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

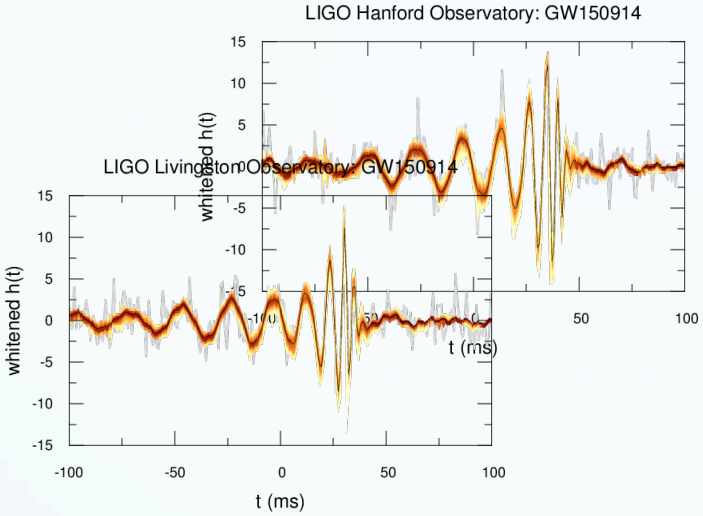
Thomas Dent (AEI Hannover) for the LSC and Virgo

LIGO-G1601017v3

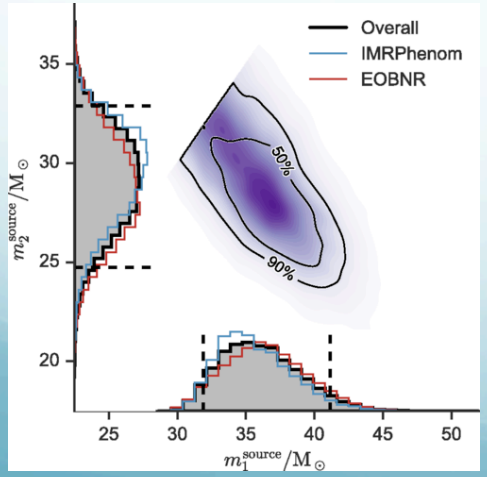
July 12th 2016, GR21 (Columbia U.)

