Searching for Dark Matter in Gravitational Waves

I.C., E. Kovetz, Y. Ali-Haimoud, S. Bird, M. Kamionkowski, J.
Munoz, A. Raccanelli PRD 94 084013 (arXiv:1606.07437)
I.C. arXiv:1609.03565
E. Kovetz, I.C., P. Breysse, M. Kamionkowski arXiv:1611:01157
Evidence for Dark Matter

- galactic rotation curves

Evidence for dark matter...

NGC 2403 rotation curve and model

- velocity dispersion of galaxies in clusters

Local Group

Virgo Cluster

Virgocentric Infall

(200 - 500 km/s)

σ ~ 600 km/s
• CMB data and SN Ia data

• Observed distribution of galaxies:

• strong lensing measurements of background objects (usually galaxies)
• collisions of galaxy clusters (e.g. bullet cluster)

• success of BBN (DM is non-baryonic)

• growth of structure (cold DM)
Signals of thermal DM
Production (accelerators)
Cosmic rays/indirect detection (PAMELA/Fermi/Planck...)
Direct detection (DAMA/XENON/CDMS...)

Direct Detection scattering off normal matter, Xe, Ar, Ge, Si:

Dark matter production at colliders

Indirect detection: annihilation into gamma-rays, cosmic rays, neutrinos
What about Gravitational Waves?

Two black holes coalescing

eLISA (future searches in space)

LIGO (WA)

LIGO (LA)

VIRGO (Italy)
Gravitational Waves

- Virtually everything you and I know about the Cosmos has been discovered via electromagnetic observations.
- Some information has recently been gleaned from astro-particle observations (neutrinos and cosmic rays).
- We are now entering an era where we are using a wide variety of detectors to probe the Cosmos with gravity.
- A full relativistic derivation of the existence and action of gravitational waves is beyond our scope here, but can be obtained by linearizing the field equations of general relativity.

Here let's convince our intuition.

- The idea that gravitational information can propagate is a consequence of special relativity: nothing can travel faster than the ultimate speed limit, $c$.

Imagine observing a distant binary star and trying to measure the gravitational field at your location. It is the sum of the field from the two individual components of the binary, located at distances $r_1$ and $r_2$ from you.

As the binary evolves in its orbit, the masses change their position with respect to you, and so the gravitational field must change. It takes time for that information to propagate from the binary to you — $\tau = \frac{d}{c}$, where $d$ is the luminosity distance to the binary.

The propagating effect of that information is known as gravitational radiation, which you should think of in analogy with the perhaps more familiar electromagnetic radiation.

Far from a source (like the aforementioned binary) we see the gravitational radiation field oscillating and these propagating oscillating disturbances are called gravitational waves.

Gravitational waves are characterized by a wavelength $\lambda$ and a frequency $f$, where $c = \lambda \cdot f$.

Gravitational waves come in two polarization states (called and $\times$).

Hand-wavy Pictures

GWs travel at speed of light

The masses are oscillating —> frequency. Energy is damped into Gravitational Waves with the quadrupole radiation being the dominant.

$$m_A x_A^2(t) + m_B x_B^2(t)$$

: effect at interferometers

m_A x_A^2(t) + m_B x_B^2(t)
What we expect to observe when two Black Holes coalesce (merge)

Energy is damped into GWs —> The system gets closer and masses rotate faster. Frequency Increases with time (“chirp”). So does the amplitude (this is not a system that will return to equilibrium)

There is a gravitational radius associated with an object of mass M:

\[ R_{Sch} = \frac{2GM}{c^2} \]

\[ R_{Sch}(1M_\odot) = 2.95\text{km} \]

\[ R_{Sch}(36M_\odot) = 106\text{km} \]

Last Stable (~Keplerian) Orbit at

\[ R = \left( \frac{GM_{tot}}{\omega_{max}^2} \right)^{1/3} \]

~3 times the Schwarzschild radius
Basic Estimates

GWs travel at the speed of light: \( \lambda = c/f \)

Take a binary of two compact objects (Kepler’s third law):

\[
    f = \sqrt{\frac{G}{4\pi} \frac{M_{tot}}{a^3}}
\]

take \( M_{tot} = 20M_\odot \) and \( a = 500\text{km} \) thus \( 2f \sim 80\text{Hz} \)

or \( \lambda \sim 5 \times 10^3 \text{km} \)  

Earth Size (ground-based Observatories)

take \( M_{tot} = 10^6M_\odot \) and \( a = 5 \times 10^6\text{km} \) thus \( 2f \sim 10^{-2}\text{Hz} \)

or \( \lambda \sim 3 \times 10^7\text{km} \)  

