The Search for Gravitational Waves from Binaries with Neutron Stars

Steven Reyes
Syracuse University / LIGO & Virgo
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UPPER LIMITS ON THE RATES OF BINARY NEUTRON STAR AND NEUTRON STAR–BLACK HOLE MERGERS FROM ADVANCED LIGO'S FIRST OBSERVING RUN

LIGO SCIENTIFIC COLLABORATION AND VIRGO COLLABORATION
(See the end matter for the full list of authors.)
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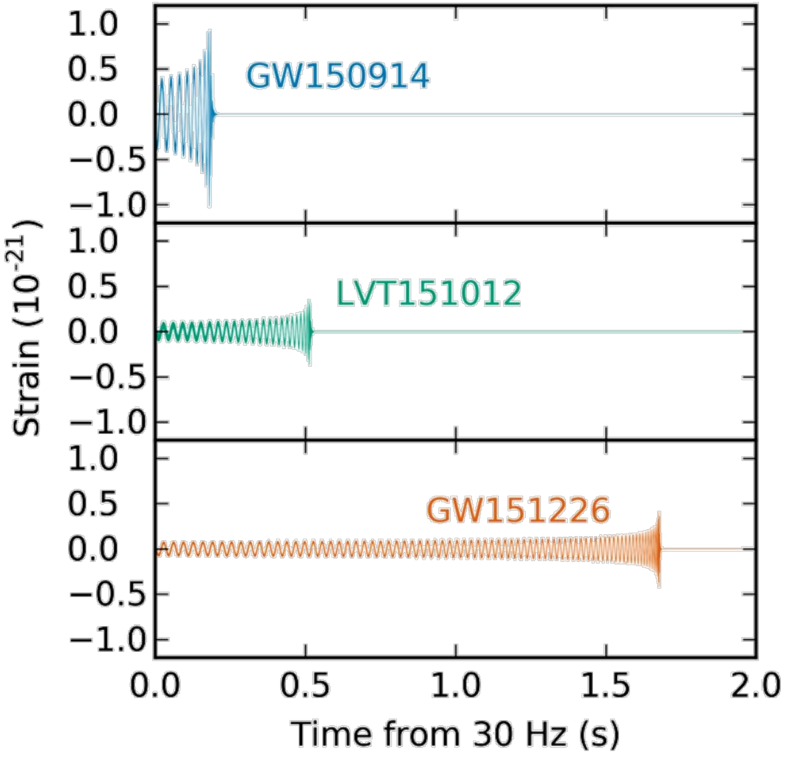
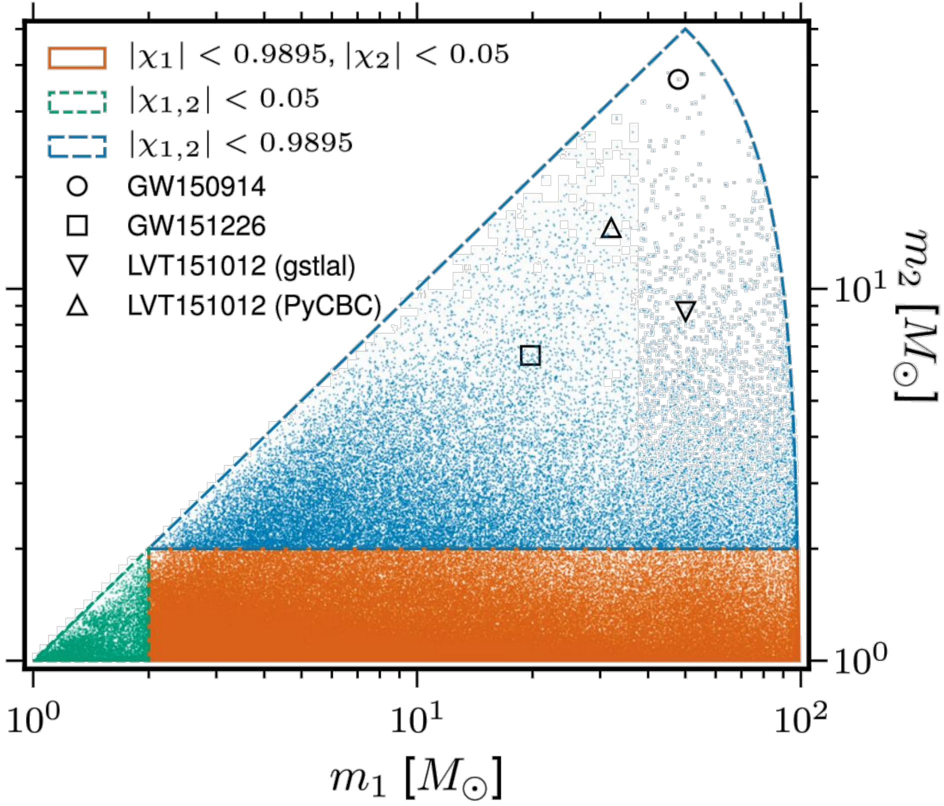
Detections and Non-Detections





