Gravitational Waves from the First Observing Run of the advanced LIGO

Hyung Mok Lee
Seoul National University

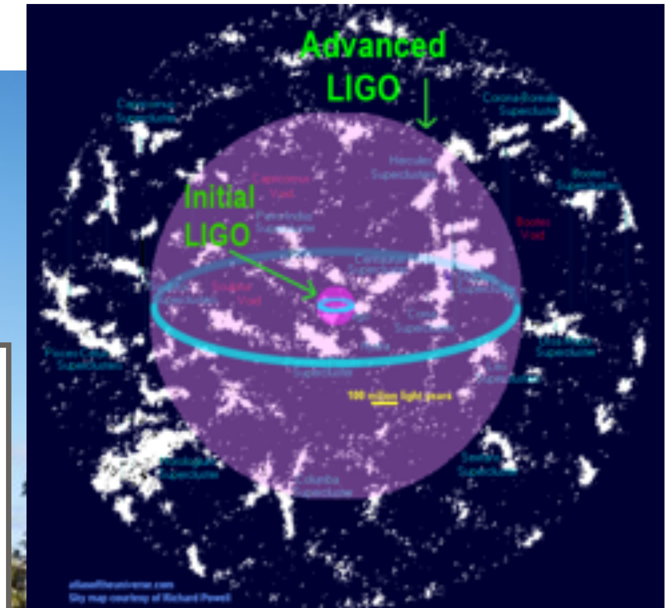
on behalf LIGO-Virgo Collaboration

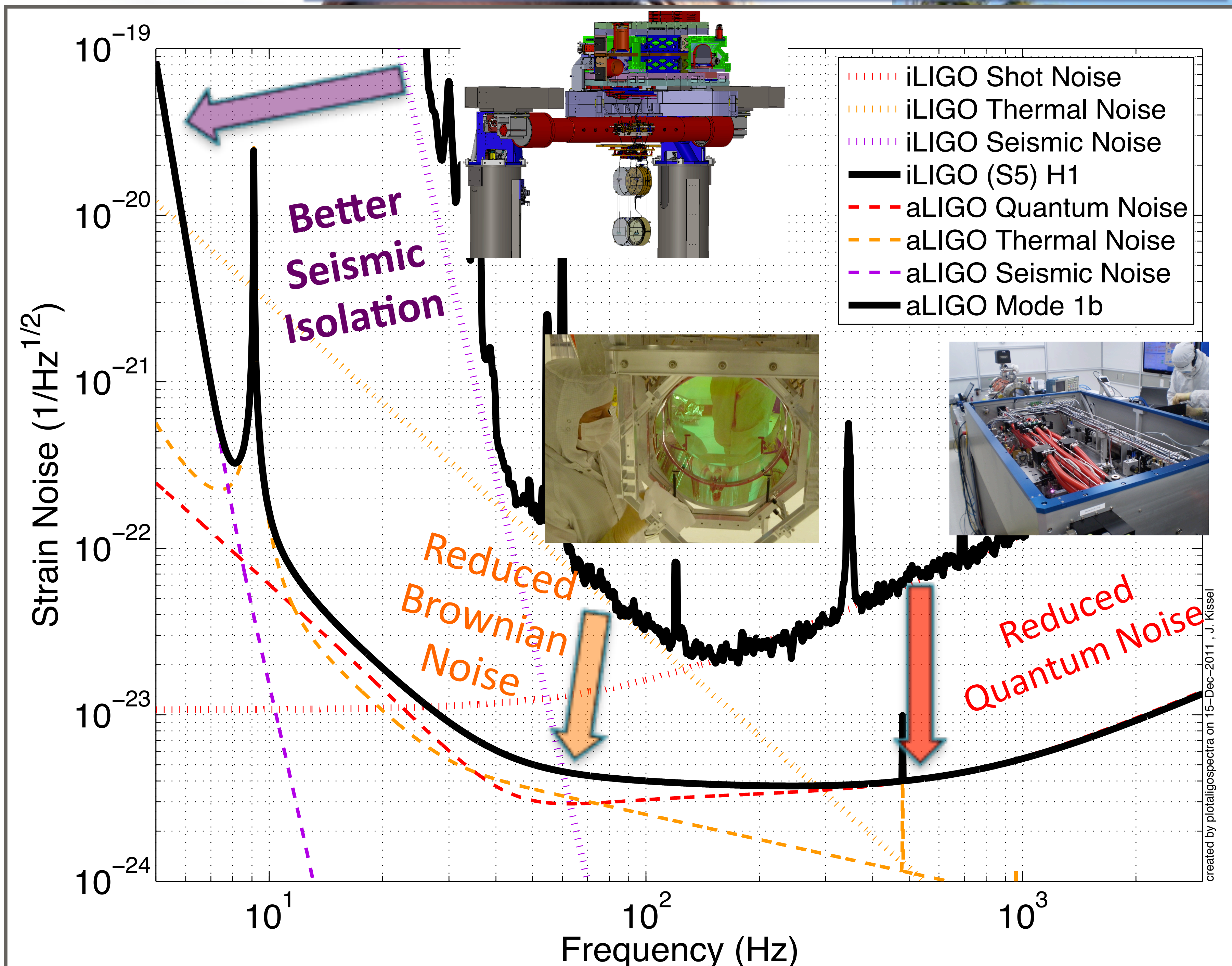
Contents

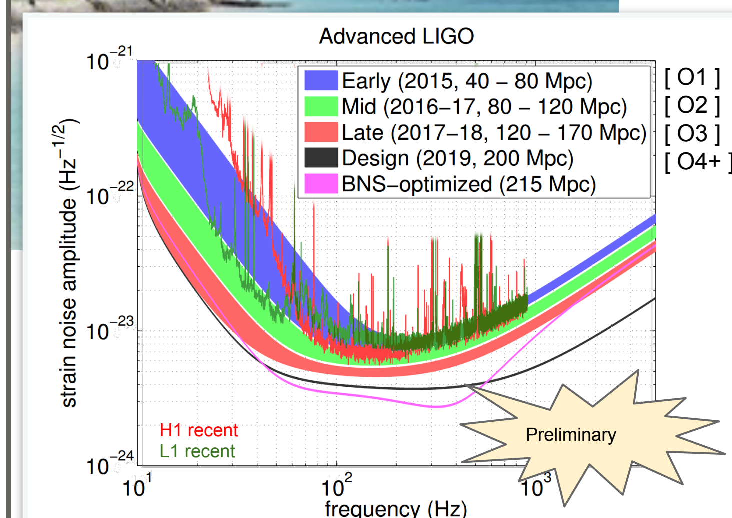
- The Observing Runs of the advanced LIGO
