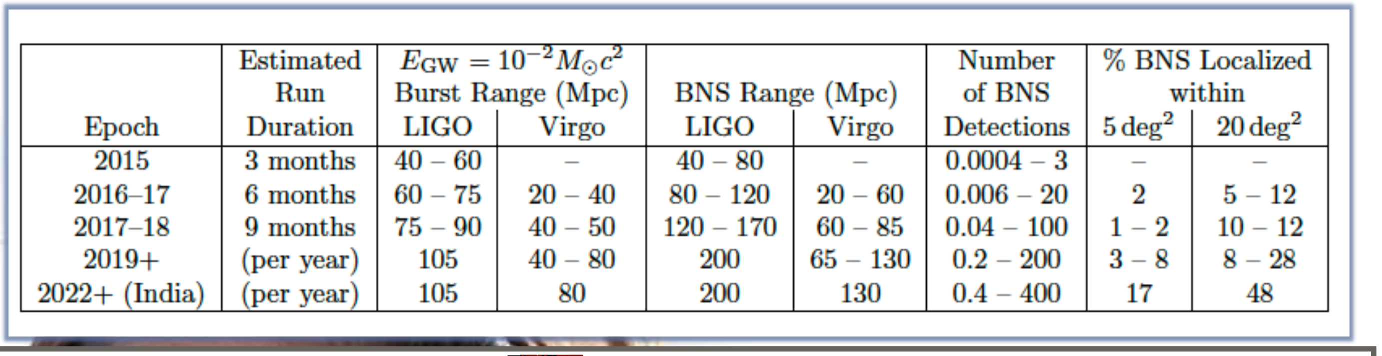
What have we learned from the detection of gravitational waves?

Hyung Mok Lee
Seoul National University

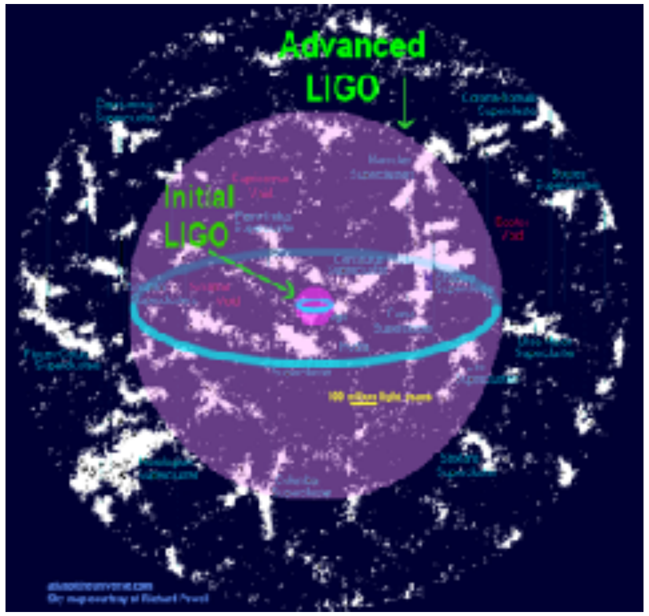
Outline

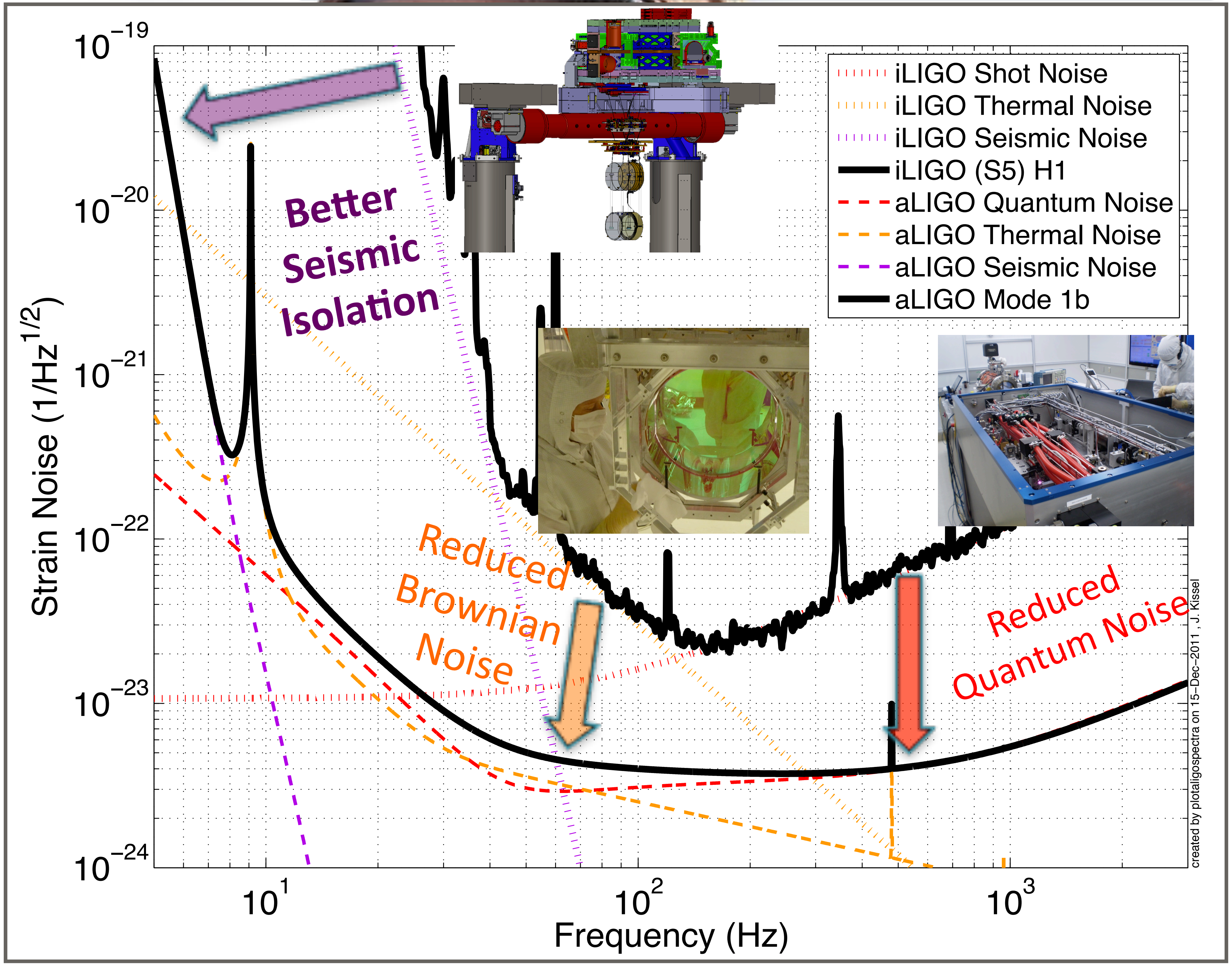
- Summary of 1st and 2nd Observing Runs
- Characteristics of detected sources
- Astrophysical Implications
- Prospects of stochastic background
- Summary

Goal of aLIGO



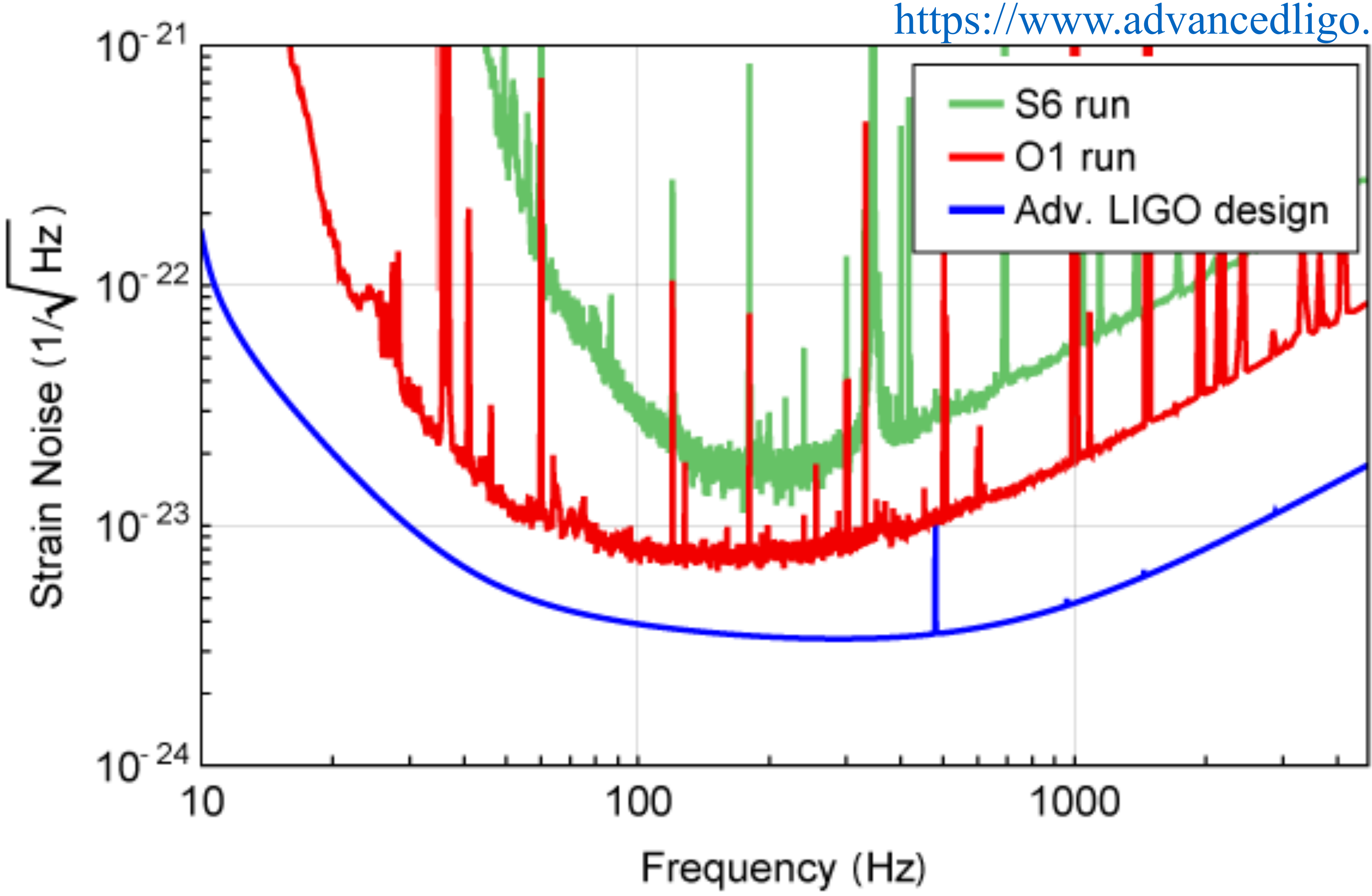
Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48