Overview: rates and mass distributions

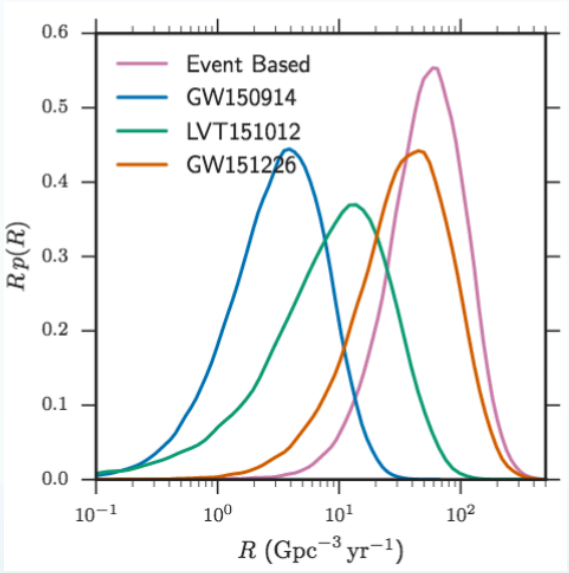
Detection



Parameter estimation

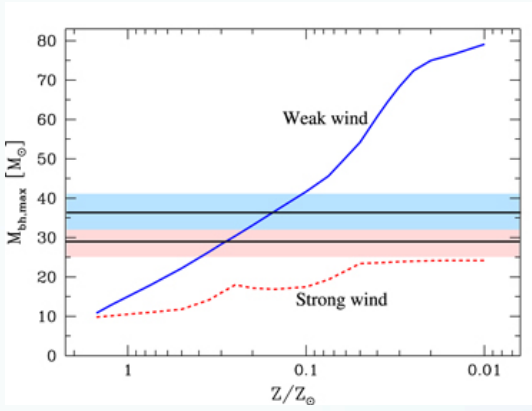


Merger rate



Mass distribution

Astrophysical interpretation



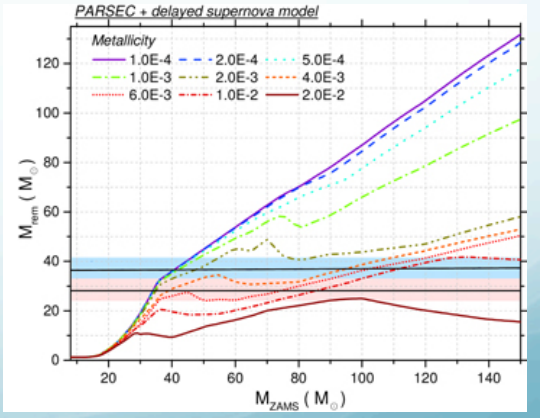


Image credits : LVC,
Belczynski et al. ApJ 2010, Spera et al. MNRAS 2015

Overview: rates and mass distributions

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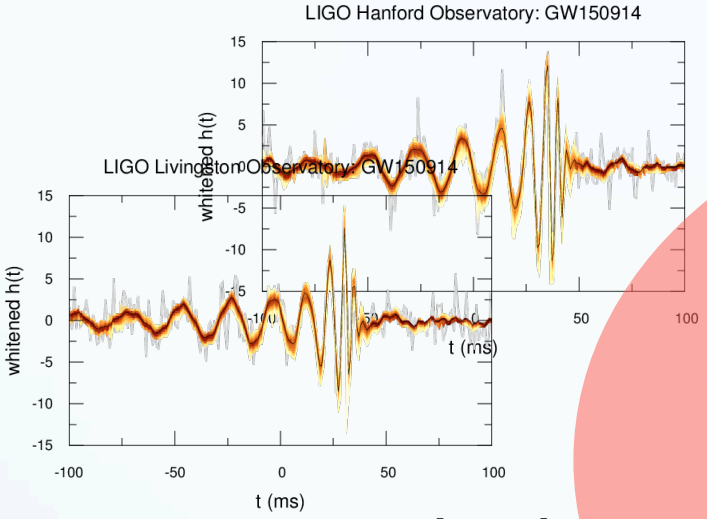

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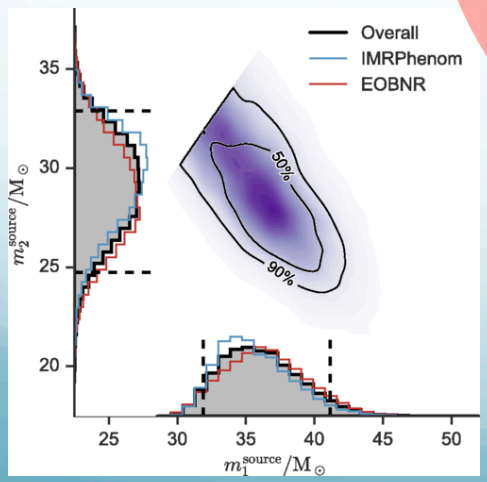
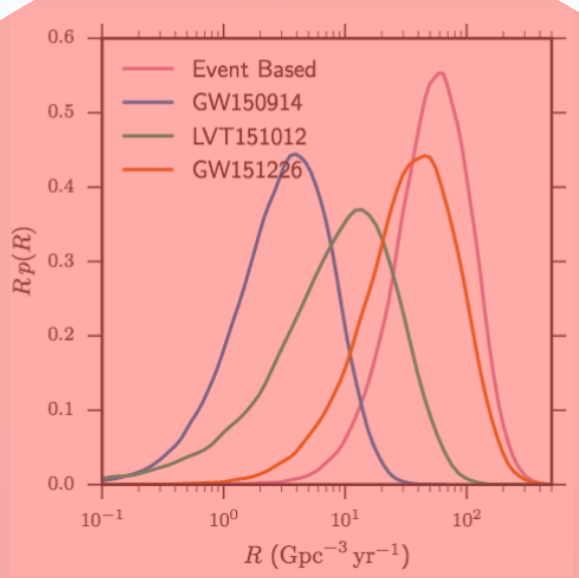


THIS TALK

Merger rate



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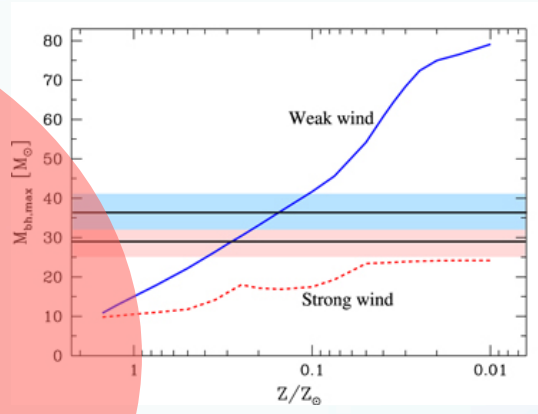

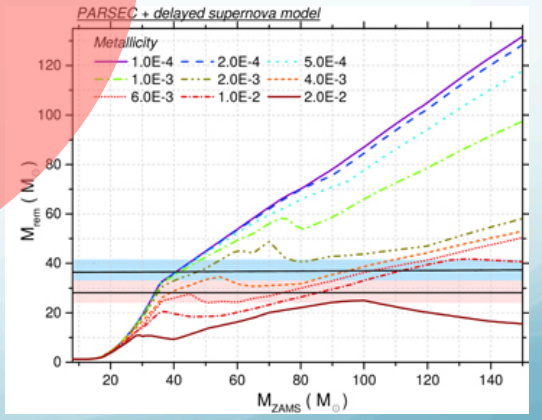

Image credits : LVC,
Belczynski et al. ApJ 2010, Spera et al. MNRAS 2015

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)
  ⟺ 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)
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WE ARE NOW HERE

