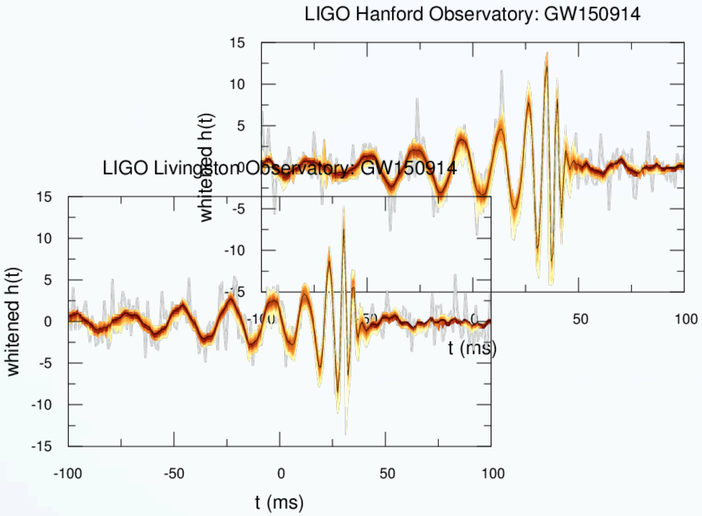
Mass Distribution **and Rates** of Binary Black Hole Mergers from LIGO Observations

Thomas Dent (AEI Hannover) for the LSC and Virgo
LIGO-G1601017v2

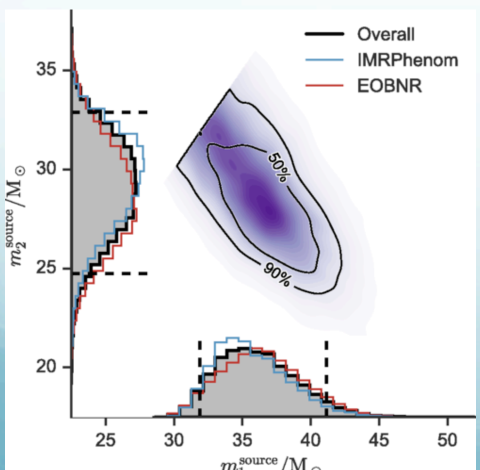
July 12th 2016, GR21 (Columbia U.)

Overview: rates and mass distributions

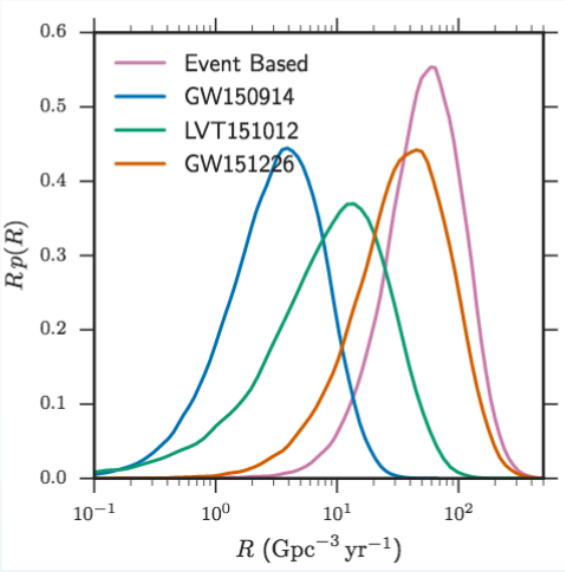
Detection



Parameter estimation

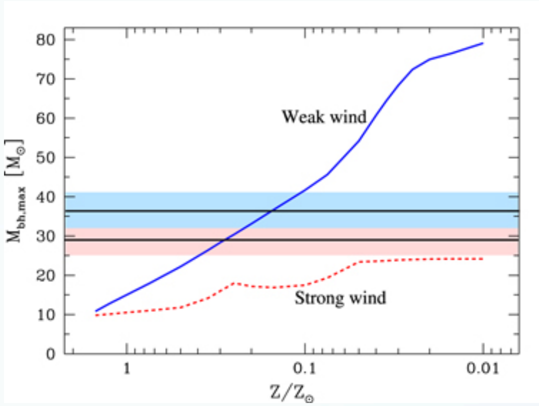


Merger rate



Mass distribution

Astrophysical interpretation



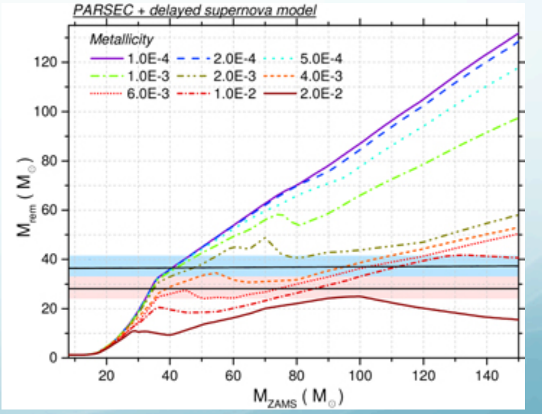
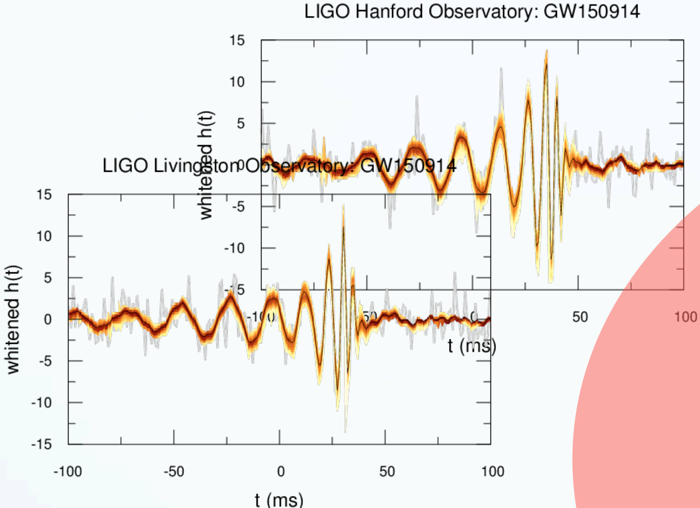


