Search for intermediate mass black hole binaries in the first observing run of Advanced LIGO

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- F. Salemi, Albert-Einstein Institut – Hannover

for the LIGO Scientific Collaboration and Virgo Collaboration

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LIGO Scientific Collaboration

VIRGO

Intermediate Mass Black Holes (IMBHs)

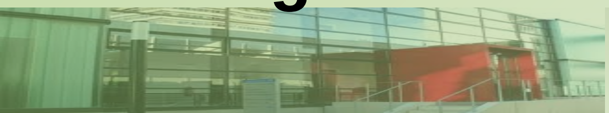
- IMBHs are thought to populate the mass range between ~100 and ~ 10^5 Msun
- IMBHs have multiple plausible formation channels, all with multiple difficulties:
  - the direct collapse of massive first-generation, low-metallicity Population III stars
  - runaway mergers of massive main sequence stars in

dense stellar clusters

  - the accretion of residual gas onto stellar-mass black holes
  - chemically homogeneous evolution

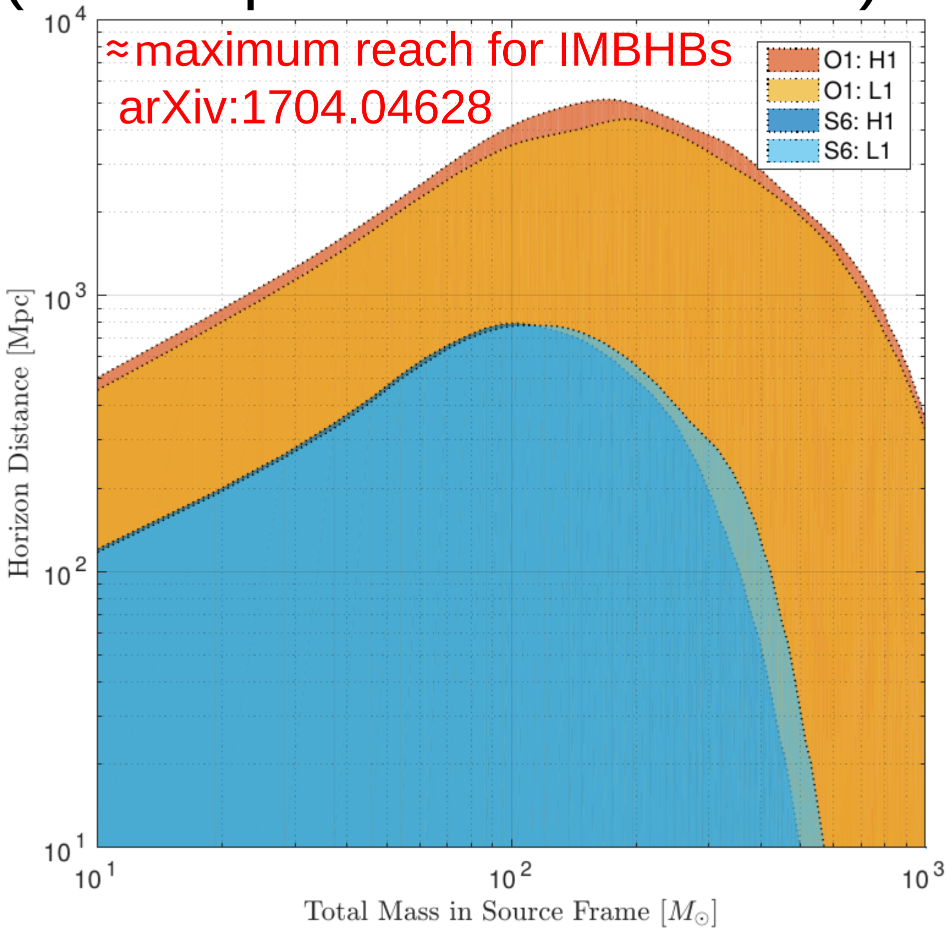
IMBHBs and previous GW searches

- No direct observational evidence of IMBH Binaries (IMBHBs)
  - their existence is supported by recent simulations of dense stellar systems [MOCCA simulations, Giersz et al. 2015]
- Major breakthrough if discovered
  - better understanding of massive black hole formation, stellar-cluster evolution and hyper/ultra-luminous x-ray sources
- Coalescing IMBHBs (if found to exist) would be the strongest gravitational-wave (GW) sources accessible to ground-based interferometric detectors such as Advanced LIGO and Virgo
- In previous IMBHB searches using initial **LIGO–Virgo** data taken in **2005–2010**,
  - **unmodeled** transient searches and
  - a **modeled** matched-filter search using only ringdowns
  - were **separately** employed to set distinct **upper limits** on the **merger rates** of IMBHBs.