- Two GW events and one candidate
  - GW 150914/GW151226
  - LVT151012
- Implications
  - Background Gravitational Waves
  - Binary Black Holes
- Prospects

Goal of aLIGO

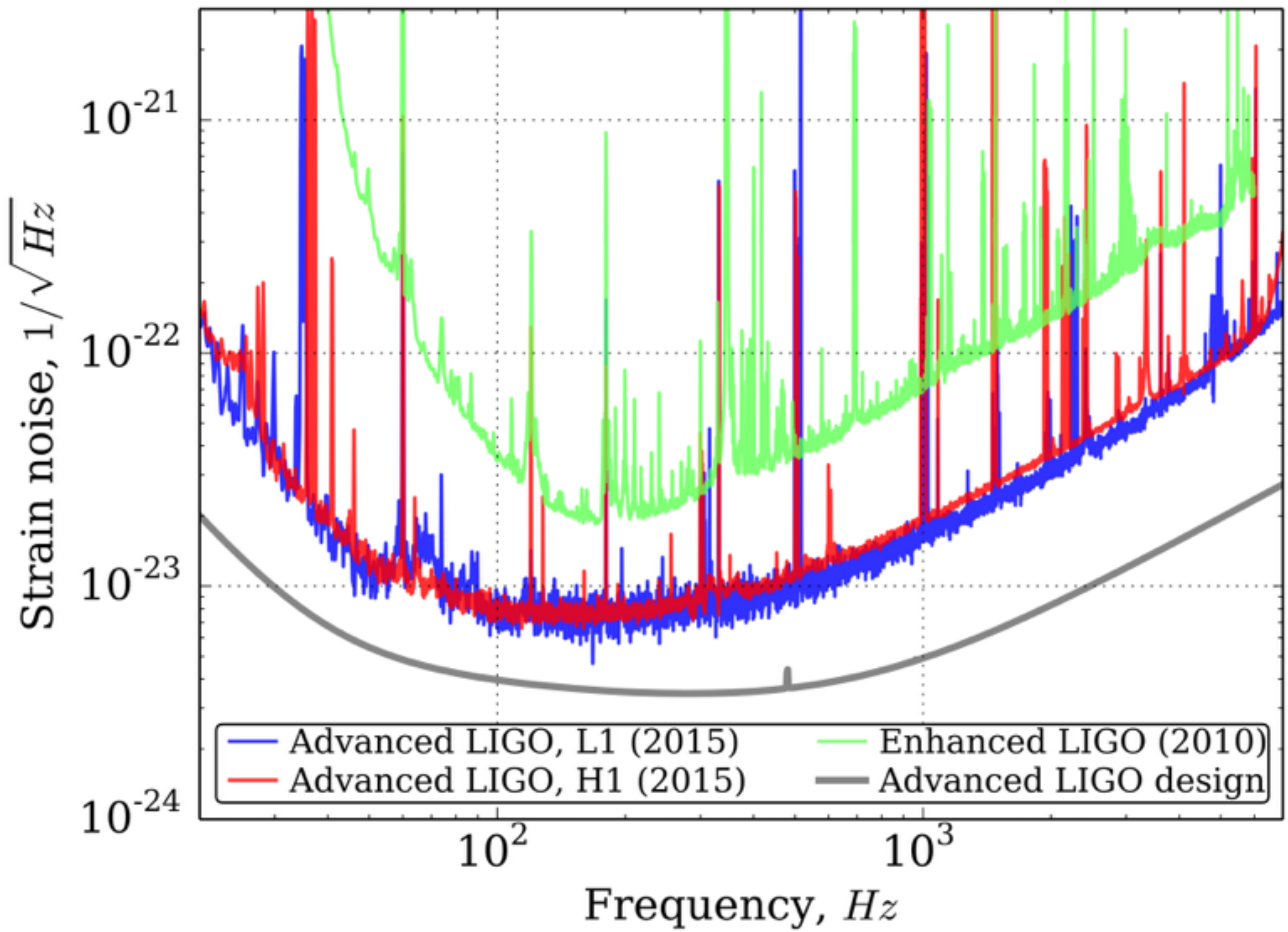
Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
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