"Binary Black Hole Mergers in the First Advanced LIGO Observing Run", B. P. Abbott, et al. (2016), **Phys. Rev. X 6, 041015**

Estimating Rate Upper Limits

- A rate can be given via:

$$R = \frac{\Lambda}{\langle VT \rangle} \sim \left(\frac{events}{Gpc^3\ Yr} \right)$$

- Use a Poisson distribution to estimate the probability of detecting a binary merger:

$$p(n, \Lambda) = \frac{1}{n!} \Lambda^n e^{-\Lambda}$$

- For a non-detection, (n=0), we can estimate an upper limit at 90% confidence as:

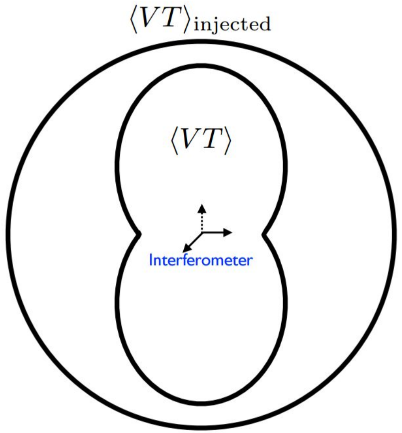
$$R_{90\%} \sim \frac{2.303}{\langle VT \rangle}$$

Estimating Rate Upper Limits (Continued…)

- Estimate a sensitive volume, $\langle VT \rangle$, via Monte-Carlo integration methods.

- Generate software injections of binary waveforms to simulate source populations. Use a FAR threshold of 0.01 yr^{-1} to recover injections.

$$\langle VT \rangle = \frac{N_{\text{found}}}{N_{\text{injected}}} \langle VT \rangle_{\text{injected}}$$