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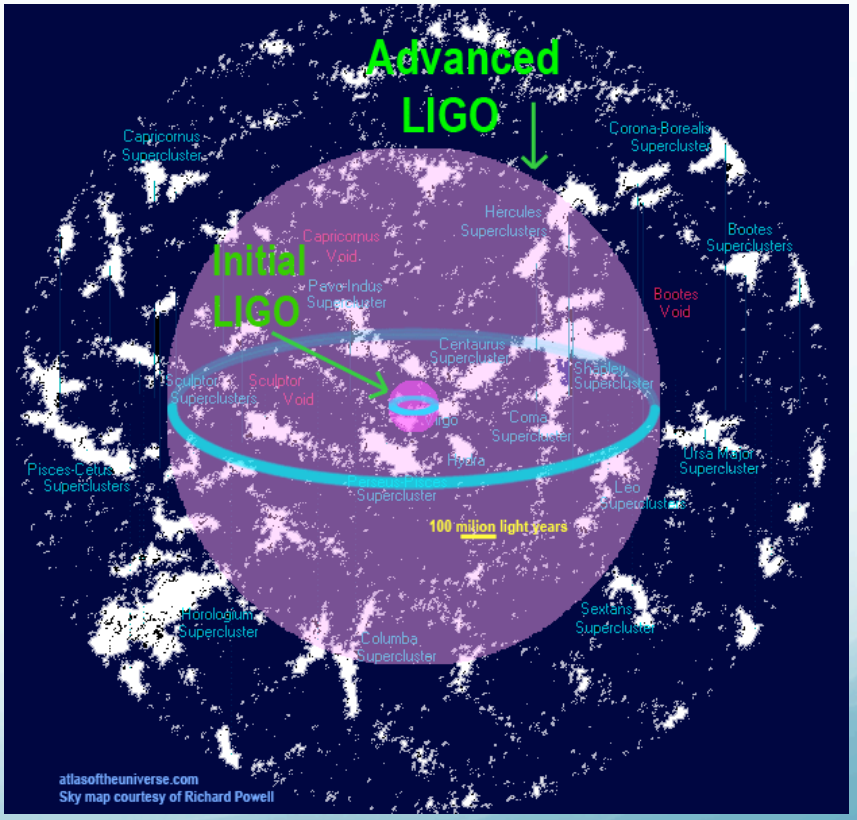
WILL MOVE TO HERE

(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 $\times$ 0.1)
- Early Advanced LIGO reach 10^2 – few$\times 10^3$ Mpc for BBH
- Plausible that universe is statistically homogeneous on these scales