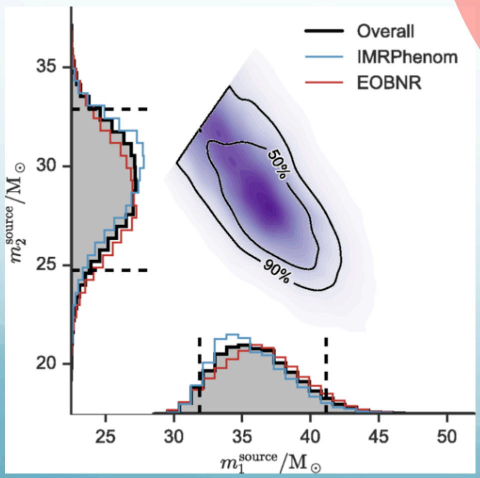
Image credits : LVC,
Belczynski et al. ApJ 2010, Spera et al. MNRAS 2015

Overview: rates and mass distributions

Detection

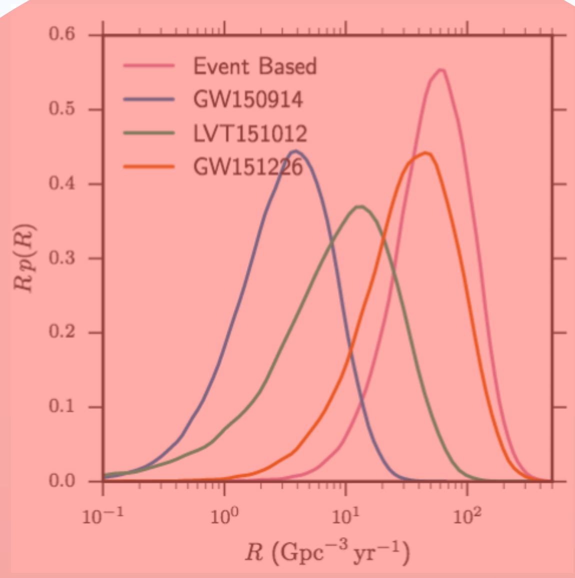


Parameter estimation



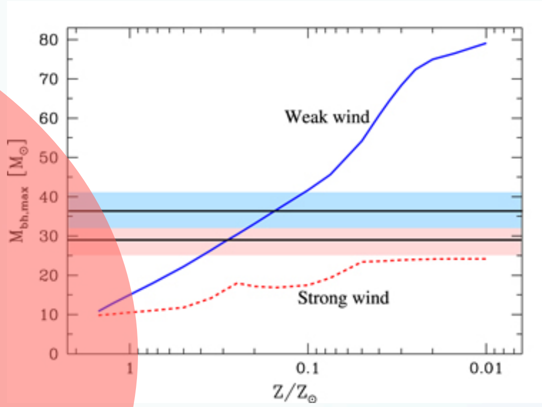
THIS TALK

Merger rate



Mass distribution

Astrophysical interpretation



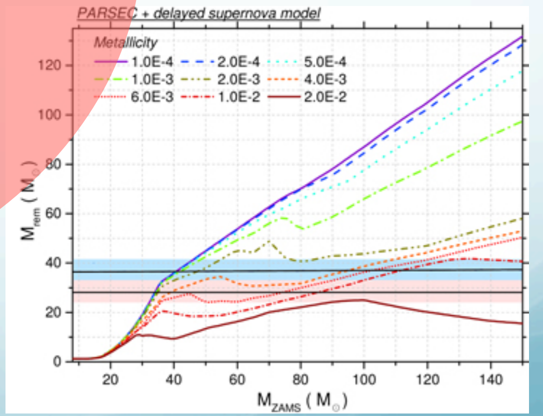


Image credits : LVC,
Belczynski et al. ApJ 2010, Spera et al. MNRAS 2015

Connecting LIGO detections with astrophysical predictions

- Astro models do not predict individual GW events
- Instead predict **populations** of events
- Describe via mean number of mergers, per (hyper)volume of space / time, per unit of component mass
  - mathematically : inhomogeneous Poisson process
- Compare specific models directly with data
- Or (this talk) constrain **simple, generalized models** of BBH merger population

From simple to complex models

- More model assumptions (simpler model)
  $\Leftrightarrow$ fewer free parameters
  $\Leftrightarrow$ fewer detections needed to constrain parameters
  $\Leftrightarrow$ smaller error bars for given data
  $\Leftrightarrow$ less realistic / accurate to true population
- Fewer model assumptions (more complex)
  $\Leftrightarrow$ more free parameters
  $\Leftrightarrow$ more detections needed to constrain parameters
  $\Leftrightarrow$ larger error bars for given data
  $\Leftrightarrow$ more realistic / accurate to true population

From simple to complex models

- More model assumptions (simpler model)
  $\Leftrightarrow$ fewer free parameters
  $\Leftrightarrow$ fewer detections needed to constrain parameters
  $\Leftrightarrow$ smaller error bars for given data
  $\Leftrightarrow$ less realistic / accurate to true population

WE ARE NOW HERE

- Fewer model assumptions (more complex)
  $\Leftrightarrow$ more free parameters
  $\Leftrightarrow$ more detections needed to constrain parameters
  $\Leftrightarrow$ larger error bars for given data
  $\Leftrightarrow$ more realistic / accurate to true population

