LIGO search for sub-solar mass compact binaries in O1 data

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Outline

- Motivation
  - Primordial or astrophysical?
  - PBH as dark matter
- Analysis Techniques
  - Analysis ‘choices’
  - The issues of scale
- Projected results in the PBH dark matter paradigm
  - PBH model
  - Actual (and early) calculation
  - LIGO’s constraints

Motivation

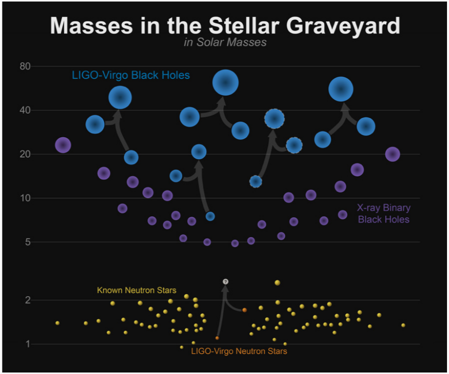
We're not that alone...

There are *lots* of compact objects:

- BNS: $1540^{+3200}_{-1220}\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ [Abbott et al., 2017]
- BBH: $9 - 240\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ [Abbott et al., 2016a]

How do we distinguish between primordial and astrophysical populations?

- [Kovetz et al., 2017]



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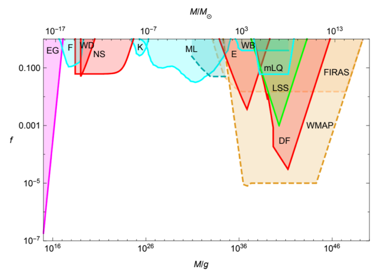
Lightest known compact objects

- Black Holes: limited by Chandrasekahr mass
  - Small white dwarfs are stable
  - Some models get around that [Shandera et al., 2018, Kouvaris et al., 2018]
- Neutron stars: Stable down to $\sim .09 M_\odot$ [Potekhin et al., 2013], verified down to $1.1 M_\odot$ [Martinez et al., 2015]
  - EOS is still a mystery (for the moment)
- New physics: ??

Dark matter

- Previous work
    - 1970s: Hawking, Chapline
    - 1990s: Thorne, Ioka, microlensing collaborations
    - today: many of you!
- 'Tightly constrained'
- Microlensing surveys disagreed–new way to probe the same region



[Carr et al., 2016]

Sub-solar mass search advantages

Any result is exciting

- Detection: new physics, PBH and better understanding of early universe
- Absolutely nothing: constraints on models of PBH dark matter, better understanding of early universe

If astrophysical and primordial populations are disjoint in this mass range, this search provides an easy way to identify primordially formed black holes.

Analysis Techniques

Matched Filtering

Optimal method for maximizing SNR in Gaussian noise

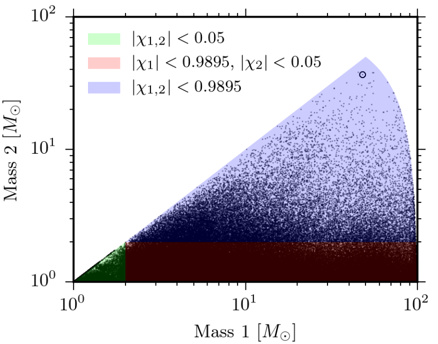
Obtain a complex snr by correlating expected signals, $h_i(f)$, with the data, $d(f)$:

$$z_i(t) = x_i(t) + iy_i(t) = 4\int_0^\infty df\, \frac{\tilde{h}_i^*(f)\tilde{d}(f)}{S_n(f)} e^{2\pi ift} \tag{1}$$

Requires a comprehensive set of templates, $\{h_i\}$ [Messick et al., 2017].

Template banks

- Extends from $0.19M_\odot - 2.0M_\odot$
- Uses non-spinning waveforms
- Generated from $f_{low} = 45$ Hz
- Set a maximum 'mismatch' between an arbitrary signal and the nearest template
    - Bank becomes denser at low mass



[Abbott et al., 2016a]

Template banks pt. 2

Lower mass $\implies$ denser template placement
[Owen and Sathyaprakash, 1999]

$$N \sim m_{min}^{-8/3} \tag{2}$$

$0.1^{-8/3} \sim 500$ times as many templates per order of magnitude in mass

LIGO is sensitive to binaries with components $\sim .01 M_{\odot}$ at extra-galactic distances