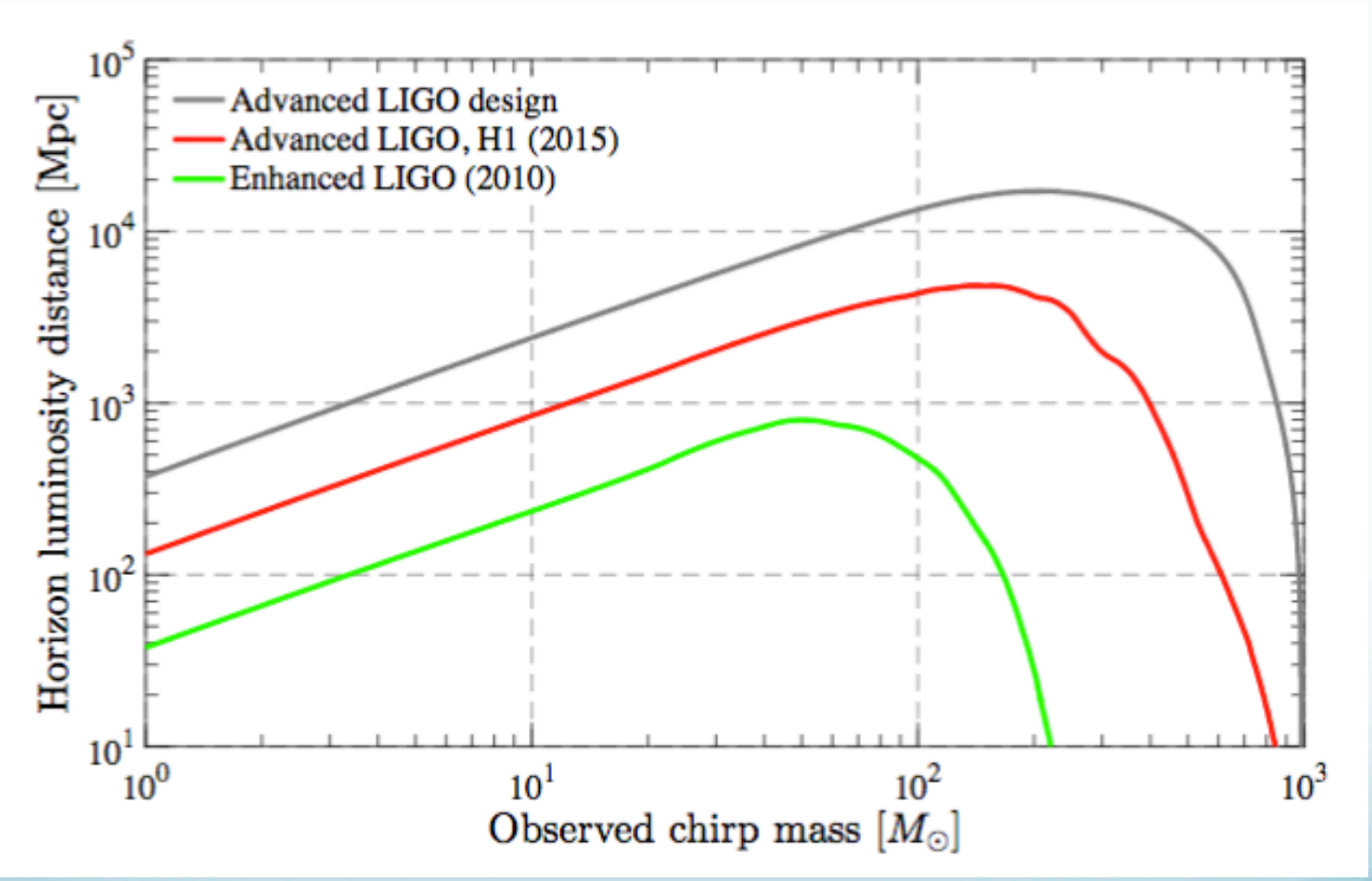


Basic rate calculation framework

- 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 $\mathrm{d}R/\mathrm{d}m_1\mathrm{d}m_2$
  - 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 $\equiv m_2/m_1$

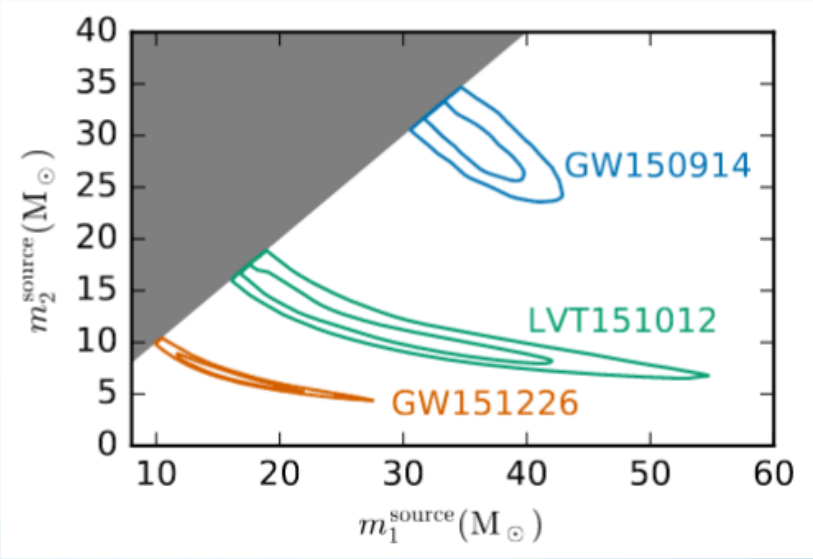
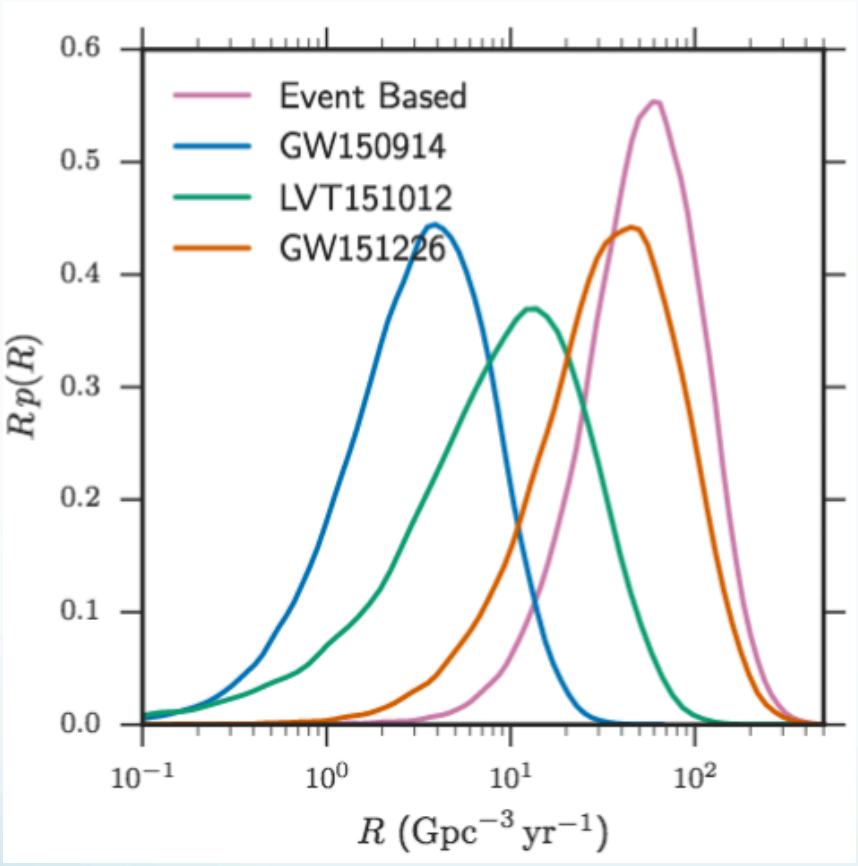
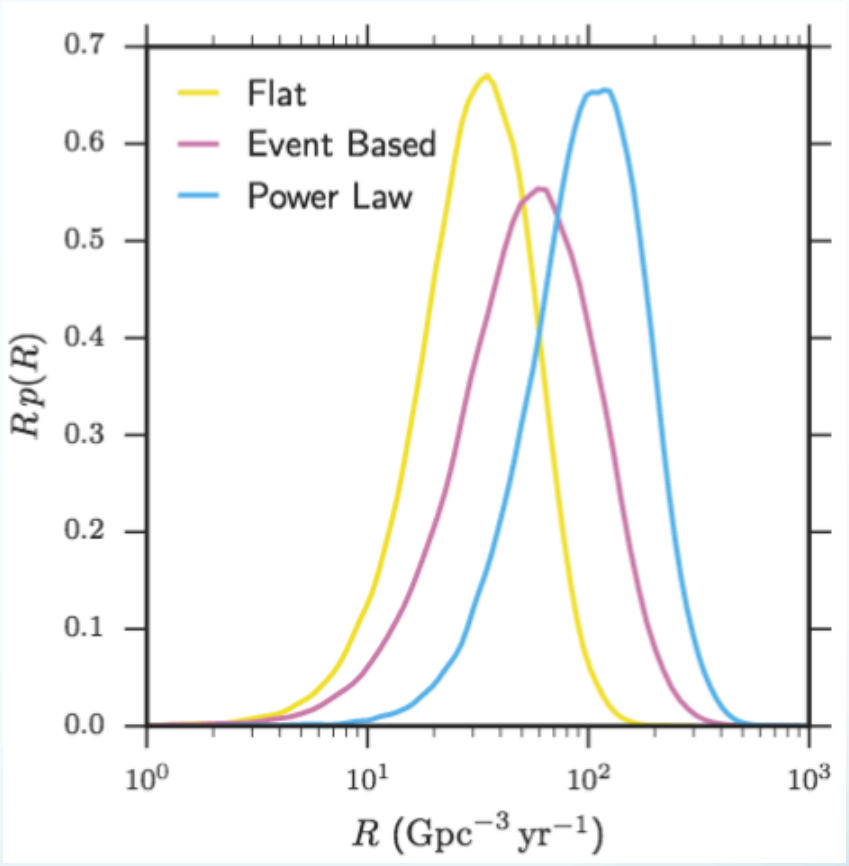