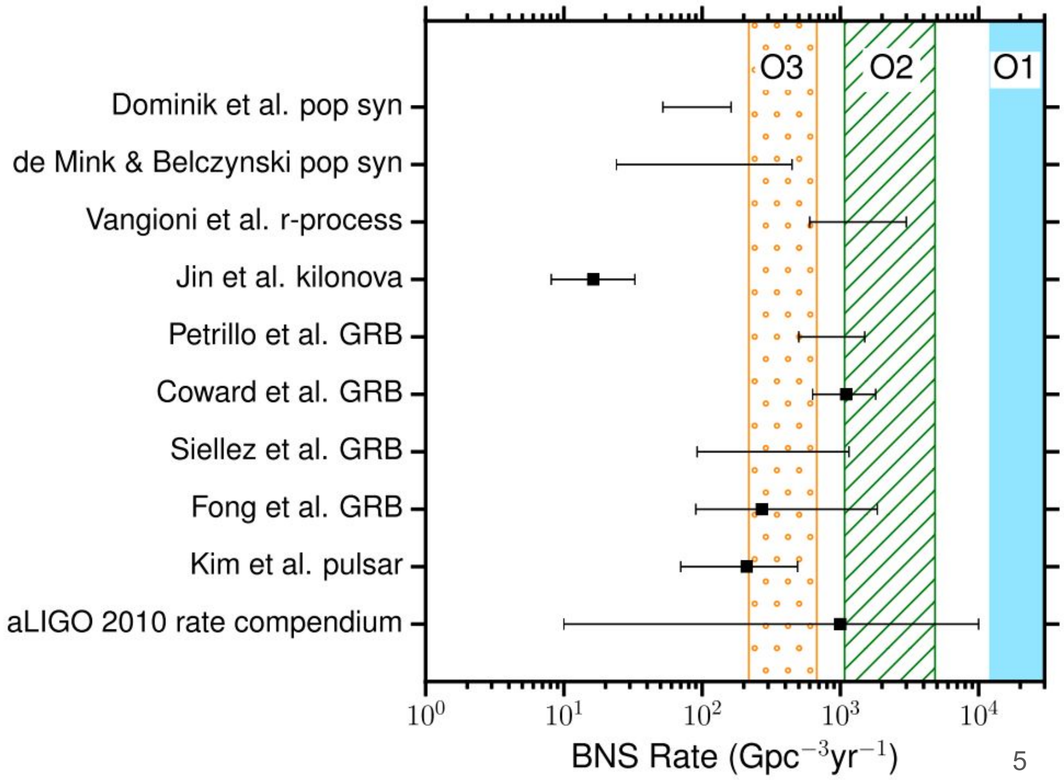
- Calibration and waveform uncertainty contribute to error on $\langle VT \rangle$ and on R.

BNS Populations Considered

- Consider four populations:
  - Gaussian in mass
    (μ : 1.35 $M_\odot$, σ: 0.13 $M_\odot$)
    Isotropic Spins
    - Low Spin: $\chi_i < 0.05$
    - High Spin: $\chi_i < 0.40$

  - Uniform in mass (1.0, 3.0) $M_\odot$
    Isotropic Spins
    - Low Spin: $\chi_i < 0.05$
    - High Spin: $\chi_i < 0.40$