LIGO Sensitivity during the first and second observing runs [O1/O2]

https://www.advancedligo.mit.edu



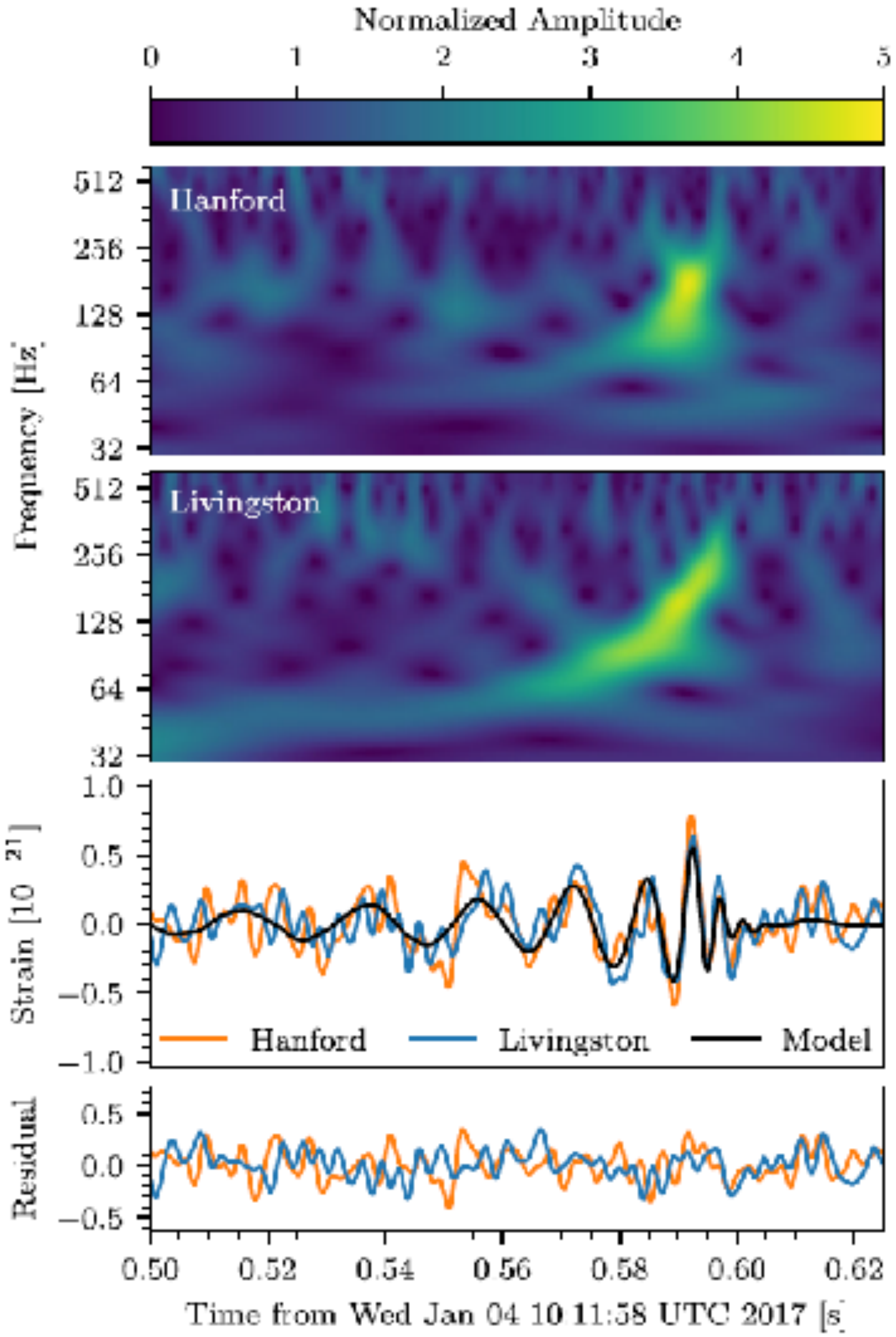
- Sensitivity improvement by x3 made a big difference
- O2 sensitivity is slightly bettern than O1

The 1st Observing Run

- September 12, 2015 - January 19, 2016
- Total coincidence analysis time: 51.5 days
- Total coincidence analysis time after removing noisy data: 48.6 days (~38%)
- Two analysis pipelines: PyCBC and GstLAL
  - PyCBC analysis: 46.1 days
  - GstLAL analysis: 48.3 days

The 2nd Observing Run

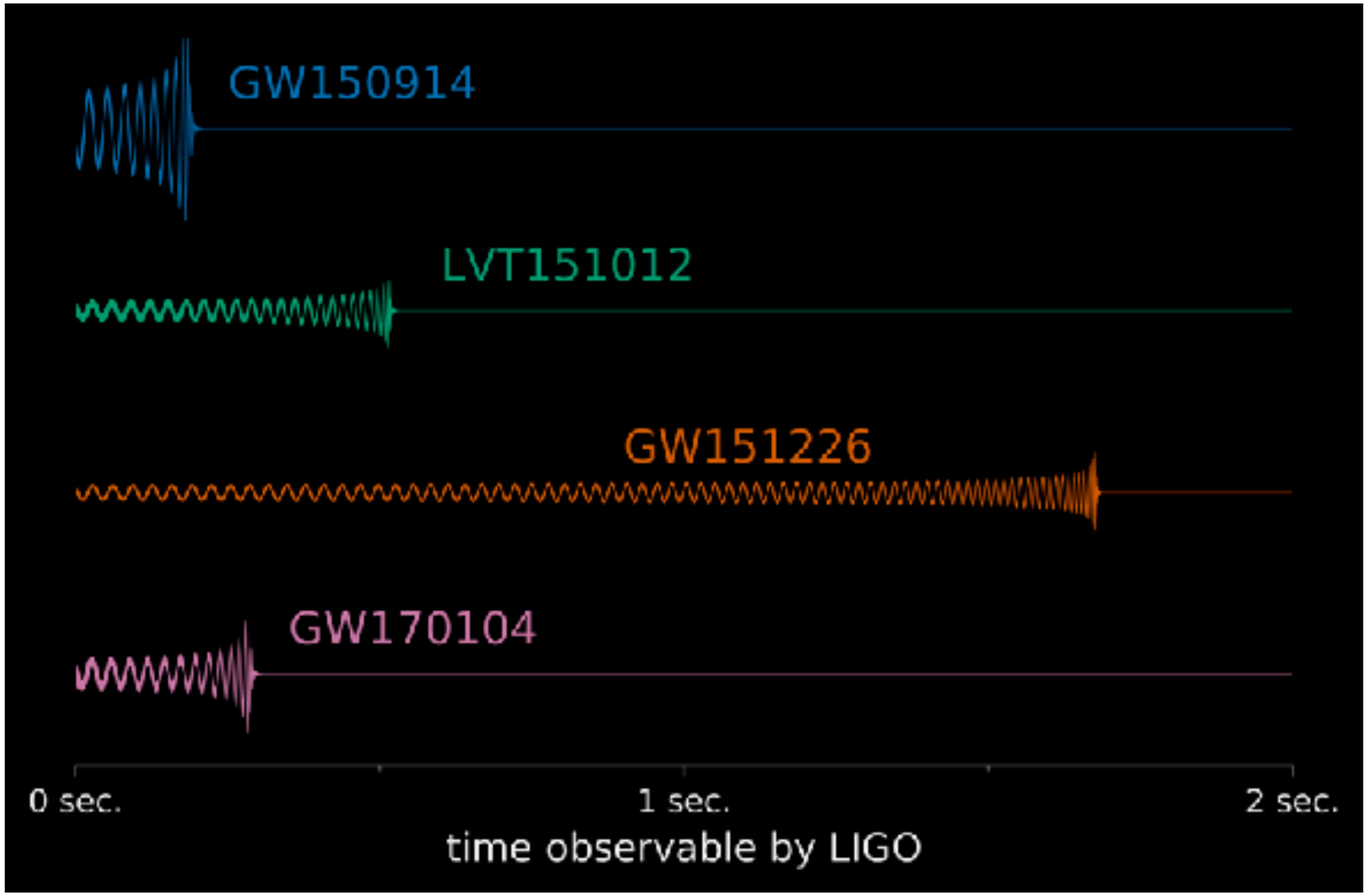
- November 30, 2016 ~
- Total coincidence data (until May 8): 74 days
- One more BH Binary merger event on Jan. 4, 2017 (GW170104) was discovered.



LIGO Collaboration, PRL 118, 221101 (2017)