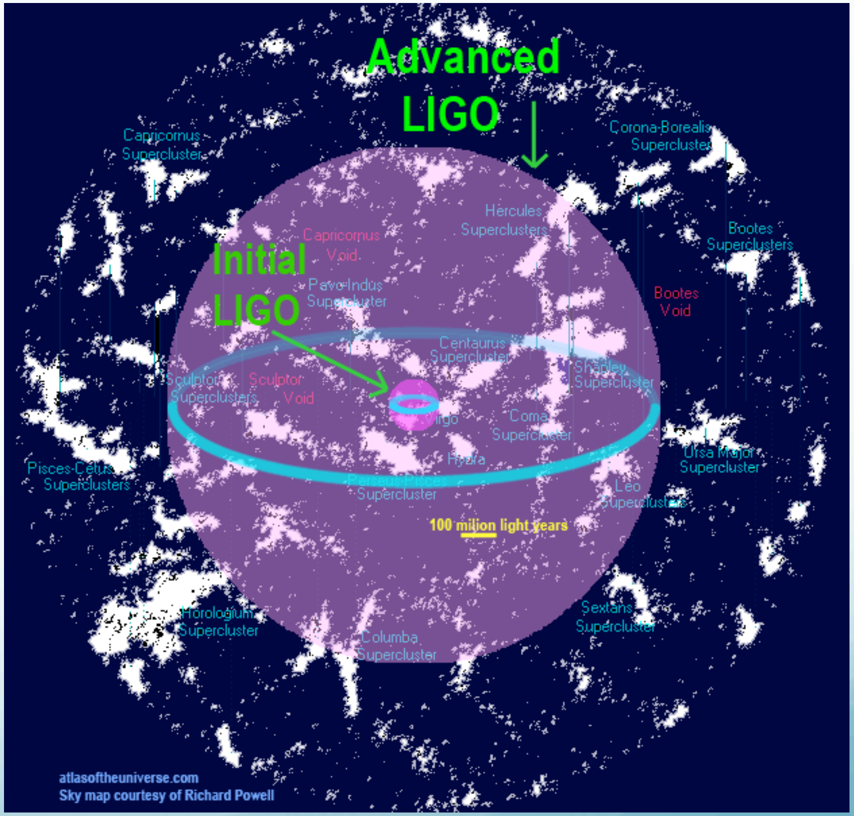
From simple to complex models

- More model assumptions (simpler model)
  - ⟺ fewer free parameters
  - ⟺ fewer detections needed to constrain parameters
  - ⟺ smaller error bars for given data
  - ⟺ less realistic / accurate to true population
- Fewer model assumptions (more complex)
  - ⟺ more free parameters
  - ⟺ more detections needed to constrain parameters
  - ⟺ larger error bars for given data
  - ⟺ more realistic / accurate to true population

WILL MOVE TO HERE (eventually)

Universal LV rates assumptions

- All current results assume constant rate of mergers
  - per unit comoving volume V_C
  - per unit source-frame time t_S
  - over local universe ($z <$ few × 0.1)
- Early Advanced LIGO reach 10^2 – few×10^3 Mpc for BBH
- Plausible that universe is statistically homogeneous on these scales