(space-based Observatories)
Basic Scalings

Chirp mass:

\[ M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \]

Amplitude of signal *during* Inspiral:

\[ h_c \sim \frac{G}{c^3} \frac{M_c}{d_L} \left( \frac{G}{c^3} \pi f M_c \right)^{2/3} \]

\( \rightarrow \) (for a given freq.):

\[ h_c \sim M_c^{5/3} / d_L \]

(observations are at a certain freq. range)

\[ \sim 10^{-21} \]

How to measure those:

\[ M_c = \frac{c^3}{G} \left( \frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right)^{3/5} \]

\[ \Delta L(t) = \delta L_x - \delta L_y = h(t) \cdot L \]
LIGO Detectors

$$\Delta L(t) \sim 10^{-21} \times 10^3 km \sim O(1) fm$$

$$L_x = L_y = L = 4 \ km$$

$$h_+(t) = A_{GW}(t)(1 + \cos^2 i)\cos\phi_{GW}(t)$$

$$h_\times(t) = -2A_{GW}(t)\cos(i)\sin\phi_{GW}(t)$$

$$h_k'(t) = F^+_k h_+(t) + F^\times_k h_\times(t)$$

The gravitational-wave signal extraction by broadening the bandwidth of the arm cavities \[51,52\]. The interferometer is illuminated with a 1064-nm wavelength Nd:YAG laser, stabilized in amplitude, frequency, and beam geometry \[53,54\]. The gravitational-wave signal is extracted at the output port using a homodyne readout \[55\].

These interferometry techniques are designed to maximize the conversion of strain to optical signal, thereby minimizing the impact of photon shot noise (the principal noise at high frequencies). High strain sensitivity also requires that the test masses have low displacement noise, which is achieved by isolating them from seismic noise (low frequencies) and designing them to have low thermal noise (intermediate frequencies). Each test mass is suspended as the final stage of a quadruple-pendulum system \[56\], supported by an active seismic isolation platform \[57\]. These systems collectively provide more than 10 orders of magnitude of isolation from ground motion for frequencies above 10 Hz. Thermal noise is minimized by using low-mechanical-loss materials in the test masses and their suspensions: the test masses are 40-kg fused silica substrates with low-loss dielectric optical coatings \[58,59\], and are suspended with fused silica fibers from the stage above \[60\].

To minimize additional noise sources, all components other than the laser source are mounted on vibration isolation stages in ultrahigh vacuum. To reduce optical phase fluctuations caused by Rayleigh scattering, the pressure in the 1.2-m diameter tubes containing the arm-cavity beams is maintained below 1 \(\mu\)Pa.

Servo controls are used to hold the arm cavities on resonance \[61\] and maintain proper alignment of the optical components \[62\]. The detector output is calibrated in strain by measuring its response to test mass motion induced by photon pressure from a modulated calibration laser beam \[63\]. The calibration is established to an uncertainty (1 \(\sigma\)) of less than 10% in amplitude and 10 degrees in phase, and is continuously monitored with calibration laser excitations at selected frequencies. Two alternative methods are used to validate the absolute calibration, one referenced to the main laser wavelength and the other to a radio-frequency oscillator.

FIG. 3. Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photodetector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth).

Inset (a): Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1).

Inset (b): The instrument noise for each detector near the time of the signal detection; this is an amplitude spectral density, expressed in terms of equivalent gravitational-wave strain amplitude. The sensitivity is limited by photon shot noise at frequencies above 150 Hz, and by a superposition of other noise sources at lower frequencies \[47\]. Narrow-band features include calibration lines (33–38, 330, and 1080 Hz), vibrational modes of suspension fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics.

PRL 116, 061102 (2016)
properties of space-time in the strong-field, high-velocity regime and confirm predictions of general relativity for the nonlinear dynamics of highly disturbed black holes.

II. OBSERVATION

On September 14, 2015 at 09:50:45 UTC, the LIGO Hanford, WA, and Livingston, LA, observatories detected the coincident signal GW150914 shown in Fig. 1. The initial detection was made by low-latency searches for generic gravitational-wave transients [41] and was reported within three minutes of data acquisition [43]. Subsequently, matched-filter analyses that use relativistic models of compact binary waveforms [44] recovered GW150914 as the most significant event from each detector for the observations reported here. Occurring within the 10-ms intersite...
The first ever Gravitational Waves signal detection

On Sept. 14th at 9:50:45 UTC (Coordinated Universal Time), the two detectors of aLIGO observed a gravitational wave signal from the coalescence of two Black Holes. It was observed between 35 and 250 Hz.

