Probability of detecting compact binary coalescence with enhanced LIGO

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[V. Kalogera, K. Belczynski]

GWDAW-12, December 13, 2007

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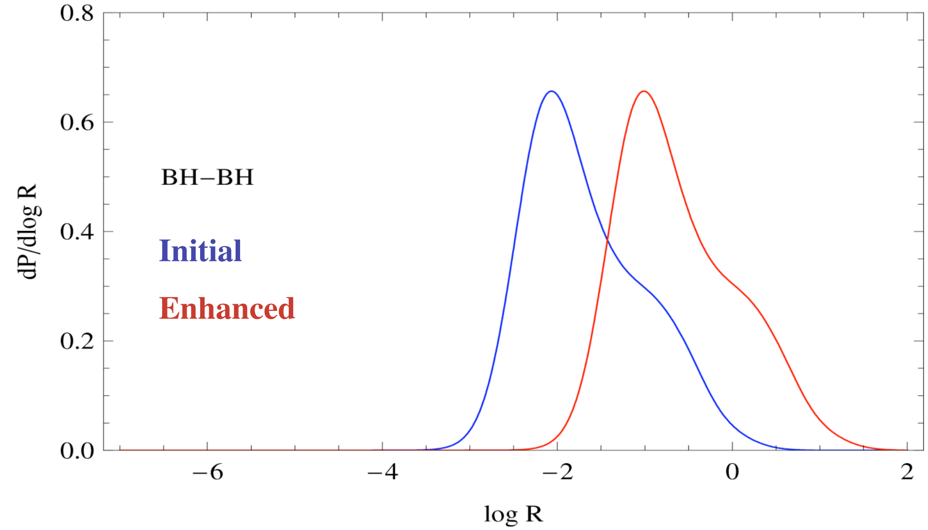
Will we see a merger soon?



Available predictions

- Isolated stars : PDFs available
- Clusters : Large range of plausible rates *including* initial LIGO detections (!)

Detection probability?

Detection rate (based on $D_{bns,0}$)

Detection rate PDF (w/ preferred range)

$$P_{\mathrm{detect}}(D_{bns}, T) = \int d\log R_D \, p(\log R_D) \times \left[1 - \exp\left(-R_D \left(\frac{D_{bns}}{D_{bns,0}}\right)^3 T\right)\right]$$

Range to BNS

Observation time

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Isolated binary evolution

Synthetic starbursts:

- *StarTrack*: simulates many binaries
- Many parameters for unknown physics (e.g., SN kicks)
- Convolved with star formation rate (SFR)

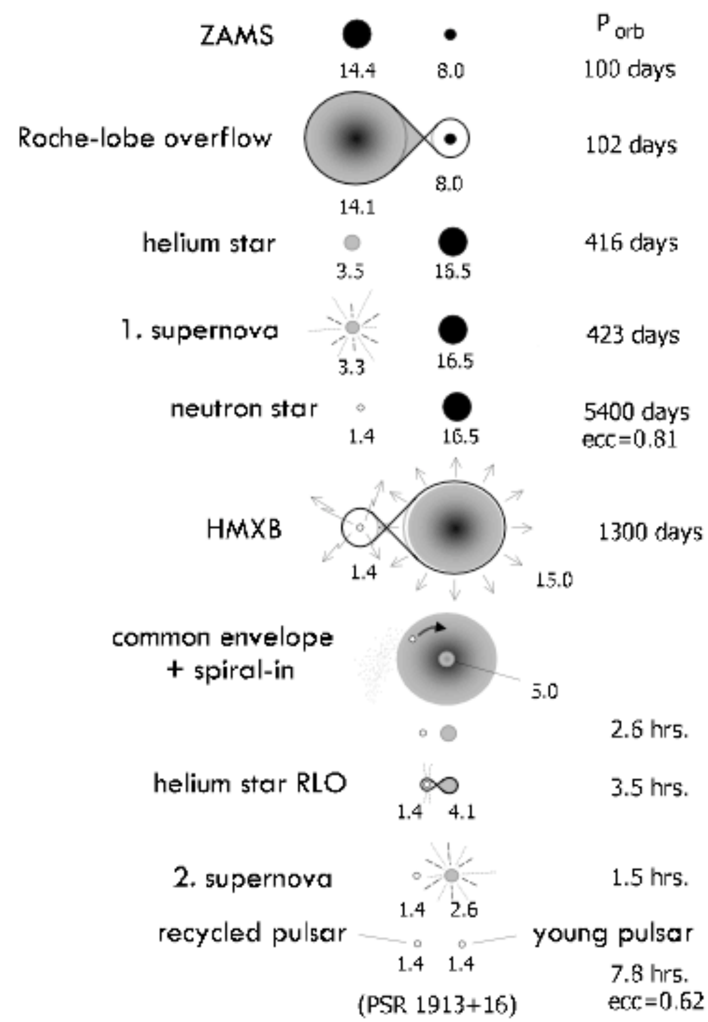
Computational tradeoffs:

BH-BH distributions: tricky

+ wide mass range

+ merging massive binaries :
  rare (stellar IMF) but
  visible much farther away

+ much rarer than NS-NS, BH-NS

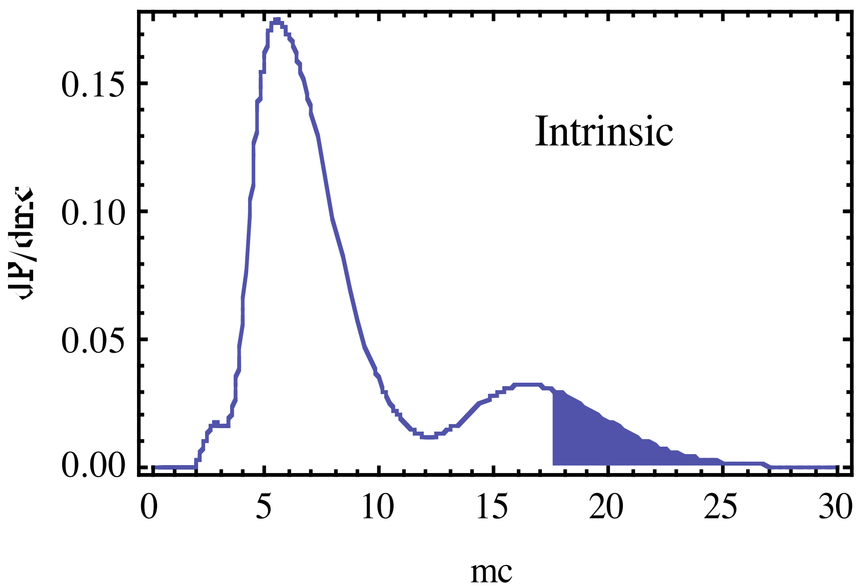


Voss and Tauris 2003

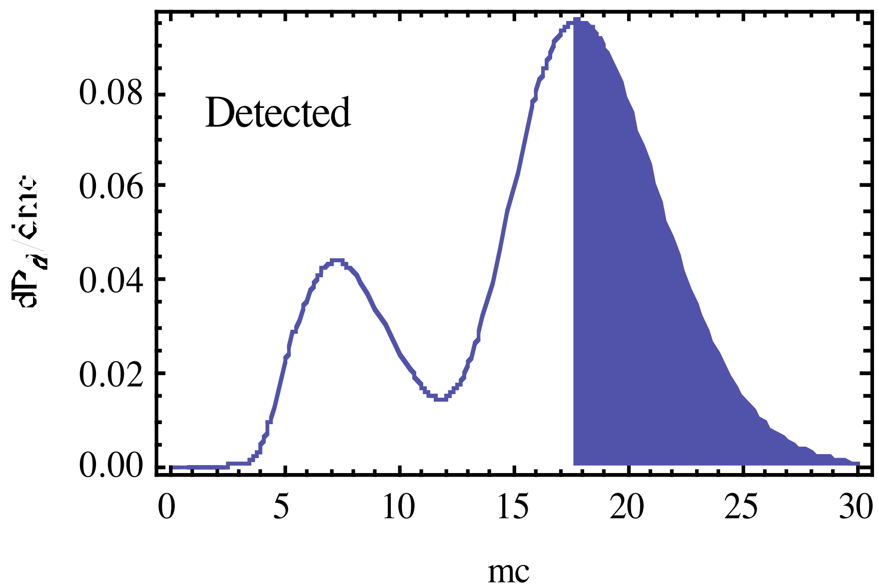
Why are BH-BH binaries tricky?