O1 Sensitivity



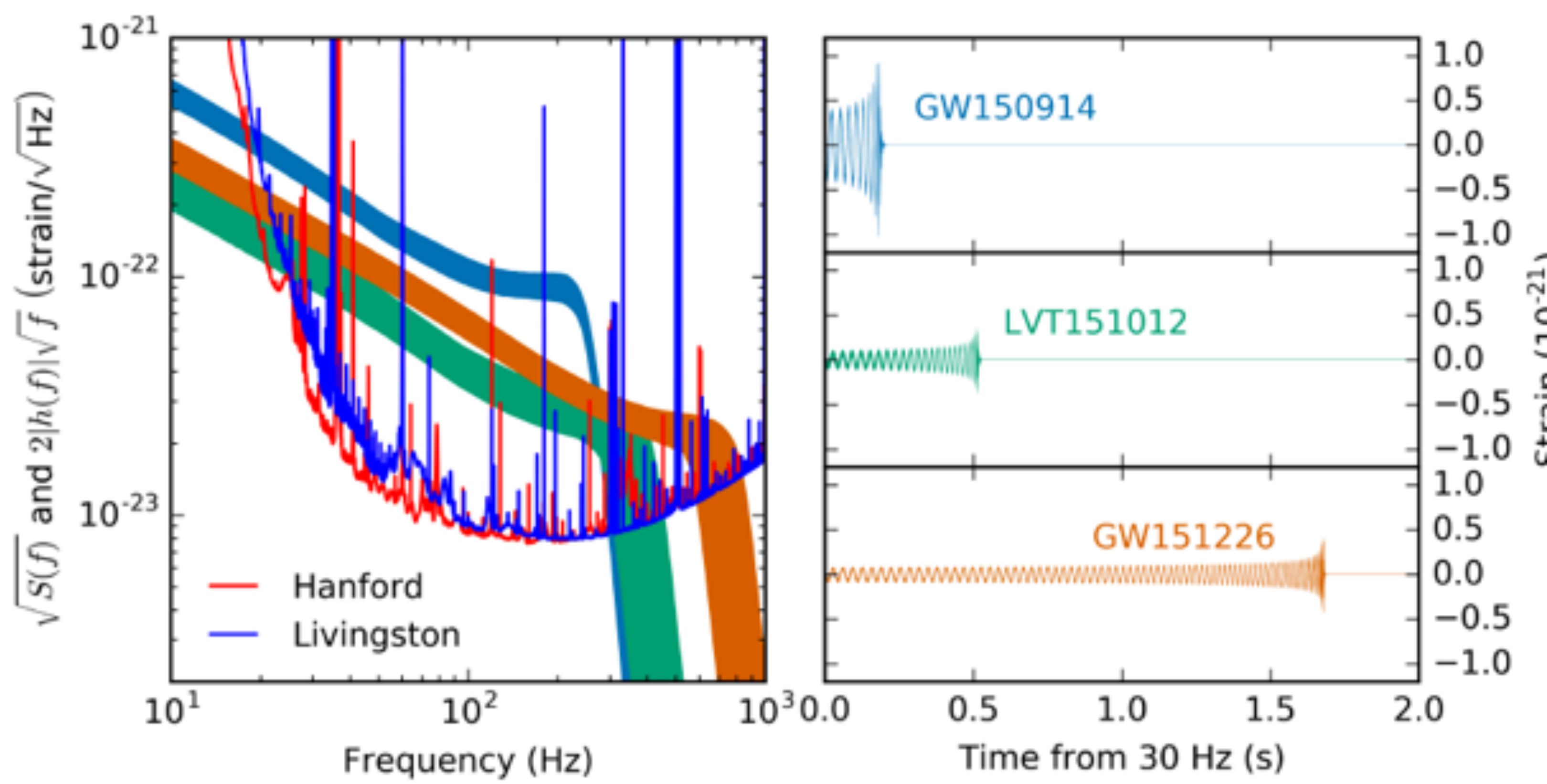
The 1st Observing Run

- 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

GW Events from O1

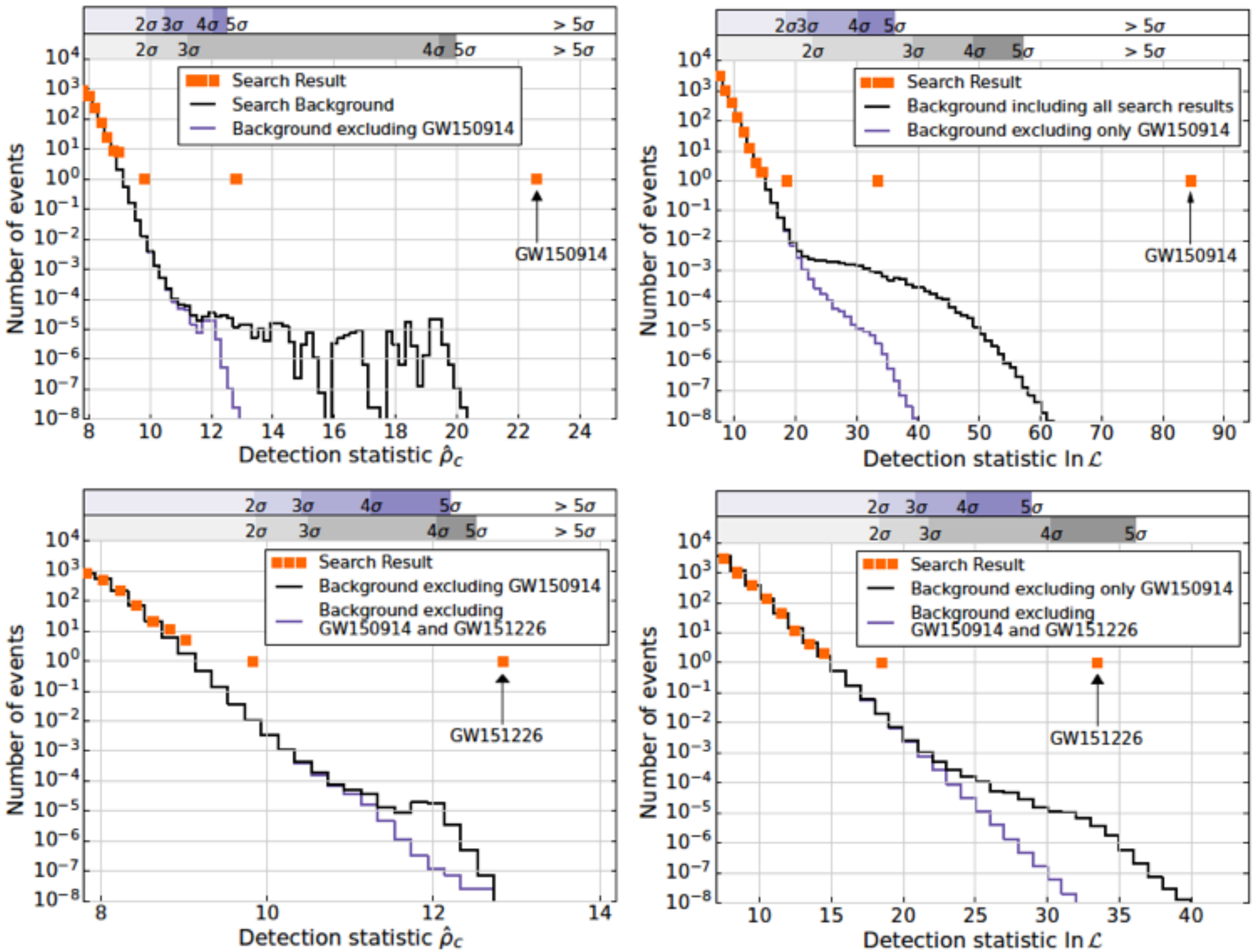
(arXiv1606.0485)

- GW150914 (>5.3σ)
- LVT151012 (Candidate, 1.7σ)