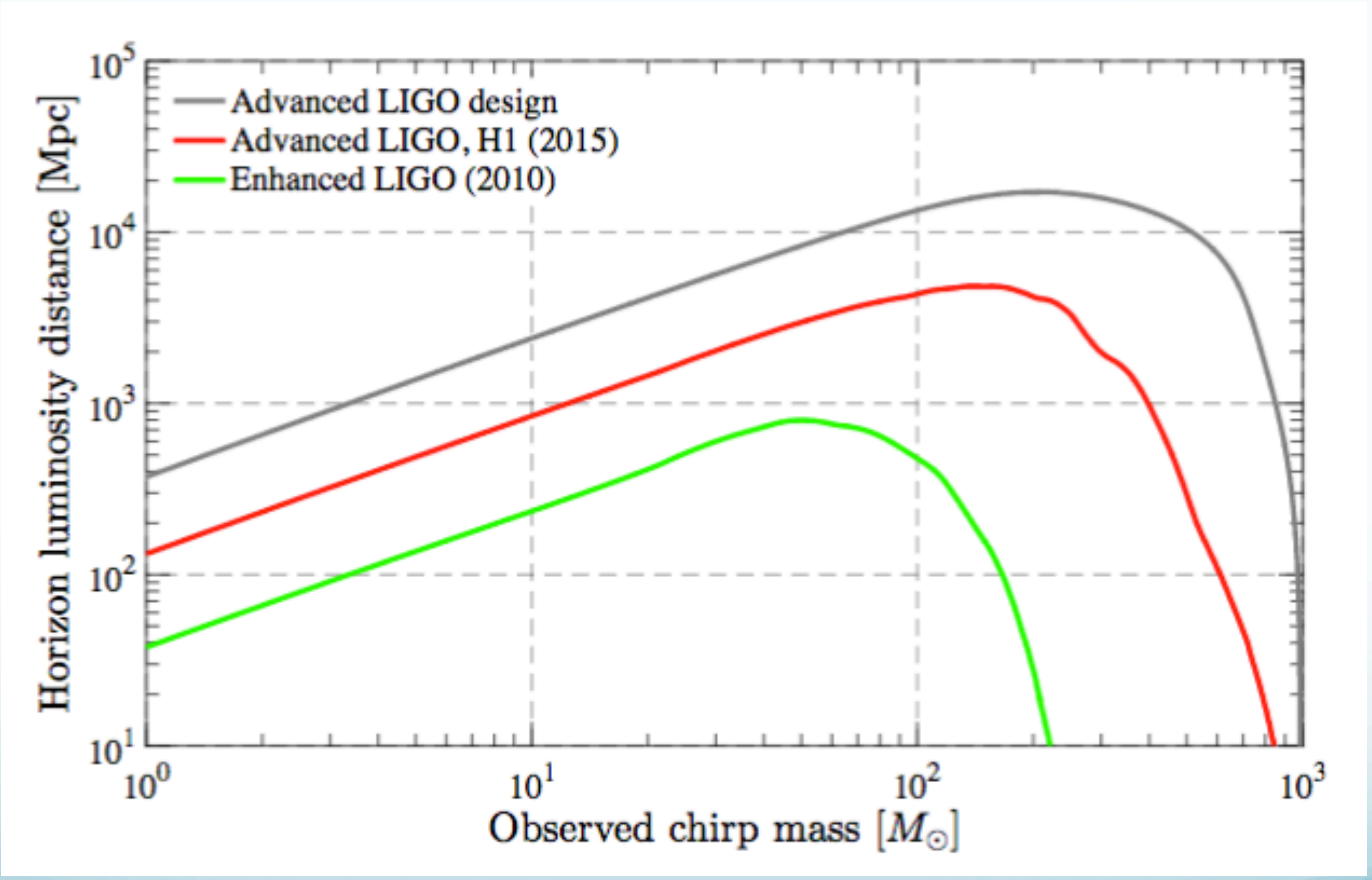


Basic rate calculation framework

- Set a threshold of signal strength (SNR)
- Count signals seen in data above threshold, N
- Simulate population model with total rate R /Gpc^3/yr, calculate number of signals $\langle N \rangle \equiv R \times VT$ *expected* in data
- Likelihood is Poisson($N | \langle N \rangle$) †
- Problem : VT measures sensitivity for population, **highly** dependent on mass distribution $dR/dm_1 dm_2$
  - Don't know much about mass distribution yet …

† Actual calculation is slightly more complex due to finite noise probability

Mass dependence of BBH horizon



arXiv:1604.00439

Rate estimates from straw-person mass distributions

3 different assumptions used to find *VT*

1. All BBH mergers in local Universe have same masses and spins as events seen so far

2. Uniform ('flat') distribution in log m_1, log m_2 [m_1,m_2 > 5 $M_\odot$, M < 100$M_\odot$]

3. Salpeter IMF-like power law $p(m_1) \propto m_1^{-2.35}$ uniform in $q \equiv m_2/m_1$

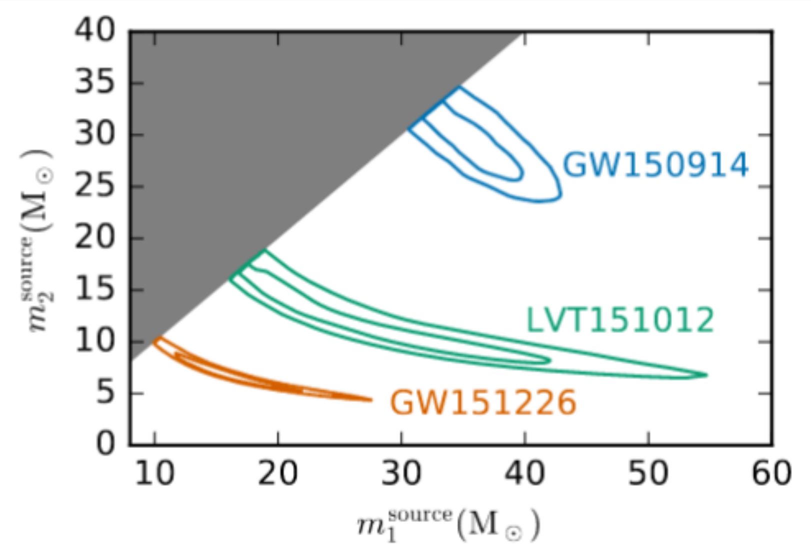
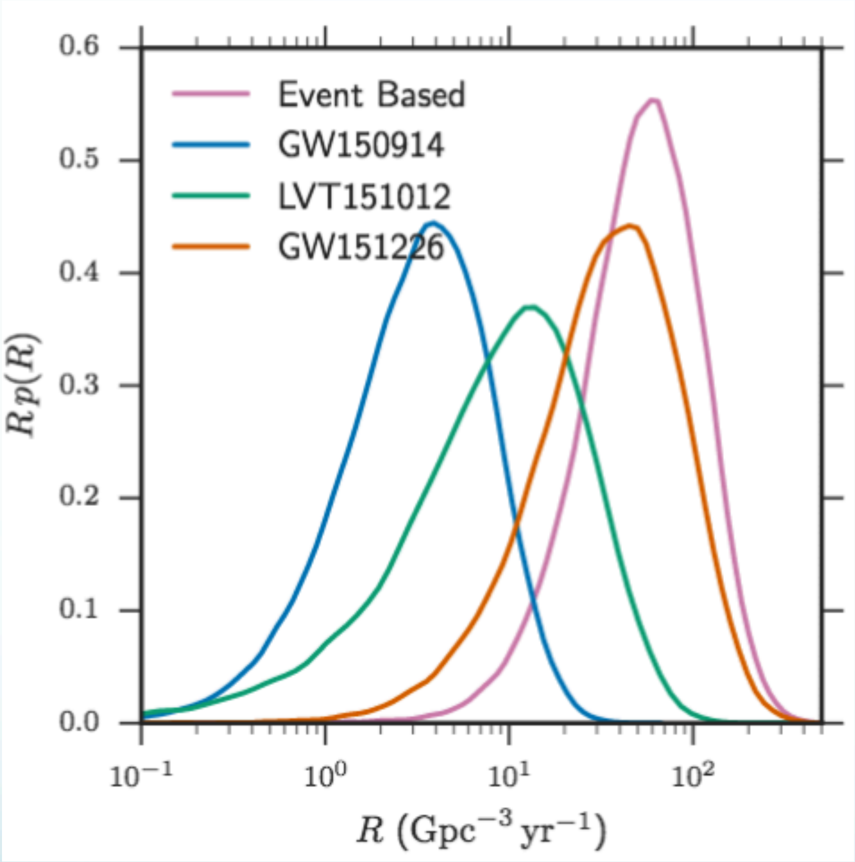
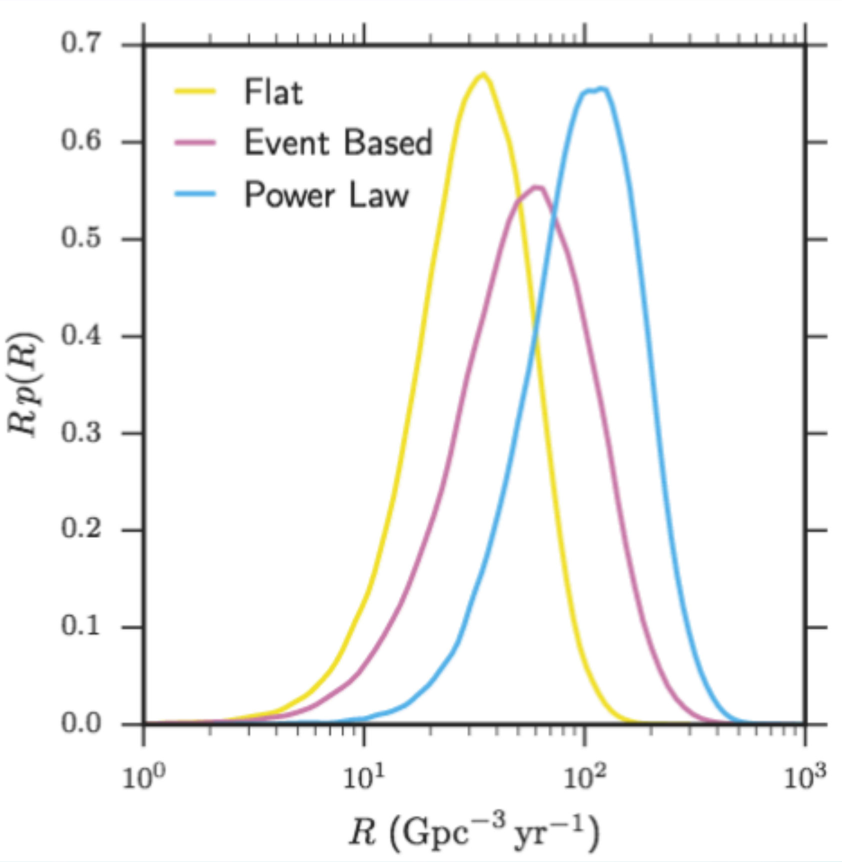