Image: LVC arXiv:1606.04856

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** /Gpc^{3}yr (**low**, **realistic**, **high**)
  (CQG 27:173001)

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}

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Median values down by factor ~0.5 since Feb '16

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(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'

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

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

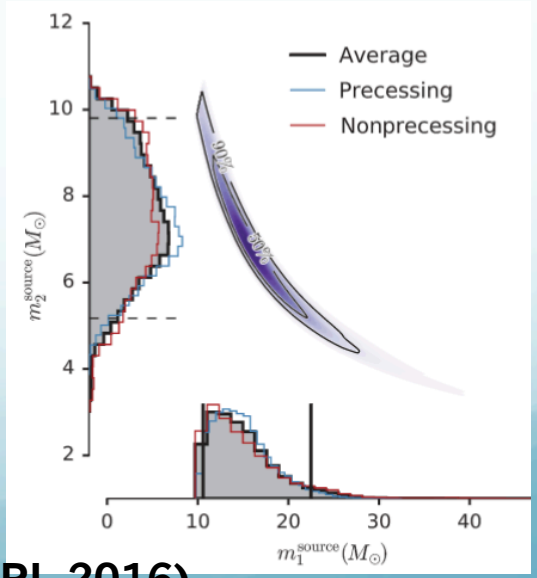

image: LVC GW151226 paper (PRL 2016)