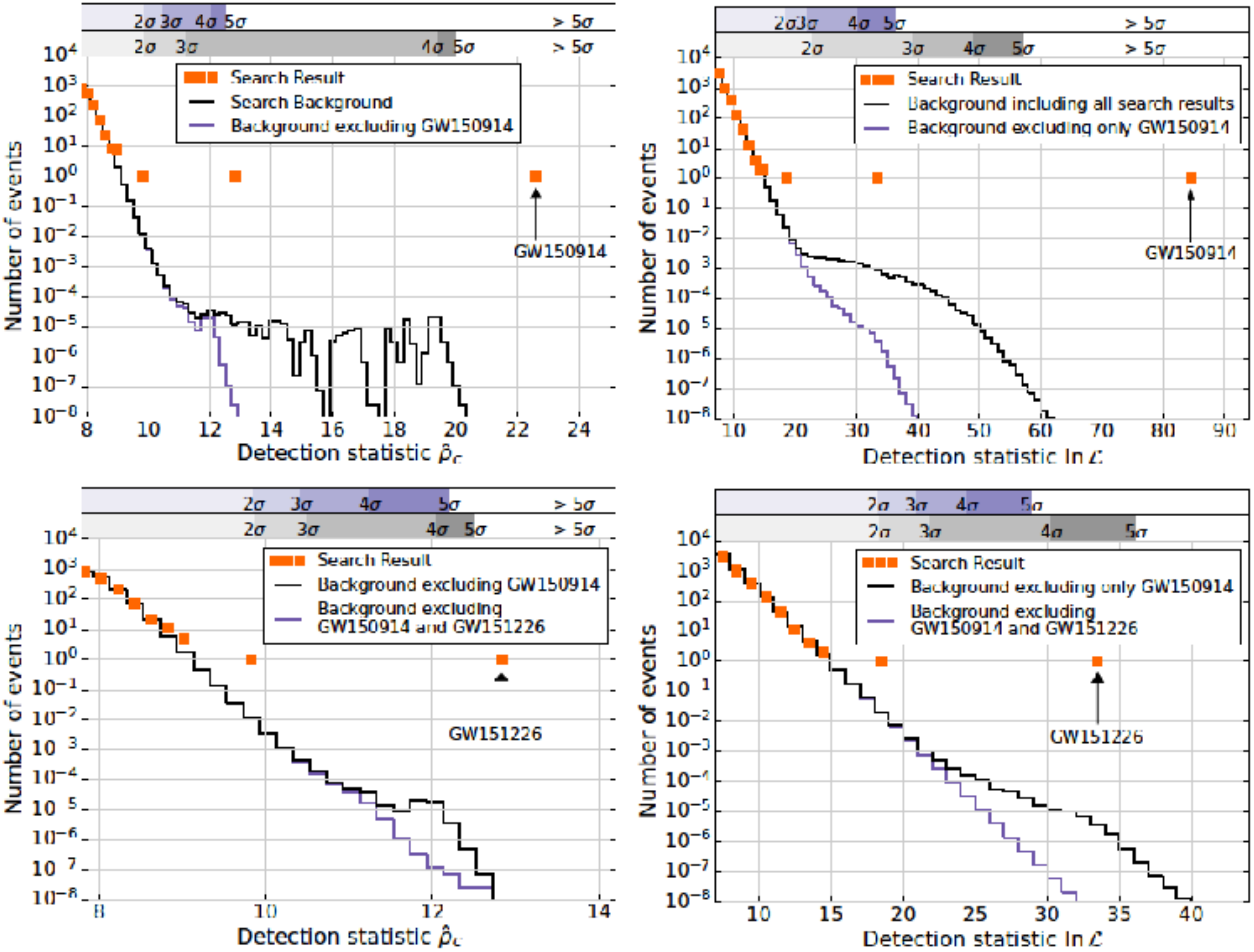
GW Events from O1/O2

- GW150914 (FAR<$6\text{x}10^{-7}$ yr^{-1})
- LVT151012 (Candidate, FAR~0.37 yr^{-1})
- GW151226 (FAR<$6\text{x}10^{-7}$ yr^{-1})
- GW170104 (<$5\text{x}10^{-5}$ yr^{-1}

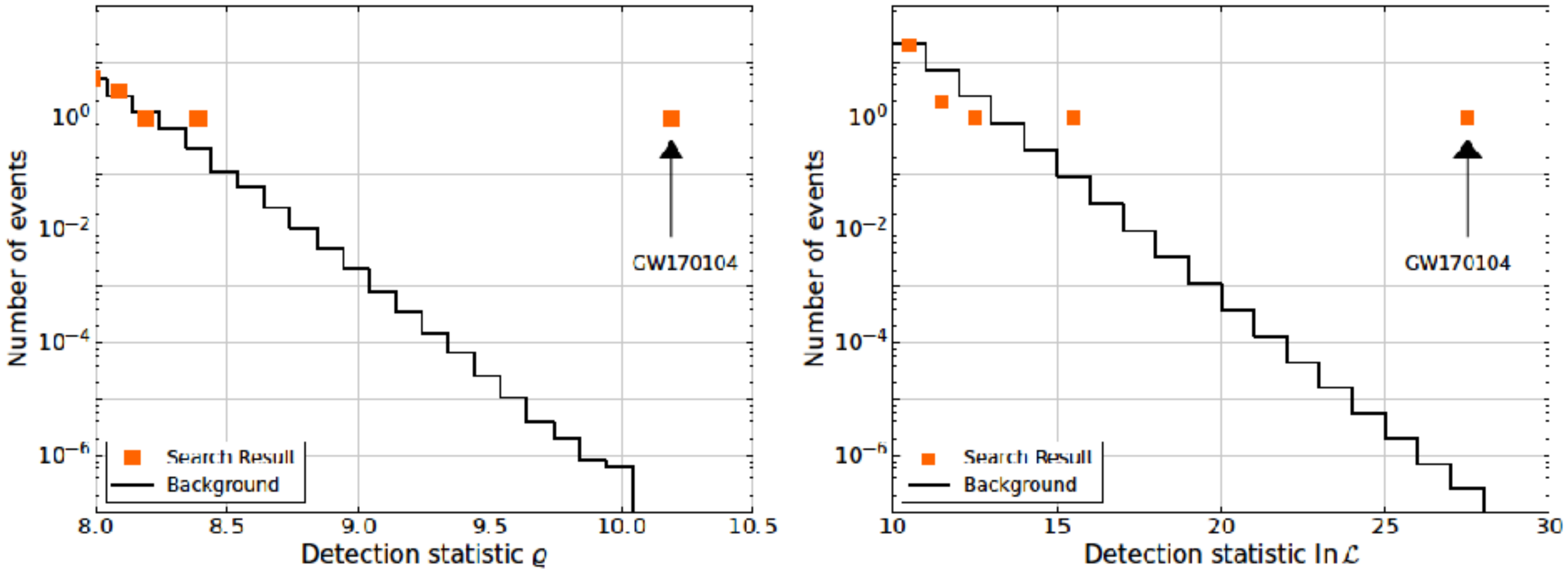


Significance of the events

Abbott et al., arXiv:1606.04856v1



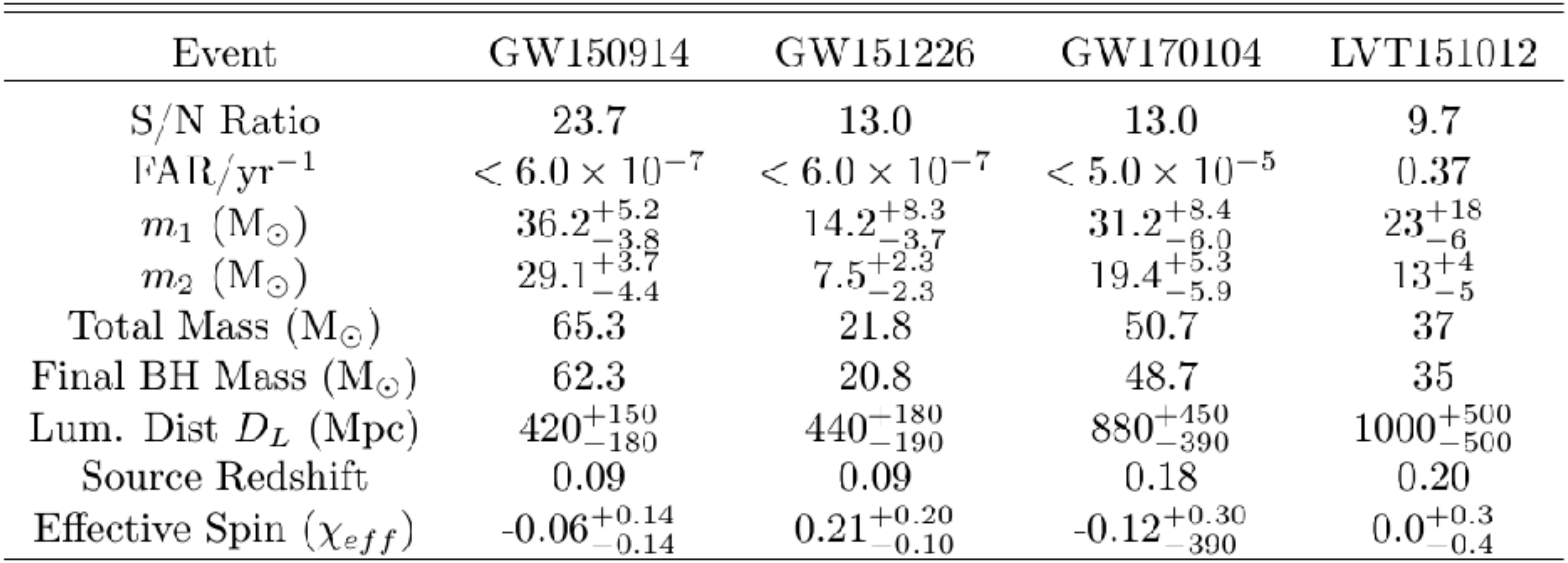
GW170104



[Supplement to PRL 118, 221101 (2017)]

Derived parameters of the events

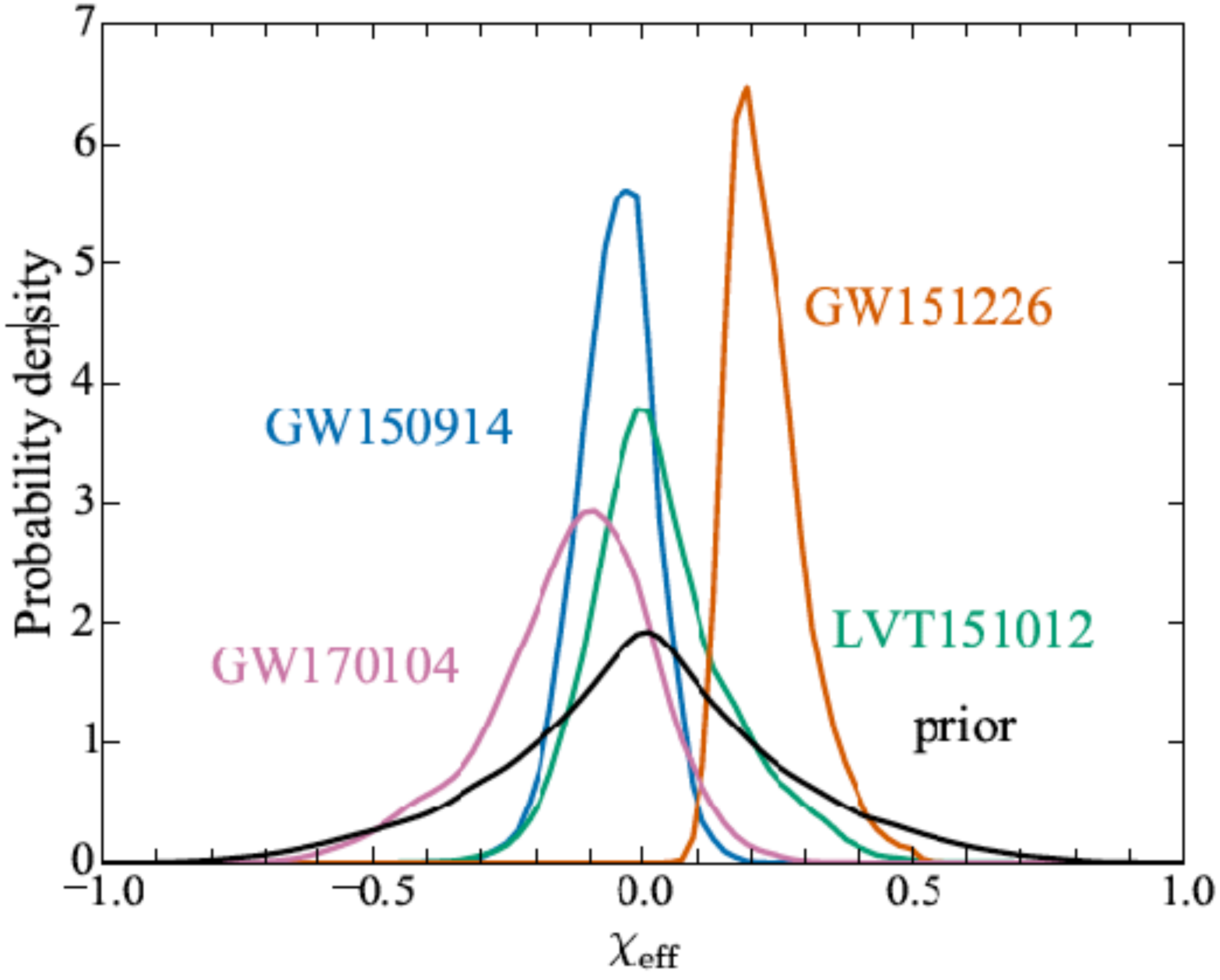
PHYSICAL REVIEW X 6, 041015 (2016)
PRL 118, 221101 (2017)



