# The detection of binary black holes in Advanced LIGO's first scientific run

arXiv:1606.04856

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CNRS/APC

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# Introduction

- Overview of O1
- Primer GW detection
- BBH detections
- Astrophysical implications
- Topics I won't touch on
  - Parameter estimation (see Vivien Raymond's talk)
  - EM follow up searchers (see Leo Singer's talk)
  - Testing GR (see Chris Van Den Broeck's talk)
  - Stochastic background (see Giancarlo Cella's talk)

# Overview of O1

Duration : Sept 12, 2015 - Jan 19, 2016

51.5 days of coincident analysis time

Detector sensitivity : 30Hz - several kHz

Search range : $2 \leqslant M/M_{\odot} \leqslant 100$

$0 \leqslant \chi_i \leqslant 0.99$

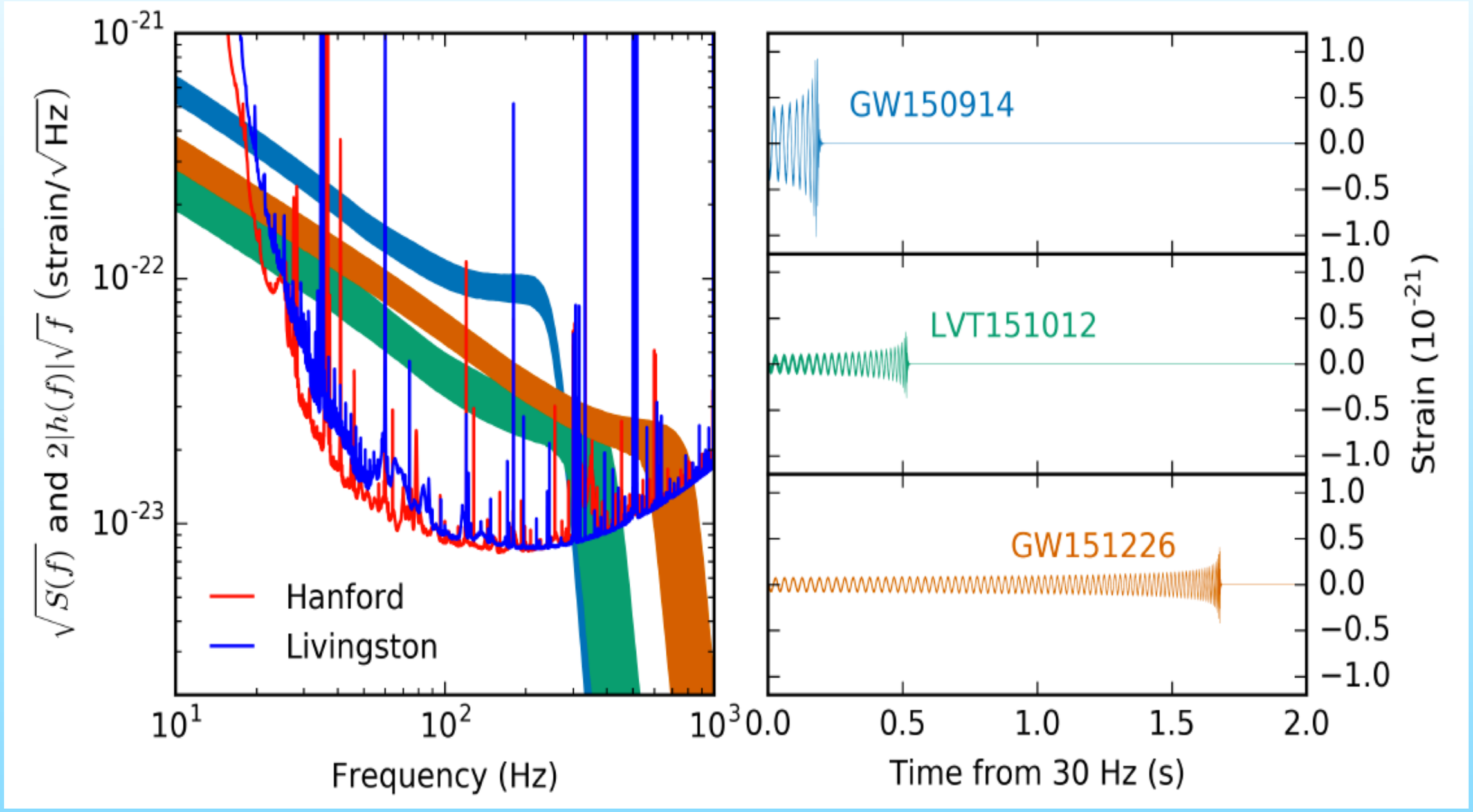
Minimum BH mass : $2\ M_{\odot}$

# Primer on GW Detection

Two methods of detection:

1) Unmodelled
   - short duration FFTs
   - Time-frequency plane
   - Search for excess power in pixels
2) Modelled
   - Construct theoretical models of the inspiral merger and ringdown (PN, EOB, NR)
   - Cross correlate each template with the data
   - Very sensitive to phase evolution

# BBH Detections



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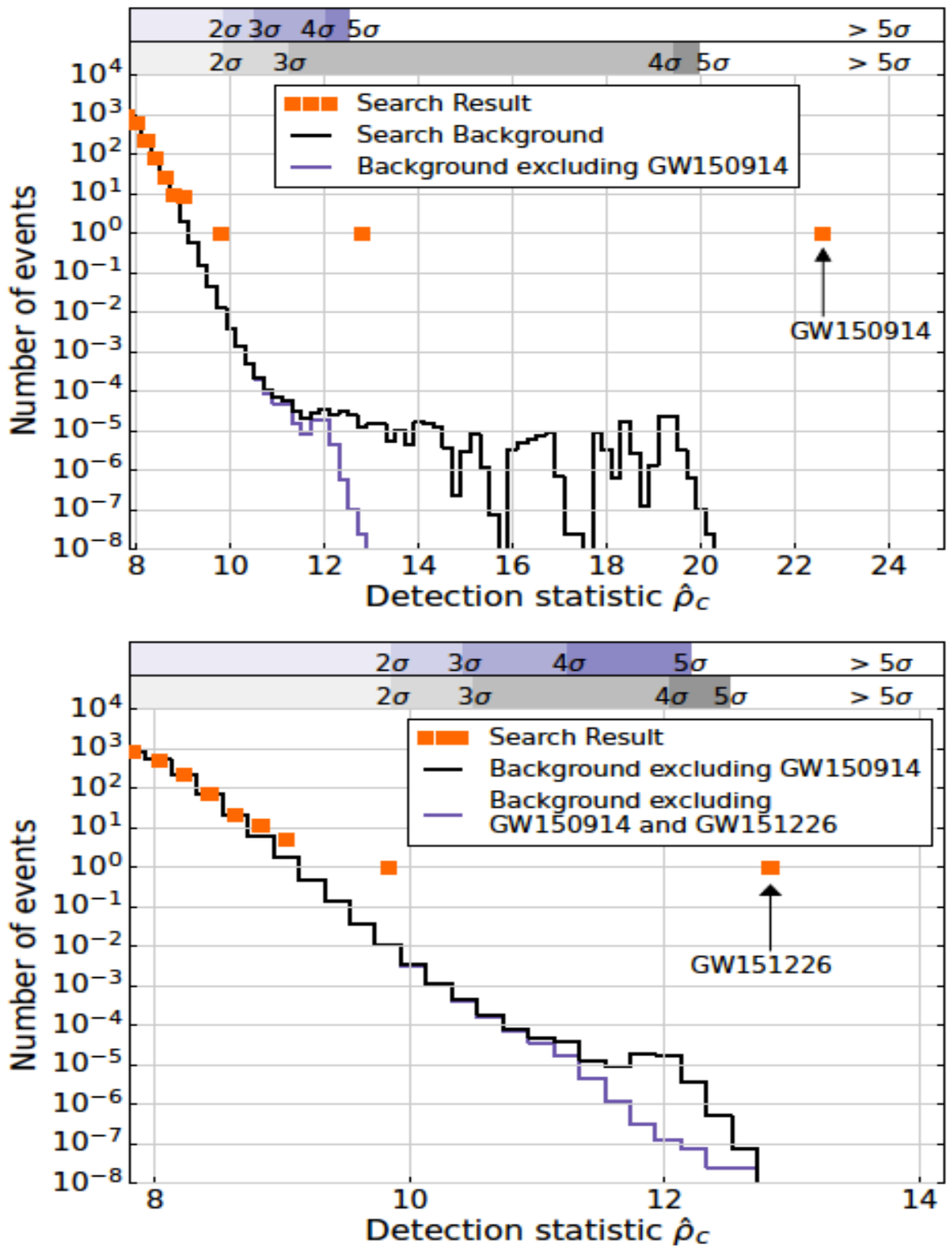