- GW151226 (>5.3σ)



Significance of the events

Abbott et al., arXiv:1606.04856v1



Derived parameters of the events

Abbott et al., arXiv:1606.04856v1

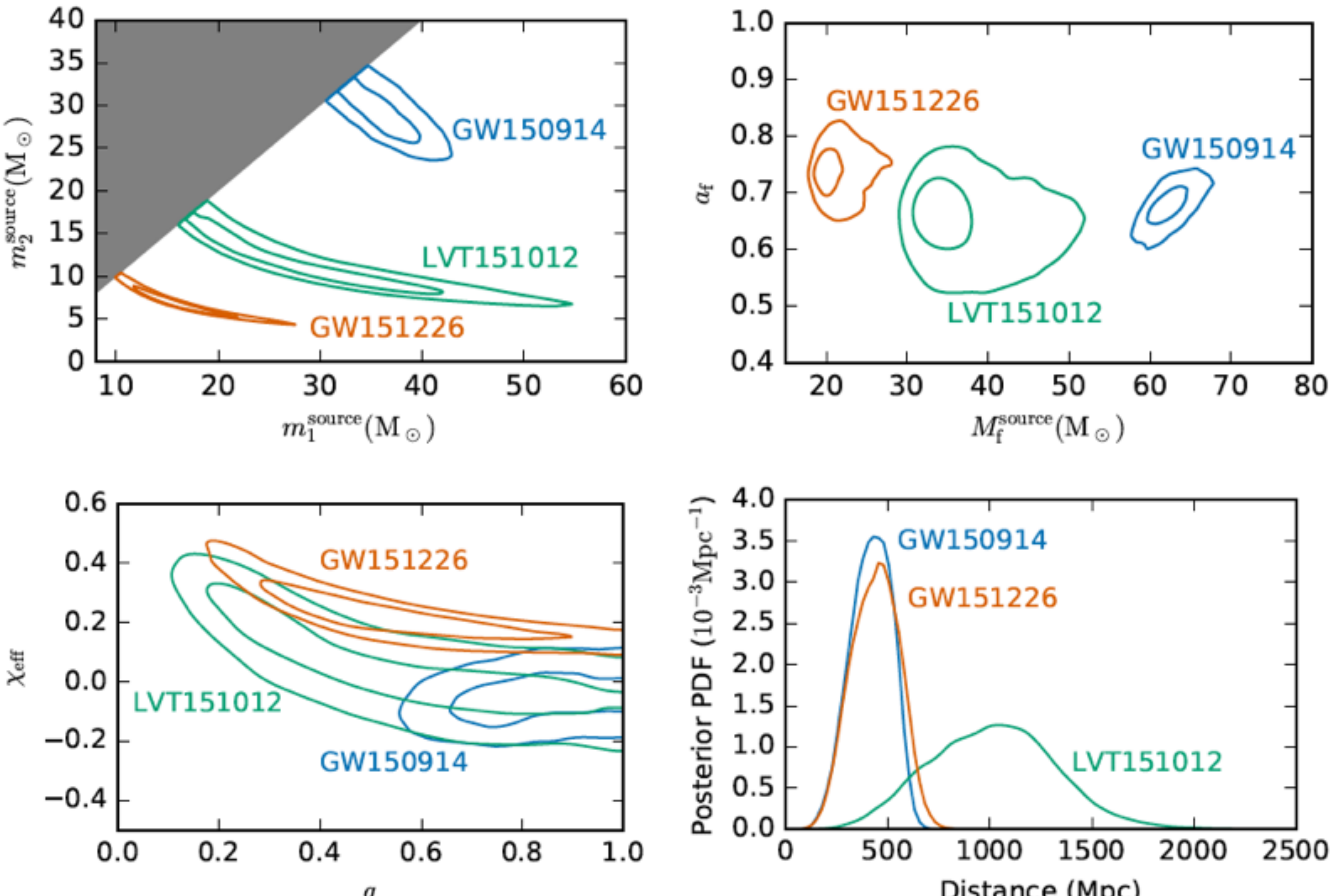
Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}

