Predictions for Detectable Coalescences of Compact Binaries Including Black Holes

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Today's Goal

To know that we know what we know, and that we do not know what we do not know, that is true knowledge.

Henry David Thoreau

There are known knowns. There are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don't know. But there are also unknown unknowns. There are things we do not know we don't know.

Donald Rumsfeld

Goal: CBCs with Black Holes $\longrightarrow$ Known Unknowns

Outline

- Mechanisms of formation and rate predictions
  - » Population synthesis models for isolated binaries
  - » Dynamical formation scenarios
- Expected characteristics of binaries
  - » Masses
  - » Spins
- The future
  - » Why do we need astrophysics to inform GW searches?
  - » How can GW searches teach us about astrophysics?

Rates predictions

- All astrophysical rates estimates depend on limited observations and/or models with many ill-understood parameters, and are still significantly uncertain at present
- Ground-based interferometric detectors (LIGO, Virgo, GEO 600, AIGO, LCGT) are sensitive @ tens/hundreds Hz: ideal for detecting NS-NS, NS-BH, BH-BH binaries
- Coalescence rate predictions from:
  - simulations of isolated binary evolution
  - dynamical-formation models
  - intermediate-mass-black holes ?
- Instrument sensitivity and conversion to detection rates

Population synthesis models

- No observed NS-BH or BH-BH binaries
- Predictions based on population-synthesis models for isolated binary evolution with StarTrack [Belczynski et al., 2005, astro-ph/0511811] or similar codes
- Thirty poorly constrained parameters
- [O’Shaughnessy et al., 2005 ApJ 633 1076, 2008 ApJ 672 479] vary seven most important parameters:

1. power-law index in binary mass ratio

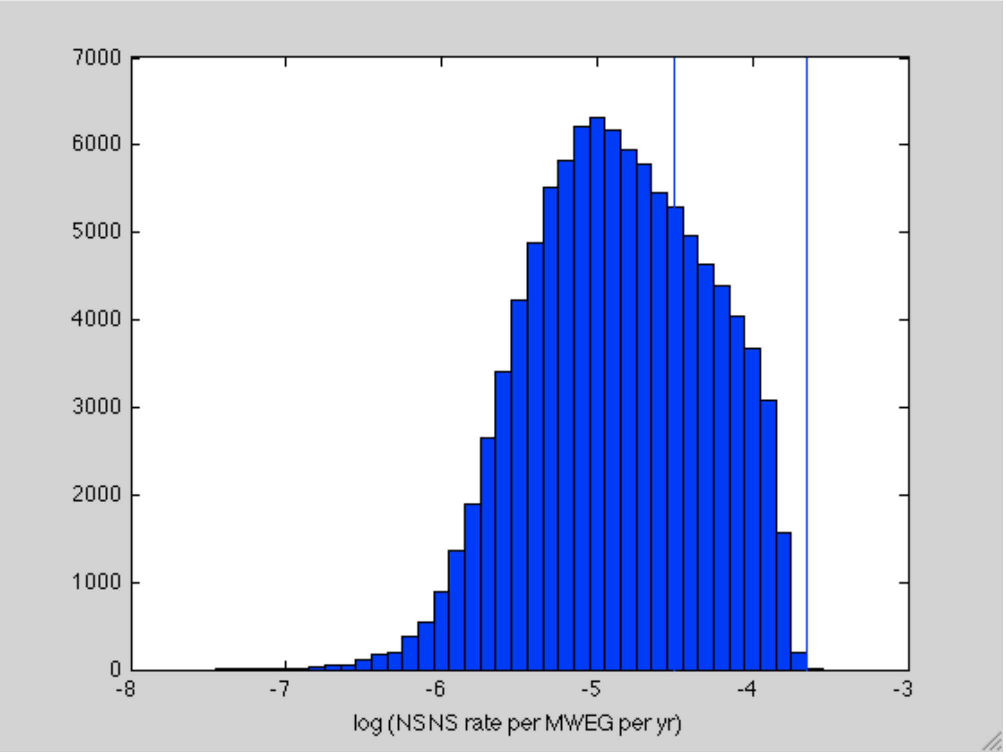
2, 3, 4. supernovae kicks described by two independent Maxwellians and their relative contribution