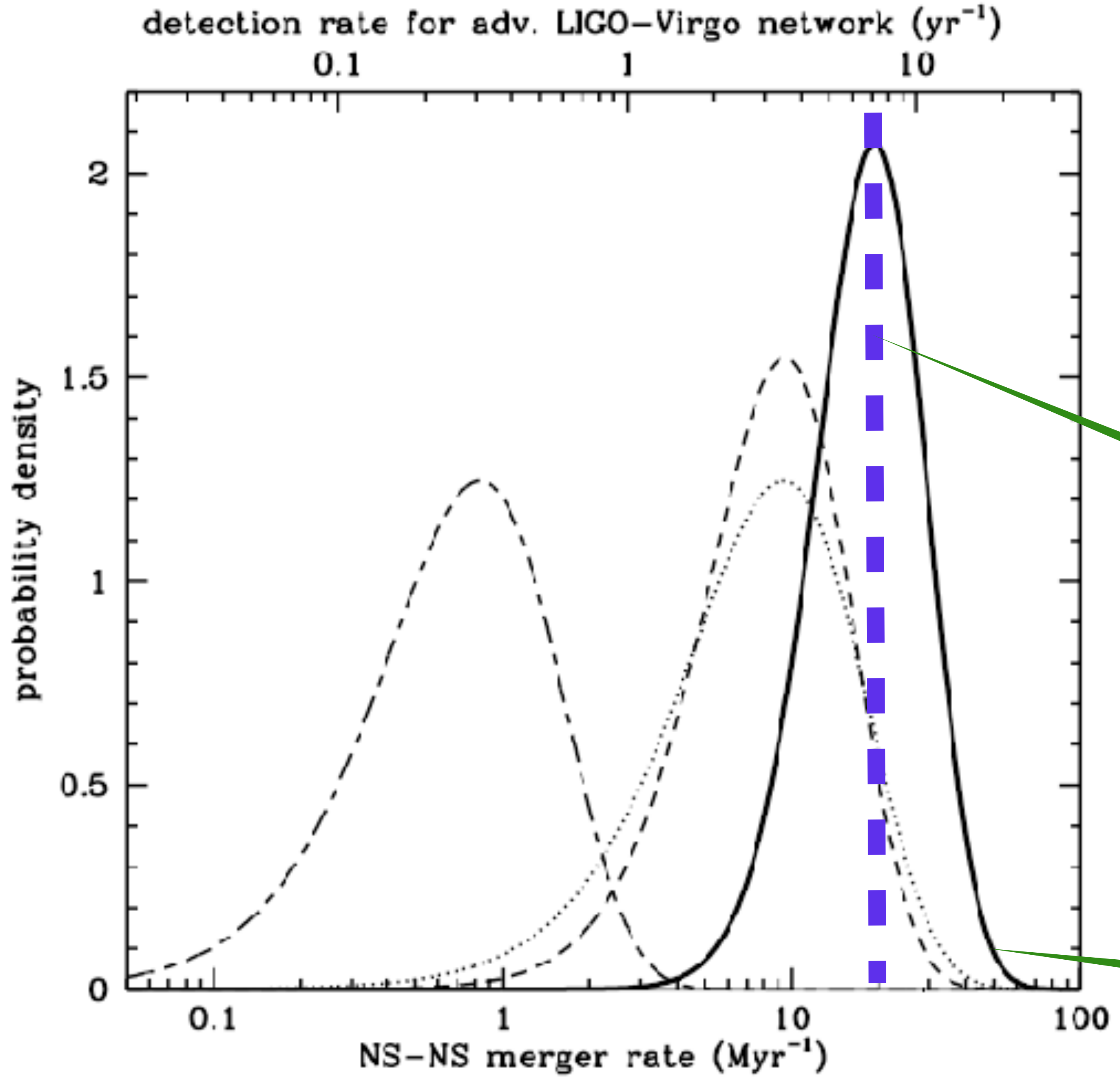
Event	GW150914	GW151226	GW170104	LVT151012
S/N Ratio	23.7	13.0	13.0	9.7
FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	$< 5.0 \times 10^{-5}$	0.37
m_1 (M$_\odot$)	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	$31.2^{+8.4}_{-6.0}$	23^{+18}_{-6}
m_2 (M$_\odot$)	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	$19.4^{+5.3}_{-5.9}$	13^{+4}_{-5}
Total Mass (M$_\odot$)	65.3	21.8	50.7	37
Final BH Mass (M$_\odot$)	62.3	20.8	48.7	35
Lum. Dist D_L (Mpc)	420^{+150}_{-180}	440^{+180}_{-190}	880^{+450}_{-390}	1000^{+500}_{-500}
Source Redshift	0.09	0.09	0.18	0.20
Effective Spin (χ_{eff})	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$-0.12^{+0.30}_{-390}$	$0.0^{+0.3}_{-0.4}$

Surprises

- Black hole binaries are more frequent than previously thought
  - 12-210 yr^{-1} Gpc^{-1}
- Black holes are not spinning rapidly
- Spins may not be aligned
  - Only effective spins are measured, but the values are small in all cases
  - There is a hint of anti-alignment for GW170104: constraint on formation channel?



How about neutron star merger



- Double pulsar PSR J0737-0309 provides better constrains on beaming angle

Kim et al. 2015

- ~7 /year within advanced detector ranges
- NS merger require better sensitivity than now.

In our galaxy, ~20/Myr

Estimation of masses

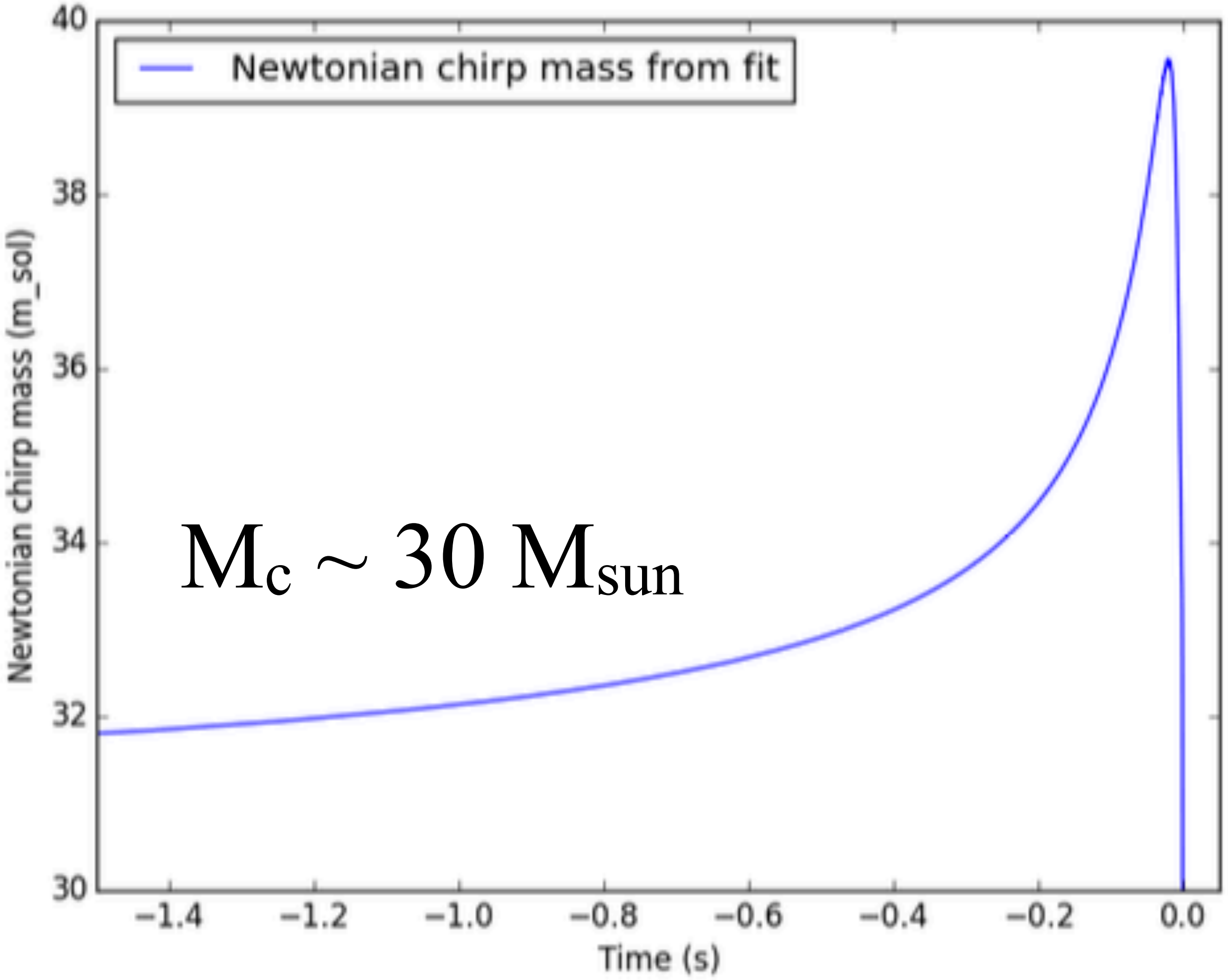
- Assuming Keplerian orbit and Einstein's quadruple formula for GW emission

$$\frac{d}{dt}E_{GW} = \frac{1}{5}\frac{G}{c^5}\sum_{i,j=1}^{3}\frac{d^3}{dt^3}Q_{ij}\frac{d^3}{dt^3}Q_{ij}$$