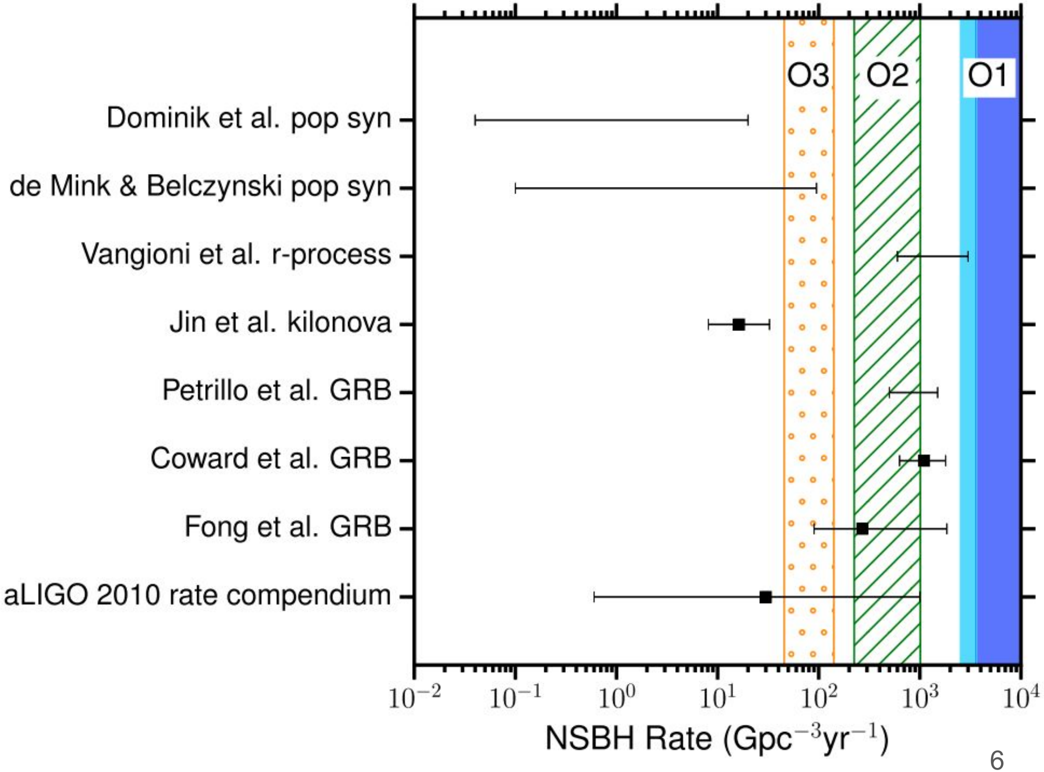
- Gaussian Mass, Low Spin



NSBH Populations Considered

- Consider six populations
  - $m_1 = 1.4\ M_\odot$
    $m_2 = 5\ M_\odot$, $10\ M_\odot$, $30\ M_\odot$
    - Isotropic spins
      $\chi_1 < 0.04$, $\chi_2 < 1.0$
    - Aligned spins
      $\chi_1 < 0.04$, $\chi_2 < 1.0$

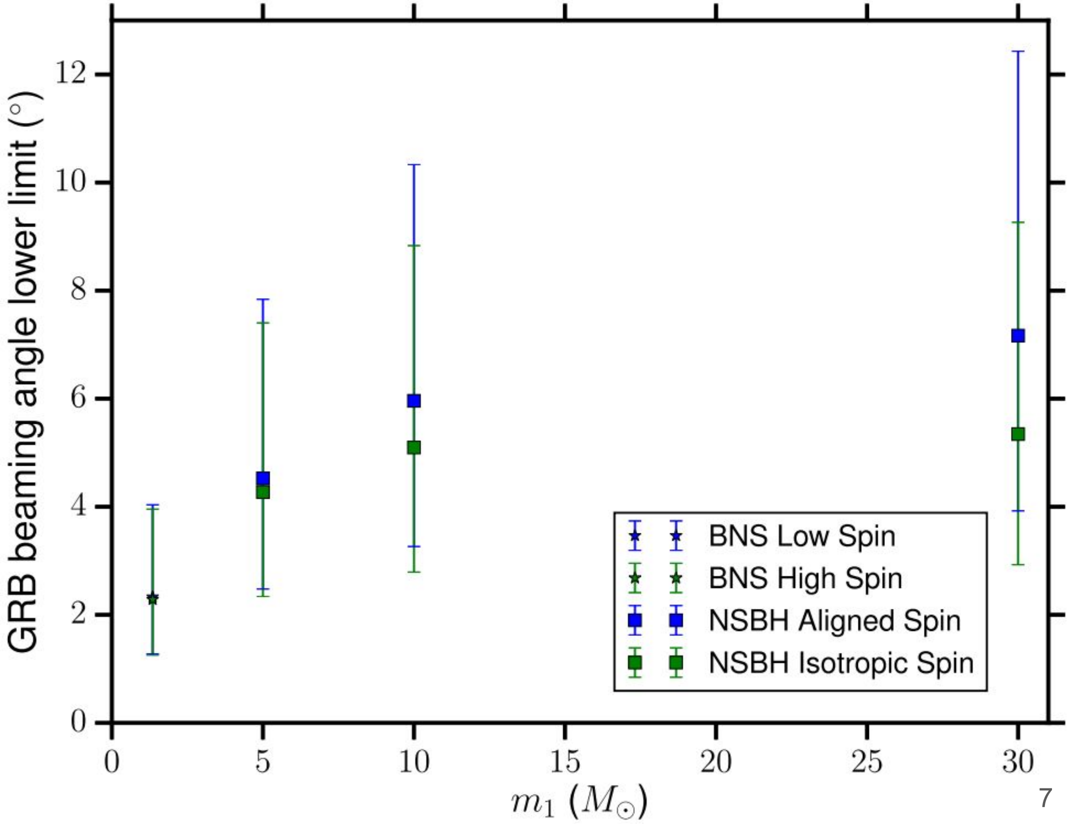
- ($1.4\ M_\odot$, $5\ M_\odot$), Isotropic Spins
  ($1.4\ M_\odot$, $10\ M_\odot$), Isotropic Spins