The observed Properties are (90 % credible intervals):

\[ m_1 = 36^{+5}_{-4} M_\odot \]
\[ m_2 = 29^{+4}_{-4} M_\odot \]
\[ m_{final} = 62^{+4}_{-4} M_\odot \]
\[ \alpha = 0.67^{+0.05}_{-0.04} \]
\[ d_L = 410^{+160}_{-180} Mpc \]
\[ z_s = 0.09^{+0.03}_{-0.04} \] (Planck Cosm. Param.)

The event was observed with a time delay of \[ t_d = 6.9^{+0.5}_{-0.4} ms \] between Livingston LA and Hanford WA. Detection Significance: \( 5.1 \sigma \)
Remaining properties

The luminosity distance is correlated to the inclination of the orbital plane to the line of sight $\theta_{JN}$. Total angular momentum $\vec{J}$.

$\vec{J}$ is almost constant during the inspiral.

$45^\circ < \theta_{JN} < 135^\circ$ with a probability of 0.35

50% probability within 140 deg^2

90% probability within 590 deg^2

Searches by EM and neutrino detectors. No evident counterpart as would be likely in any case.
### All (~3) events

<table>
<thead>
<tr>
<th>Event</th>
<th>GW150914</th>
<th>GW151226</th>
<th>LVT151012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal-to-noise ratio $\rho$</td>
<td>23.7</td>
<td>13.0</td>
<td>9.7</td>
</tr>
<tr>
<td>False alarm rate FAR/yr$^{-1}$</td>
<td>$&lt; 6.0 \times 10^{-7}$</td>
<td>$&lt; 6.0 \times 10^{-7}$</td>
<td>0.37</td>
</tr>
<tr>
<td>p-value</td>
<td>$7.5 \times 10^{-8}$</td>
<td>$7.5 \times 10^{-8}$</td>
<td>0.045</td>
</tr>
<tr>
<td>Significance</td>
<td>$&gt; 5.3\sigma$</td>
<td>$&gt; 5.3\sigma$</td>
<td>1.7$\sigma$</td>
</tr>
<tr>
<td>Primary mass $m_1^{\text{source}}/M_\odot$</td>
<td>36.2$^{+5.2}_{-3.8}$</td>
<td>14.2$^{+8.3}_{-3.7}$</td>
<td>23$^{+18}_{-6}$</td>
</tr>
<tr>
<td>Secondary mass $m_2^{\text{source}}/M_\odot$</td>
<td>29.1$^{+5.7}_{-4.4}$</td>
<td>7.5$^{+2.3}_{-2.3}$</td>
<td>13$^{+14}_{-5}$</td>
</tr>
<tr>
<td>Chirp mass $M_c^{\text{source}}/M_\odot$</td>
<td>28.1$^{+1.8}_{-1.5}$</td>
<td>8.9$^{+0.3}_{-0.3}$</td>
<td>15.1$^{+1.4}_{-1.1}$</td>
</tr>
<tr>
<td>Total mass $M^{\text{source}}/M_\odot$</td>
<td>65.3$^{+4.1}_{-3.4}$</td>
<td>21.8$^{+5.9}_{-1.7}$</td>
<td>37$^{+13}_{-4}$</td>
</tr>
<tr>
<td>Effective inspiral spin $\chi_{\text{eff}}$</td>
<td>$-0.06^{+0.14}_{-0.14}$</td>
<td>0.21$^{+0.20}_{-0.10}$</td>
<td>0.0$^{+0.3}_{-0.2}$</td>
</tr>
<tr>
<td>Final mass $M_f^{\text{source}}/M_\odot$</td>
<td>62.3$^{+3.7}_{-3.1}$</td>
<td>20.8$^{+6.1}_{-1.7}$</td>
<td>35$^{+14}_{-4}$</td>
</tr>
<tr>
<td>Final spin $a_f$</td>
<td>0.68$^{+0.05}_{-0.06}$</td>
<td>0.74$^{+0.06}_{-0.06}$</td>
<td>0.66$^{+0.09}_{-0.10}$</td>
</tr>
<tr>
<td>Radiated energy $E_{\text{rad}}/(M_\odot c^2)$</td>
<td>3.0$^{+0.5}_{-0.4}$</td>
<td>1.0$^{+0.1}_{-0.2}$</td>
<td>1.5$^{+0.3}_{-0.4}$</td>
</tr>
<tr>
<td>Peak luminosity $\ell_{\text{peak}}/(\text{erg s}^{-1})$</td>
<td>$3.6^{+0.5}_{-0.4} \times 10^{56}$</td>
<td>$3.3^{+0.8}_{-1.6} \times 10^{56}$</td>
<td>$3.1^{+0.8}_{-1.8} \times 10^{56}$</td>
</tr>
<tr>
<td>Luminosity distance $D_L/$Mpc</td>
<td>420$^{+150}_{-180}$</td>
<td>440$^{+180}_{-190}$</td>
<td>1000$^{+500}_{-500}$</td>
</tr>
<tr>
<td>Source redshift $z$</td>
<td>0.09$^{+0.03}_{-0.04}$</td>
<td>0.09$^{+0.03}_{-0.04}$</td>
<td>0.20$^{+0.09}_{-0.09}$</td>
</tr>
<tr>
<td>Sky localization $\Delta \Omega$/deg$^2$</td>
<td>230</td>
<td>850</td>
<td>1600</td>
</tr>
</tbody>
</table>
Rate of gravitational waves from BH-BH