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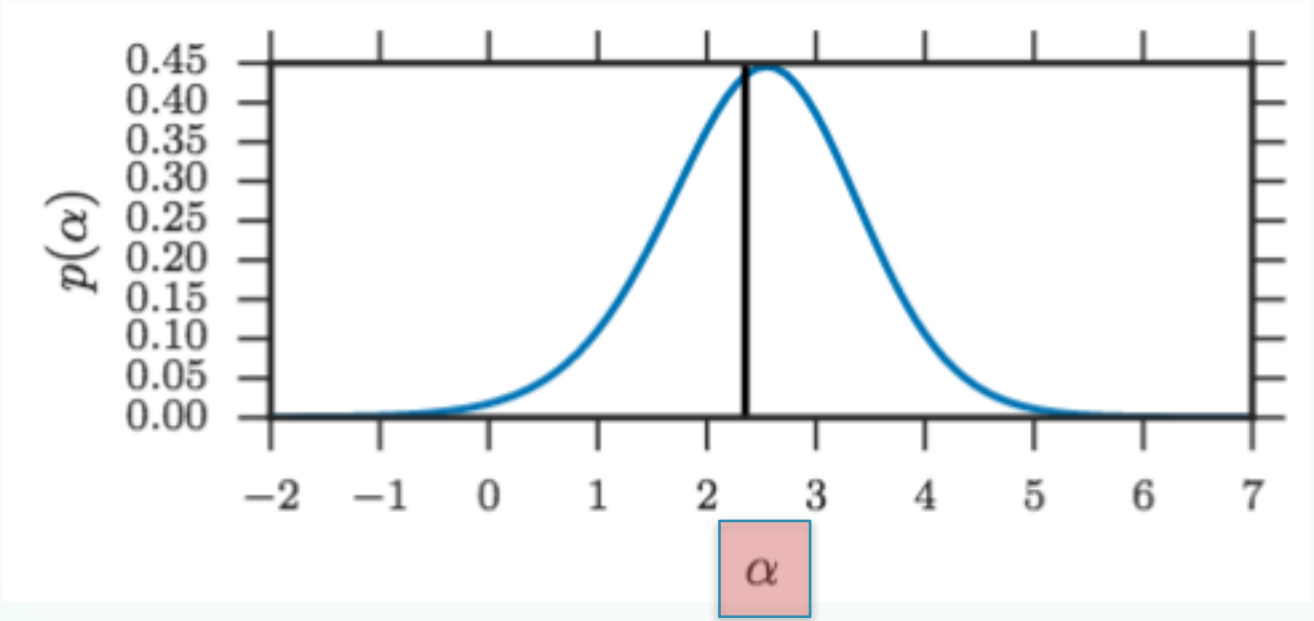


- Choose $M_{\text{min}} = 5$ as for Rates distribution
- *Weak* constraint : highest likelihood at $\alpha \sim 2.5$
- Consistent with Rates choice $\alpha = 2.35$

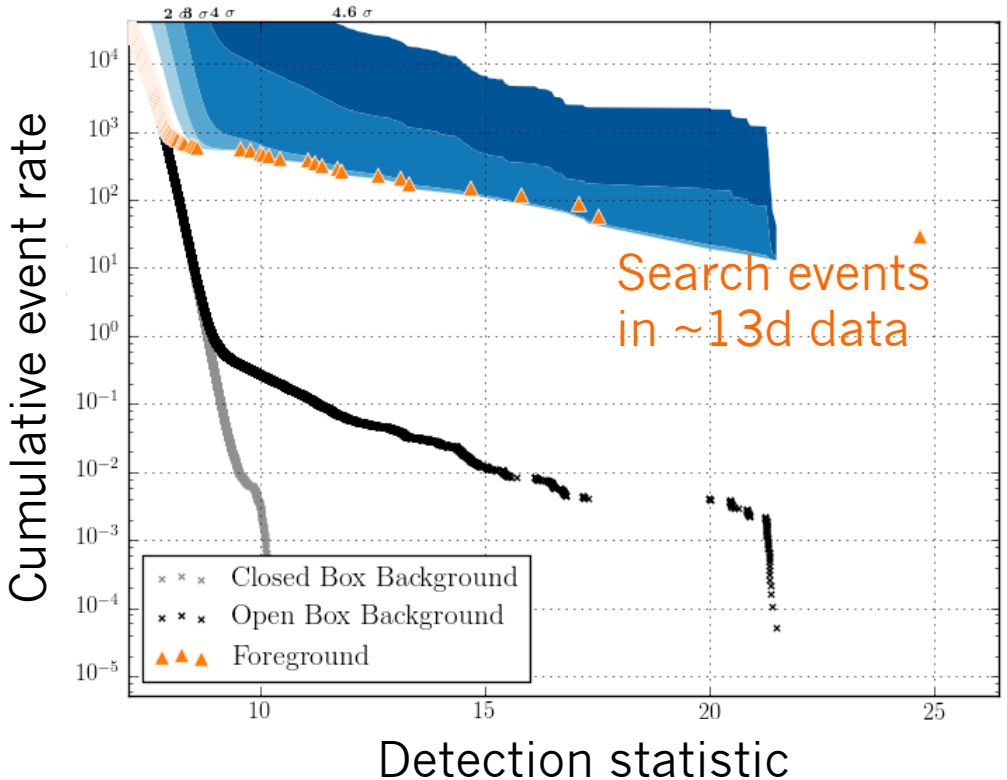
LVC arXiv:1606.04856

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?