- The chirp mass is related with frequency and frequency derivative

$$M_c = \frac{c^3}{G}\left[(5/96)^3\pi^{-8}f^{-11}\dot{f}^3\right]^{1/5}$$

where $$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$



$M_c \sim 30\ M_{sun}$

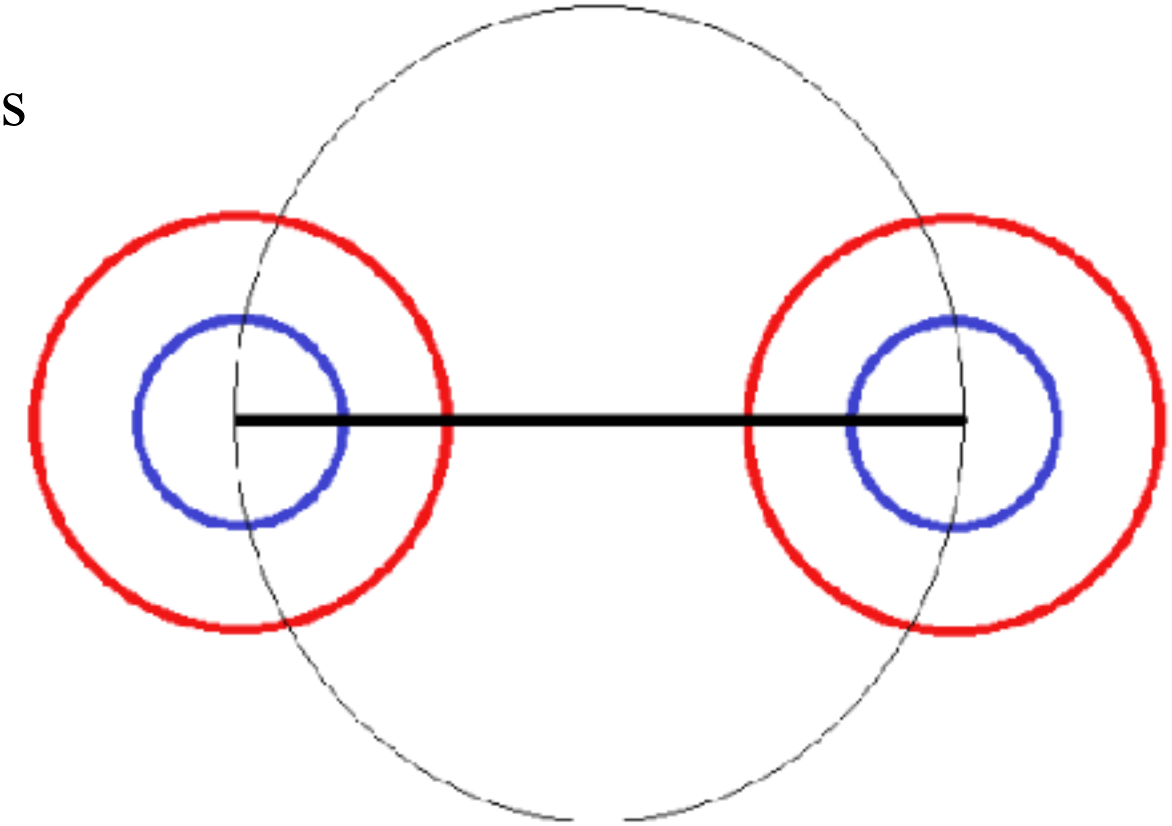
Allen et al., LIGO T1500566-v7

Nearest approach before the merger

- If the binary was composed of equal mass, Mc= 30 M_{sun} corresponds to $m_1 = m_2 \sim 35\ M_{sun}$.
- If we assume Keplerian motion of BH, the highest freq. before merger 150 Hz corresponds to Keplerian freq. of 75 Hz.
- The orbital separation at that point is

$$R = \left[\frac{GM}{\omega^2_{Kep,max}}\right]^{1/3} = 347\ \mathrm{km}$$

- Note that the Schwarzschild radius of 70 M_{sun} BH is 103 km.
- Neutron stars can sufficiently compact (~20 km), but the 30 M_{sun} is well above NS mass

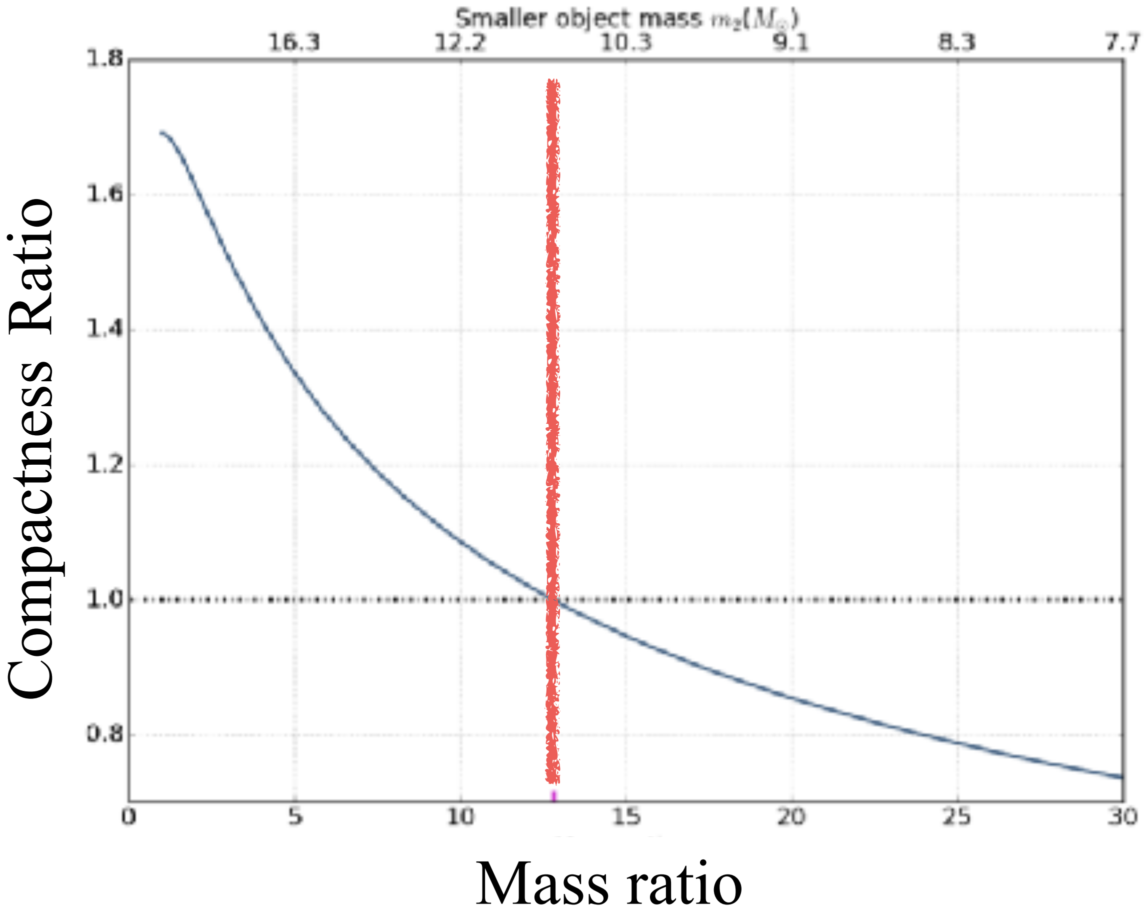


Red: 3 R_s, Blue 1 R_s

Allen et al., LIGO T1500566-v7

Can one star be a neutron star?

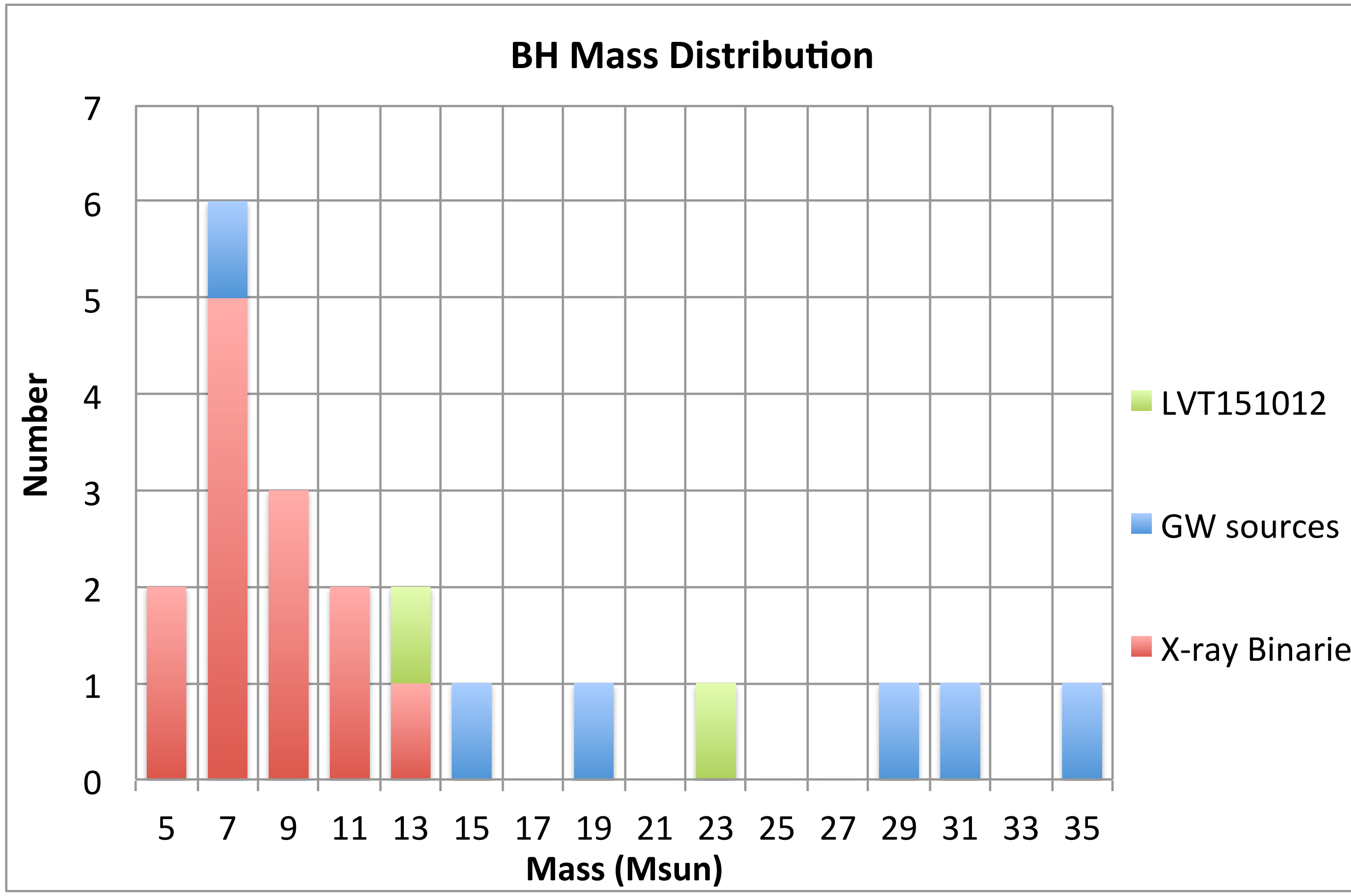
- If the binary was composed of unequal masses, the compactness ration $\mathcal{R}=R/0.5R_s$ decreases as mass ratio increases ($0.5R_s$ was used for minimum size to allow extremal Kerr BH)
- In order to keep $\mathcal{R}>1.0$, $q<12.8$.
- Maximum $m_1= 432$ M_{sun}, and thus minimum $m_2\sim 11$ M_{sun}.
  - More massive than NS mass.