*Very* simple one:
1 event in 16 live days. —> 25 per yr.
sensitivity redshift, $z$ of 0.3, 1.6 Gpc
—> $Vol \sim 7 \text{ Gpc}^3$

$$3.5 \text{Gpc}^{-3} \text{yr}^{-1}$$

The GW was observed at high S/N, there are going to be other events (as the LVT151012). Also if BHs are from Pop III stars or are at globular clusters or at regions of low metallicity and high grav. potential they will have some mass distribution and also will have some redshift distribution.

Going over astrophysical uncertainties in the above assumptions:
Using only GW150914 (fixing the masses, spins): $2 - 53 \text{Gpc}^{-3} \text{yr}^{-1}$
Using both GW150914 and LVT151012: $6 - 400 \text{Gpc}^{-3} \text{yr}^{-1}$
LIGO’s combined range: $2 - 400 \text{Gpc}^{-3} \text{yr}^{-1}$
LIGO’s upgraded O1 (2015-16) run:

<table>
<thead>
<tr>
<th>Mass distribution</th>
<th>PyCBC</th>
<th>GstLAL</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GW150914</td>
<td>$3.2^{+8.3}_{-2.7}$</td>
<td>$3.6^{+9.1}_{-3.0}$</td>
<td>$3.4^{+8.6}_{-2.8}$</td>
</tr>
<tr>
<td>LVT151012</td>
<td>$9.2^{+30.3}_{-8.5}$</td>
<td>$9.2^{+31.4}_{-8.5}$</td>
<td>$9.4^{+30.4}_{-8.7}$</td>
</tr>
<tr>
<td>GW151226</td>
<td>$35^{+92}_{-29}$</td>
<td>$37^{+94}_{-31}$</td>
<td>$37^{+92}_{-31}$</td>
</tr>
<tr>
<td>All</td>
<td>$53^{+100}_{-40}$</td>
<td>$56^{+105}_{-42}$</td>
<td>$55^{+99}_{-41}$</td>
</tr>
<tr>
<td>Astrophysical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat in log mass</td>
<td>$31^{+43}_{-21}$</td>
<td>$30^{+43}_{-21}$</td>
<td>$30^{+43}_{-21}$</td>
</tr>
<tr>
<td>Power Law ($-2.35$)</td>
<td>$100^{+136}_{-69}$</td>
<td>$95^{+138}_{-67}$</td>
<td>$99^{+138}_{-70}$</td>
</tr>
</tbody>
</table>

TABLE II. Rates of BBH mergers based on populations with masses matching the observed events, and astrophysically motivated mass distributions. Rates inferred from the PyCBC and GstLAL analyses independently as well as combined rates are shown. The table shows median values with 90% credible intervals.

Different estimates on the coalescence rates come from different astrophysical assumptions.
Making a connection with DM

Work with Simeon Bird, Julian B Munoz, Yacine Ali-Haimoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli and Adam Riess (JHU)

Assuming Dark Matter is composed by Primordial BHs.

There is some allowed parameter space around \( \sim 20-70 \, M_\odot \)

For the remainder I will assume that all DM is composed of PBHs and set their mass to \( 30 \, M_\odot \)

Limits on spectral distortions of the CMB are efficient above \( 100 \, M_\odot \)

Ali-Haimoud & Kamionkowski (1612.05644)

Limits from GC in dwSphs (e.g. Eridanus II) (Tim Brandt arXiv:1605.03662) are robust below \( 15 \, M_\odot \).