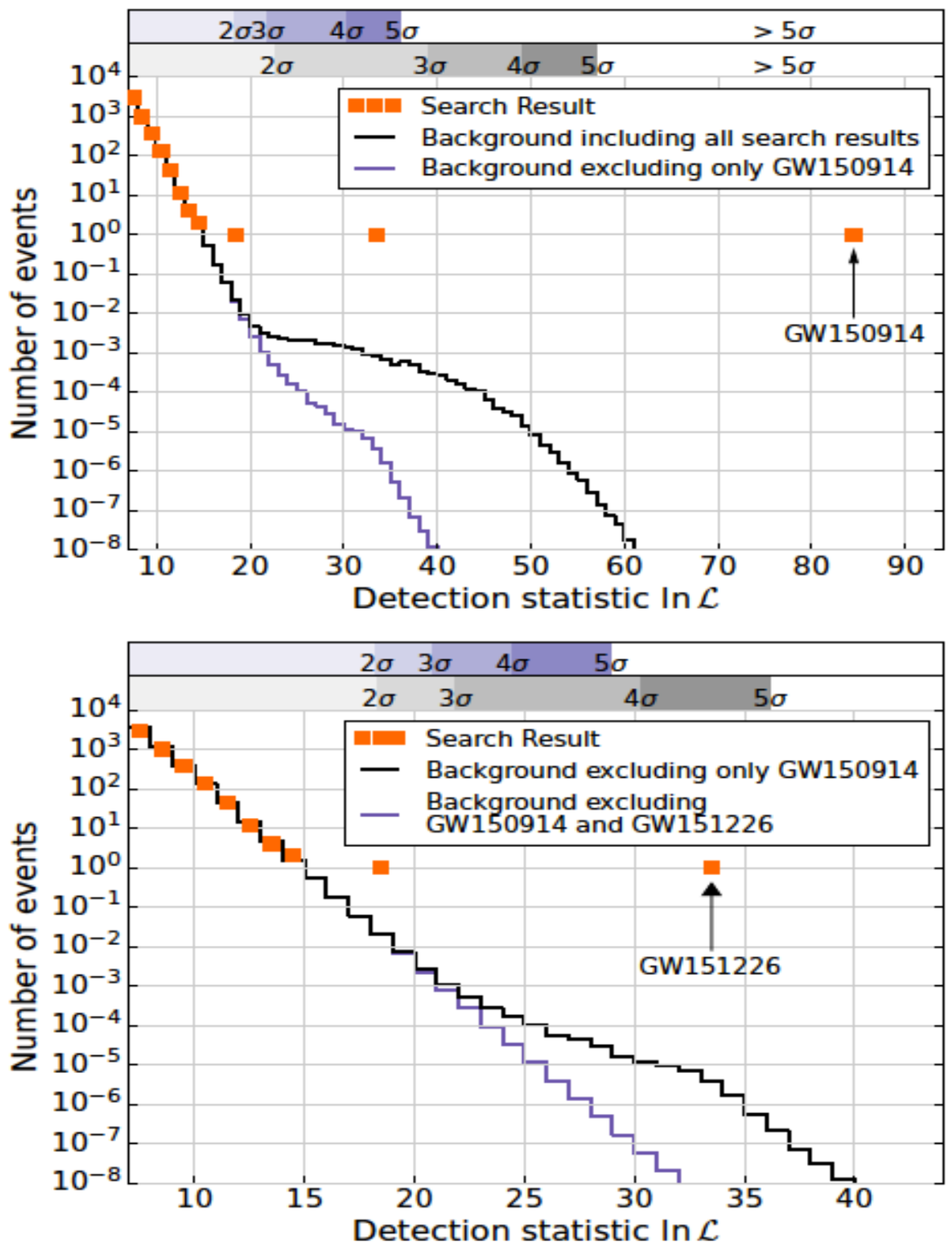

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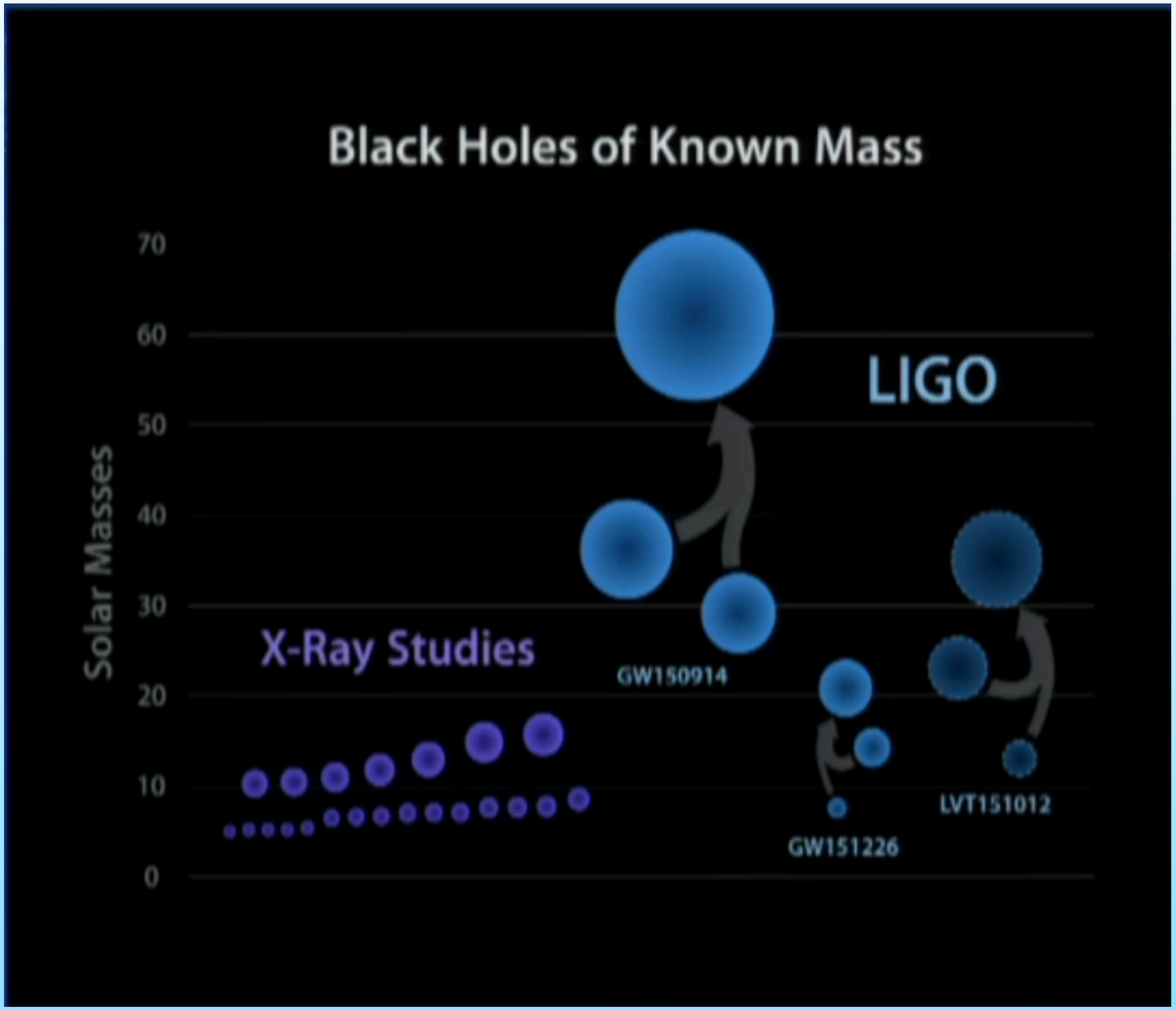


We now have parameters for 9 BHs

# BBH Detections

| Event | GW150914 | GW151226 | LVT151012 |
|---|---|---|---|
| Signal-to-noise ratio $\rho$ | 23.7 | 13.0 | 9.7 |
| False alarm rate FAR/yr$^{-1}$ | $< 6.0 \times 10^{-7}$ | $< 6.0 \times 10^{-7}$ | 0.37 |
| p-value | $7.5 \times 10^{-8}$ | $7.5 \times 10^{-8}$ | 0.045 |
| Significance | $> 5.3\sigma$ | $> 5.3\sigma$ | $1.7\sigma$ |
| Primary mass $m_1^{\rm source}/{\rm M}_\odot$ | $36.2^{+5.2}_{-3.8}$ | $14.2^{+8.3}_{-3.7}$ | $23^{+18}_{-6}$ |