Abbott et al., arXiv:1606.04856v1

Event	GW150914	GW151226	LVT151012
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_{\odot}$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_{\odot}c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

Posterior probability densities

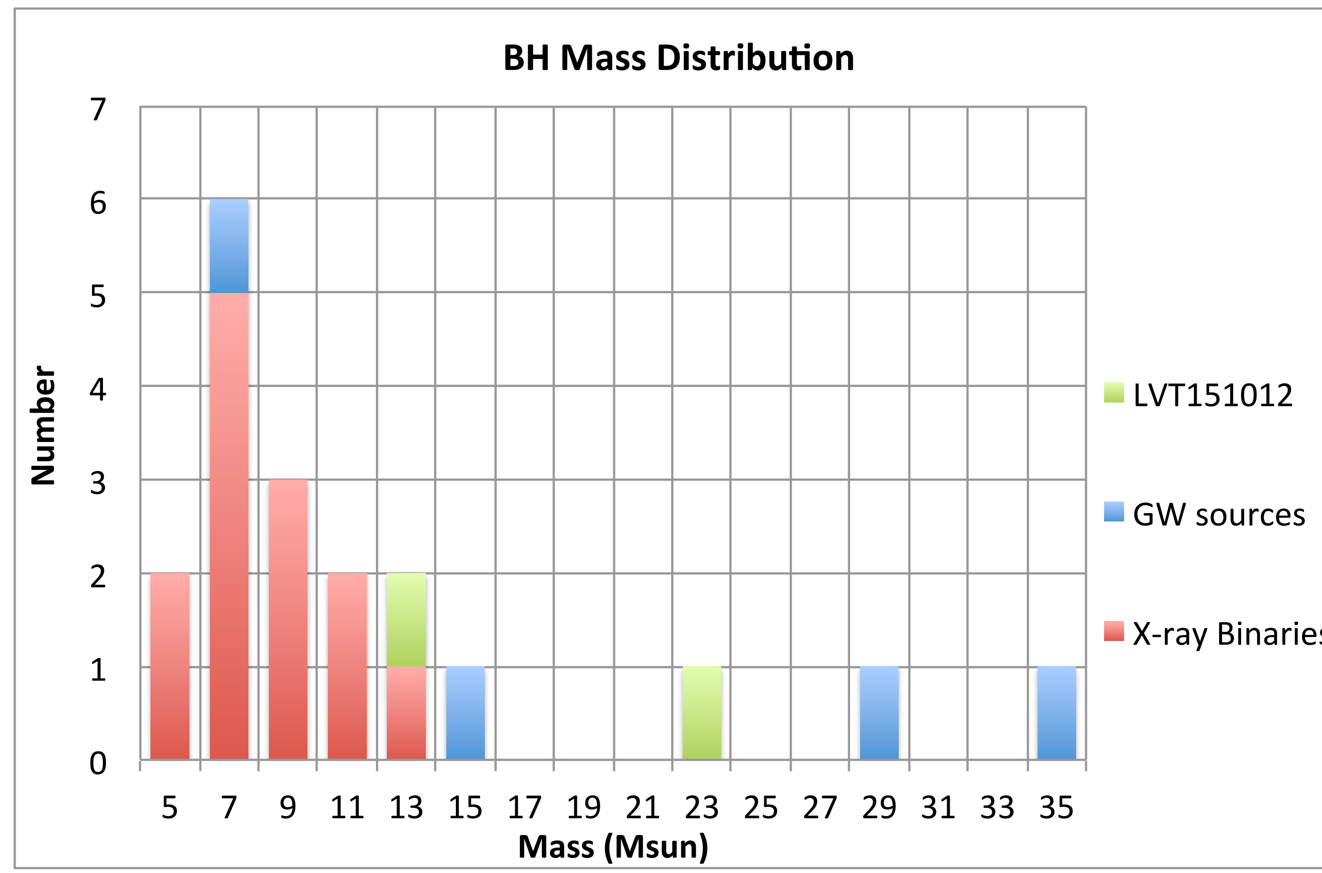
Abbott et al., arXiv:1606.04856v1



What O1 results tell us?