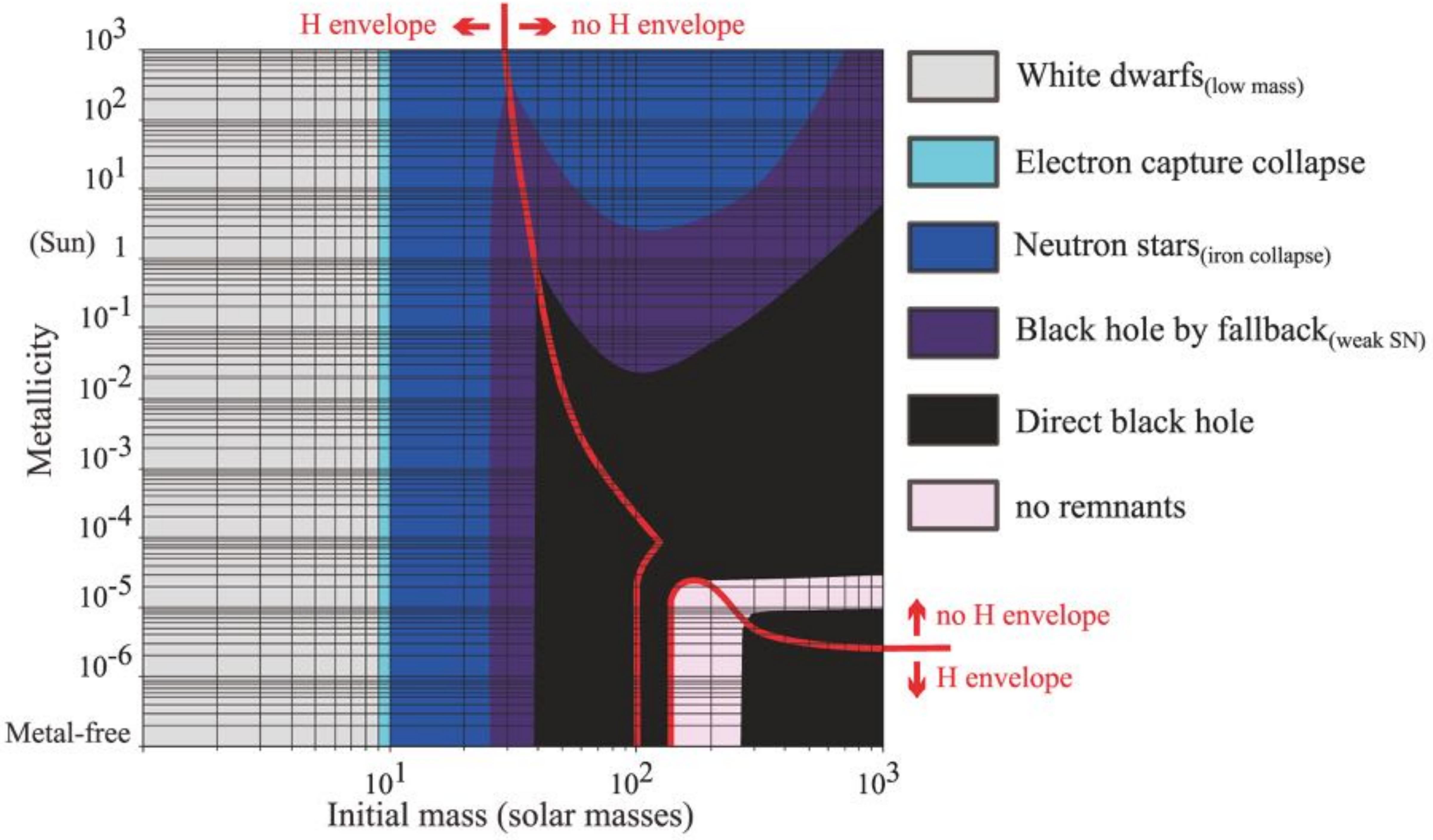
Allen et al., LIGO T1500566-v7

Black Hole Masses: X-ray binary versus GW sources

- Most of the known black holes from X-ray sources have typical mass between 5-15 M_{sun}.
- GW sources cover much wider mass range
- GW merger also leaves BHs of higher masses (up to 62 M_{sun})



Remnants of massive single stars

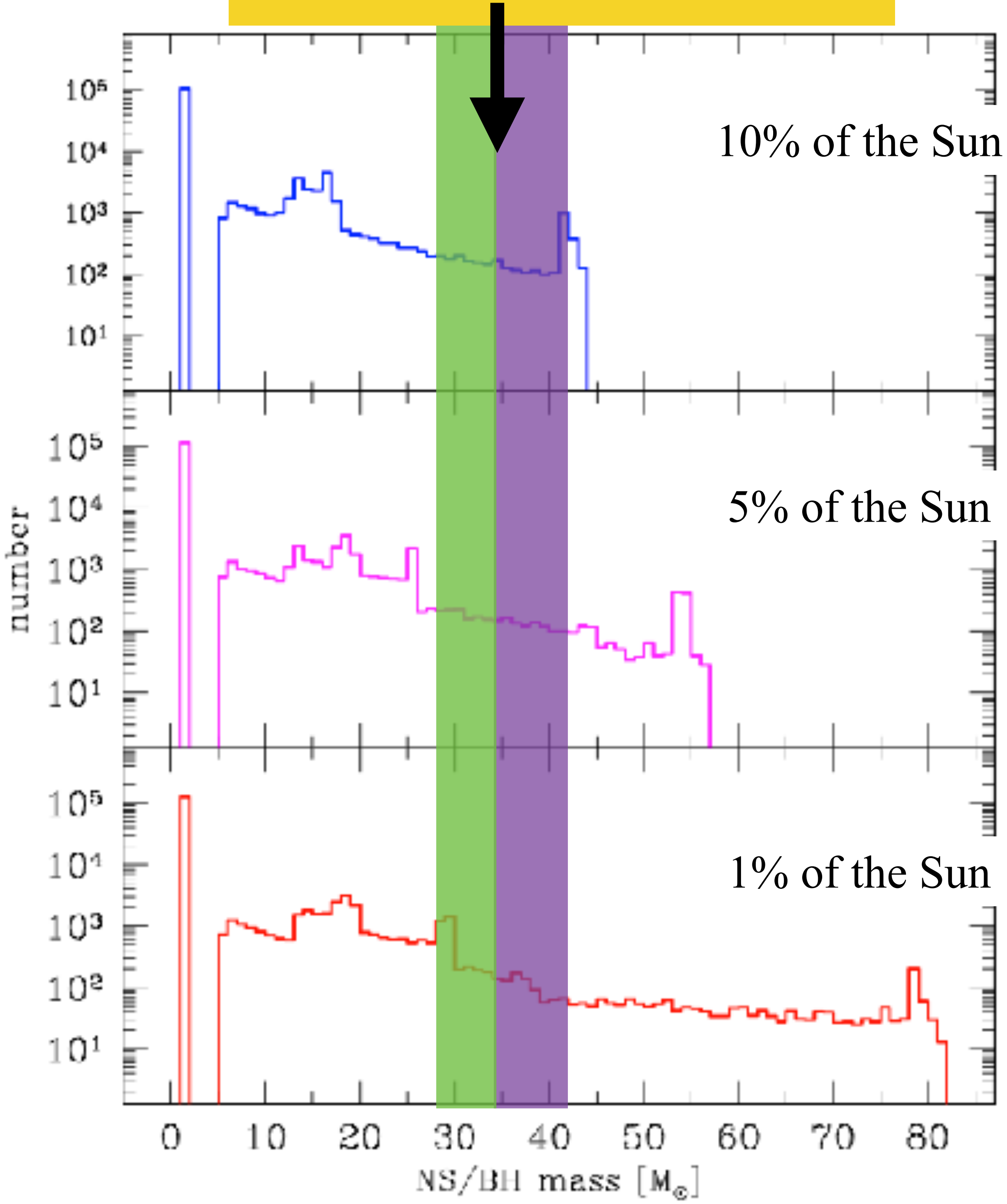


Heger et al. 2000

What determines the mass of the black holes?

- BH mass depends on the progenitor star
- Mass also determines the remnant mass
- Stellar winds depends on metallicity
- Lower metallicity stars leave higher mass BHs
- GW 150914 may have formed from stars with $Z<0.1\ Z_\odot$.