Astrophysical Implications on GRBs

- Assume that short GRBs are recovered jets from BNS or NSBH mergers.
- $R_{GRB} = 3 - 30\ \mathrm{Gpc^{-3}\ yr^{-1}}$

$$R_{\mathrm{GRB}} = (1 - \cos\theta_j) R_{\mathrm{merger}}$$



(Coward et al. 2012; Nakar et al. 2006)
(Chen and Holz 2013)

Conclusions

- Estimates on upper limits on rate of BNS/NSBH mergers from **O1** are not enough to rule out predictions from theoretical models.

- Continued non-detections in **O2** and **O3** <u>**may**</u> begin to yield upper limits on the rate of BNS/NSBH mergers that begin to conflict with some theoretical models.

Thanks

Extra Slides

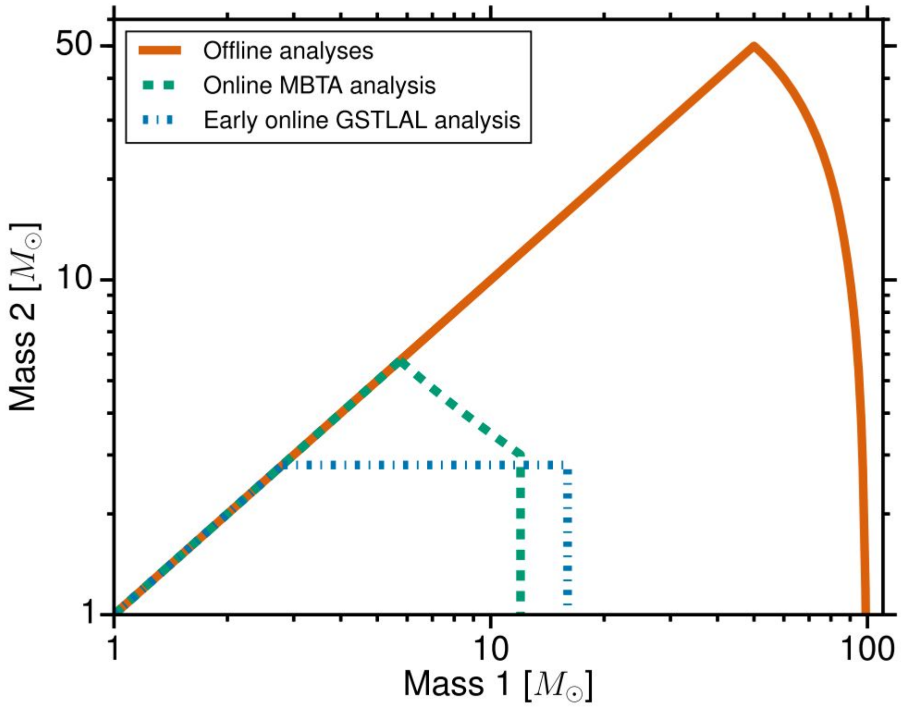
The Search for Coalescence of Compact Binaries

- The first Observing Run (O1) spanned from September 12th, 2015 to January 19th, 2016.
    - ***49.0*** days of coincident data accumulated between Hanford and Livingston detectors.
    - A total of ***52.0*** days of data were analyzed by the online analyses.
    - Between offline analyses, `gstLAL` analyzed ***48.3*** days of data, and `pyCBC` analyzed ***46.1*** days of data.
- The second Observing Run (O2) began on November 15th, 2016, and is still ongoing.