LIGO O1 run: Sept. 12, 2015 to Jan. 19, 2016

- **51.5 days of coincident time** between Hanford, WA (**H1**) and Livingston, LA (**L1**) detectors with **unprecedented sensitivity**
- 2 BBH detections + a lower significance candidate: all consistent with stellar evolutionary scenarios (7≤component masses ≤36)
  - Further hierarchical merging of similar BH remnants in globular clusters could be a possible IMBH formation channel
- O1 IMBHB search recently on arXiv [arXiv:1704.04628] and accepted for publication by PRD



O1 IMBHB all-sky search

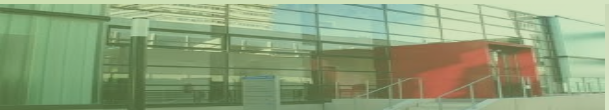
- For O1, for the first time, two distinct analyses (**the modeled and the unmodeled**) were **combined** to form a single search
- **Modeled analysis**: matched filter algorithm (**GstLAL**) that uses inspiral-merger-ringdown templates
  - Optimal for known signals in stationary Gaussian noise; potentially affected by the accuracy of the waveform model used for templates and by the X^2 cut
- **Unmodeled analysis**: coherent WaveBurst (**cWB**) is a search algorithm that looks for coherent excess power on GW detectors
  - can potentially extend the IMBHB parameter space searched by current modeled searches to higher total masses; robust against waveform uncertainties; usually more affected by non-Gaussian noise than modeled.

O1 IMBHB all-sky search (2)

- **Modeled analysis** - GstLAL (f min = 15 Hz)
  - Bank: M_{tot}= [50,600] Msun , q = [1:10,1:1], $\chi_{1,2}$= [-0.99,0.99]
  - Triggers found only in one detector are used to estimate the probability distribution of noise events in each detector
  - Coincident triggers are considered GW candidates and are ranked against each other via a likelihood ratio
- **Unmodeled analysis** - cWB (f min = 16 Hz)
  - Similar setup to all-sky O1 Burst search with frequency dependent post-production cuts to focus on IMBH sources
  - Empirical estimate of significance; >9000 indipendent time shifts, ~1100 yrs of background
- **Combining analyses**
  - $P_{comb} = 1 - (1 - P)^2$, where P is most significant from either analysis

Search results

- **No GWs from IMBHBs were detected**
- The three most significant events correspond to **GW150914**, **LVT151012** and **GW151226**
- Since parameter-estimation studies have placed these events outside of the IMBH mass range, we have removed these triggers from our analysis.
- Excluding GW150914, LVT151012 and GW151226, **the most significant trigger has P_{comb} = 0.26** .



Upper limits on rates

- Used loudest event threshold (P_{comb}= 0.26) to calculate R90%

$$R_{90\%} = -\frac{\ln(0.1)}{\langle VT \rangle} = \frac{2.303}{\langle VT \rangle}$$

where <VT> is the averaged space-time volume to which our search is sensitive

- We estimate the <VT> using a MonteCarlo technique as

$$\langle VT \rangle = \frac{N_{\text{below cutoff}}}{N_{\text{total}}} \langle VT \rangle_{\text{total}} \qquad \langle VT \rangle_{\text{total}} \simeq 35 \text{ Gpc}^3 \text{ yr}$$

- The luminosity distances of the sources are uniform in comoving volume (z = 1) and time (i.e. with a correction factor to account for time dilation at the detector)
- The total number of injections in each set is N_{total} ~ 112000

MonteCarlo details

- Since the true population of IMBHBs is unknown, we focus on placing limits on **twelve specific locations in the IMBHB parameter space**.
- 10 specific combinations of masses
- nonspinning black holes
- For m1 = m2 = 100 Msun two spinning cases