(Abbott et al., 2016, ApJL, 828, L22; Abbott et al., arXiv:1606.04856v1)

- Existence of stellar mass black holes in binaries
- Individual masses in wide range (7-35 Msun)
- How often BH merger takes place?
  - 9-240 yr^{-1} Gpc^{-1}



GW background

- Incoherent superposition of merging BH could generate stochastic GW background

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

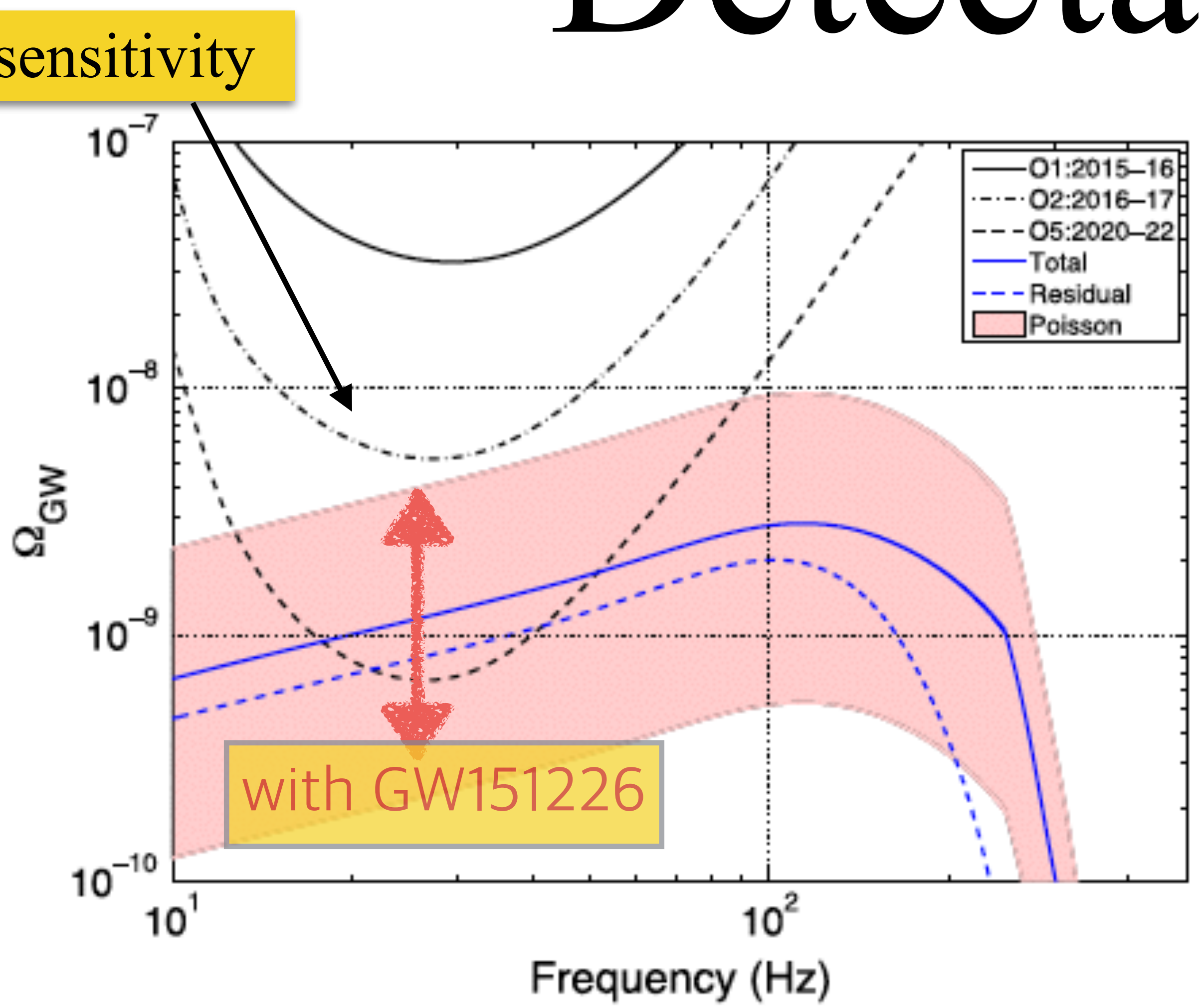
- Consider a BBH of class k with parameters θ_k merge at a rate $R_m(z;\theta_k)$ per unit comoving volume, then Ω_{GW} can be obtained by