Online Analysis

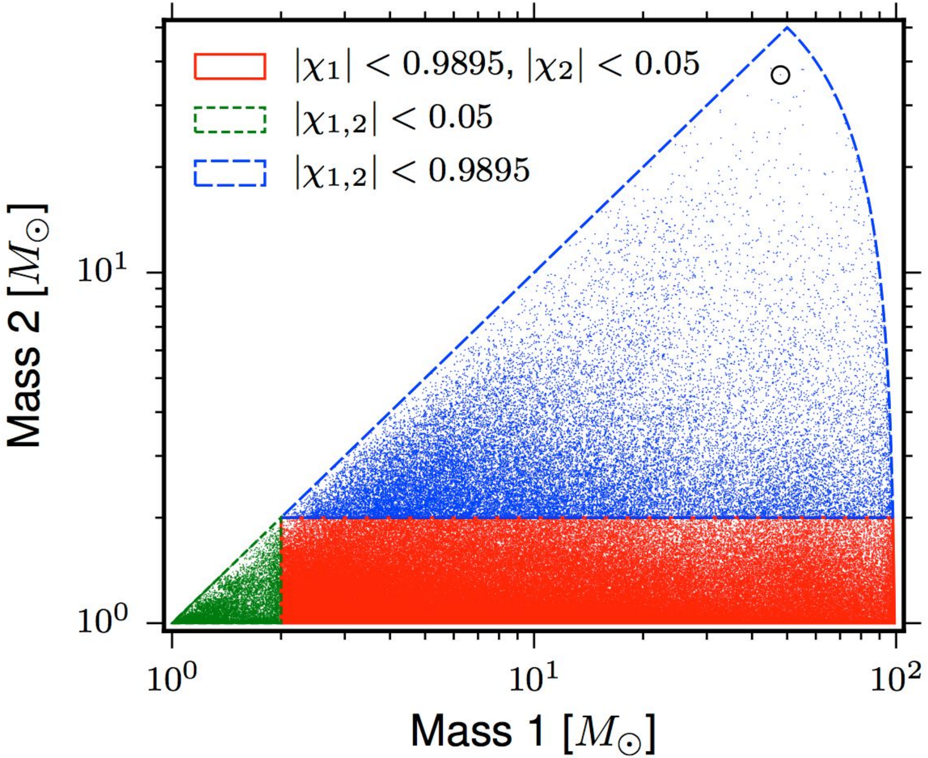
- `gstLAL` pipeline:
  - $m_1 \in [1, 16]\ M_\odot$
  - $m_2 \in [1, 2.8]\ M_\odot$
  - $\chi_i < 0.05$ for $m_i < 2.8\ M_\odot$
  - $\chi_i < 1.0$ otherwise

- `mbta` pipeline:
  - $m_1, m_2 \in [1, 12]\ M_\odot$
  - $M_{chirp} < 5\ M_\odot$
  - $\chi_i < 0.05$ for $m_i < 2\ M_\odot$
  - $\chi_i < 1.0$ otherwise