High masses: <u>one</u> random example (~100 merging BH-BH binaries)

Intrinsic



Detected



High mass: 10%

High mass: 50%

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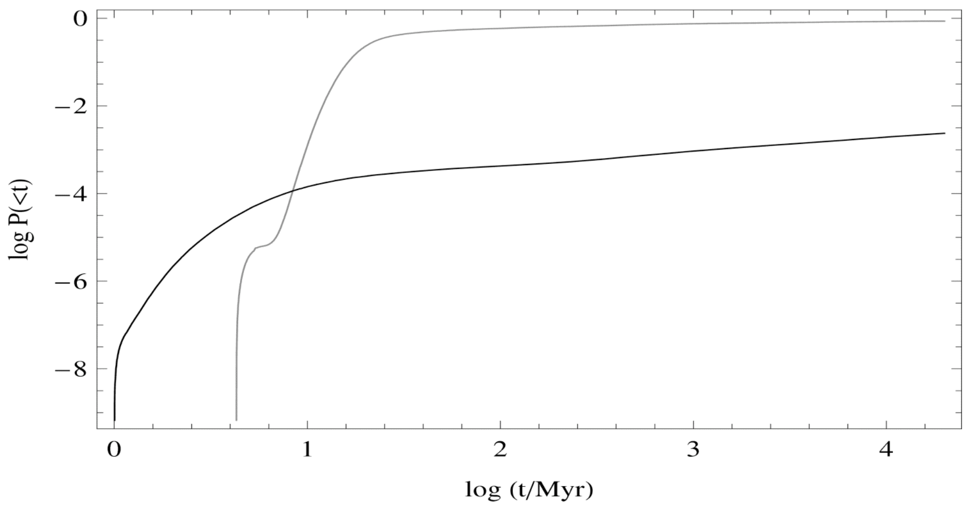
…**and**

strong variations when different assumptions used

Why are BH-BH binaries tricky?

Long delays: (same example model)



log [dP/d log (t)]

NS-NS : Gray

- 100x more from **short** delays (extremely short in example)

BH-BH : Black

- mostly from **long** delays (Gyr) (note *log* scale)

Implications:

- BH-BH mergers preferentially in old populations ("elliptical galaxies")
  - little/no blue light
- Old populations have significant fraction (~ 60%) of all mass

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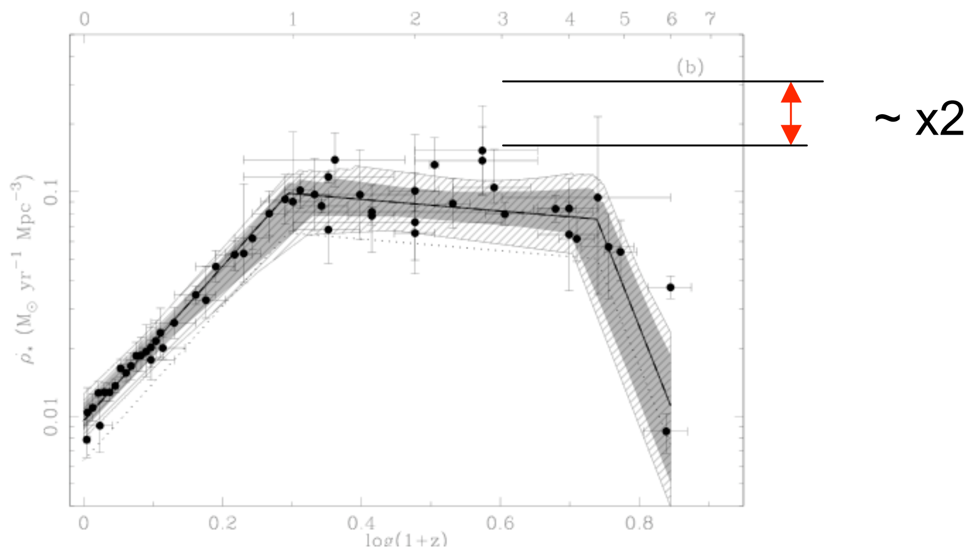
Other factors: Systematics