GW150914 masses



Data provided by Belczynski

Formation channels of black hole binaries

- Evolutionary formation channels
  - Evolution of binaries composed of two massive stars
  - How to get black holes close enough to merge within Hubble time
- Dynamical formation Channels
  - Three-body processes, direct capture etc
  - How to form binaries efficiently from single black holes?
- Primordial Black Hole Binaries

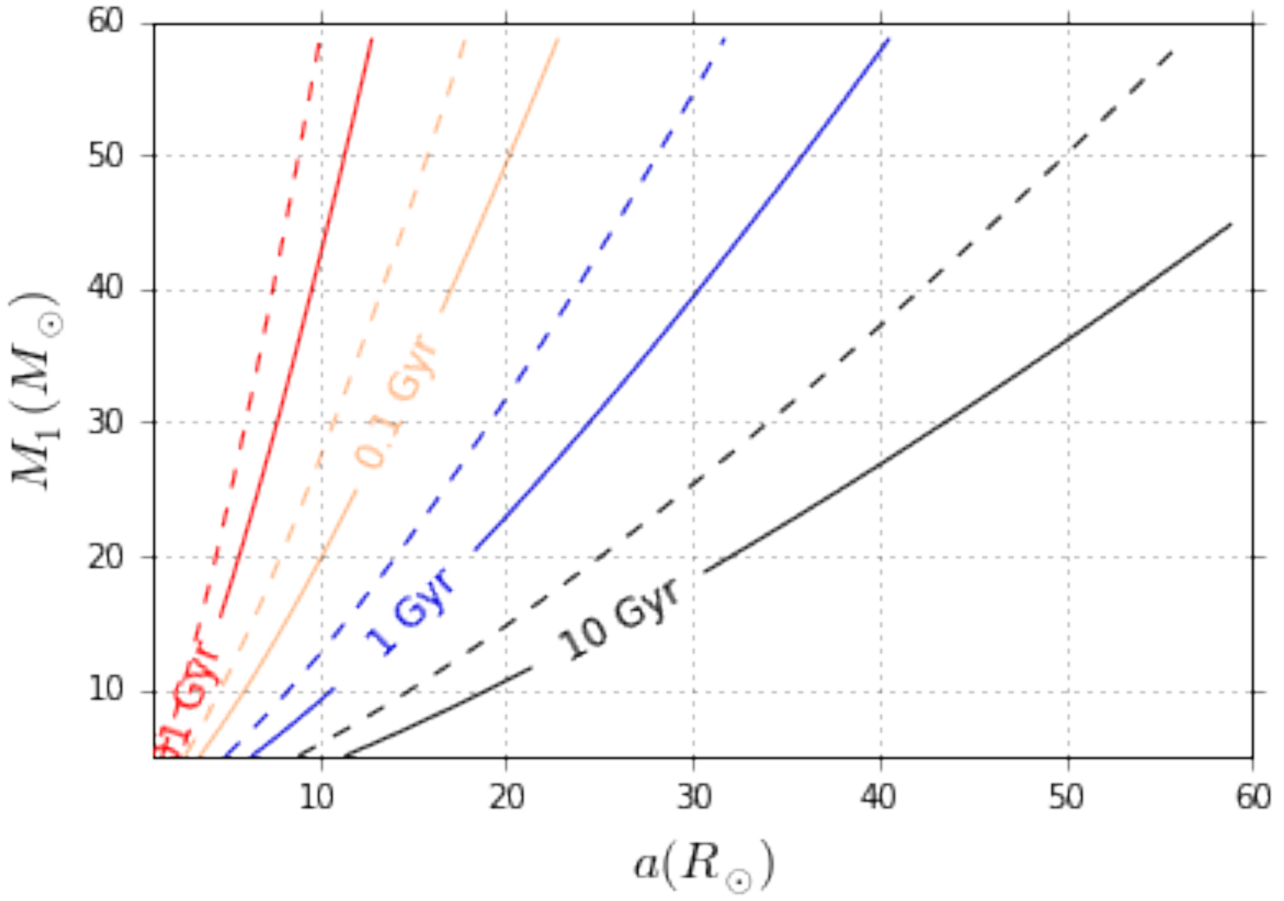
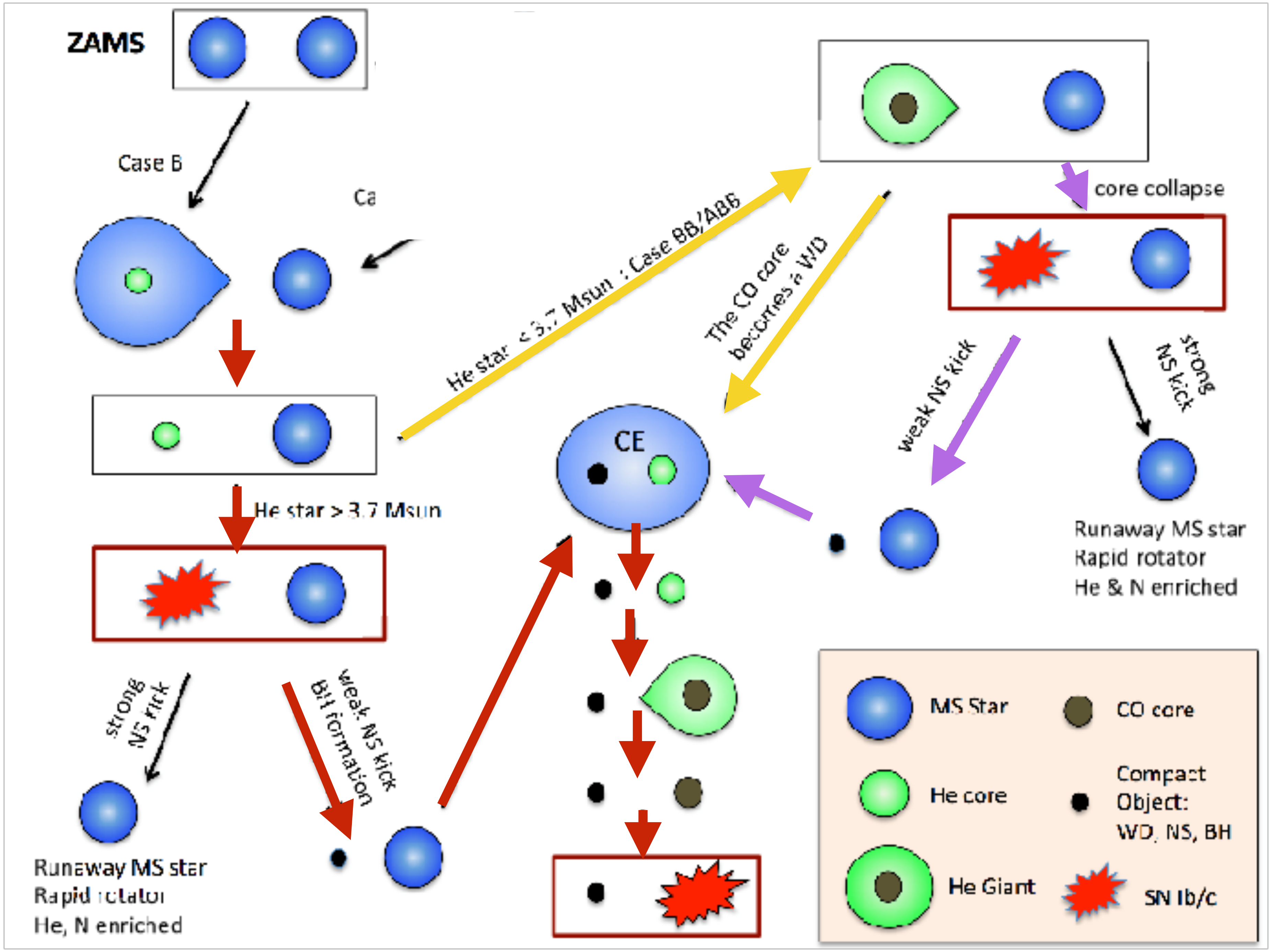


Figure credit: de Mink

Formation of Compact BH (or NS) binaries

(Sung Chul Yoon, 2015)

Common envelope phase is necessary for the formation of very compact BH (or NS) binaries



Formation Rates of BH Binaries

- Gravitational Wave Capture in parabolic approximation

$$\Sigma_{cap} \approx 17 \frac{G^2 m^2}{c^{10/7} v_\infty^{18/7}} \qquad \left(\frac{dn}{dt}\right)_{cap} = \frac{1}{2} < n^2 \Sigma_{cap} v_{rel} >$$

- Three-body processes (Goodman & Hut 1983)

$$\left(\frac{dn}{dt}\right) \approx 0.2 n^3 \frac{(Gm)^5}{\sigma^9}$$

Which is more efficient?

- Capture versus 3-body processes

$$\frac{(dn/dt)_{cap}}{(dn/dt)_{3B}} \approx 0.37 \left(\frac{10^5\ \mathrm{pc}^{-3}}{n_{BH}}\right)\left(\frac{\sigma}{10\ \mathrm{km/s}}\right)^{52/7}$$

- Globular clusters : $\sigma < 10$ km/s
  - Three-body processes are more efficient [talk by D. Park this afternoon]
- Galactic Nuclei: $\sigma \sim 100$ km/s
  - Direct capture is more efficient
  - However, direct capture gives only small number of events (<1 yr^{-1} Gpc^{-3}, Hong & Lee 2015)

Estimation of rates

- Wide range of predictions for the evolutionary formation models (up to 1000 yr^{-1} Gpc^{-3})
- Dynamical scenario predicts ~ 10 yr^{-1} Gpc^{-3} (Park et al. 2017 and Others)
    - Probably dynamical formation could be more efficient
- One channel dominates?