- Would require $\mathcal{O}(10^3)$ more templates

Time samples

Time in band (seconds)			
Binary mass	From 45 Hz	30 Hz*	15 Hz**
$(30M_\odot, 30M_\odot)$	< 1	< 1	~ 2
$(1.0M_\odot, 1.0M_\odot)$	~ 30	~ 100	~ 600

*used in stellar mass O1 searches

**LIGO's lower limit in sensitive frequency

Time samples

Time in band (seconds)			
Binary mass	From 45 Hz	30 Hz*	15 Hz**
$(30M_\odot, 30M_\odot)$	< 1	< 1	~ 2
$(1.0M_\odot, 1.0M_\odot)$	~ 30	~ 100	~ 600
$(.2M_\odot, .2M_\odot)$	~ 500	~ 1400	~ 9000
$(.01M_\odot, .01M_\odot)$	$\sim 70,000$	??	??

*used in stellar mass O1 searches

**LIGO's lower limit in sensitive frequency

Scaling

LIGO analyses scale approximately as:

$$\text{computational cost} \approx NTlogT \tag{3}$$

where N is the number of templates and T is the number of time samples in template waveforms.

Searching to lowest mass*:

- 10^3 in templates
- At least 10^2 in time samples
- Spinning search adds another factor of 10-100
- Overall increase of $10^5 - 10^7$ in computational cost

What is a reasonable parameter space?

*that LIGO is sensitive to at extra-galactic distances

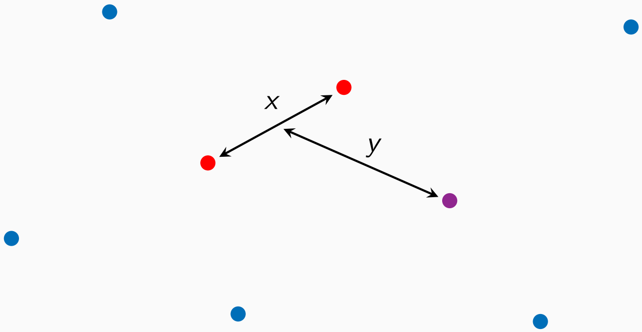
Wishlist

- Spin range for primordial black holes
    - Low vorticity $\implies$ low spin?
- Accretion effects
    - Mass evolution/incorporation into merger rate
    - Spin up by accretion?
- Mass ratios for compact binaries

Projected results in the PBH dark matter paradigm

Formation model

- We follow previous work by [Nakamura et al., 1997, Ioka et al., 1998, Sasaki et al., 2016]
- Model PBH population as component of dark matter, i.e. $\Omega_{PBH} = f\Omega_{DM}$
- Monochromatic distribution of PBH with mass M, mean separation $\bar{x}$, nearest neighbors separated by x, third closest by y



Coalescence rate

$$dP = \begin{cases} \frac{3\, f^{\frac{37}{8}}}{58} \left[f^{-\frac{29}{8}} \left(\frac{t}{t_c}\right)^{\frac{3}{37}} - \left(\frac{t}{t_c}\right)^{\frac{3}{8}} \right] \frac{dt}{t}, & t < t_c \\ \frac{3\, f^{\frac{37}{8}}}{58} \left[f^{-\frac{29}{8}} \left(\frac{t}{t_c}\right)^{-\frac{1}{7}} - \left(\frac{t}{t_c}\right)^{\frac{3}{8}} \right] \frac{dt}{t}, & t \geq t_c \end{cases} \tag{4}$$

where $t_c = Q\bar{x}^4 f^{25/3}$ and $Q = 3\,(Gm_i)^{-3}/170$.
[Sasaki et al., 2016]

Evaluated at the time today t_0 and multiplied by n_{BH}, the average number density of PBHs, gives the event rate:

$$\text{event rate} = n_{\mathrm{BH}} \left. \frac{dP}{dt} \right|_{t=t_0} . \tag{5}$$

LIGO rates

Assuming a null result, we adopt the loudest event statistic formalism [Biswas et al., 2009, Abbott et al., 2016b] to constrain the binary merger rate for a given mass bin, m_i, to 90% confidence.

$$\mathcal{R}_{90,i} = \frac{2.3}{(VT)_i}. \tag{6}$$

where $(VT)_i$ is the sensitive volume-time over the duration of the search.