5. strength of massive stellar wind

6. common-envelope efficiency

7. fractional mass-loss during nonconservative mass transfer

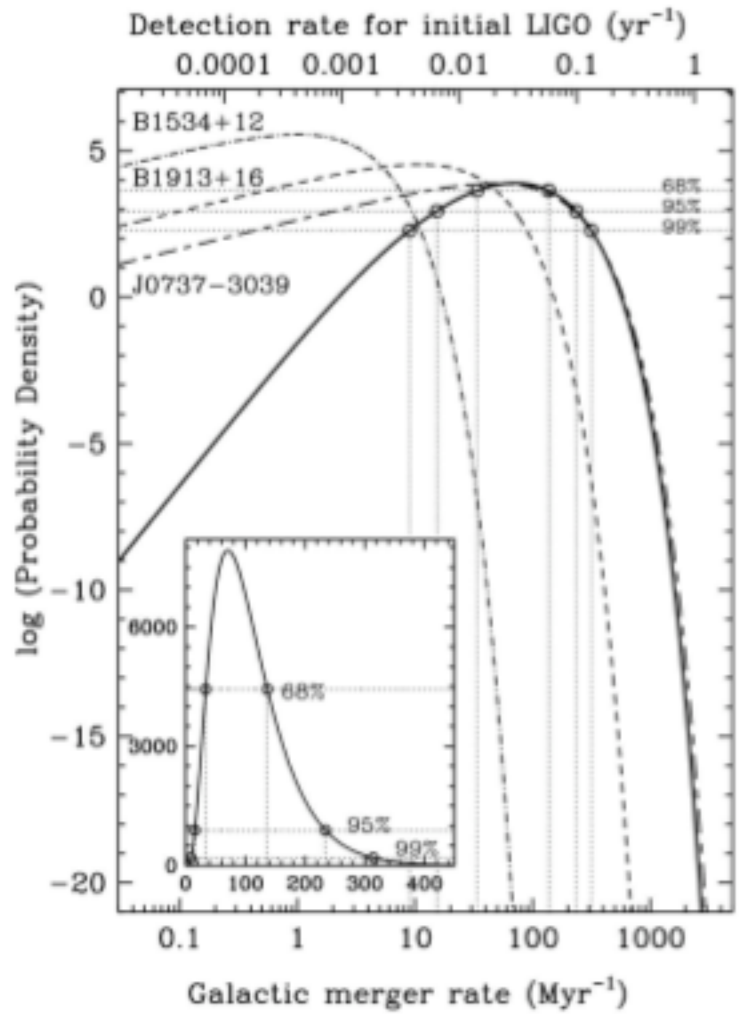
Constraining models



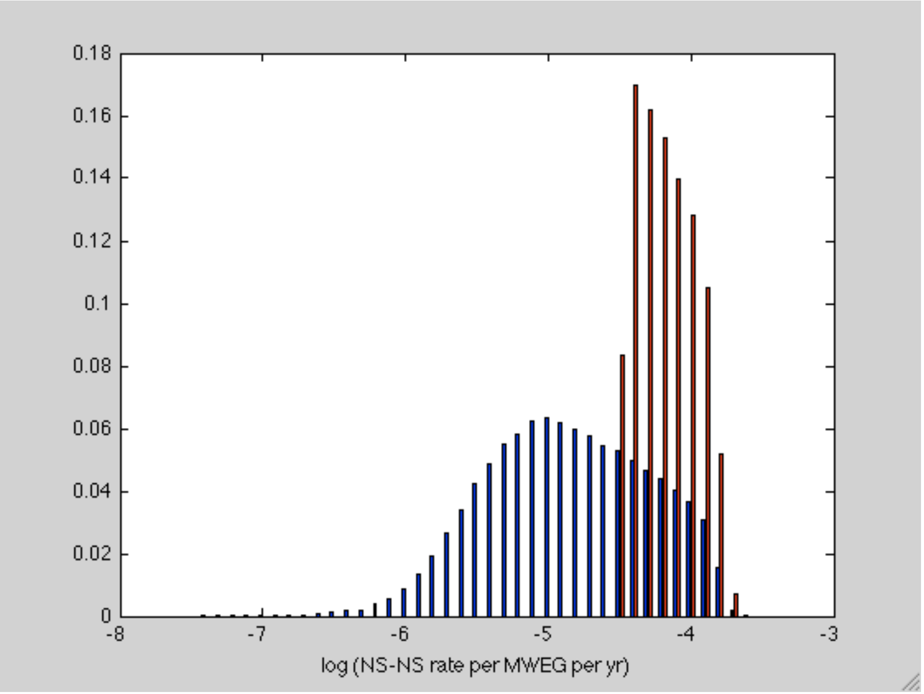
- Add constraints from observations; binary pulsars: NS-NS, NS-WD, supernovae, etc.
- Average over models that satisfy constraints

Constraints from BNS observations

- Best NS-NS merger-rate estimates come from observed Galactic binary pulsars
- Small-number statistics (~8 total, ~4 merging in 15 Gyr)
- Selection effects (pulsar luminosity distribution)
- [Kim et al., 2003 ApJ 584 985, 2006 astro-ph/0608280; Kalogera et al., 2004, ApJ 601 L179]