Binary fraction (rate down)

15-100%

Abt 1983; Duquennoy and Mayor 1991; Lada 2006

Star formation history: (up/down)



Hopkins & Beacom ApJ 651 142 2006 (astro-ph/0601463): Fig. 4

Implications:

- Must propagate systematic errors: O(few)
- Influences probability of high detection rates

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Previous results

Motivation:

O'Shaughnessy et al. astro-ph/0610076

- Explore dominant uncertainty: binary evolution
  - check for surprises
- Compare with several (4) observations of <u>pulsar</u> binaries <u>in Milky Way</u>(!)
- Interpret as constraints in *model* space (7-dimensional)

Key features

- Thousands of "short" simulations [O(100) NS-NS binaries]
- Computational tradeoff:

  Many models --> low accuracy for each

  Use **one chirp mass** for each type of binary for **every** model

- Dominant uncertainty propagated (binary evolution).

  Ignores several factors O(few)
  - Constant SFR assumed. Cosmological SFR not included.
  - All star form in binaries
  - Range uses low-mass estimate
    independent of mass or mass ratio
    [+ based on fixed mass for each binary type]

$$D = D_{bns}(M_c/1.2M_\odot)^{5/6}$$

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Previous results

Expressions Used

K = one set of assumptions

Reliable MW estimate

Binary formation rate

Fraction which **can** merge

Merger rate:

$$R_K = \left.\frac{d\rho}{dt}\right._{\text{now,MW}} \lambda_K P_K(< 10\text{Gyr})$$

Mass distribution:

$$dP/dm_c = \delta(m_c - m_o)$$

Detection rate (preferred):

$$R_{D,K} = R_K \left[\frac{4\pi}{3} D_{\text{bns}}^3 \left(\frac{m_o}{1.2 M_\odot} \right)^{15/6} \right]$$

Fixed mass
(for each binary type)

Additional systematic errors: **G**

Sampling; fitting in 7d. Overall error (constant)

Detection rate PDF :

$$p(\log R_D) = \frac{1}{N} \sum_K G(\log R_D - \log R_{D,K})$$

Errors *could be* O(few) for LIGO

…+ observational constraints

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Today's results

O'Shaughnessy et al astro-ph/0706.4139
O'Shaughnessy et al (in prep)

Motivation

- LIGO detection rate, including BH-BH
- Propagate all uncertainties ~ O(x 1) effect on rates

Key features:

- Fewer [O(300)] larger [O(10^5) NS-NS binaries] simulations
  - 1d PDFs extracted: **mass** and **merger time**
  - Include sampling errors: $N_{simulations}$ and $N_{binaries}$
- Vary fraction of stars forming in binaries
- Convolve with star formation history of <u>universe</u>, not MW
  - **Estimated** uncertainty x 2

Preliminary

- Only *one* constraint applied: reproducing Milky Way merger rate
  - Bayesian constraints incorporate above uncertainties
- Simple range model…

  but propagate O(10%) "errors"

  for neglected params

$$D = D_{bns}(M_c/1.2M_\odot)^{5/6}$$

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Today's results

Expressions Used

Merger rate:

$$R_K(t) = \int_{-T}^{0} d\tau \frac{d\rho}{d\tau} \lambda_K \frac{dP_K}{d\tau}(t-\tau)$$

Detection rate:

$$R_{D,K} = R_K \left[\frac{4\pi}{3} D_{\rm bns}^3\right] \times \int dm_c \left(\frac{m_c}{1.2 M_\odot}\right)^{15/6} \frac{dP}{dm_c}$$

Additional systematic errors: $G_K(X)$

Kernel includes binary fraction, SFR, sampling (accuracy of dP/dt, dP/dm_c)

Propagates logarithmic errors.