Limits from micro-lensing of macro-lensed quasars depend on the DM profile and vel. dips. prof.
How fast do two BHs form a binary?

$$\sigma = 2^{3/7} \pi \left( \frac{85 \pi}{6\sqrt{2}} \right)^{2/7} R_s^2 \left( \frac{v}{c} \right)^{-18/7}$$

In easy units:
$$\sigma = 1.37 \times 10^{-14} M_{30}^2 v_{199}^{-18/7} \text{ pc}^2$$

Assuming an NFW profile for the PBHs:
$$\rho_{NFW}(r) = \frac{\rho_0}{(r/R_s) \cdot (1 + r/R_s)^2}$$

One gets a Rate of PBHs mergers:
$$\mathcal{R} = 4\pi \int_0^{R_{vir}} r^2 \frac{1}{2} \left( \frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle \ dr$$
After including information regarding the difference DM halos properties (concentration, and velocity dispersions) and effects on the smallest DM halos:

\[ \sim 2Gpc^{-3}yr^{-1} \]
(within the LIGO obs. rate)

\[ \sim 4 \times 10^{-3}Gpc^{-3}yr^{-1} \]

S. Bird, IC, J. Munoz et al. (2016)
By 2019 the sensitivity will have increased to $z < 0.75$

We expect $O(10^2)$ events from PBHs (if they compose 100% of DM) by 2025.

All may be in a narrow mass range around 30 solar masses.

No other EM or neutrino signals. (typical though given that BH-BH give GW only)

Following the DM distribution (need better angular resolution though).

Basic Uncertainties in the rate calculation:
DM profile (factor of ~3)
Mass-Concentration relationship (factor of ~3)
Sub-halo contribution (previous slide) and discreteness of smallest halos.
Future directions for DM by PBHs

When these binaries form they have high initial eccentricities and small peri-center distances:

\[
(1 - e_0)_{\text{peak}} \simeq 2.6 \xi \eta^{2/7} (w/c)^{10/7} \quad \xi \simeq 1, \eta = 1/4 \quad \text{for equal BH masses}
\]

\[
r_{p_0} \simeq 2 \times 10^4 \text{ km} \left( \frac{v_{DM}}{20 \text{ km/s}} \right)^{-4/7}
\]

Which in turn result in **dramatically different** timescales until merger:

By the time of LIGO observation fully circularized.

\[ M_{\text{vir}} = 10^{12} (M_\odot/h) \]

\[ M_{\text{vir}} = 10^{9} (M_\odot/h) \]

\[ M_{\text{vir}} = 10^{6} (M_\odot/h) \]
Occurrence for PBH binaries at $M_{\text{vir}}=10^{12} (M_\odot/h)$

$m_1=m_2=30 M_\odot$

Circularized binaries (long lived)

Highly eccentric binaries (short lived: year <)

$r_p=6 \cdot R_{\text{Sch}}$

$r_p=14 \cdot R_{\text{Sch}}$

$r_p=22 \cdot R_{\text{Sch}}$

Time from formation to merger

Log$_{10} T_m$ (sec)

(observable at pericenter dist. of 6/14/22 Rsch)
A rare case? (see many more modes of grav. waves)

With LIGO we expect $O(1)$ events while with the Einstein Telescope we expect $O(10)$ events with multiple modes detected from PBH binaries. Other astrophysical mechanisms for Binary BHs have typical time-scales of evolution that is $\sim$Myrs-Gyrs. With Future eLISA we will also be able to trace back some PBH systems to earlier stages (days-years before the merger event) and thus observe the binaries at even higher eccentricities.
Future Direction: The stochastic GW background

For every event like the GW150914 there are many more too distant or not powerful enough to be resolved above the threshold. These create a “stochastic” grav. wave background.

The energy density of GWs can be described by:

$$\Omega_{GW} = \frac{f}{\rho_c H_0} \int_0^{z_{max}} dz \frac{R_m(z, \theta_k)}{(1 + z) \sqrt{\Omega_\Lambda + \Omega_M (1 + z)^3}} \frac{dE_{GW}(f_s, \theta_k)}{df_s}$$

- $\Omega_{GW}$: energy density between $f$ and $f+df$
- $f$: frequency at source
- $\rho_c$: cosmological density parameter
- $H_0$: Hubble constant
- $z$: redshift
- $R_m(z, \theta_k)$: rate of BH-BH merger (mass distr. of BHs and z-distr.)
- $dE_{GW}(f_s, \theta_k)$: energy density spectrum, for inspiral typically
- $df_s$: frequency at source
- $\theta_k$: astrophysics assumptions, distri. of time delay
- $max$: maximum time delay
- $min$: minimum time delay
- $P(t_d, \theta_k)$: rate of BH-BH merger (binary formation rate)
Star Formation Rate doesn’t affect much such a calculation (“AltSFR”).

“Long Delay”: it takes at least 5 Gyrs for a merger to occur (largely separated objects with slow rel. velocity before binary creation). “Flat delay” : 1 Gyr.