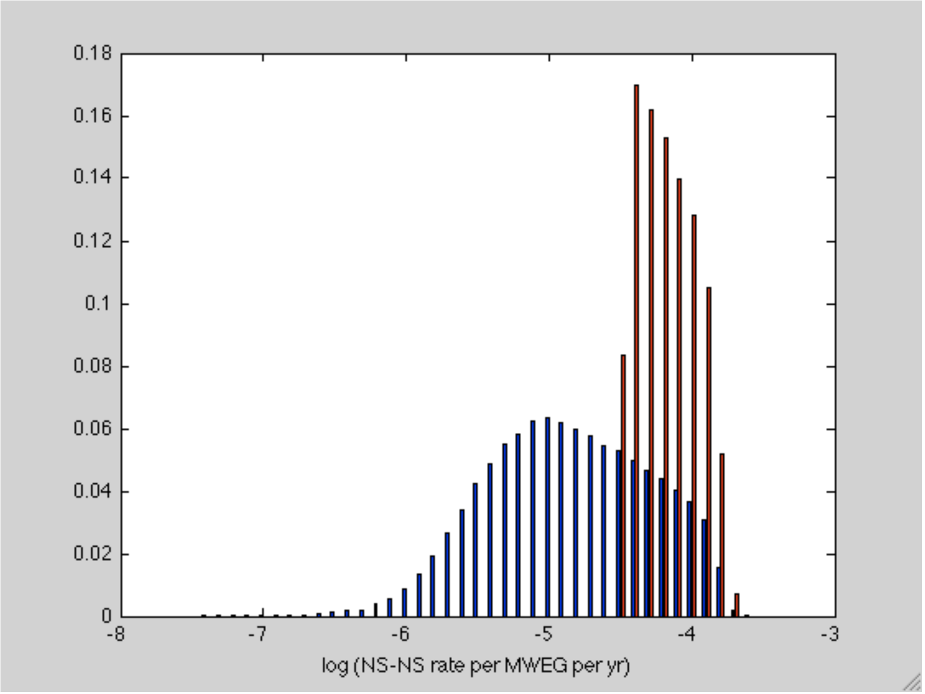


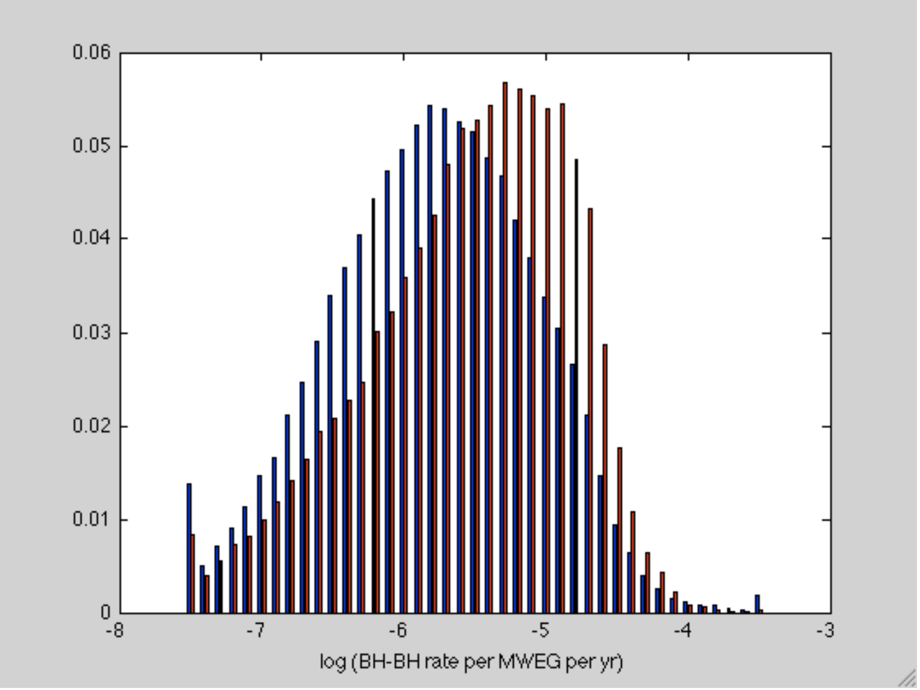
Effect of adding constraints, 1



Single constraint satisfaction - no accounting for sampling uncertainties or model fitting errors

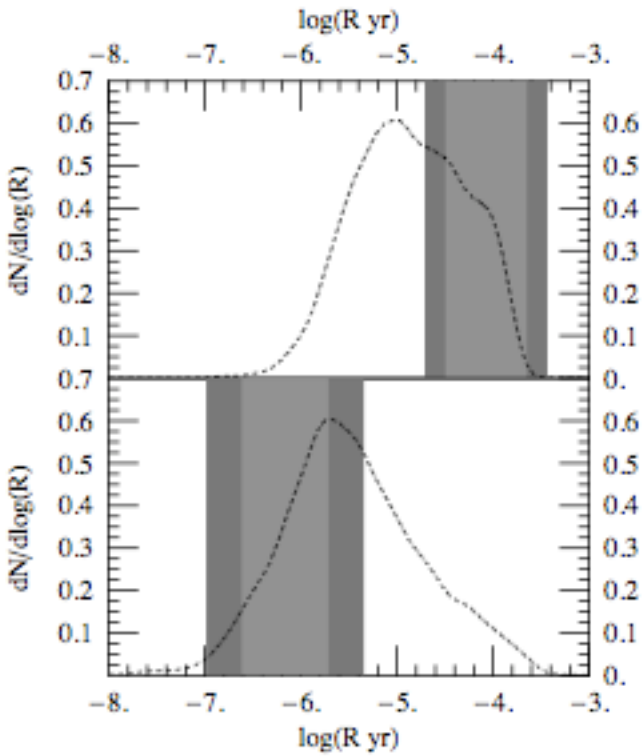
Effect of adding constraints, 1

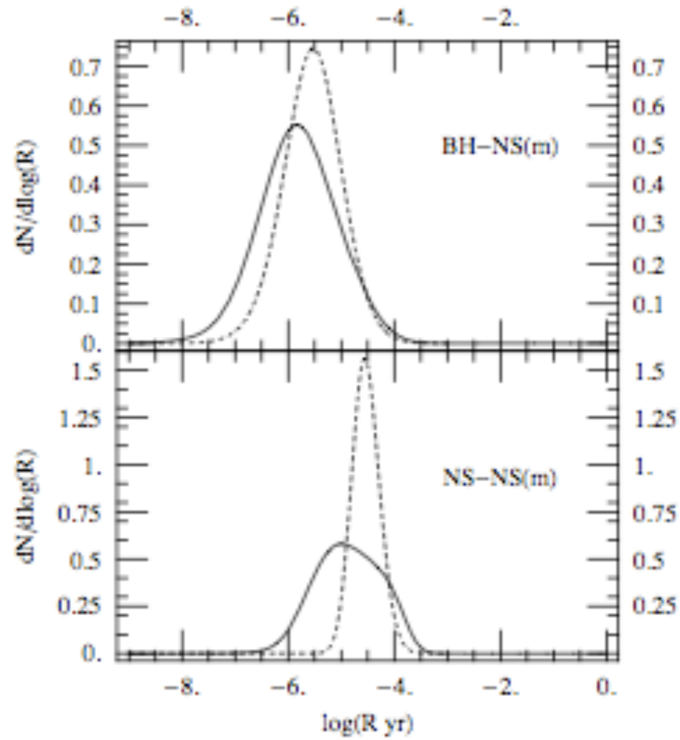




Single constraint satisfaction - no accounting for sampling uncertainties or model fitting errors

Effect of adding constraints, 2





Constraints from observed binary pulsars

BH-NS and NS-NS rate/MWEG predictions

[O'Shaughnessy et al., 2008, ApJ 672 479]

Rates per Galaxy

Source	R_{low}	R_{re}	R_{pl}
NS-NS (L_{10}^{-1} Myr^{-1})	0.6	50	500
NS-BH (L_{10}^{-1} Myr^{-1})	0.03	2	60
BH-BH (L_{10}^{-1} Myr^{-1})	0.006	0.2	20

- In simplest models, coalescence rates are proportional to stellar-birth rates in nearby spiral galaxies, so we quote rates in units of L_{10} (blue-light luminosity of 10^{10} Suns)
- However, this does not properly account for delay of coalescence relative to star formation (esp. elliptical galaxies)

LIGO sensitivity

[Kopparapu et al., 2008 ApJ 675 1459]