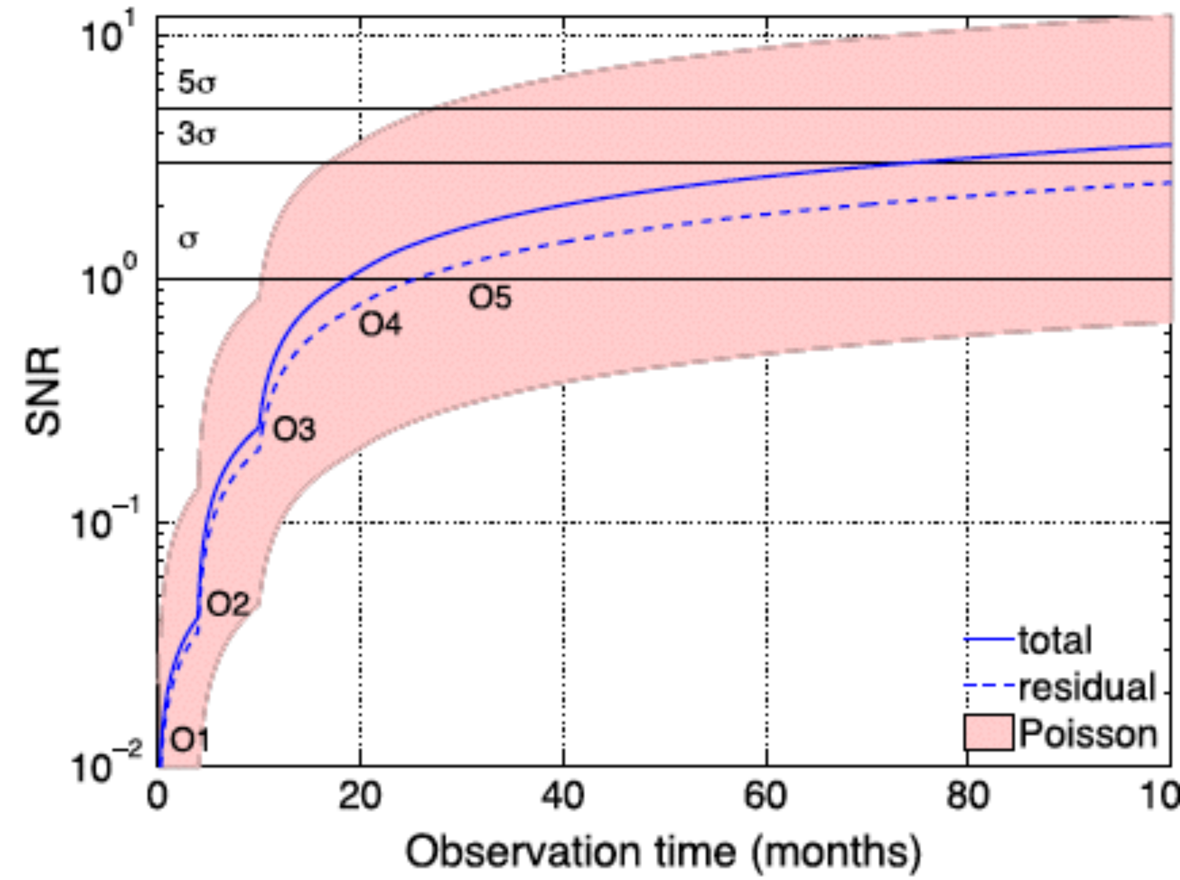
$$\Omega_{GW}(f) \equiv \frac{f}{\rho_c H_0} \int_0^{\infty} dz \frac{R_m(z,\theta_k)\frac{dE_{GW}}{df_s}(f_s,\theta_k)}{(1+z)E(\Omega_M,\Omega_\Lambda,z)}$$

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

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

Detectability

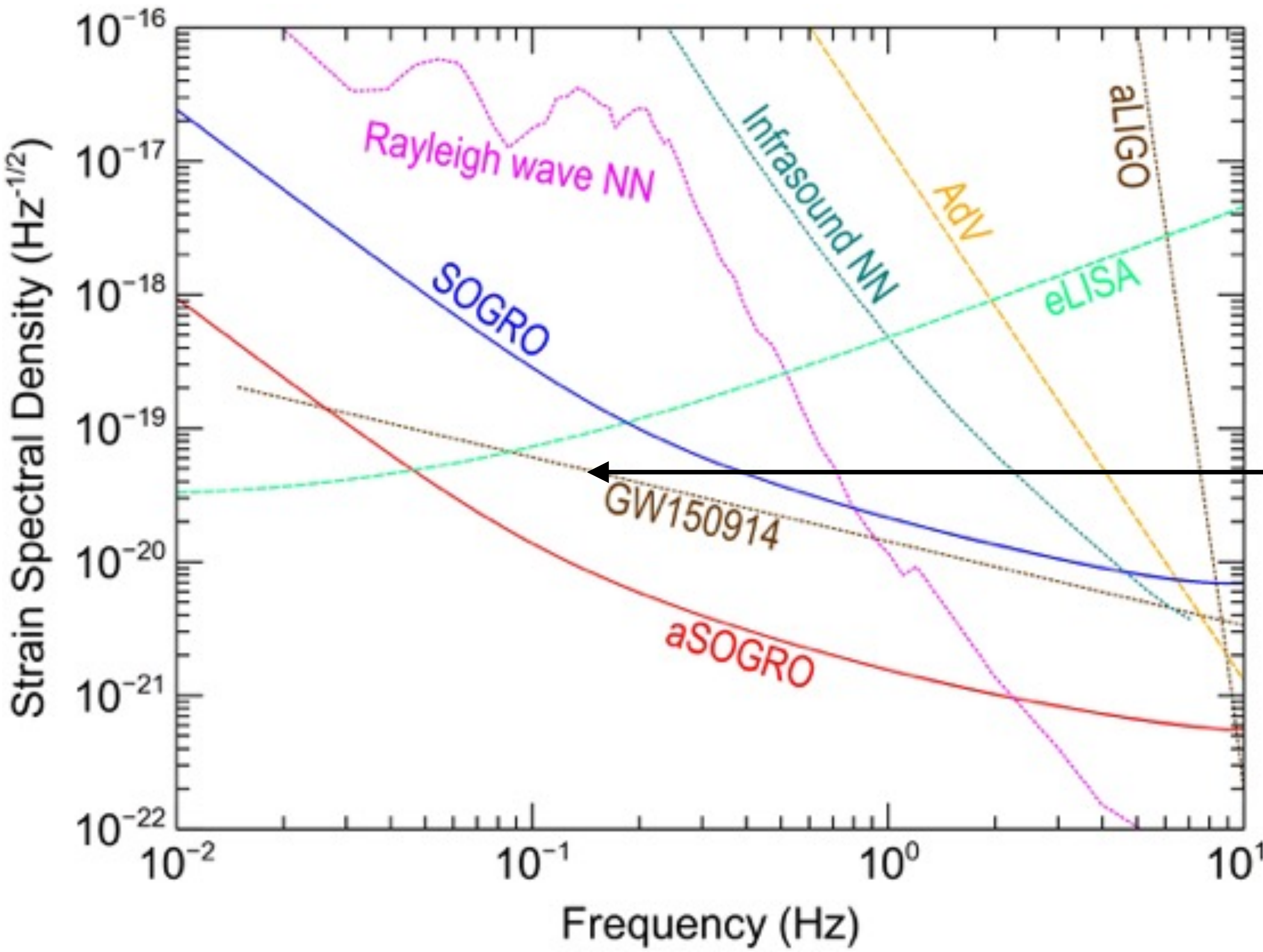




Abbott et al. 2016, PRL, 116, 131102 , GW150914 only

- 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} does not change significantly with GW151226.