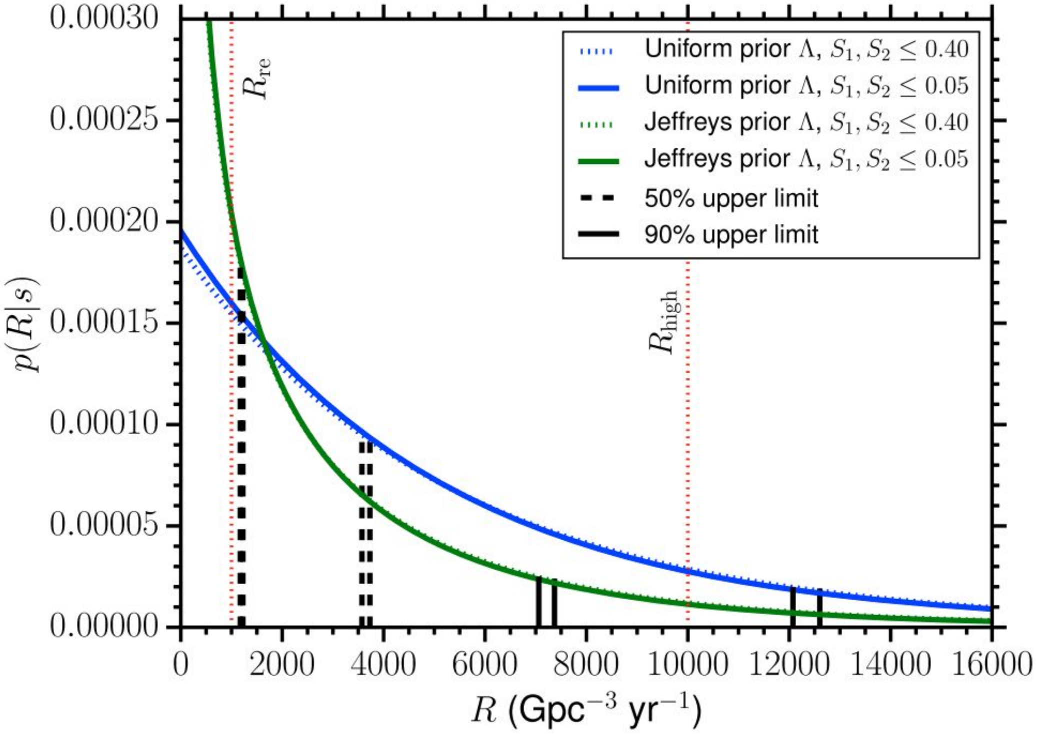


Offline Analysis

- gstLAL & pyCBC pipelines:
  - $m_i \in [1, 99]\ M_\odot$
  - $M_{total} < 100\ M_\odot$
  - $\chi_i < 0.05$ for $m_i < 2\ M_\odot$
  - $\chi_i < 0.9895$ otherwise



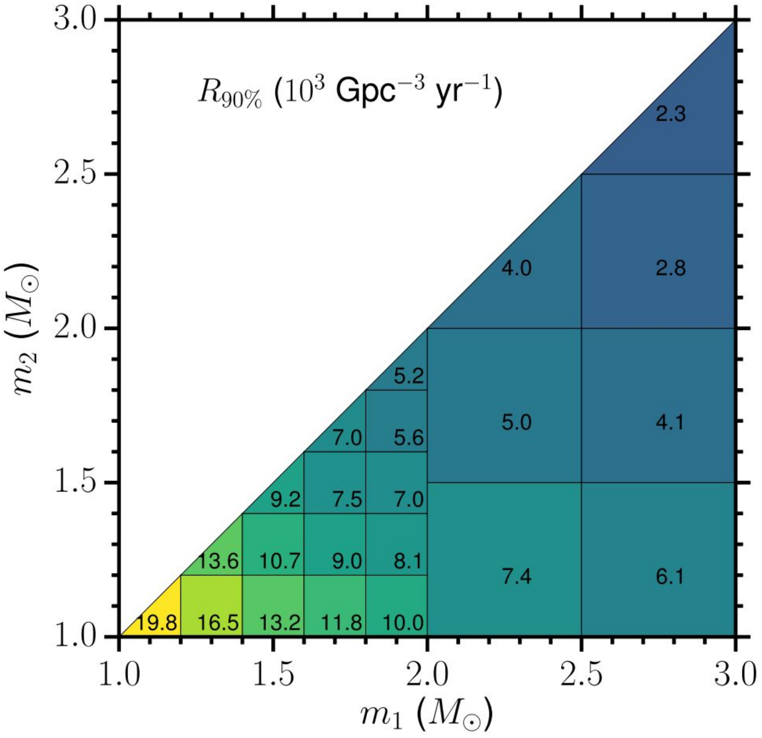
Rate of BNS Mergers (Gaussian Mass Distribution)



