac{(\phi_V - \phi_{env})}{2\pi} \]

- **Gravitational atom**
- **Dark matter spike**
- **Accretion disk**

![Graph showing the relationship between N and f [Hz]](image_url)
Assuming we’ve detected a signal, can we measure the parameters?

Parameter estimation with correct model
Parameter estimation with vacuum waveform

<table>
<thead>
<tr>
<th>Vacuum template</th>
<th>Accretion disk signal</th>
<th>Dark dress signal</th>
<th>Grav atom signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M - M_0 \ [M_\odot]$</td>
<td>$M - M_0 \ [M_\odot]$</td>
<td>$M - M_0 \ [M_\odot]$</td>
<td></td>
</tr>
</tbody>
</table>

- **Accretion disk signal**
- **Dark dress signal**
- **Grav atom signal**
SNR loss: biased PE or miss signal entirely
Bayesian model comparison shows confident preference for correct model over any other environment

<table>
<thead>
<tr>
<th>$\log_{10} B$</th>
<th>Dark dress signal</th>
<th>Accretion disk signal</th>
<th>Gravitational atom signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum template</td>
<td>34</td>
<td>6</td>
<td>39</td>
</tr>
<tr>
<td>Dark dress template</td>
<td>-</td>
<td>3</td>
<td>39</td>
</tr>
<tr>
<td>Accretion disk template</td>
<td>17</td>
<td>-</td>
<td>33</td>
</tr>
<tr>
<td>Gravitational atom template</td>
<td>24</td>
<td>6</td>
<td>-</td>
</tr>
</tbody>
</table>
What about future ground-based detectors?

IMRI PBHs must have a dark matter spike
What about future ground-based detectors?

1 week should be enough!

Cole, Coogan, Kavanagh, Bertone 2022
Conclusions

• We can measure the properties of environments around binaries with future GW detectors

• We have an opportunity to learn about the nature of dark matter from IMRI gravitational waveforms

• We can distinguish between environments and avoid confusion with, for example, accretion disks

• Biased parameter reconstruction is possible if the wrong model is used

Future work:

• More accurate waveforms required

• Include for example eccentricity, spins…

• Go to higher dimensions in parameter estimation to check for degeneracies with extrinsic parameters

Thank you for listening!