Approximating $(VT)_i$

For O1, $T \sim 48$ days is the coincident live-time. We can approximate:

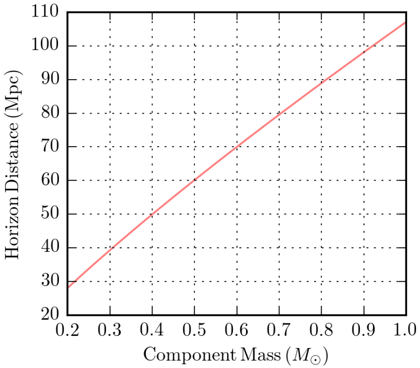
$$(VT)_i = T \int 4\pi r^2 \epsilon_i(r) dr, \tag{7}$$

$\epsilon_i(r)$: inject signals into the data, measure the fraction found above the loudest event [Messick et al., 2017]

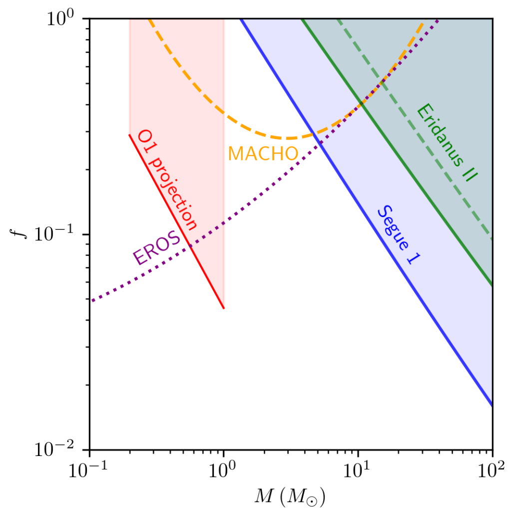
$n_{BH} \left. \frac{dP}{dt} \right|_{t=t_0} = \mathcal{R}_{90,i}$: invert to find limit on f

Early estimated rates

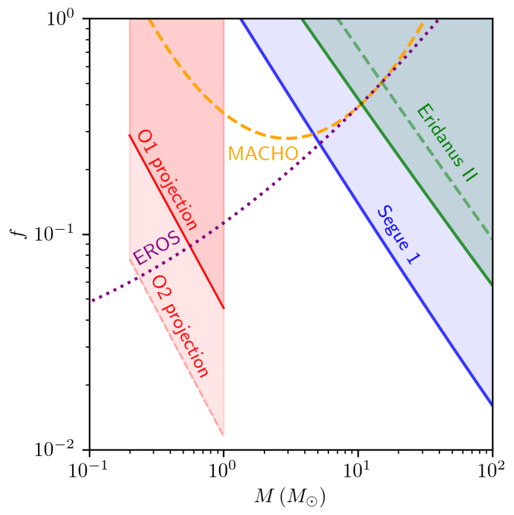
- We can perform a similar estimate before the search has completed.
- Estimate the horizon distance from the PSD [Abadie et al., 2010]
- Use $T = 48$ days, $V = \frac{4\pi r_{horizon}^3}{3}$, to find $\mathcal{R}_{90,i}$
- Set $n_{BH} \left.\frac{dP}{dt}\right|_{t=t_0} = \mathcal{R}_{90,i}$ and invert to obtain limit on f



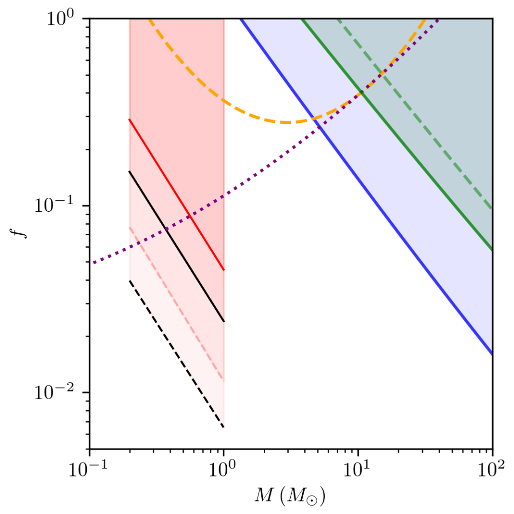
Projected O1 results



Projected O2 results



Projected results with [Ali-Haïmoud et al., 2017] correction



Solid lines = Projected O1 results with Sasaki (red) and YAH (black) rate models
Dashed lines = Projected O2 results

Conclusions

- LIGO offers a new way to search for sub-solar mass compact objects
- Regardless of the results, the future is bright:
  - Constraining neutron star EOS
  - Constraining PBH abundance
  - Test for new and/or exotic physics and compact objects
- Lots of room to improve
  - Extend to distributions
  - Add more physics to model
  - Perform a spinning search
- O2 alone has much more sensitive $\langle VT \rangle$

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