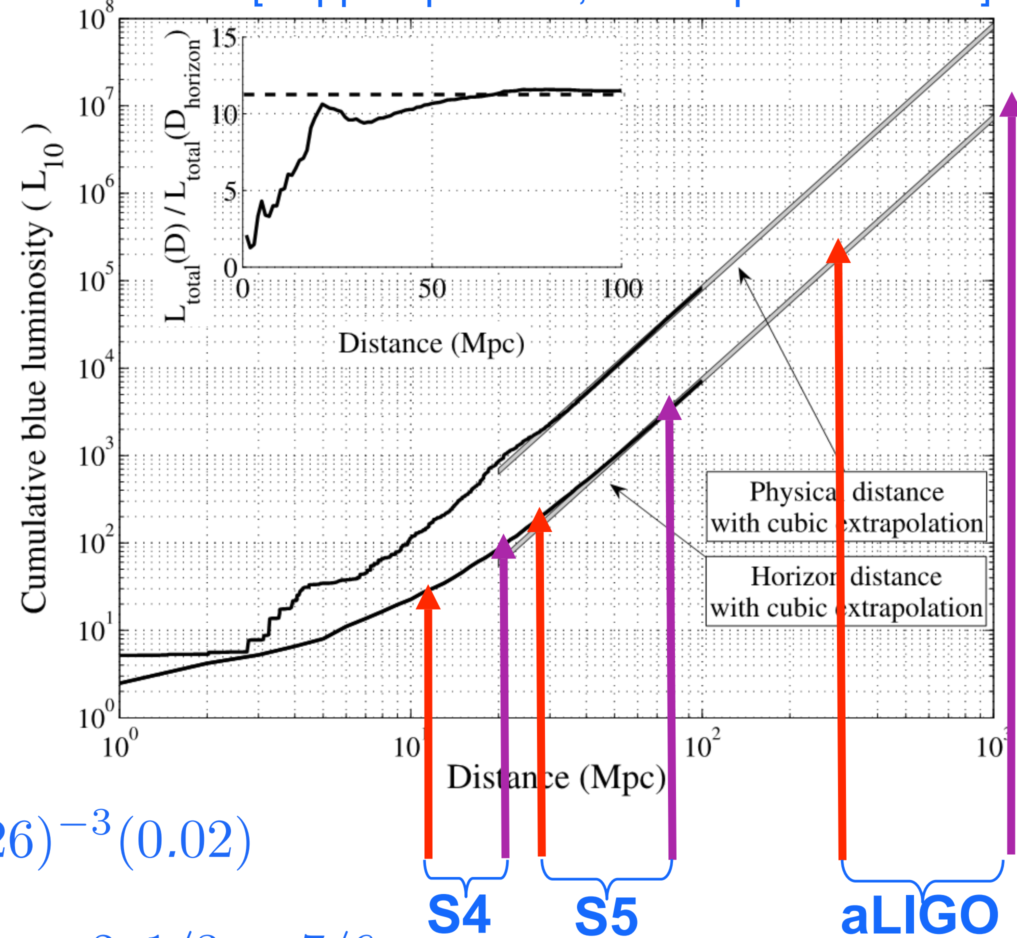
$$\dot{N} = R \times N_G$$

(merger rate) =
(merger rate per L10) *
(Ng in L10's)

$$\rho \equiv \sqrt{4 \int_0^{f_{\rm ISCO}} \frac{|\tilde{h}(f)|^2}{S_n(f)} df}$$

$$\rho(D_{\rm horizon}) \equiv 8$$

1/2.26 -- sky and orientation averaging; 0.02 L_{10} per Mpc^3



$$N_G\ (\mathrm{L}_{10}) = \frac{4}{3}\pi \left(\frac{D_{\rm horizon}}{\rm Mpc}\right)^3 (2.26)^{-3}(0.02)$$

$$|\tilde{h}(f)| = 2/D * (5\mu/96)^{1/2}(M/\pi^2)^{1/3} f^{-7/6}$$

Detection Rates

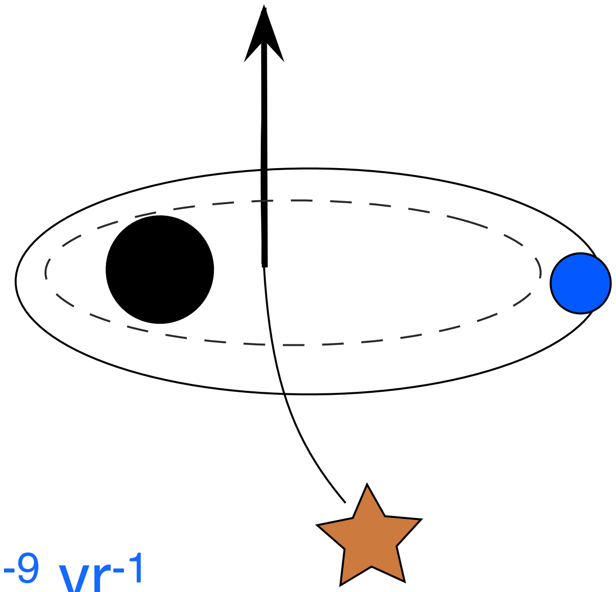
IFO	Source	$\dot{N}_{\mathrm{low}}$ yr^{-1}	$\dot{N}_{\mathrm{re}}$ yr^{-1}	$\dot{N}_{\mathrm{pl}}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2
	NS-BH	9×10^{-5}	0.006	0.2
	BH-BH	2×10^{-4}	0.009	0.7
Advanced	NS-NS	0.4	40	400
	NS-BH	0.2	10	300
	BH-BH	0.5	20	1000

Dynamical Formation

- BH-BH mergers in dense black-hole subclusters of globular clusters
  - » [O'Leary, O'Shaughnessy, Rasio, 2007 PRD 76 061504]
  - » Predicted rates 10^{-4} to 1 per Mpc^3 per Myr
  - » Plausible optimistic values could yield 0.5 events/year for Initial LIGO
- BH-BH scattering in galactic nuclei with a density cusp caused by a massive black hole (MBH)
  - » [O'Leary, Kocsis, Loeb, 2009 arXiv:0807.2638]
  - » Based on a number of optimistic assumptions
  - » Predicted detection rates of 1 to 1000 per year for Advanced LIGO
- BH-BH mergers in nuclei of small galaxies without an MBH
  - » [Miller and Lauburg, 2009 ApJ 692 917]
  - » Predicted rates of a few X 0.1 per Myr per galaxy
  - » Tens of detections per year with Advanced LIGO