Low-frequency detector and GW150914



~1 week before September 14, 2015

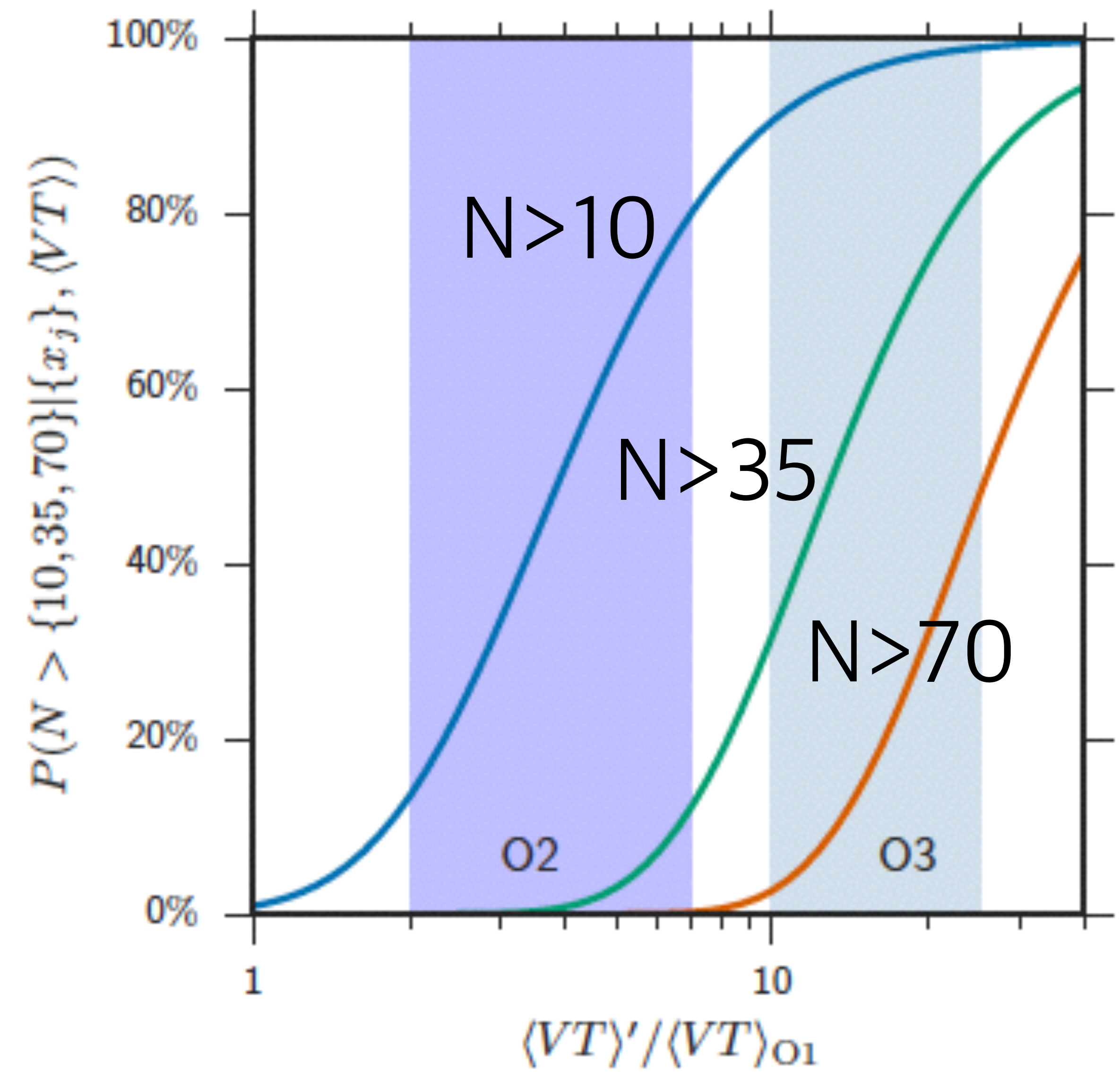
Paik et al. 2016, CQG, 33, 075003

Summary

- GW150914:
  - First Unambiguous detection of stellar mass black holes and a BH binary
  - Accurate measurement of black hole masses (within ~10%)
  - Higher mass of stellar mass BH than previously thought: low metallicity environment?
- GW151226:
  - Lower masses than GW150914, similar to the X-ray binary BH mass
  - Lower mass progenitor or high metallicity environment?
- Origin
  - Isolated or dynamical?

Prospects

- O2 (from September 2016) ~ 6 months
- O3: 2017, ~9 Months
- More detections will follow in the upcoming runs
- Accumulation of BBH events will enable us to constrain formation models



Abbott et al., arXiv:1606.04856v1