Image: LVC arXiv:1606.04856

LVC, arXiv:1602.03842

Rates from full O1 BBH search





- Total merger rate via addition of event-like rates
- Dominated by **lightest** BBH

- Event-like estimate bracketed by simple distributions

LVC arXiv:1606.04856

Rates from full O1 BBH search

Mass distribution	$R/(\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$
	Combined
GW150914	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.4^{+30.4}_{-8.7}$
GW151226	37^{+92}_{-31}
All	55^{+99}_{-41}
Flat in log mass	30^{+43}_{-21}
Power Law (−2.35)	99^{+138}_{-70}

LVC arXiv:1606.04856

- Conservative 90% credible range $9\text{–}240\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- LVC 2010 'Rates' prediction paper : **0.1**, **5**, **300** /$\mathrm{Gpc}^3\mathrm{yr}$
  (CQG 27:173001) (**low**, **realistic**, **high**)

Rates from full O1 BBH search

Two independent implementations agree

Mass distribution	$R/(\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$		
	PyCBC	GstLAL	Combined
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.4^{+30.4}_{-8.7}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	37^{+92}_{-31}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+99}_{-41}
	Astrophysical		
Flat in log mass	31^{+43}_{-21}	30^{+43}_{-21}	30^{+43}_{-21}
Power Law (−2.35)	100^{+136}_{-69}	95^{+138}_{-67}	99^{+138}_{-70}

- Conservative 90% credible range $9\text{–}240\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- LVC 2010 'Rates' prediction paper : **0.1**, **5**, **300** /Gpc^{3}yr (CQG 27:173001) (**low**, **realistic**, **high**)

Rates from full O1 BBH search

Two independent implementations agree

Mass distribution	$R/(\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$		
	PyCBC	GstLAL	Combined
	Event based		
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.4^{+30.4}_{-8.7}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	37^{+92}_{-31}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+99}_{-41}
	Astrophysical		
Flat in log mass	31^{+43}_{-21}	30^{+43}_{-21}	30^{+43}_{-21}
Power Law (−2.35)	100^{+136}_{-69}	95^{+138}_{-67}	99^{+138}_{-70}

Median values down by factor ~0.5 since Feb '16

- Conservative 90% credible range $9\text{–}240\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- LVC 2010 'Rates' prediction paper : **0.1**, **5**, **300** /Gpc^{3}yr (**low**, **realistic**, **high**)
  (CQG 27:173001)

(Brief) astrophysical implications

- Merging BBH with components ~30 $M_\odot$ exist !
- Merging BBH with components ~10 $M_\odot$ exist !
- Some merging BBH have nonzero (but probably not very large) spin !
- Total merger rate is not low !
- ‘Standard’ formation mechanisms [isolated binary / dynamical] not strongly constrained (yet) !
- See S. Nissanke’s talk / read references …

LVC arXiv:1602.03846, arXiv:1606.04856

Constraining the straw-person mass distribution

- Model BBH merger mass dist as **general power law**

$$p(m_1, m_2 \mid \alpha) \propto \frac{m_1^{-\alpha}}{m_1 - M_{\min}}$$

- *Detected* mass dist has selection effects (detection probability P_{det})
  - need to ‘divide this out’

$$P_{\mathrm{det}}(m_1, m_2) \propto \langle VT \rangle |_{m_1, m_2}$$

- Significant (and non-Gaussian) errors on mass measurements
  - use PE likelihood samples for 3 BBH events in O1