“Low mass”: assuming 15 $M_\odot$ BHs. More power at higher frequencies.

Lower metallicity increases the number density of BHs.

“Constant (in z) rate”: $R_m(z) = 16 Gpc^{-3} yr^{-1}$

Based on the rate of $2 - 53 Gpc^{-3} yr^{-1}$ and assuming a conventional Star Formation Rate (SFR) “Fiducial.”
Updated Rates on the BH-BH mergers
(some room a PBH component to be seen in the Stoch. Background)


With Einstein Telescope we might be able to probe the PBH model
An other future direction:
Cross-Correlations with Galaxies

A. Raccanelli, E. Kovetz, S. Bird, I.C. J. Munoz
PRD 94 023516 (arXiv:1605:01405)

If the GW signal comes from BHs originating by standard astrophysical sources e.g. BH in globular clusters, then the binary systems should preferentially reside in galaxies where most of the stars are. So GW and star forming galaxy (SFG) maps would be highly correlated.

If the BH binaries are mostly populating halos with different mass range, bias, redshift and angular distributions, then the correlation with SFGs galaxies in halos of masses $\sim 10^{11} - 10^{12} \, M_\odot$ would be lower.

If the GW signal comes from PBHs that constitute the DM then their distribution will be more uniform on the sky.

We can calculate angular projections:

$$C_{\ell}^{XY} = \langle a_{\ell m}^X a_{\ell m}^{Y*} \rangle = 4\pi \int \frac{dk}{k} \Delta^2(k) W^X_\ell (k) W^Y_\ell (k)$$

Window functions
and more heavily biased halos than mergers from PBHs, which are expected to be a function of the star formation rate and the sources from the linear matter power spectrum. GW events reaction by the intervening mass distribution [33–35]. However, observed of BH mergers is independent of the rate of 30 Gpc\(^{-3}\). As discussed above, our goal is to distinguish between different GW shots, but this is hard to quantify theoretical uncertainties. To reflect this, we assume that the progenitors of BH-binaries in this mass range are primarily dark matter PBHs, we would expect a bias assumption that the progenitors of BH-binaries in this mass range are primarily dark matter PBHs, we would expect a bias

\[ b \approx 3 \text{ Gpc}^{-3} \]

Thus, if we cross-correlate a GW event map (filtered to \(5 < \ell < 10\)) with the

\[ N_{GW}(z) = \hat{n}_{GW}(z) T_{\text{obs}} V(z) \]

Window function:

\[
W^{X}_{\ell}(k) = \int N_{X}(z) b_{X}(z) j_{\ell}(kX(z)) dz
\]

\(\# / \text{sr}\)

bias (progenitor infor.)

coop-moving distance

co-moving distance

Forecasted Cross-correlation amplitude of of Galaxies with BH-BH mergers. PBH binaries have a smaller bias \(b\) (~0.5) compared to stellar BHs (since the PBH rate is dominated by the smallest DM halos)
An other future possible indication: Mass-Spectrum of BH-BH binaries

E. Kovetz, I.C., P. Breysse, M. Kamionkowski arXiv:1611:01157
More about the future of GWs in general
The LIGO-VIRGO network

- The LIGO-VIRGO network factors are largely common between two similar detectors, so the time difference between the two detectors is relatively uncorrelated with these nuisance parameters.
- The triangulation approach underestimates how well a source can be localized, since it does not include all the relevant information. Its predictions can be improved by introducing the requirement of phase consistency between detectors [60]. Triangulation always performs poorly for a two-detector network, but, with the inclusion of phase coherence, can provide an estimate for the average performance of a three-detector network [31].
- Source localization using only timing for a two-site network yields an annulus on the sky; see Figure 4. Additional information such as signal amplitude, spin, and precession effects resolve this to only parts of the annulus, but even then sources will only be localized to regions of hundreds to thousands of square degrees [99, 31]. An example of a two-detector BNS localization is shown in Figure 5. The posterior probability distribution is primarily distributed along a ring, but this ring is broken, such that there are clear maxima.

**Figure 4**: Source localization by triangulation for the aLIGO–AdV network. The locations of the three detectors are indicated by black dots, with LIGO Hanford labeled H; LIGO Livingston as L and Virgo as V. The locus of constant time delay (with associated timing uncertainty) between two detectors forms an annulus on the sky concentric about the baseline between the two sites (labeled by the two detectors). For three detectors, these annuli may intersect in two locations. One is centered on the true source direction (S), while the other (S0) is its mirror image with respect to the geometrical plane passing through the three sites. For four or more detectors there is a unique intersection region of all of the annuli. Figure adapted from [41].