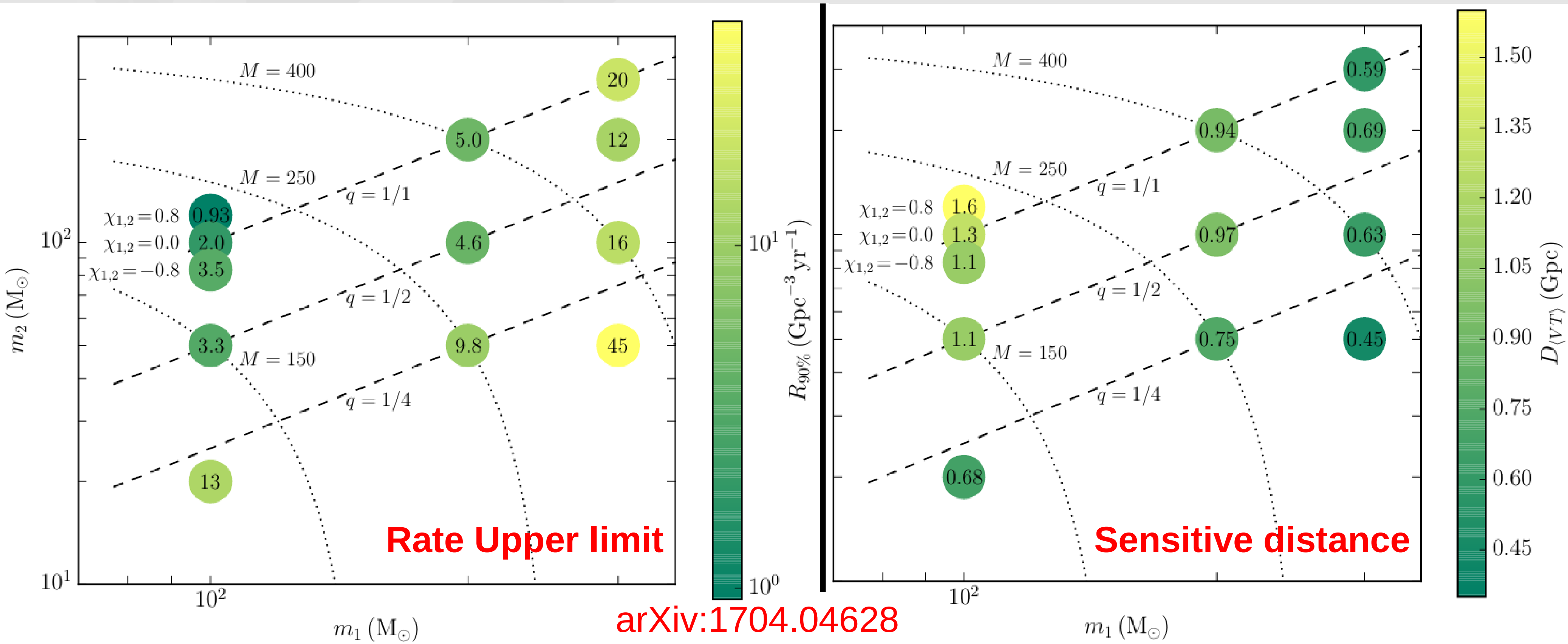
- Sensitive distance:

$$D_{\langle VT \rangle} = \left(\frac{3 \langle VT \rangle}{4\pi T_{\mathrm{a}}} \right)^{1/3}$$

arXiv:1704.04628

m_1 [$M_\odot$]	m_2 [$M_\odot$]	$\chi_{1,2}$	$R_{90\%}$ [$\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$]	[$\mathrm{GC}^{-1}\,\mathrm{Gyr}^{-1}$]	$D_{\langle VT \rangle}$ GstLAL cWB [Gpc]
100	100	0.8	0.93	0.3	$1.6\ ^{1.7}_{1.3}$
100	100	0	2.0	0.7	$1.3\ ^{1.3}_{1.0}$
100	100	-0.8	3.5	1	$1.1\ ^{1.1}_{0.89}$
100	20	0	13	4	$0.68\ ^{0.69}_{0.46}$
100	50	0	3.3	1	$1.1\ ^{1.1}_{0.78}$
200	50	0	9.8	3	$0.75\ ^{0.76}_{0.66}$
200	100	0	4.6	2	$0.97\ ^{0.98}_{0.84}$
200	200	0	5.0	2	$0.94\ ^{0.95}_{0.78}$
300	50	0	45	20	$0.45\ ^{0.46}_{0.37}$
300	100	0	16	5	$0.63\ ^{0.64}_{0.52}$
300	200	0	12	4	$0.69\ ^{0.70}_{0.58}$
300	300	0	20	7	$0.59\ ^{0.60}_{0.45}$

Main Results



arXiv:1704.04628

- 90% confidence rate upper limit in Gpc $^{-3}$ yr $^{-1}$ (left panel) and sensitive distance in Gpc (right panel)
- The straight dashed lines represent contours of constant mass ratio q = m2 /m1 ; the curved dotted lines are those of constant total mass M = m1 + m2 .

Caveats

- Injections do not include:
  - **Higher-order modes**
  - **Precession**
- Higher-order mode study suggests:
  - Main result (100+100) Msun is unaffected
  - High mass results are conservative, since threshold is at low significance
- Results are calculated on single points in the IMBHB parameter space and not to an astrophysical distribution!
  - Cannot compare directly with predictions, or with the O1 “stellar” BBH merger rate (9–240 Gpc^{-3} yr^{-1} , [Astrophys. J. 833, L1 (2016),1602.03842])
  - we have deferred this comparison to future studies.

Astrophysical implications and Conclusions

- Minimal **R90% ≈ 0.3 GC $^{-1}$ Gyr $^{-1}$** (**0.93 Gpc $^{-3}$ yr $^{-1}$**)
  For (100+100) Msun with $\chi_{1,2} = +0.8$
- Nearly two orders of magnitude lower than previous ULs with LIGO-Virgo data
- A factor of a few from 0.1 GC $^{-1}$ Gyr $^{-1}$, i.e. 1 event in each GC within GC's lifetime, assumed to be 10 Gyr (Note last caveat from previous slide)
- Exciting prospects for gravitational-wave astronomy
  - In the next few years, further improvements to our detectors will allow us to improve our rates estimates and may lead to the first detections of IMBHBs.