Detection rate PDF :

$$p(\log R_D) = \frac{1}{N} \sum_K G(\log R_D - \log R_{D,K})$$

…+ observational constraints

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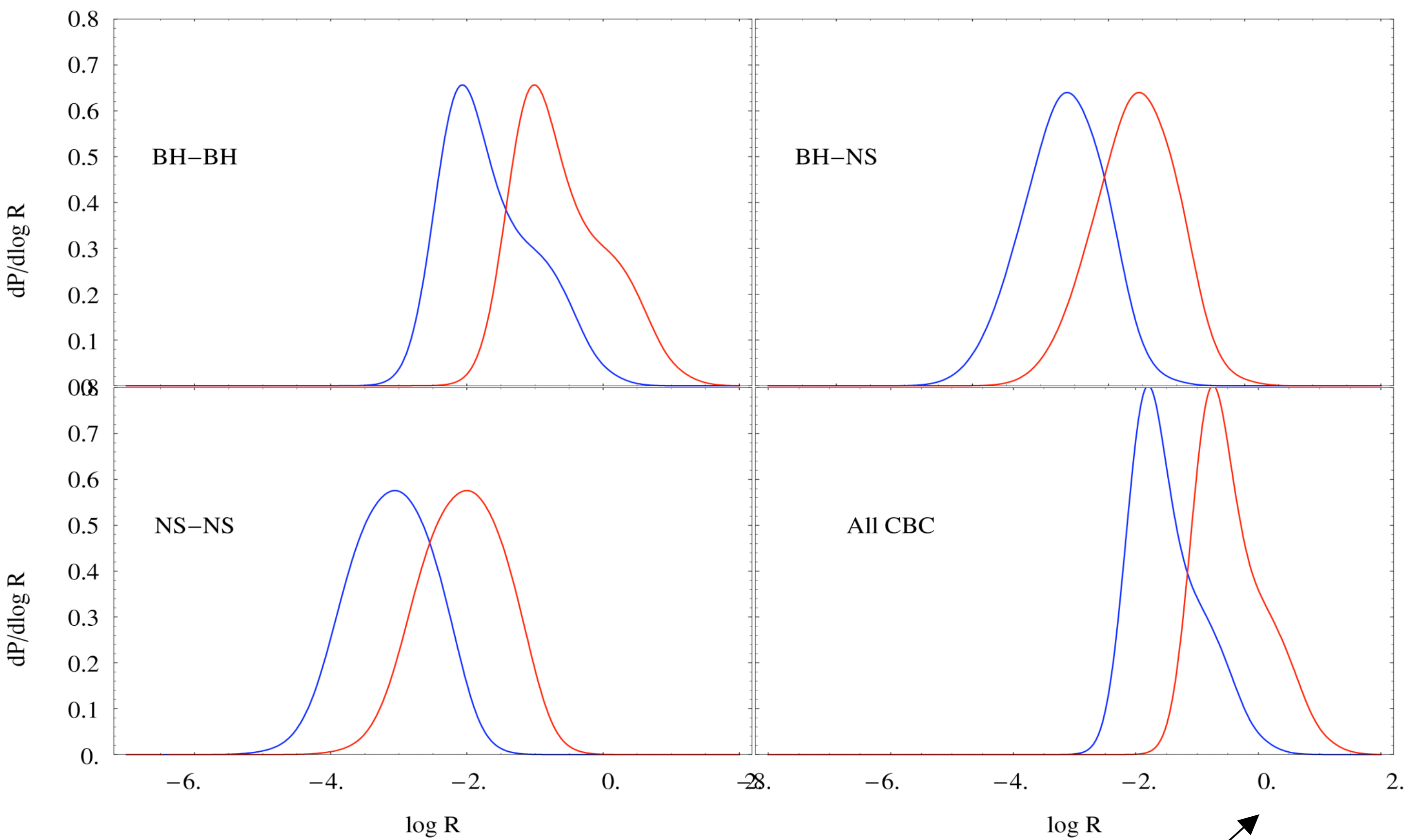
Results I: Rate PDFs