Inspirals into IMBHs

- Intermediate-mass-ratio inspirals of compact objects (1.4 solar-mass NSs or 10 solar-mass BHs) into intermediate-mass black holes in globular clusters
- Dominant mechanism:
  IMBH swaps into binaries,
  3-body interactions tighten
  IMBH-CO binary, merger
  via GW radiation reaction
  [IM et al., 2008 ApJ 681 1431]

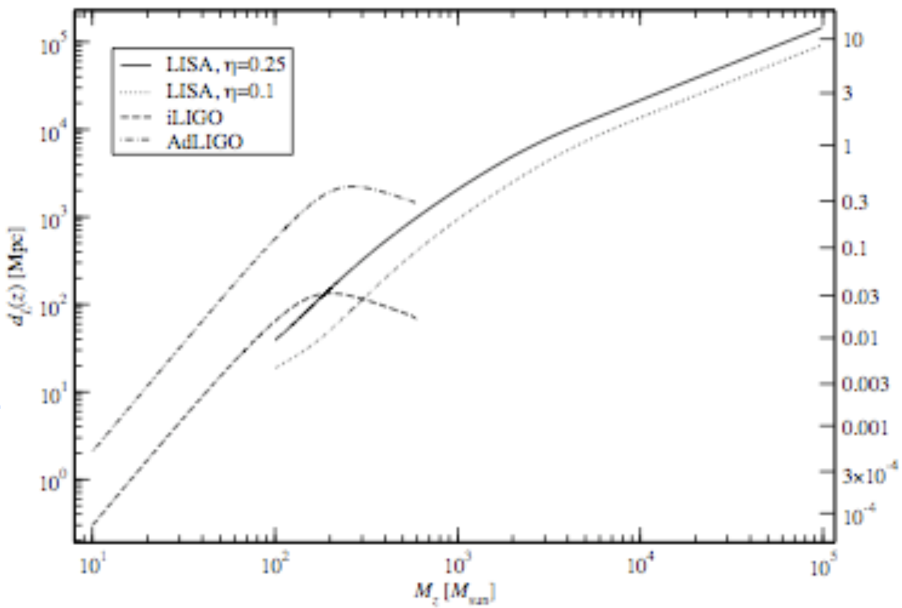


- Rate per globular cluster: few x 10^{-9} yr^{-1}
- Predicted Advanced LIGO event rates between 1/few years and ~30/year

Inspirals of two IMBHs

- Two very massive stars could form in globular clusters with sufficient binary fraction, then grow through run-away collision to form two IMBHs in same GC

- Rates of order 1/year are possible for Advanced LIGO [Fregeau et al., 2006 ApJ 646 L135]
- IMBH binaries could also form when two GCs merge [Amaro-Seoane and Freitag, 2006, ApJ 653 L53]



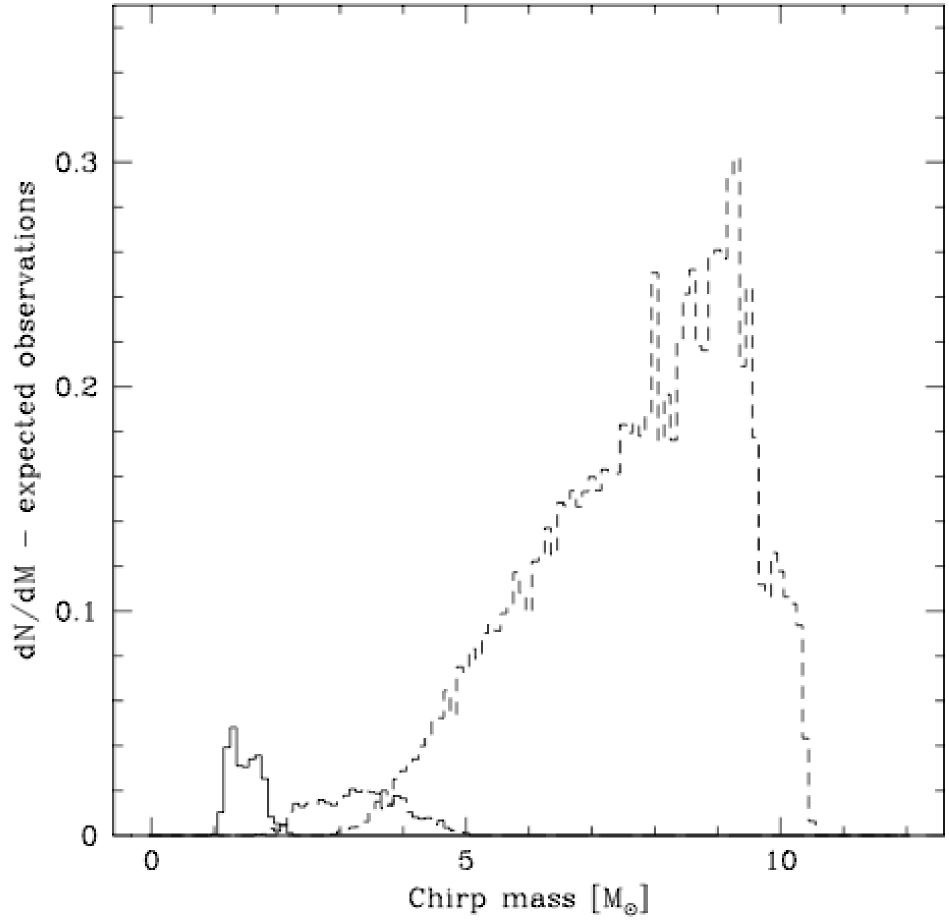
Binary characteristics: masses, 1

- Masses of BHs in binaries
  - ~40 black-hole X-ray binaries known, masses of ~20 measured by observing companion dynamics [Remillard and McClintock 2006 ARAA 44:49; Orosz et al., 2007 Nature]
  - BH masses vary between ~4 and ~20 solar masses
  - Because of mass-transfer episodes involving common envelopes (see below), these are not necessarily reflective of BH-BH or BH-NS systems