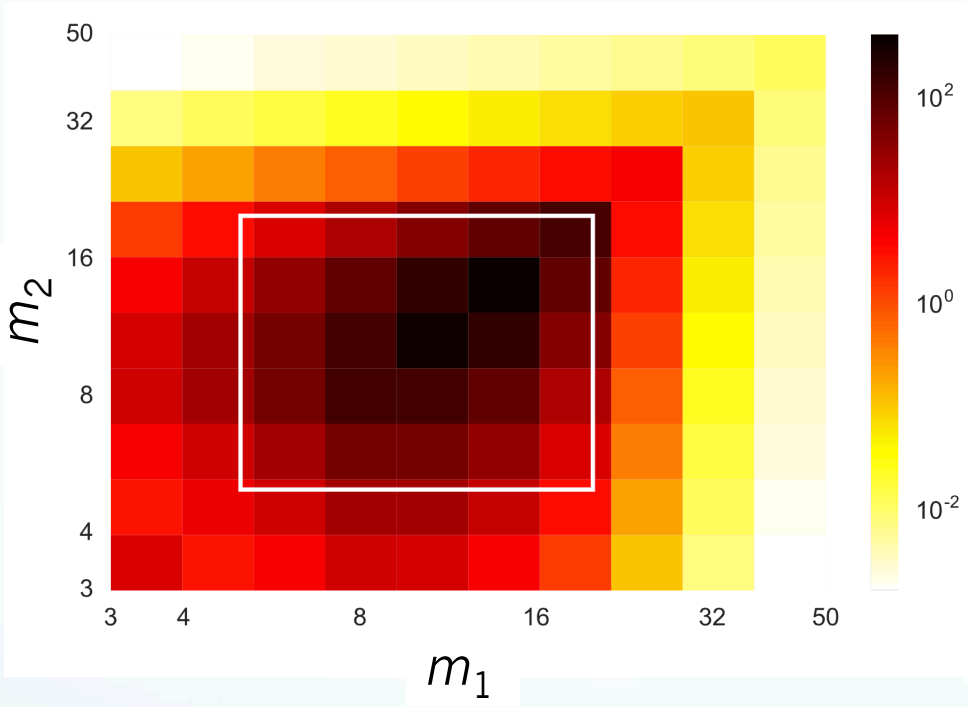


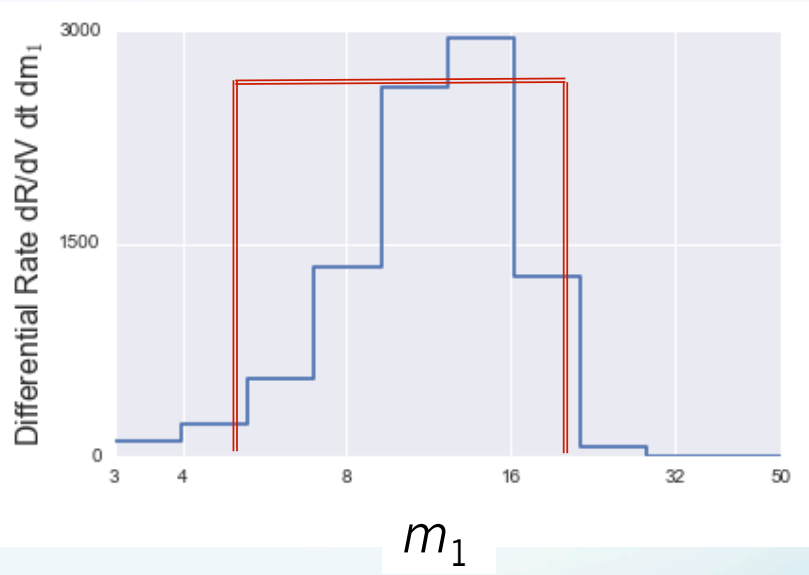
study done in collaboration with **S. Gaebel, J. Veitch, W. Farr** (B’ham)

PRELIMINARY

NOT AN LVC RESULT

Case study: MDC on fake aLIGO data





- piecewise constant model over m_1, m_2
- Bayesian prior to 'smooth' between different bins