| Secondary mass $m_2^{\rm source}/{\rm M}_\odot$ | $29.1^{+3.7}_{-4.4}$ | $7.5^{+2.3}_{-2.3}$ | $13^{+4}_{-5}$ |
| Chirp mass $\mathscr{M}^{\rm source}/{\rm M}_\odot$ | $28.1^{+1.8}_{-1.5}$ | $8.9^{+0.3}_{-0.3}$ | $15.1^{+1.4}_{-1.1}$ |
| Total mass $M^{\rm source}/{\rm M}_\odot$ | $65.3^{+4.1}_{-3.4}$ | $21.8^{+5.9}_{-1.7}$ | $37^{+13}_{-4}$ |
| Effective inspiral spin $\chi_{\rm eff}$ | $-0.06^{+0.14}_{-0.14}$ | $0.21^{+0.20}_{-0.10}$ | $0.0^{+0.3}_{-0.2}$ |
| Final mass $M_{\rm f}^{\rm source}/{\rm M}_\odot$ | $62.3^{+3.7}_{-3.1}$ | $20.8^{+6.1}_{-1.7}$ | $35^{+14}_{-4}$ |
| Final spin $a_{\rm f}$ | $0.68^{+0.05}_{-0.06}$ | $0.74^{+0.06}_{-0.06}$ | $0.66^{+0.09}_{-0.10}$ |
| Radiated energy $E_{\rm rad}/({\rm M}_\odot c^2)$ | $3.0^{+0.5}_{-0.4}$ | $1.0^{+0.1}_{-0.2}$ | $1.5^{+0.3}_{-0.4}$ |
| Peak luminosity $\ell_{\rm peak}/({\rm erg\,s}^{-1})$ | $3.6^{+0.5}_{-0.4} \times 10^{56}$ | $3.3^{+0.8}_{-1.6} \times 10^{56}$ | $3.1^{+0.8}_{-1.8} \times 10^{56}$ |
| Luminosity distance $D_{\rm L}/{\rm Mpc}$ | $420^{+150}_{-180}$ | $440^{+180}_{-190}$ | $1000^{+500}_{-500}$ |
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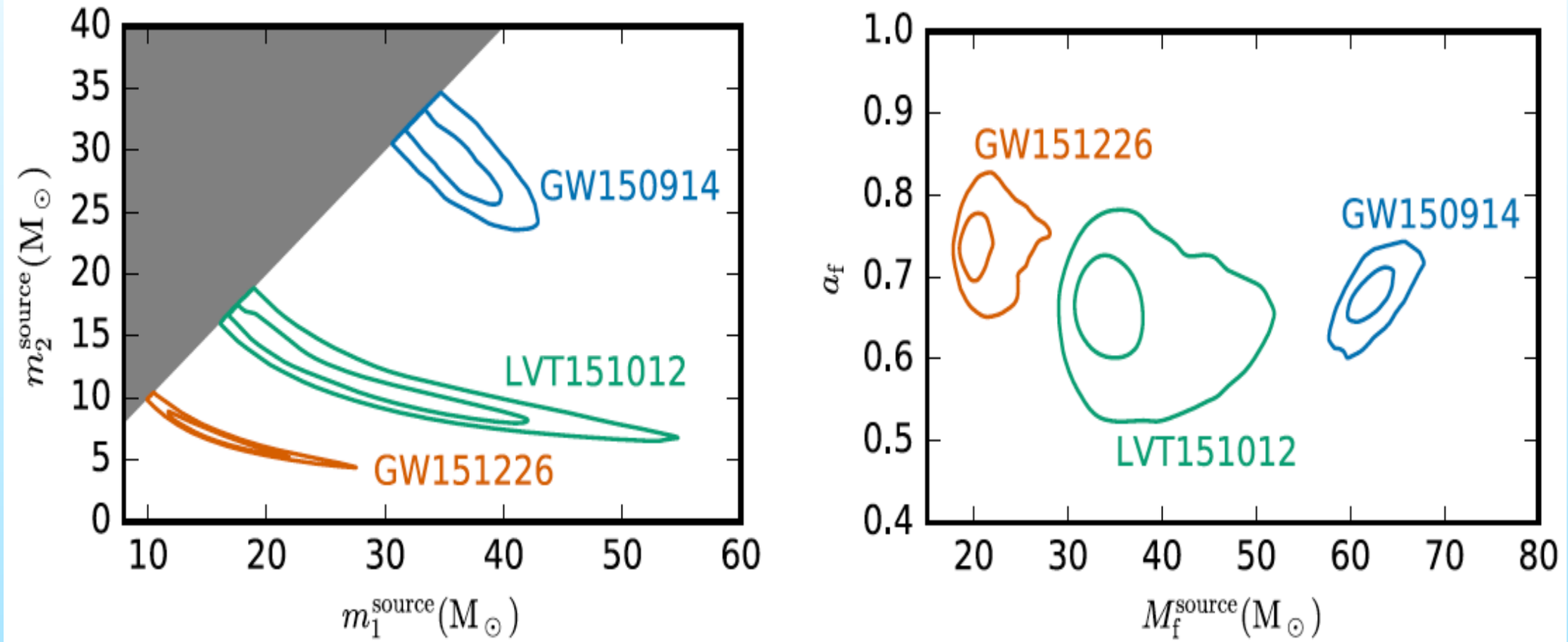
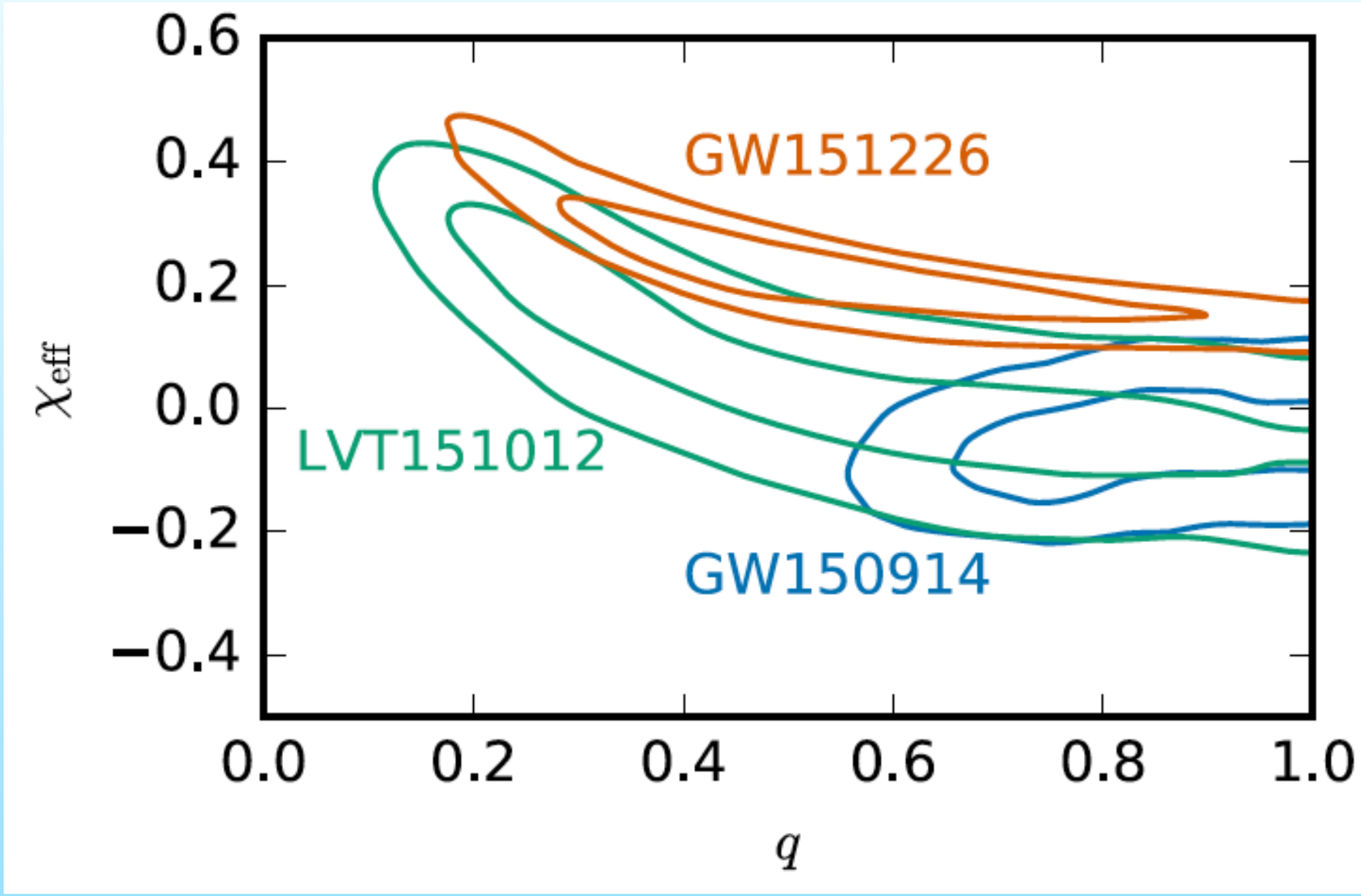
$\approx 10^{23}\ L_\odot$