For three detectors, the time delays restrict the source to two sky regions which are mirror images with respect to the plane passing through the three sites. It is often possible to eliminate one of these regions by requiring consistent amplitudes in all detectors. For signals just above the detection threshold, this typically yields regions with areas of several tens to hundreds of square degrees. Additionally, for BNSs, it is often possible to obtain a reasonable estimate of the distance [109, 31], which can be used to further aid electromagnetic observations [79, 32]. If there is significant difference in sensitivity between detectors, the source is less well localized and we may be left with the majority of the annulus on the sky determined by the two most sensitive detectors. We do not intend to produce timing-only sky maps, but timing triangulation can be useful for order-of-magnitude estimates of sky-localization accuracy averaged across the population of signals.
The next decades

<table>
<thead>
<tr>
<th>Experiment</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>beyond</th>
</tr>
</thead>
<tbody>
<tr>
<td>aLIGO (O1+)</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>aLIGO (design)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Voyager &amp; Cosmic Explorer</td>
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<tr>
<td>ET</td>
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<tr>
<td>DECIGO</td>
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<td>(e)LISA</td>
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<tr>
<td>BBO</td>
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</tbody>
</table>
Understanding the BH mass-function can lead to understanding the progenitors of these systems.
Combining space and ground-based observations

I.C. Ely Kovetz, Julian Munoz, Marc Kamionkowski (work in progress + with many extensions)

We will be able to observe the evolution of individual systems over periods of years, thus measure evolving eccentricities, masses -> progenitors.
Conclusions

• Taking the first detection of GWs we made a connection to a long standing problem, the nature of dark matter (assuming it is BHs produced at the Early Universe).

• The rate that these BHs merge currently is of the same order of magnitude as the one observed (it could have been many orders of magnitude off) PRL 116 201031.

• These can be very short-lived objects (shorter than this presentation or the time it will take me to go through that slide). Thus with properties very unique and Testable! in the next ~decade PRD 94 084013.

• One can also search for a signal in the mass-spectrum of observed BHs in the next ten years arXiv:1611:01157 and even derive limits on PBHs from GWs (in progress).

• We can also search for a signal in the overall background GW emission PRL 117 201102 & arXiv:1609.03565 testable with the next generation of detectors (2030s).

• Make a connection with other observables as is the distributions of galaxies PRD 94 023516 (2030s++).

• Ask more general questions regarding what are the sources of the GWs and what can we learn in terms of astrophysical systems PRD 94 023516, arXiv:1609.03565 & arXiv:1611:01157.

• A GREAT NEW PROBE TO STUDY THE COSMOS
Thank you!
Additional slides
observations are directly sensitive to the luminosity distance to a
time \[94\].

alternatives, e.g., boson stars \[93\], do exist. This result estab-

the mass of a stable neutron star is \[2\]. For comparison, the highest observed neutron star mass is

waveform models.

90%.

Figure 5. The Overall results are computed by averaging the posteriors for the two models. For the Overall results we quote both the

Bayes factor for a signal compared to Gaussian noise we report the mean and its

ratio to the range of the symmetric

TABLE I. Summary of the parameters that characterise GW150914. For model parameters we report the median value as well as