- Masses predicted by population-synthesis codes
  - The mass ratio power-law parameter is currently unconstrained
  - Most cited constraints refer to chirp mass

Binary characteristics: masses, 2

- Chirp-mass predictions
  - Early predictions from [Bulik and Belczynski, 2003 ApJ 589 L37]
  - BH-BH chirp mass is typically in the [5,10] solar-mass range for most systems that merge in less than 10 Gyr [O'Shaughnessy, Kalogera, Belczynski, 2009, in prep.]
  - [O'Shaughnessy et al., 2005 ApJ 633 1076]: $\left\langle (\mathcal{M}_c)^{15/6} \right\rangle_{\mathrm{BH-BH}} = 111 M_\odot^{15/6}$
    $$\left\langle (\mathcal{M}_c)^{15/6} \right\rangle_{\mathrm{BH-NS}} = 5.8 M_\odot^{15/6}$$
  - [O'Shaughnessy et al., 2008 ApJ 672 479]: value for BH-NS ~doubled

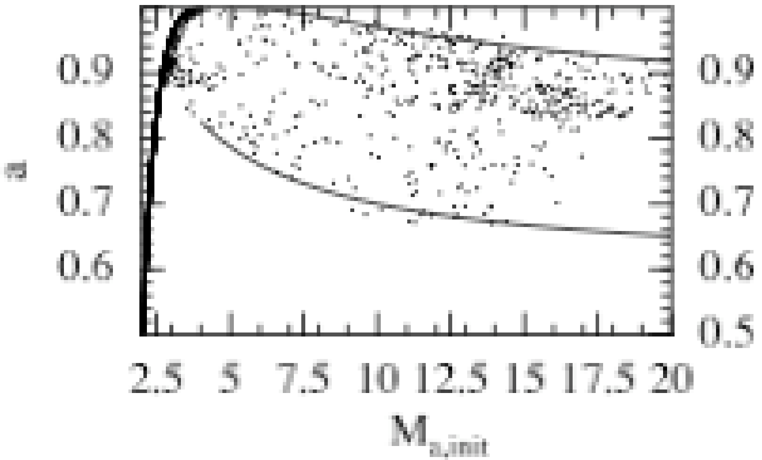


Binary characteristics: spins, 1

- Extrapolations from NS spins
  - If formation mechanism for NSs and low-mass BHs is similar through direct collapse, BHs should be very slowly spinning: observed pulsar periods correspond to $a/M \sim 0.01$
  - If spin-up during accretion-induced collapse can be modeled by recycled pulsars, spins should still be low, $a/M \sim 0.01$
- Spins of BHs in X-ray binaries
  - Measurements through quasi-periodic oscillations [Torok et al. 2005] or continuum spectra of inner edge of disk [Narayan, McClintock, Shaffee, 2007] or iron-line profiles [Miller et al. 2004].
  - Significant fraction of BHs very rapidly spinning ($a/M > 0.7$), with some near maximum spin; but a few could have low spin ($a/M \sim 0.1$).
  - All potentially suffer from model-dependent assumptions
  - These spins could be enhanced by accretion - not relevant for birth spins in BH-BH or BH-NS binaries

Binary characteristics: spins, 2

- Population synthesis studies indicate that a majority of both BH-NS and BH-BH systems include a common-envelope phase with hypercritical accretion (highly super-Eddington, neutrino-cooled) [Kalogera, Belczynski, Kim, O'Shaughnessy, Willems, 2007]
- Hypercritical accretion poorly understood; [O'Shaughnessy, Kaplan, Kalogera, Belczynski, 2005] assumed maximal spin by giving all LSO angular momentum to BH