# Source masses




- GW151226 produced the lowest mass final BH
- However, still more massive than all x-ray binary BHs

# Source spins




- As the effective spin is < 0.35 -> large parallel spins either aligned or anti-aligned with the orbital angular momentum are disfavoured

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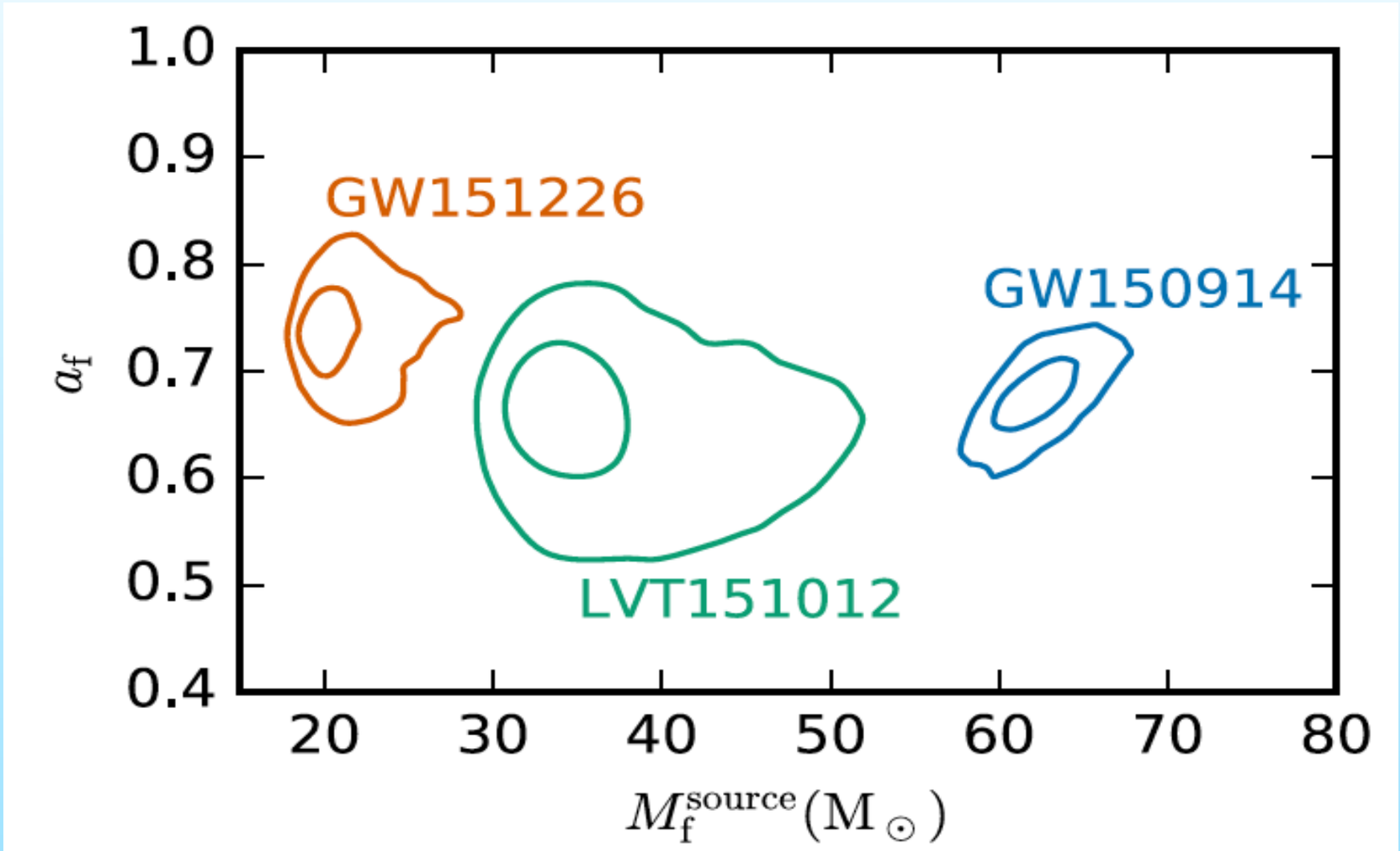
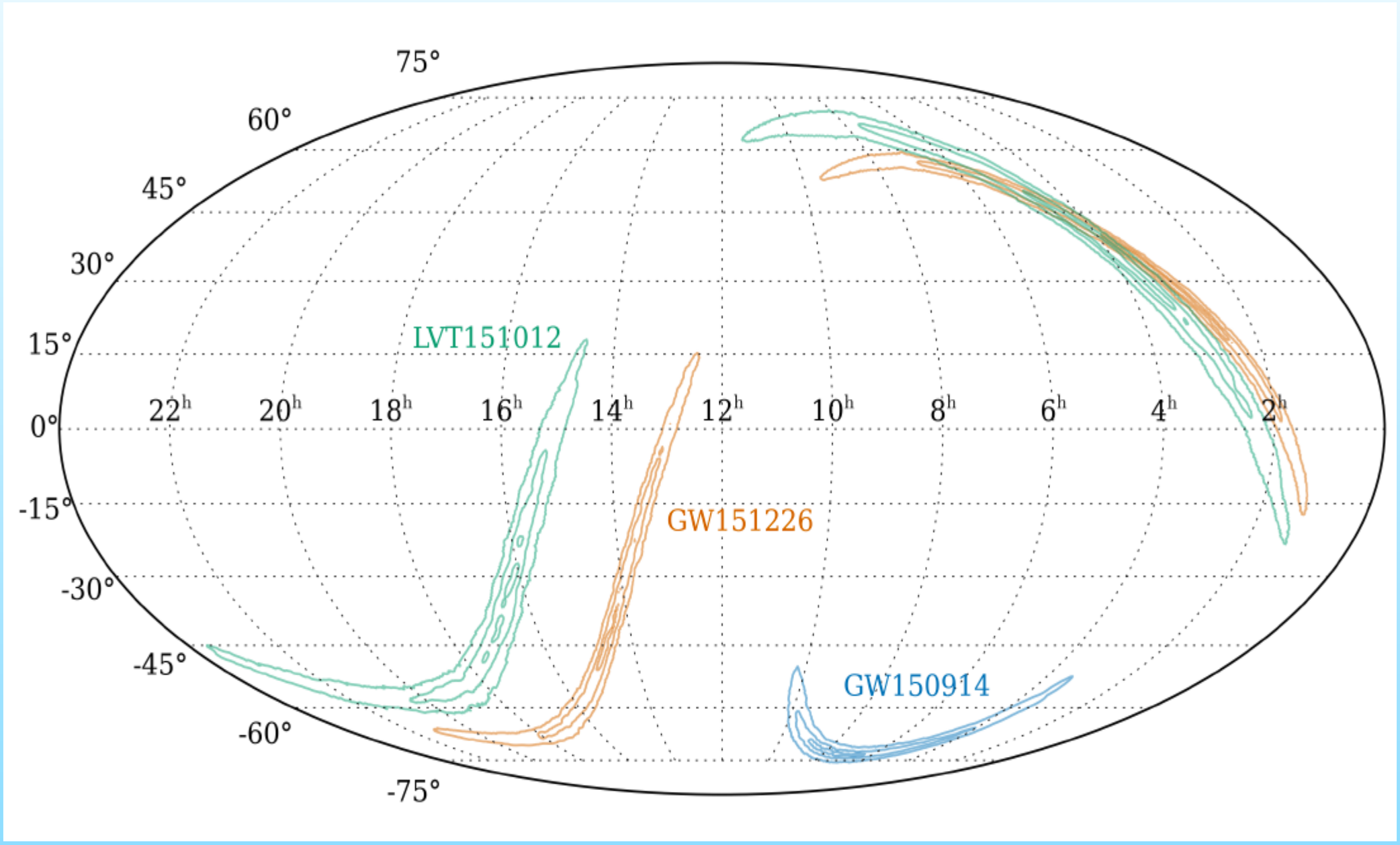