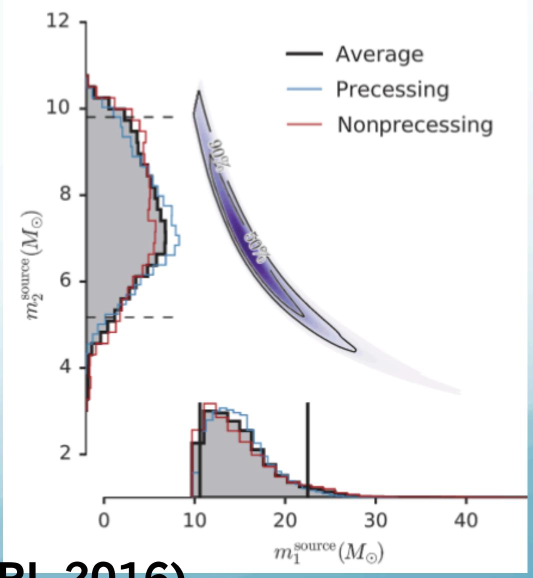
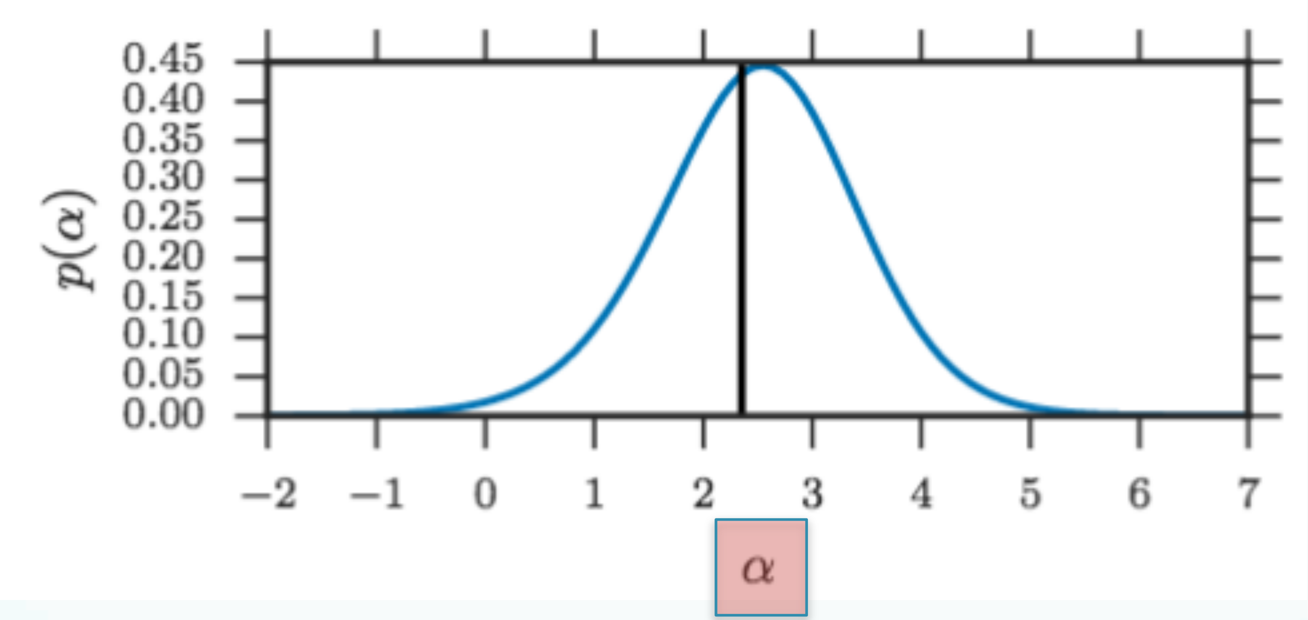


image: LVC GW151226 paper (PRL 2016)

Constraining the straw-person mass distribution



- Choose M_{min} = 5 as for Rates distribution
- Obtain *weak* constraint : highest likelihood around $\alpha \sim 2.5$
- Consistent with Rates choice $\alpha = 2.35$