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EOBNR</th>
<th>IMRPhenom</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector-frame total mass (M/M_\odot)</td>
<td>70.3±5.3</td>
<td>70.7±3.8</td>
<td>70.5±4.6±0.9</td>
</tr>
<tr>
<td>Detector-frame chirp mass (M/M_\odot)</td>
<td>30.2±2.5</td>
<td>30.5±1.7</td>
<td>30.3±2.1±0.4</td>
</tr>
<tr>
<td>Detector-frame primary mass (m_1/M_\odot)</td>
<td>39.4±5.5</td>
<td>38.3±5.5</td>
<td>38.8±5.6±0.9</td>
</tr>
<tr>
<td>Detector-frame secondary mass (m_2/M_\odot)</td>
<td>30.9±4.8</td>
<td>32.2±3.6</td>
<td>31.6±4.2±0.1</td>
</tr>
<tr>
<td>Detector-frame final mass (M_f/M_\odot)</td>
<td>67.1±4.6</td>
<td>67.4±3.4</td>
<td>67.3±4.1±0.8</td>
</tr>
<tr>
<td>Source-frame total mass (M_{\text{source}}/M_\odot)</td>
<td>65.0±5.0</td>
<td>64.6±4.1</td>
<td>64.8±4.6±0.9</td>
</tr>
<tr>
<td>Source-frame chirp mass (M_{\text{source}}/M_\odot)</td>
<td>27.9±2.3</td>
<td>27.9±1.8</td>
<td>27.9±2.1±0.4</td>
</tr>
<tr>
<td>Source-frame primary mass (m_{1_{\text{source}}}/M_\odot)</td>
<td>36.3±5.3</td>
<td>35.1±5.2</td>
<td>35.7±5.4±1.1</td>
</tr>
<tr>
<td>Source-frame secondary mass (m_{2_{\text{source}}}/M_\odot)</td>
<td>28.6±4.4</td>
<td>29.5±3.3</td>
<td>29.1±3.8±0.2</td>
</tr>
<tr>
<td>Source-frame final mass (M_{f_{\text{source}}}/M_\odot)</td>
<td>62.0±4.4</td>
<td>61.6±3.7</td>
<td>61.8±4.2±0.9</td>
</tr>
<tr>
<td>Mass ratio (q)</td>
<td>0.79±0.18</td>
<td>0.84±0.14</td>
<td>0.82±0.16±0.01</td>
</tr>
<tr>
<td>Effective inspiral spin parameter (\chi_{\text{eff}})</td>
<td>−0.09±0.19</td>
<td>−0.03±0.14</td>
<td>−0.06±0.17±0.01</td>
</tr>
<tr>
<td>Dimensionless primary spin magnitude (a_1)</td>
<td>0.32±0.45</td>
<td>0.31±0.51</td>
<td>0.31±0.48±0.04</td>
</tr>
<tr>
<td>Dimensionless secondary spin magnitude (a_2)</td>
<td>0.57±0.40</td>
<td>0.39±0.50</td>
<td>0.46±0.42±0.01</td>
</tr>
<tr>
<td>Final spin (a_f)</td>
<td>0.67±0.06</td>
<td>0.67±0.05</td>
<td>0.67±0.05±0.00</td>
</tr>
<tr>
<td>Luminosity distance (D_L/\text{Mpc})</td>
<td>390±170</td>
<td>440±140</td>
<td>410±160±20</td>
</tr>
<tr>
<td>Source redshift (z)</td>
<td>0.083±0.033</td>
<td>0.093±0.028</td>
<td>0.088±0.031±0.004</td>
</tr>
<tr>
<td>Upper bound on primary spin magnitude (a_1)</td>
<td>0.65</td>
<td>0.71</td>
<td>0.69±0.05</td>
</tr>
<tr>
<td>Upper bound on secondary spin magnitude (a_2)</td>
<td>0.93</td>
<td>0.81</td>
<td>0.88±0.10</td>
</tr>
<tr>
<td>Lower bound on mass ratio (q)</td>
<td>0.64</td>
<td>0.67</td>
<td>0.65±0.03</td>
</tr>
<tr>
<td>Log Bayes factor (\ln B_{s/n})</td>
<td>288.7±0.2</td>
<td>290.1±0.2</td>
<td>—</td>
</tr>
</tbody>
</table>
An event as the GW150914 was bellow the threshold of S/N=8 to be detected by initial LIGO detectors.
The ~second Event: LVT151012

LVT: Ligo Virgo Trigger

2015, October, 12th

\[ m_1 = 23^{+18}_{-5} M_\odot \]

\[ m_2 = 13^{+4}_{-5} M_\odot \]

\[ z = 0.2^{+0.1}_{-0.1} \]

False rate 1 every 2.3 yrs (GW150914 was < 1 every 203000 yrs)

Combined S/N is 9.6 but H1 and L1 individually <8.

Higher Inspiral freq. -> lower masses
Sensitivity plots of current aLIGO in terms of sources parameters.

$M_c \propto f^{-11/5}$ for fixed $\dot{f}$ assuming 5% of initial mass goes in GWs.
Searches for a signal

- Using waveforms (or “templates”) of merging compact objects (250,000 templates), $1 - 99 M_\odot$ and $\alpha \in (0, 0.99)$

- searching for transient signals (using linear combinations of Sine-Gaussian wavelets). GW150914 was detected by both methods.

- LIGO measures, frequency-range during the inspiral phase

  - $f_{\text{merge}}$ from the end of the inspiral phase

  - $\dot{f} \equiv df/dt$ during the inspiral phase

  - $h_c$ during the inspiral and merger phases

  - $f_{\text{ring down}}$ from the end of the merger phase

- $S/N$ main contribution from the merger phase but also some from the inspiral.
Lower mass halos —> lower velocity dispersion (i.e. higher cross-section for the binary formation) and higher concentration:

But there are many more (in terms on number) low mass DM halos:

$$\frac{dn}{dM} \sim M^{-1.85}$$

Impose a cut-off at \(\sim 400 M_\odot\)