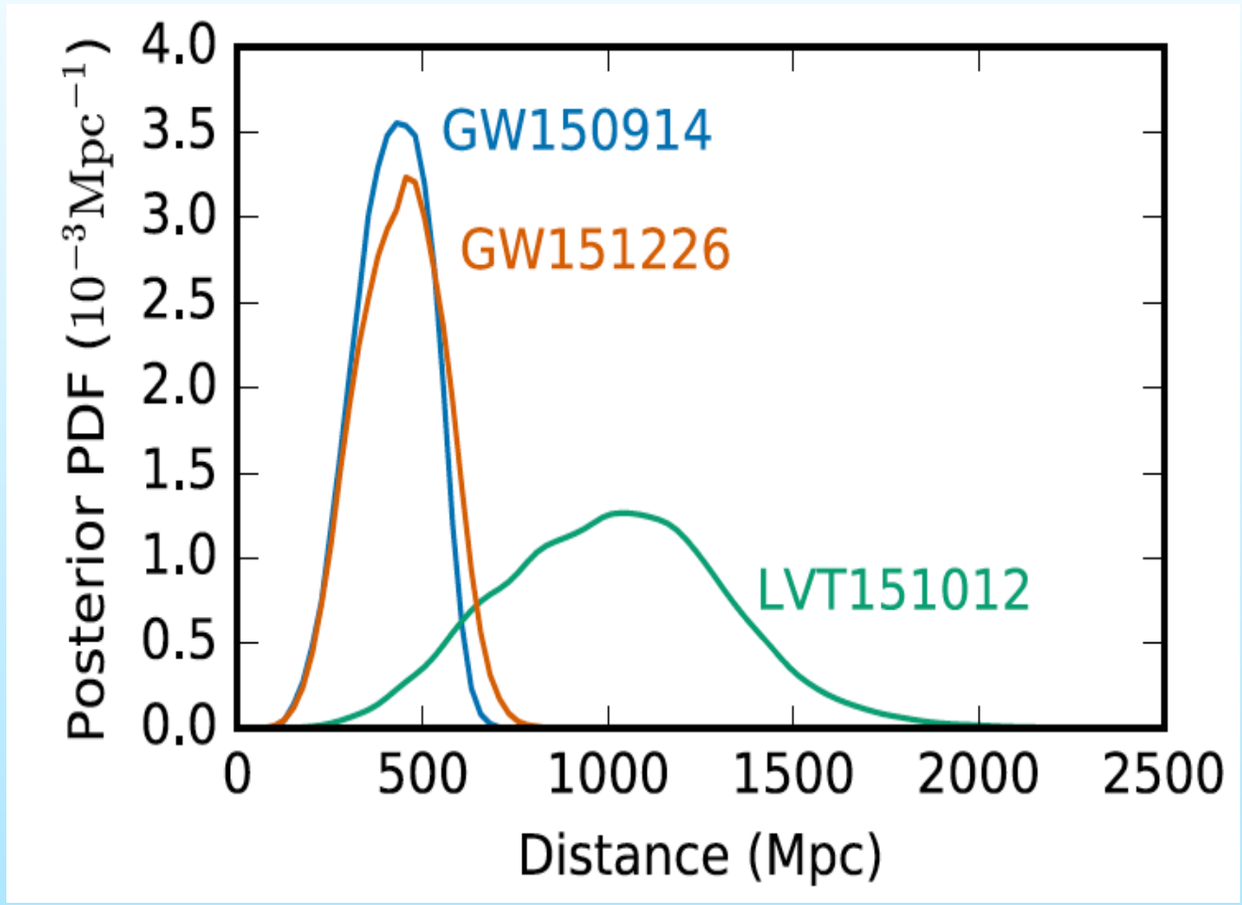

- Can measure final spin much better
- No extremal BHs - all quite low spin

# Source Location



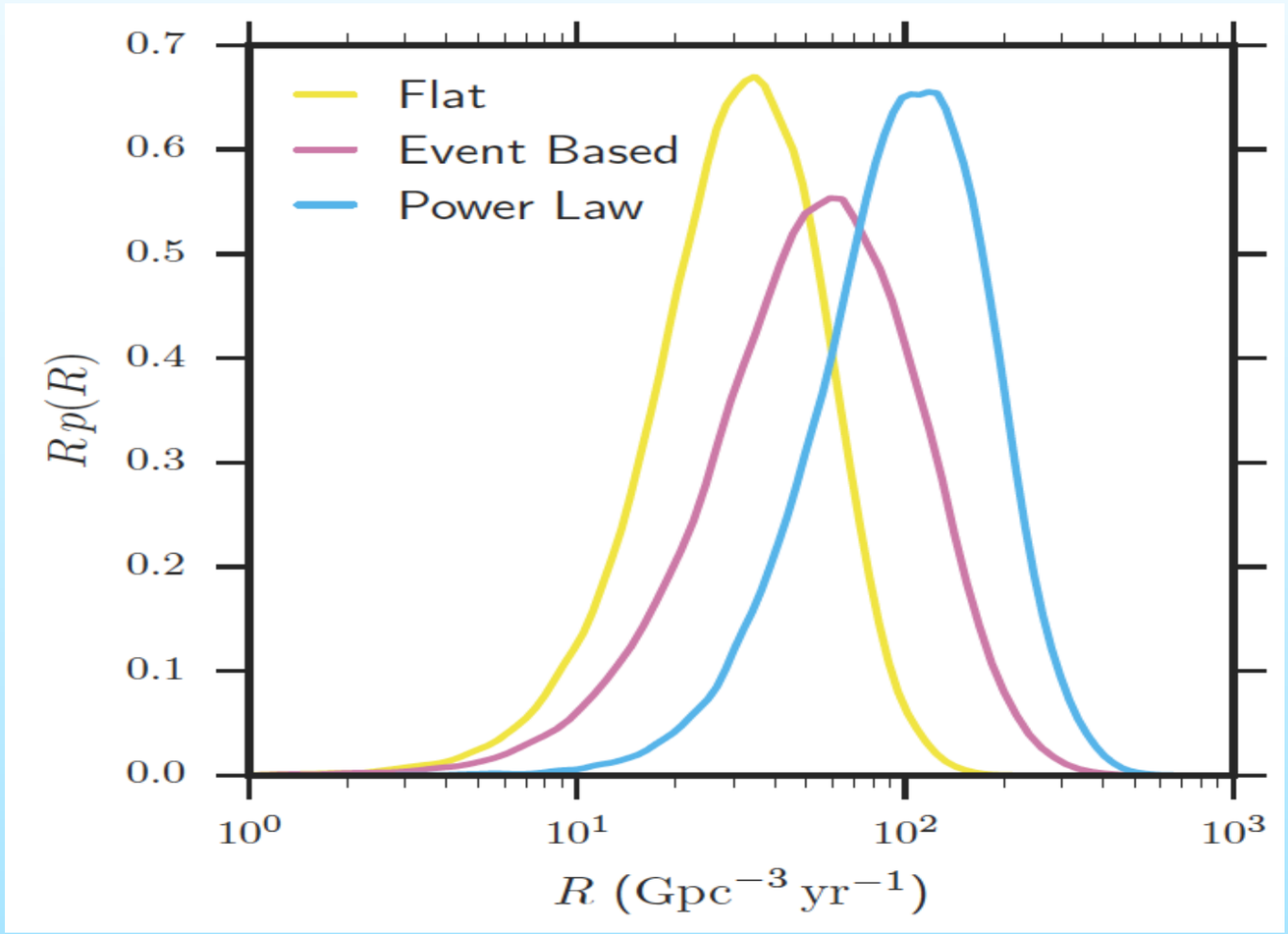
# Astrophysical Implications

# Distance and Inclination




- Large error in distance estimate due to detector alignment and high correlation with inclination
- Greatest posterior support for either face-on or face-off systems
- No EM counterpart, so no independent redshift measurement