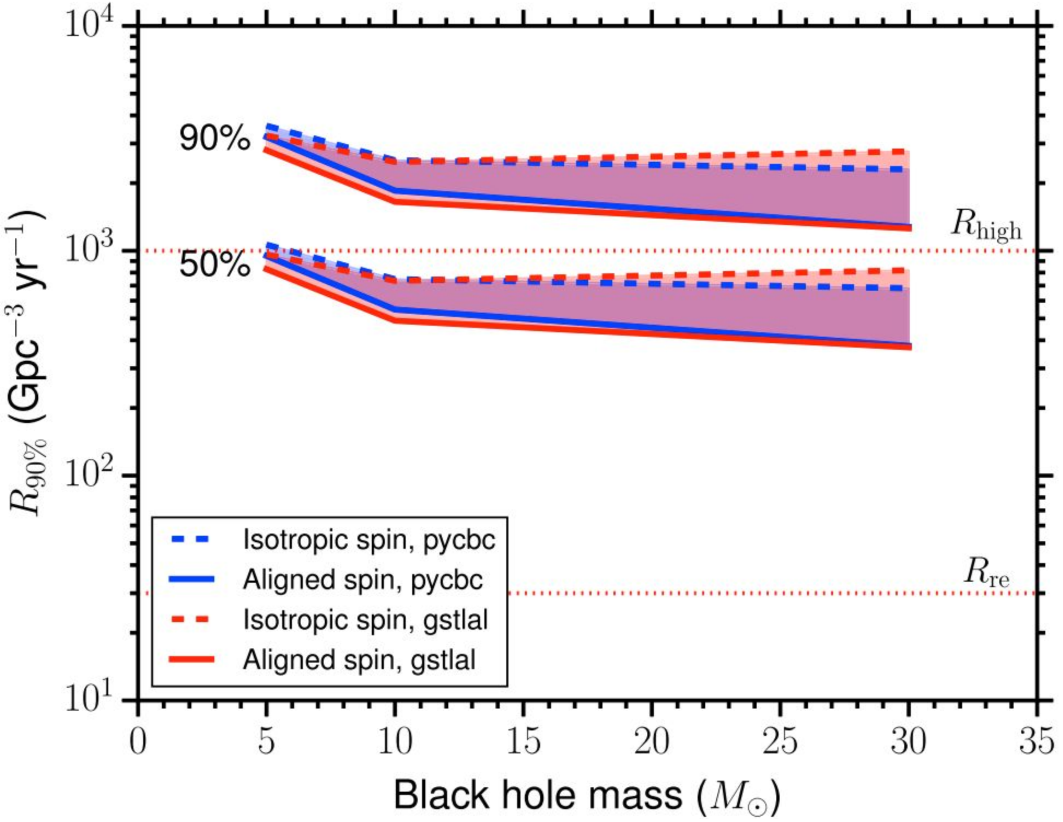
BNS Rates Upper Limits / Inspiral Range

Injection set	Range of spin magnitudes	$\langle VT \rangle$ (Gpc^3 yr)		Range (Mpc)		$R_{90\%}$ (Gpc^{-3} yr^{-1})	
		PyCBC	GstLAL	PyCBC	GstLAL	PyCBC	GstLAL
Isotropic low spin	[0, 0.05]	2.09×10^{-4}	2.20×10^{-4}	73.2	73.4	12,100	11,500
Isotropic high spin	[0, 0.4]	2.00×10^{-4}	2.07×10^{-4}	72.1	72.0	12,600	12,200

Rate of BNS Mergers (Isotropic Mass Distribution)



Upper Limits on NSBH Merger Rates



NSBH Rates Upper Limit / Inspiral Range

NS mass ($M_\odot$)	BH mass ($M_\odot$)	Spin distribution	$\langle VT \rangle$ (Gpc^3 yr)		Range (Mpc)		$R_{90\%}$ (Gpc^{-3} yr^{-1})	
			PyCBC	GstLAL	PyCBC	GstLAL	PyCBC	GstLAL
1.4	5	Isotropic	7.01×10^{-4}	7.71×10^{-4}	110	112	3,600	3,270
1.4	5	Aligned	7.87×10^{-4}	8.96×10^{-4}	114	117	3,210	2,820
1.4	10	Isotropic	1.00×10^{-3}	1.01×10^{-3}	123	122	2,530	2,490
1.4	10	Aligned	1.36×10^{-3}	1.52×10^{-3}	137	140	1,850	1,660
1.4	30	Isotropic	1.10×10^{-3}	9.02×10^{-4}	127	118	2,300	2,800
1.4	30	Aligned	1.98×10^{-3}	1.99×10^{-3}	155	153	1,280	1,270