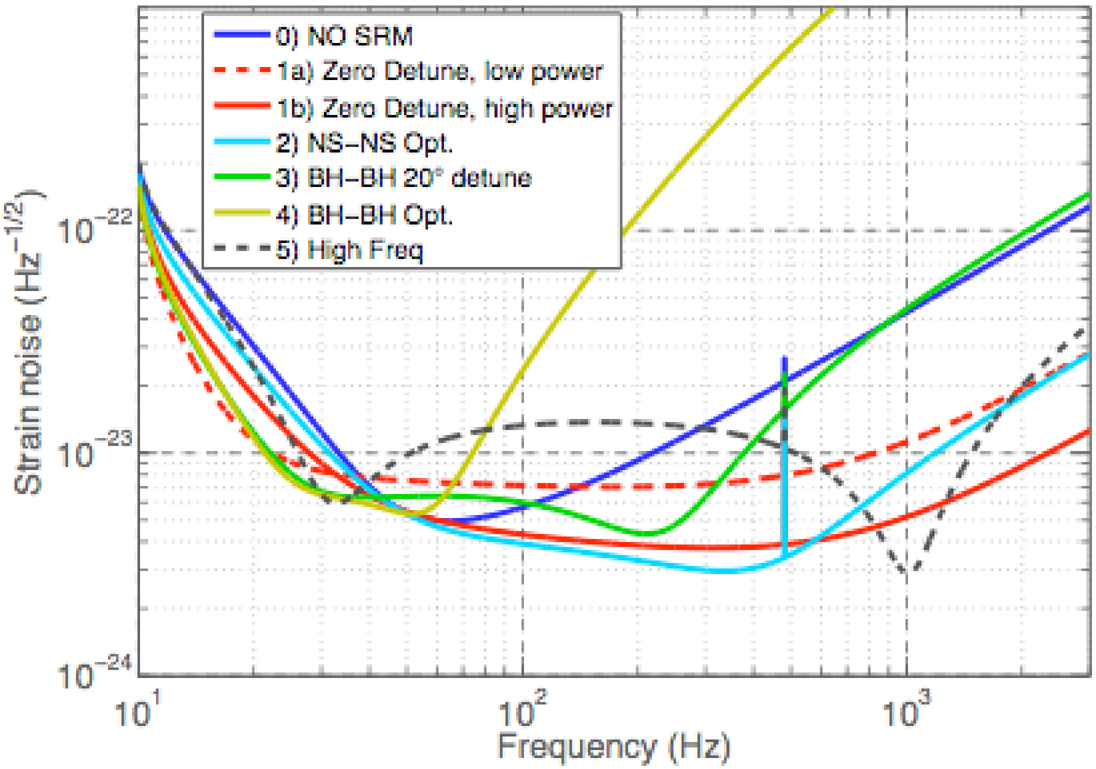


Future improvements to astro studies

- Better accounting for long delays between formation and mergers of BH-BH sources
  - » Elliptical galaxies with low present SFR / blue-light luminosity can contribute signficantly to CBC rates
  - » These may have flatter IMFs, different metallicities
  - » [O'Shaughnessy et al., 2009, in prep.]
- Larger population-synthesis runs based on improving models
- More sophisticated numerical simulations of dynamical formation scenarios
- Detailed studies of all input uncertainties
  - » Astro parameters, metallicity, SFR, detector sensitivity, etc.
  - » Partially explored in [O'Shaughnessy et al., 2009, arXiv:0812.0591]

Informing GW searches with Astro, 1

- Selecting IFO configuration based on astro predictions



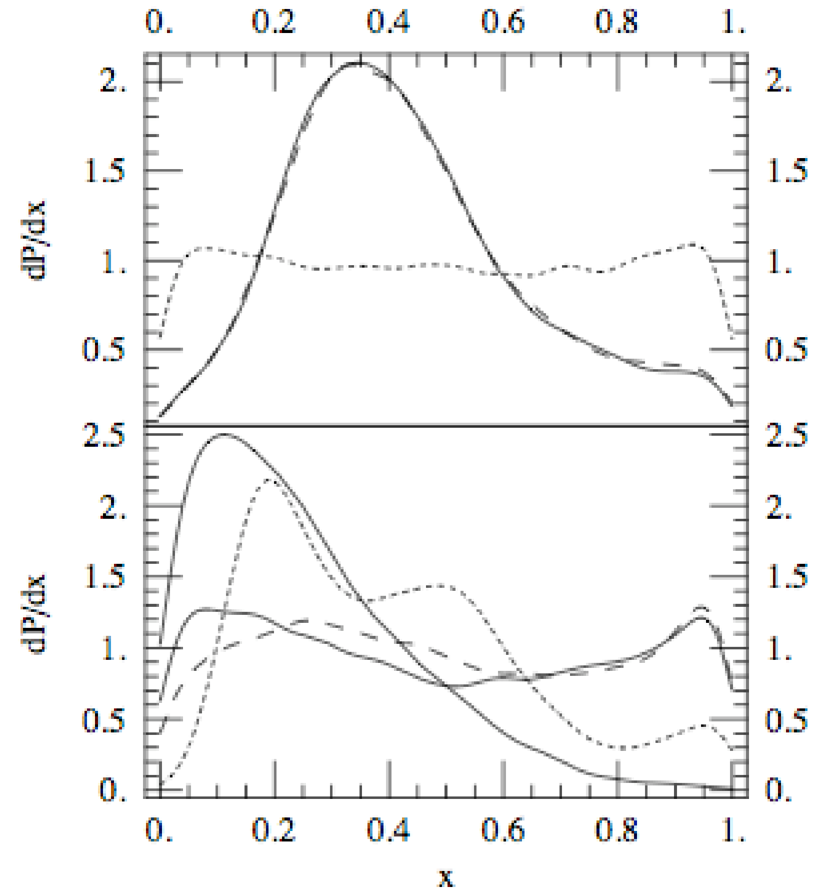
Public LIGO document T-070247

Informing GW searches with Astro, 2

- Rates predictions can help to determine which searches we should focus resources on
- Choice of waveform templates for detection:
  - » Example 1: Low chirp masses may make merger/ringdown waveforms unnecessary for most stellar-mass BH-BH mergers; however, searches with the full inspiral-merger-ringdown waveforms informed by numerical relativity will be necessary for GWs from IMBH sources (see talks by Chad, Ajith, Lucia, et al.)
  - » Example 2: Spin is important for accurate parameter estimation of BH-NS and BH-BH binaries (see talk by Vivien)
  - » Example 3: Could cut down on template number (and reduce FAR) for spinning BH-NS template banks since very massive BHs will be hard to spin up [Pan et al., 2004, PRD 69 104017]

Astrophysics with GW searches

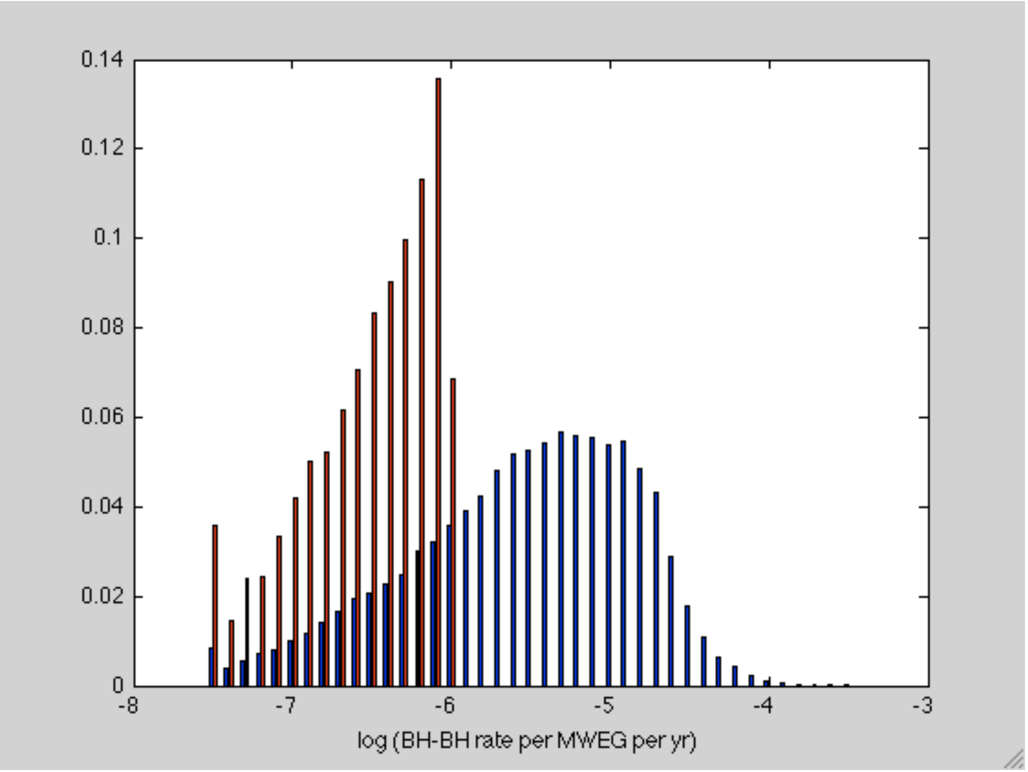
- Constraints on astrophysical parameters from existing electromagnetic observations [O'Shaughnessy et al., 2008 ApJ 672 479]:
- Observed GW event rates can be compared with models to determine important astrophysical parameters;
- Could match measured mass distributions, etc. to models (requires accurate parameter determination)
- As detector sensitivity improves, even upper limits can be useful in constraining parameter space for birth kicks, common-envelope efficiency, winds, etc.