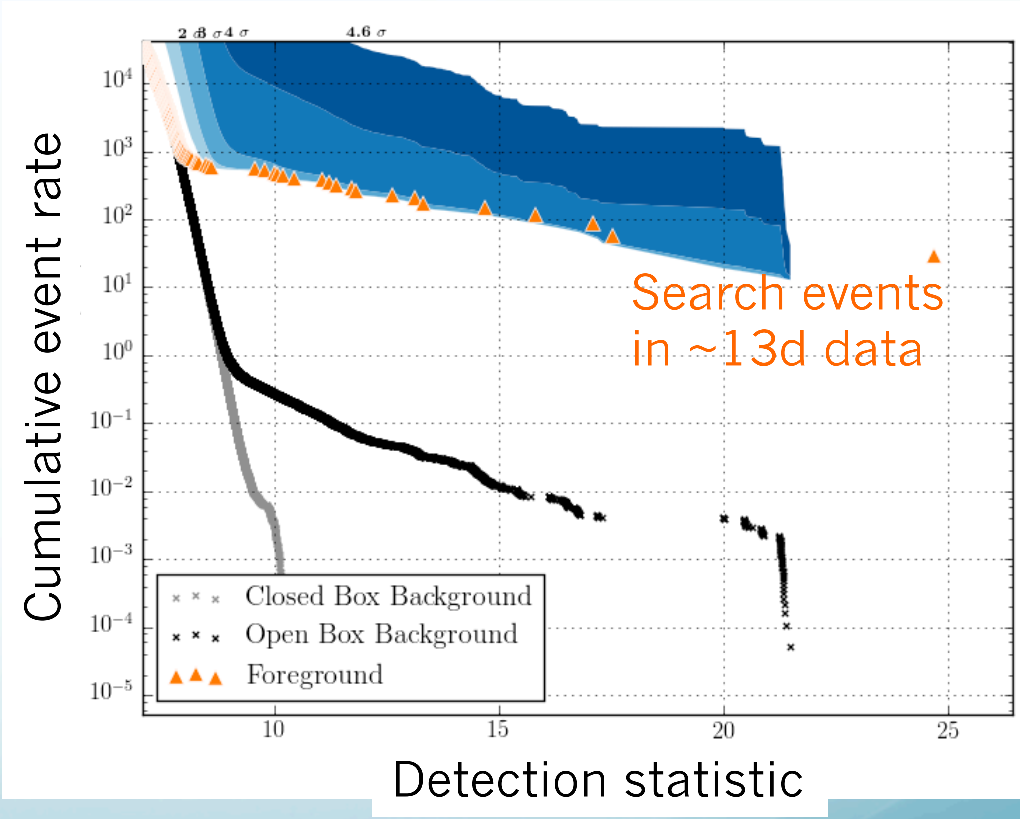
LVC arXiv:1606.04856

BBH distributions into the far future

- Can anticipate 10s-100s of detections in upcoming LIGO-Virgo science runs (2016-7+)
- Relax assumptions on population model
- Measure mass and spin distributions
  - Test for peaks, cutoffs : e.g. maximum binary BH mass ; NS-BH 'mass gap' ...
- Measure distributions over redshift / sky location ?
  - BBH as probe of cosmological evolution, homogeneity / anisotropy?

Case study: MDC on fake aLIGO data

- 'Engineering Run 4' : recolored subsystem data mimicking full aLIGO (2018+) sensitivity
- High rate of 'blind injected' BBH signals
- Can mass distribution be recovered?

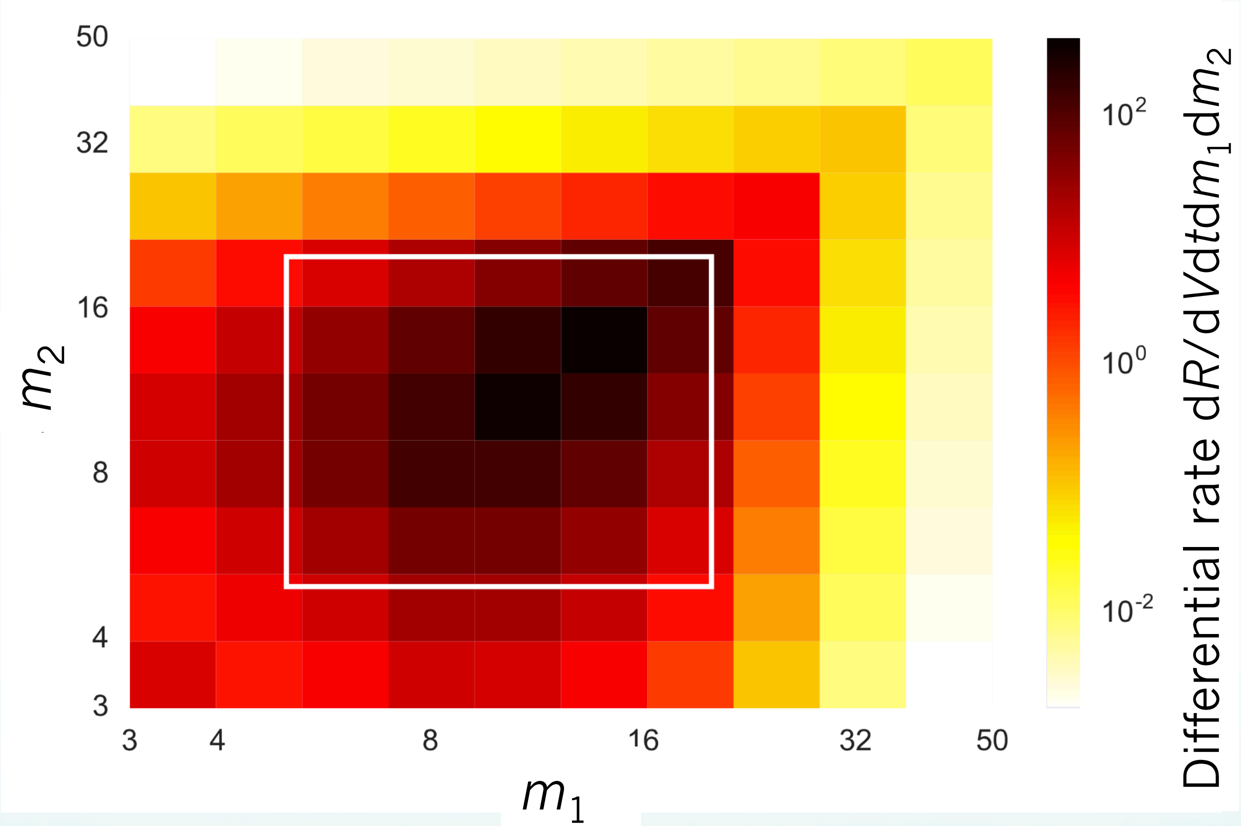


study done in collaboration with **S. Gaebel, J. Veitch, W. Farr** (B'ham)

PRELIMINARY

NOT AN LVC RESULT

Case study: MDC on fake aLIGO data



- model distribution as constant over bins in m_1, m_2
- Bayesian prior to 'smooth' over different bins