# Astrophysical Rates

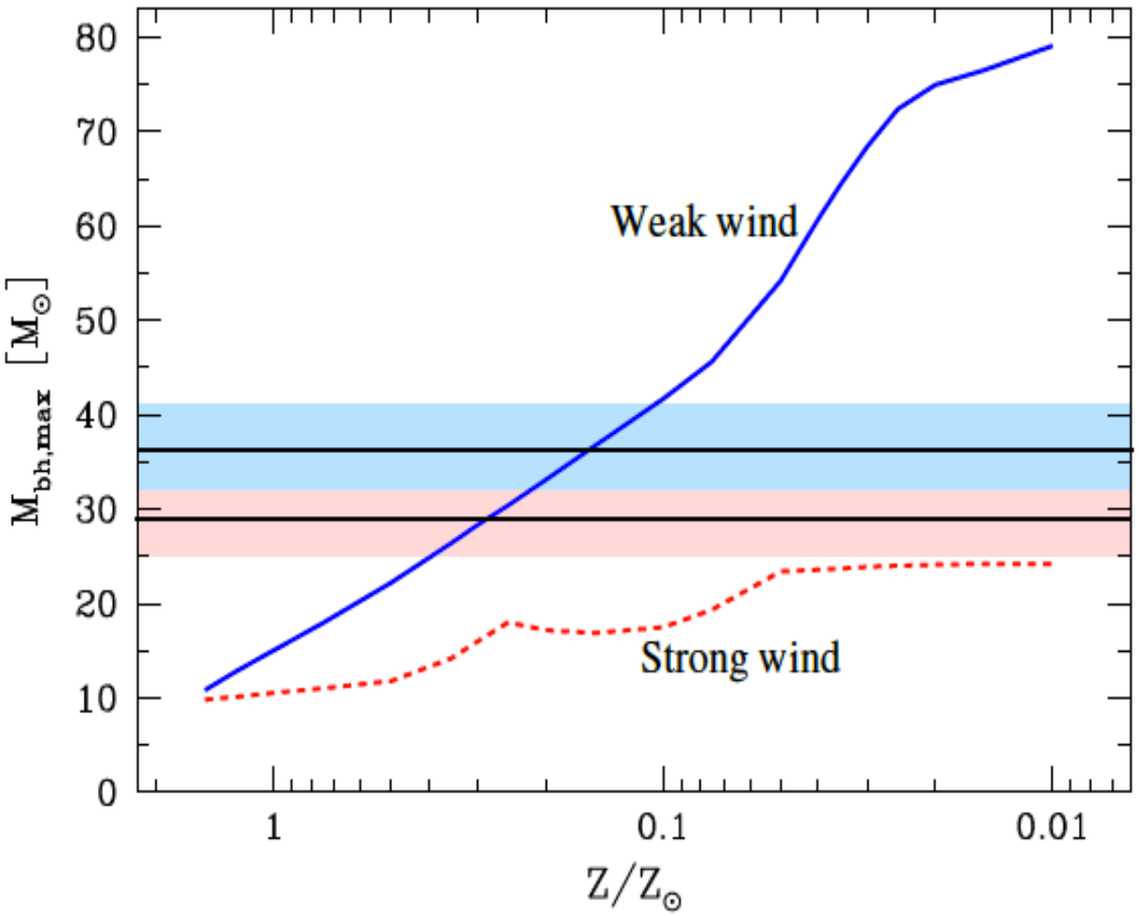


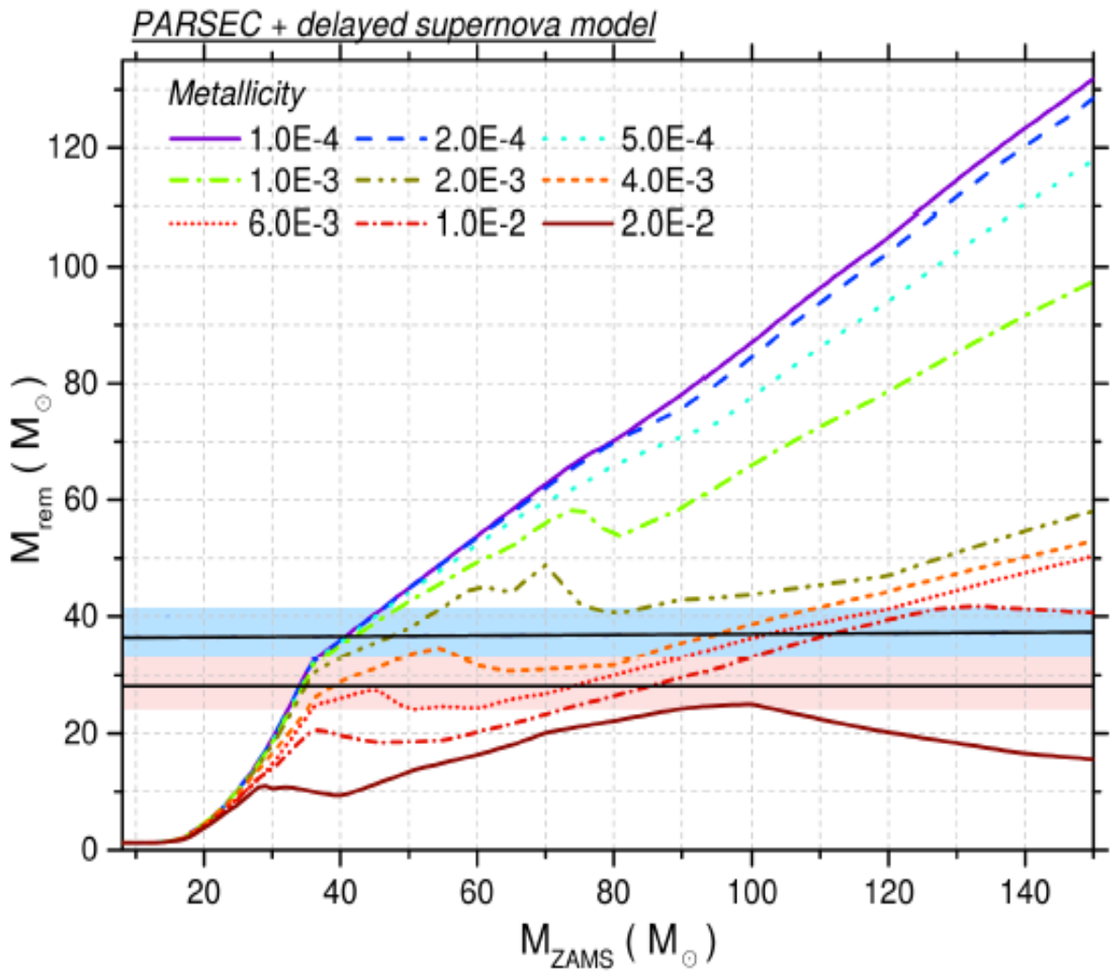

- Rates from GW150914 : 2-600 $Gpc^{-3}$ $yr^{-1}$
- New combined rate estimate : 9-240 $Gpc^{-3}$ $yr^{-1}$

# Mass & Spins

- Large error in spin measurements
- Hard to distinguish possible formation channels
- Have shown that at least one BH in GW151226 is spinning
- No evidence for precession