Key

Blue : D_{bns} =15 Mpc

Red : D_{bns} =27 Mpc

One detection/year

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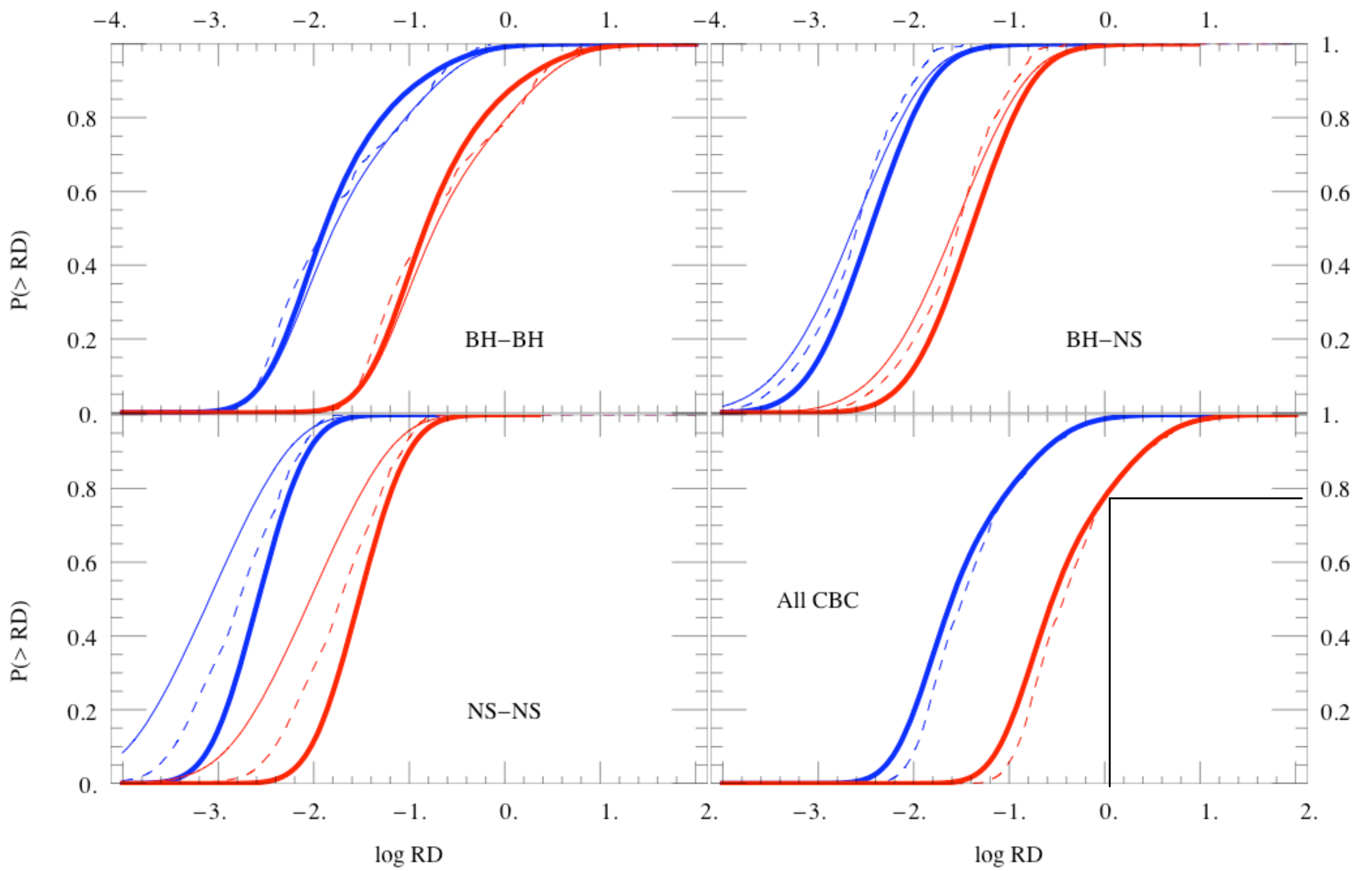
Results I: Rate Cumulative