PRELIMINARY **NOT AN LVC RESULT**

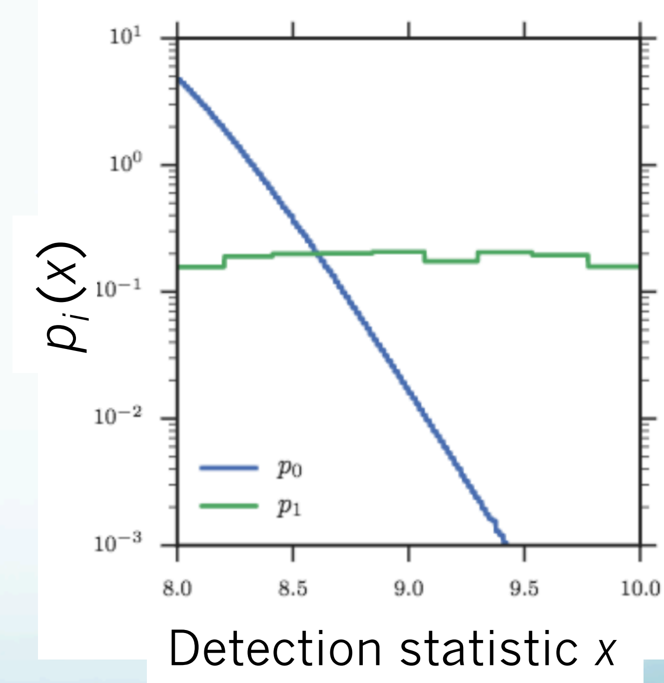
Summary

- LIGO sees BBH mergers with a range of masses
- Mass distribution : essential part of astrophysical interpretation
- Nontrivial to extract from observations
  - small number statistics (at present!)
  - selection effects
  - statistical errors on masses
  - (finite probability of noise events ..)
- Gearing up for more detections, more detailed models in O2+

Extra slide: Counting signal & noise events

Counting number of signals in GW search if events have nonzero false alarm probability

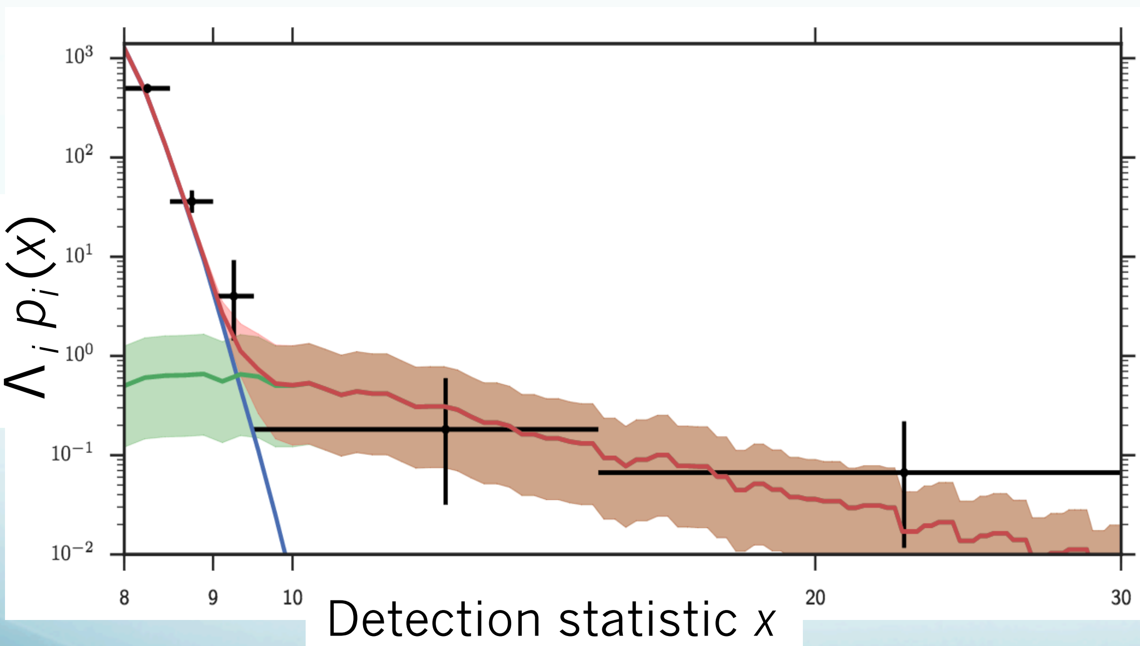
- Search pipeline assigns detection statistic '*x*' to each event
- Estimate distributions of **signal** and **noise** events via Monte Carlo
- Assign each event probability P_1 of being signal ($1-P_1$ of noise)
- Infer *mean counts* of signal / noise events Λ_1, Λ_0 (with uncertainties) from observed $\{x^j\}$



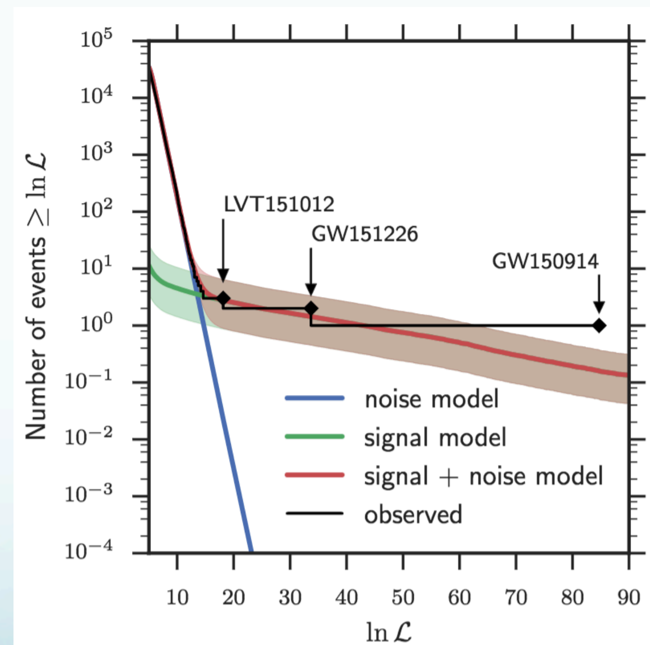
W. Farr et al. PRD 2015, LVC arXiv:1602.03842v2+supplement 1606.03939

Extra slide: Counting signal & noise events

- Choose threshold x_{th} to have many noise events at $>x_{th}$ $\Rightarrow$ Λ_0 well determined
- Small number of signals $\Rightarrow$ significant error in Λ_1



differential rate, pycbc,
16 days coinc data



cumulative rate, gstlal,
full O1 coinc data