# BH formation

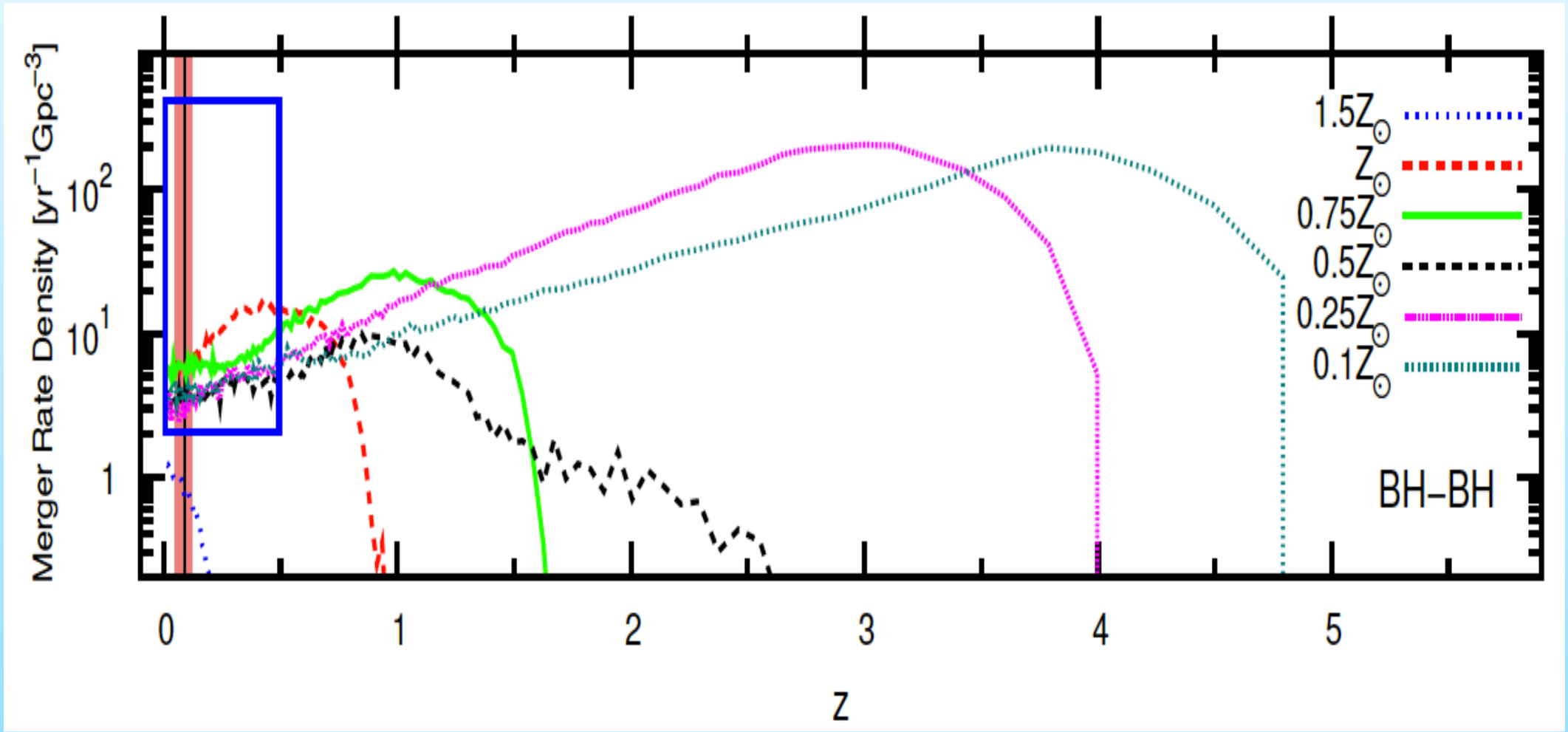



e.g. GW150914

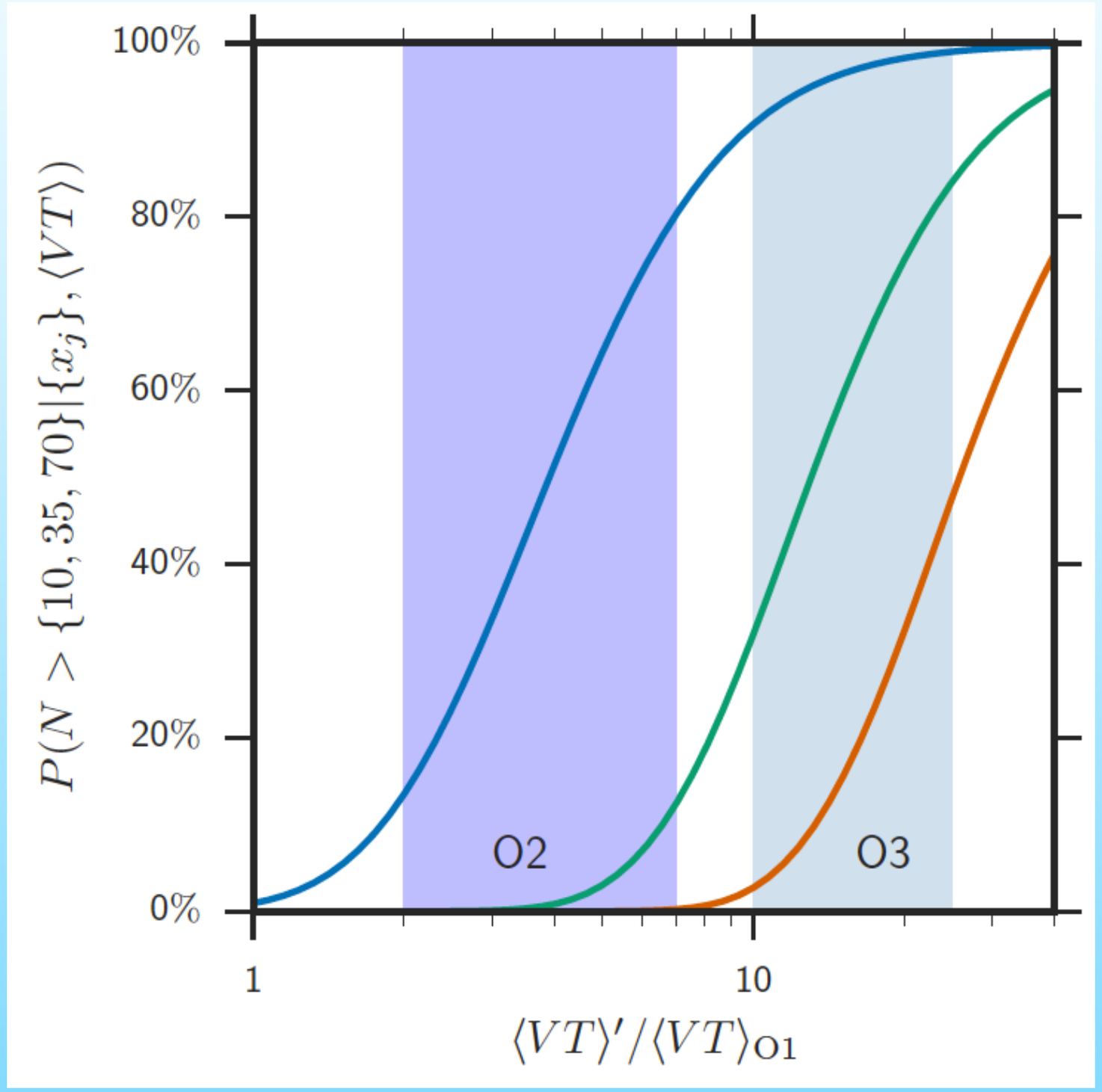
$Z_\odot = 0.02$

# BBH mergers in the local Universe




- Not possible to measure the BH mass function with 3 detection

# O2 - Oct 2016


100%
80%
60%
40%
20%
0%
$P(N > \{10, 35, 70\} | \{x_j\}, \langle VT \rangle)$
O2
O3
1
10
$\langle VT \rangle' / \langle VT \rangle_{O1}$

# Conclusion

- Very successful O1
  - 3 direct measurements of BBH mergers
  - BBHs come in a range of flavours
  - Total mass still heavier than anything seen in x-ray binaries
  - Evidence that at least one of the BHs had a spin of > 0.2, no evidence for precession, final spins quite low ~0.7, no extremal BHs
  - BBH astrophysical event rate is 9-240 $Gpc^{-3}$ $yr^{-1}$
  - Still cannot determine formation channel or IMF
  - Expect more detections in O2