Key

Blue : D_{bns} =15 Mpc

Red : D_{bns} =27 Mpc

Heavy : best
(errors+ constraints)

Dashed :
raw simulation data

Thin :
no PSR constraints

Significant fraction of models predict R_D>1/yr

Most have R_D>1/10 yr

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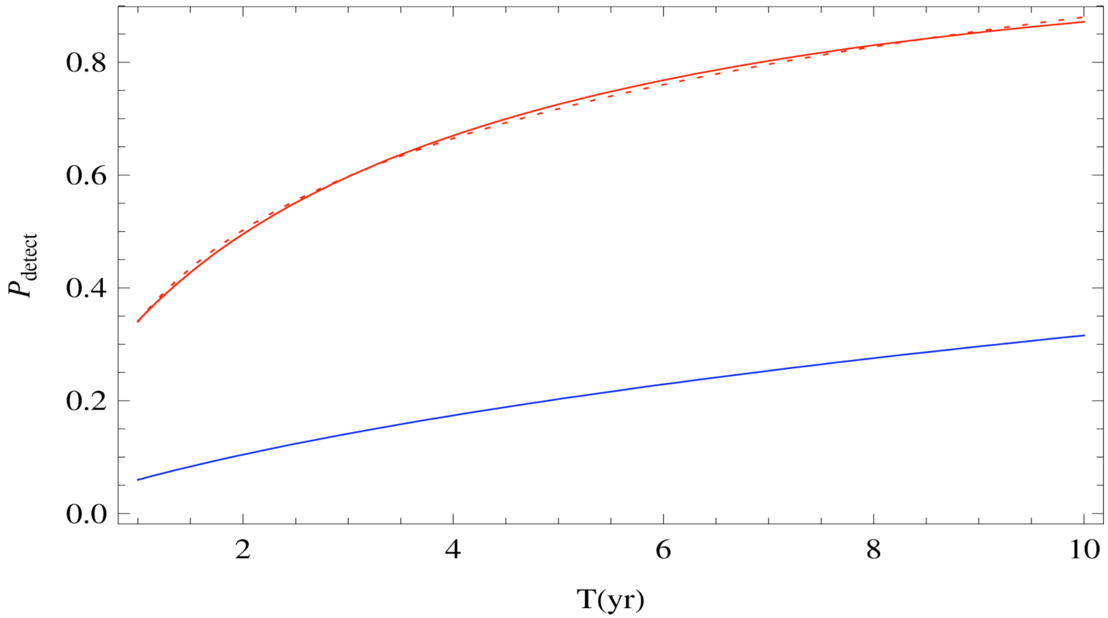
Results II: Detection probability

Probability of *something* being seen:

- Initial : Low (too few models to trust P ~5% ~O(1/100))
- Advanced: High (" 1-P <~ O(1/100))
- Enhanced :

$$P_{\rm detect} \cong 0.34 + 0.64 \log \frac{VT}{V_c {\rm yr}}$$



$$T = T_1 {\rm yr}$$

$$V_c = \frac{4\pi}{3}(27{\rm Mpc})^2$$

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…remember, binaries in globuar clusters not included !

Results III: Interpreting nondetection

Implications of upper limit:

- Few *high-rate* models implausible
- Many *low-rate* models unchanged
- Some *moderate-rate* models less plausible

…but not much information "overall" (P=67%)

Rate PDFs : almost unchanged

Physical impact:

Very high rate models become less plausible

These models have:

- elliptical galaxies with many BH-BH mergers
- low CE efficiency, which drives these mergers together

(this low CE efficiency is ~ ruled out in spiral galaxies due to PSRs)

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Summary and future directions

- Present detctors: SFR uncertainty

  High SFR permits highest *a priori* rates

- Advanced detectors: Guarantee detection?

  Find how few models *wouldn't* lead to detections

  Add large-z effects (beampattern, NR-accurate range)

- Clusters: Already constrained

… future estimates should involve output from GW detectors!

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