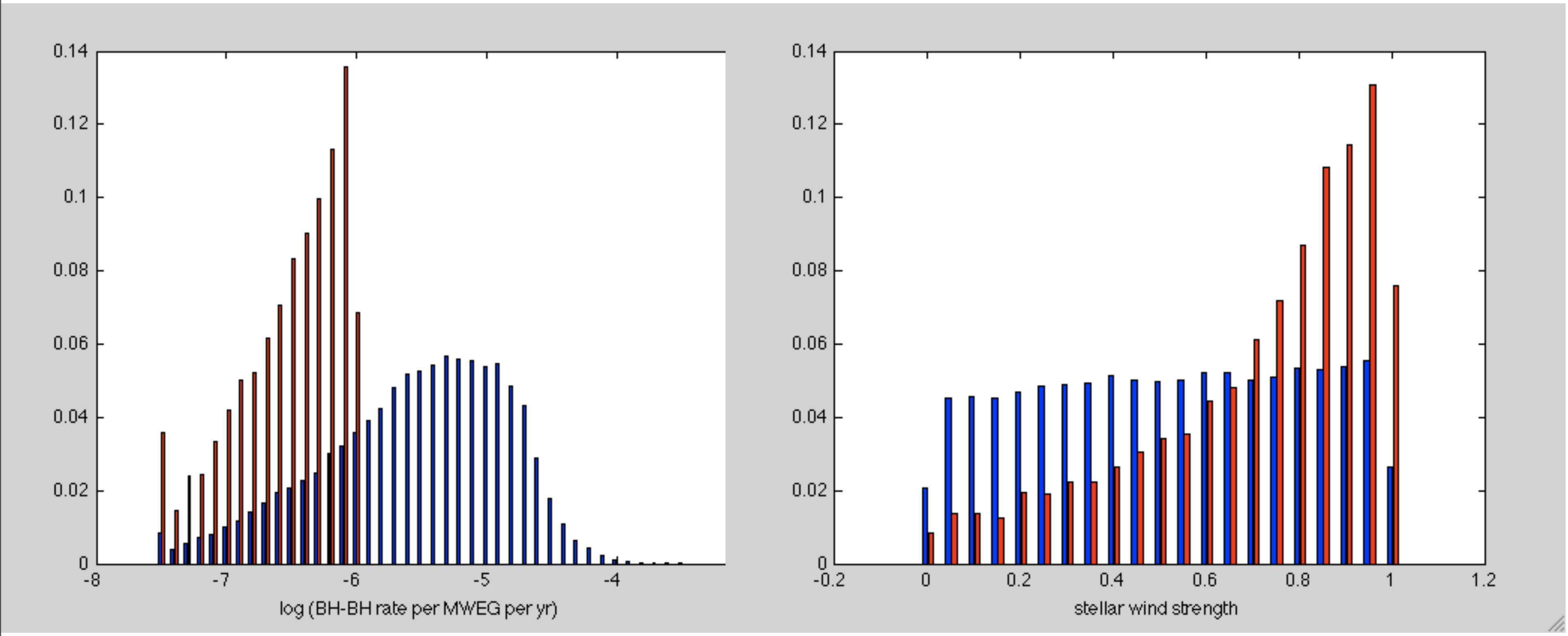
Rates to parameter constraints - theory

- Let f(R) be the measured rates distribution
- The constrained distribution of astrophysical parameters is given by Bayes Rule: $$p(\vec{\Theta}|f(R)) = \frac{p(f(R)|\vec{\Theta})p(\vec{\Theta})}{p(f(R))}$$
- For a given choice of model parameters, population synthesis codes coupled to information about galaxy distributions and detector sensitivity provide a distribution of the detectable event rate, $p(\hat{R}|\vec{\Theta})$
- If an actual rate R is measured, then the likelihood that the model with a given choice of parameters fits the measurement is $$\mathcal{L}(R|\vec{\Theta}) = e^{-\frac{|R-\hat{R}|^2}{2\sigma_R^2}}$$
- Then $p(f(R)|\vec{\Theta}) = \int d\hat{R}\mathcal{L}(R|\vec{\Theta})p(\hat{R}|\vec{\Theta})$

Constraints from upper limits - example



Constraints from upper limits - example



Conclusion

- Current understanding of coalescence rates and properties of compact binaries including black holes is imperfect
- Advanced LIGO is likely to see some NS-BH and BH-BH coalescences; tens or more coalescences may be seen according to some models, including dynamical formation
- Chirp masses for binaries formed via isolated evolution are likely ≤ 10 solar masses; rapid spins are possible
- Improved understanding of astrophysics can help GW search by informing detector configuration, template family
- GW detections and upper limits for systems with BHs will allow us to constrain the astrophysical parameters