PRELIMINARY **NOT AN LVC RESULT**

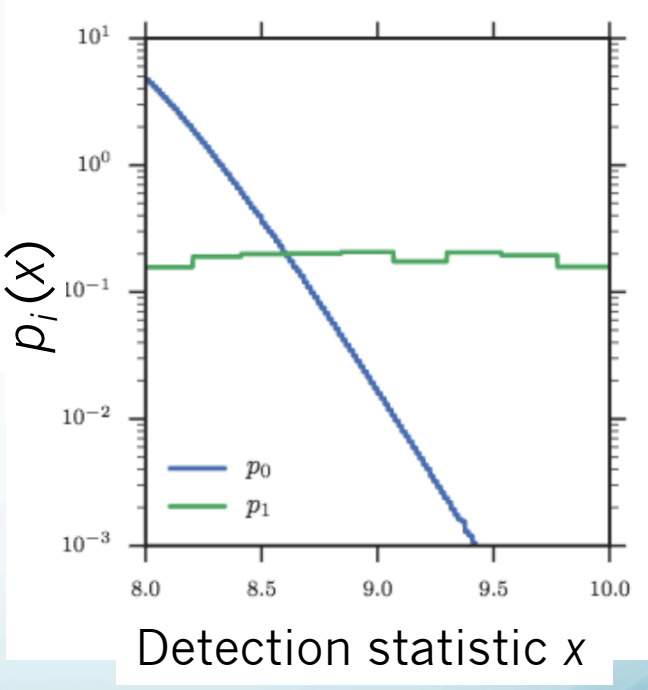
Summary

- 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

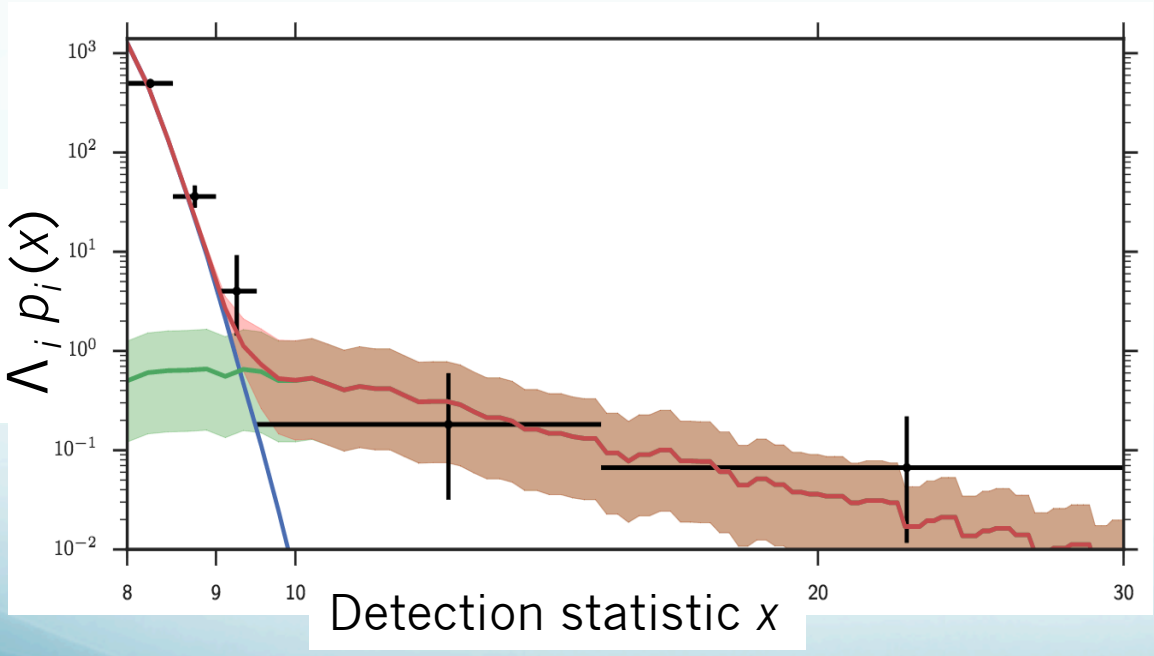
- Search pipeline assigns detection statistic 'x' to each event
- Estimate distributions of **signal** and **noise** events via Monte Carlo
- Assign each event probability P_1 of being signal ($1-P_1$ of noise)
- Infer *mean counts* of signal / noise events Λ_1, Λ_0 with uncertainties from observed $\{x^j\}$



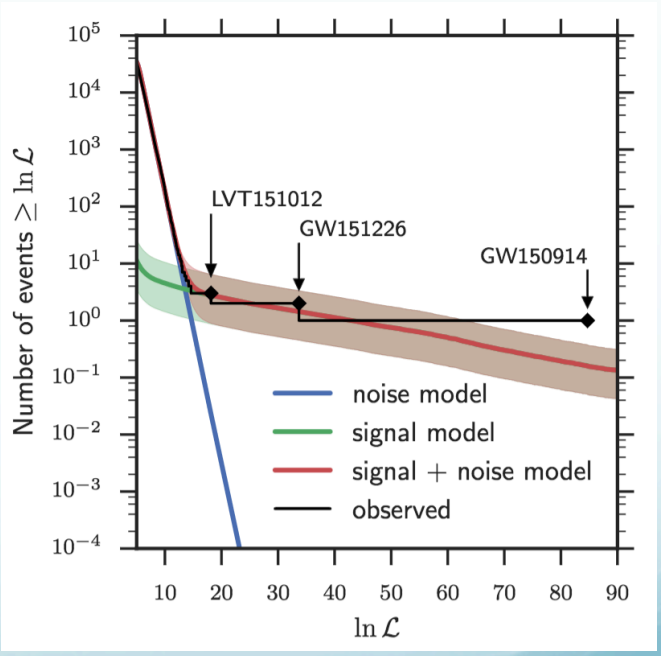
W. Farr et al. PRD 2015, LVC arXiv:1602.03842v2+supplement 1606.03939

Extra slide: Counting signal & noise events

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



differential rate, pycbc, 16 days coinc data



cumulative rate, gstlal, full O1 coinc data