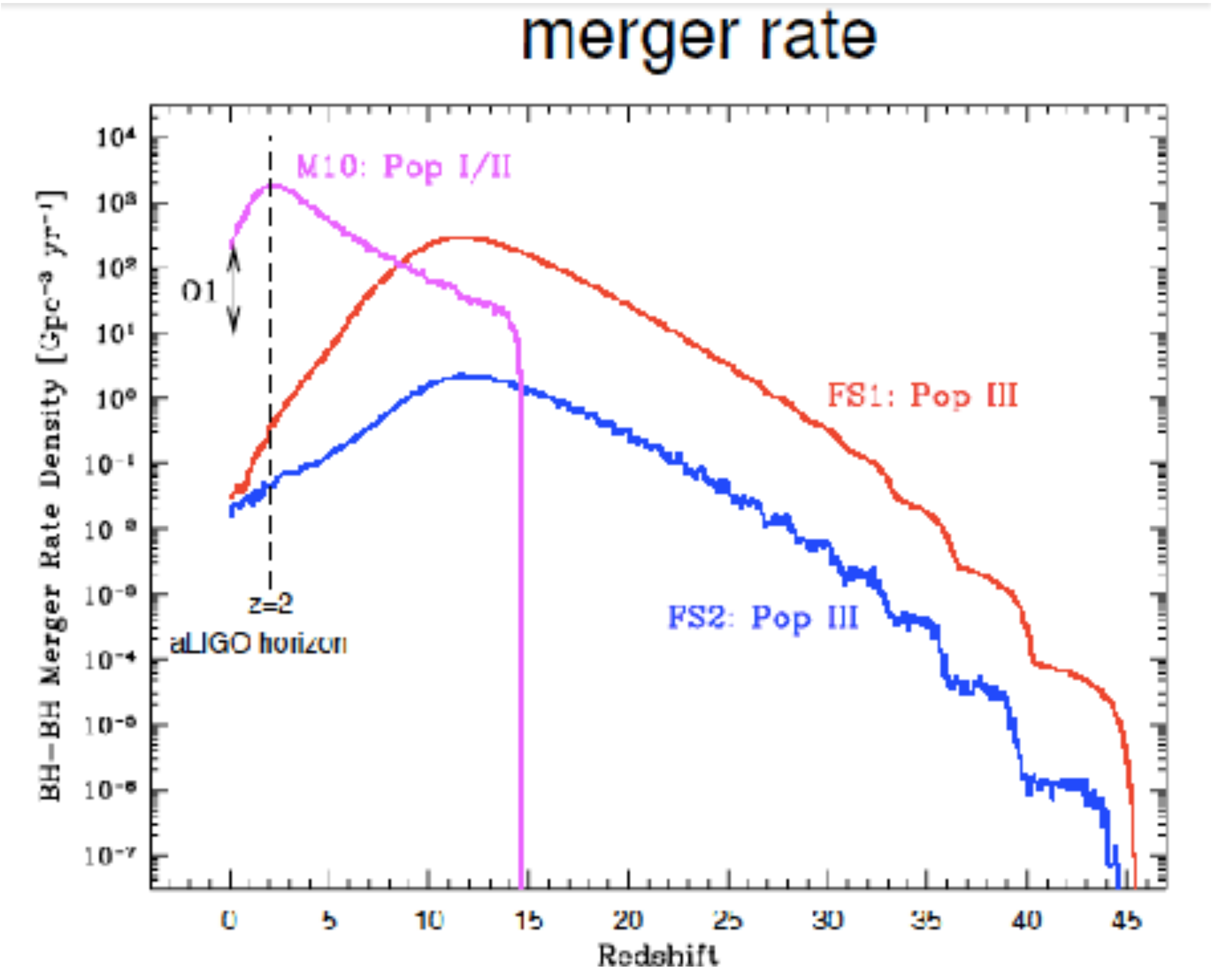


Figure courtesy: Belczynski

GW background

- Incoherent superposition of merging BH could generate stochastic GW background

$$\Omega_{GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$$

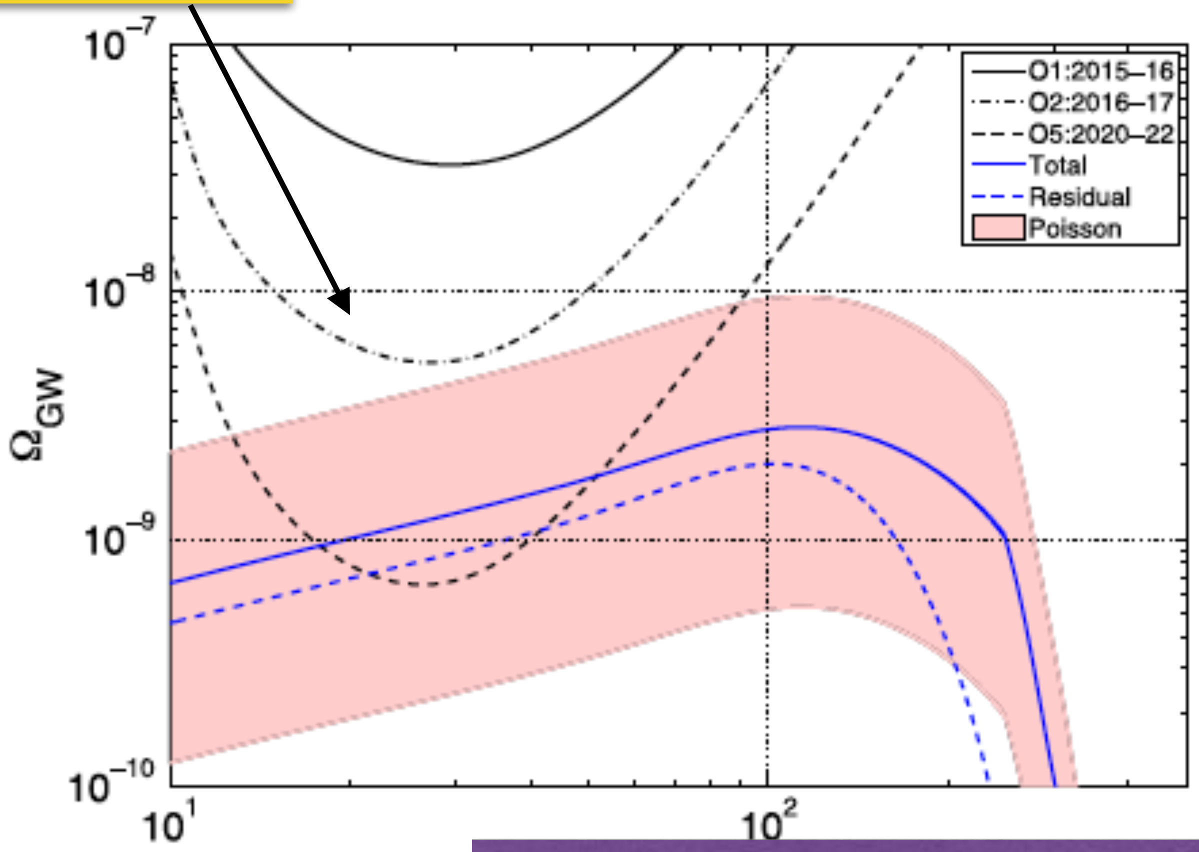
- Consider a BBH of class *k* with parameters θ_k merge at a rate $R_m(z;\theta_k)$ per unit comoving volume, then Ω_{GW} can be obtained by

$$\Omega_{GW}(f) \equiv \frac{f}{\rho_c H_0}\int_0^\infty dz \frac{R_m(z,\theta_k)\frac{dE_{GW}}{df_s}(f_s,\theta_k)}{(1+z)E(\Omega_M,\Omega_\Lambda,z)}$$

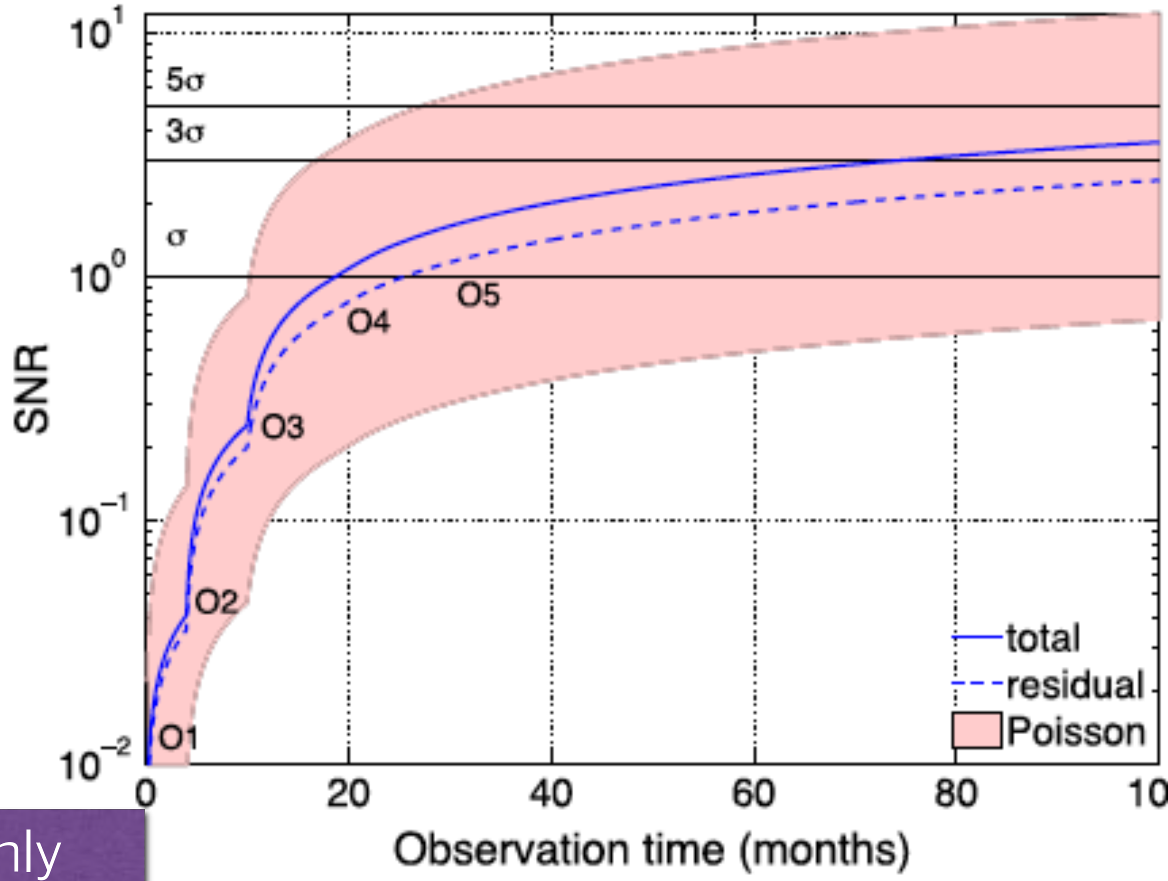
- $E(\Omega_M,\Omega_\Lambda,z)$ captures the dependence of comoving volume on z.
- Fiducial model based on GW150914: mass, rates, spin, etc. and

$$R = 16\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

Detectability



1-σ sensitivity



PRL, 116, 131102 , GW150914 only
PRL, 118, 121101, entire O1 data analysis

- Expected sensitivity of LIGO and Virgo detectors to the fiducial model based on GW150914 mass
  - 33% coincidence for O1 and 50% for all other runs
- The estimation of Ω_{GW} is quite uncertain, but detection may be possible in early 2020

Summary

- LIGO Detected 3 GW events and one candidate
- All detections are black hole binaries, no NS binaries
- NS binary can be detected when LIGO reaches design sensitivity of aLIGO.
  - Expected rate is ~7 per year
- Black holes are typically more massive than those in X-ray binaries
  - They could have been formed in low metallicity environment
- Effective spins are very small.
- There are several channels for the formation of binaries
  - Spin alignment is a good way to distinguish, but measurement of spin is difficult
- Stochastic background of astrophysical origin could be measured in a few years