LSC LIGO Scientific Collaboration

VIRGO

# Gravitational Waves from the First Observing Run of the advanced LIGO

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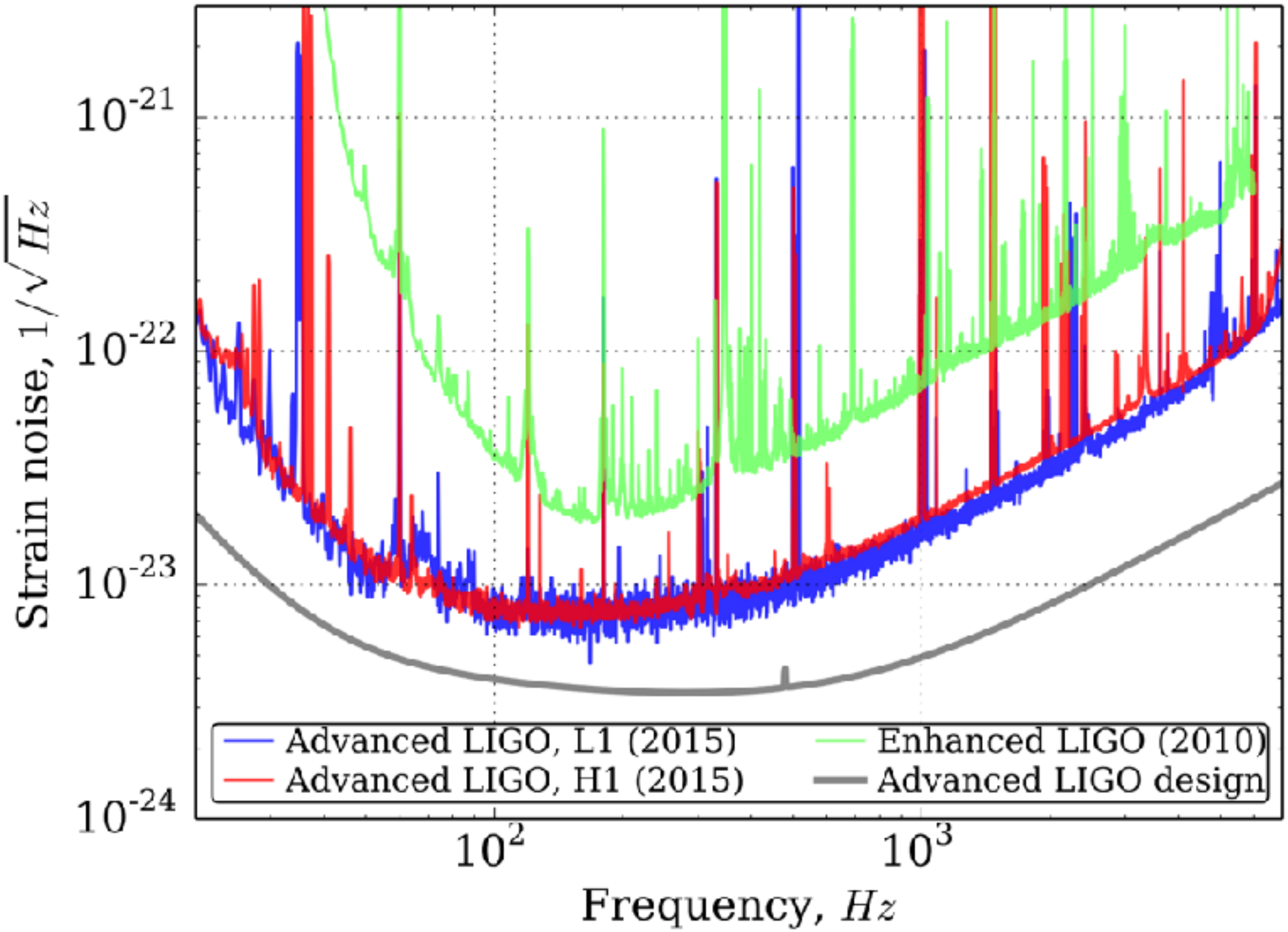
한국 중력파 연구 협력단

# Outline

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

# O1 Sensitivity



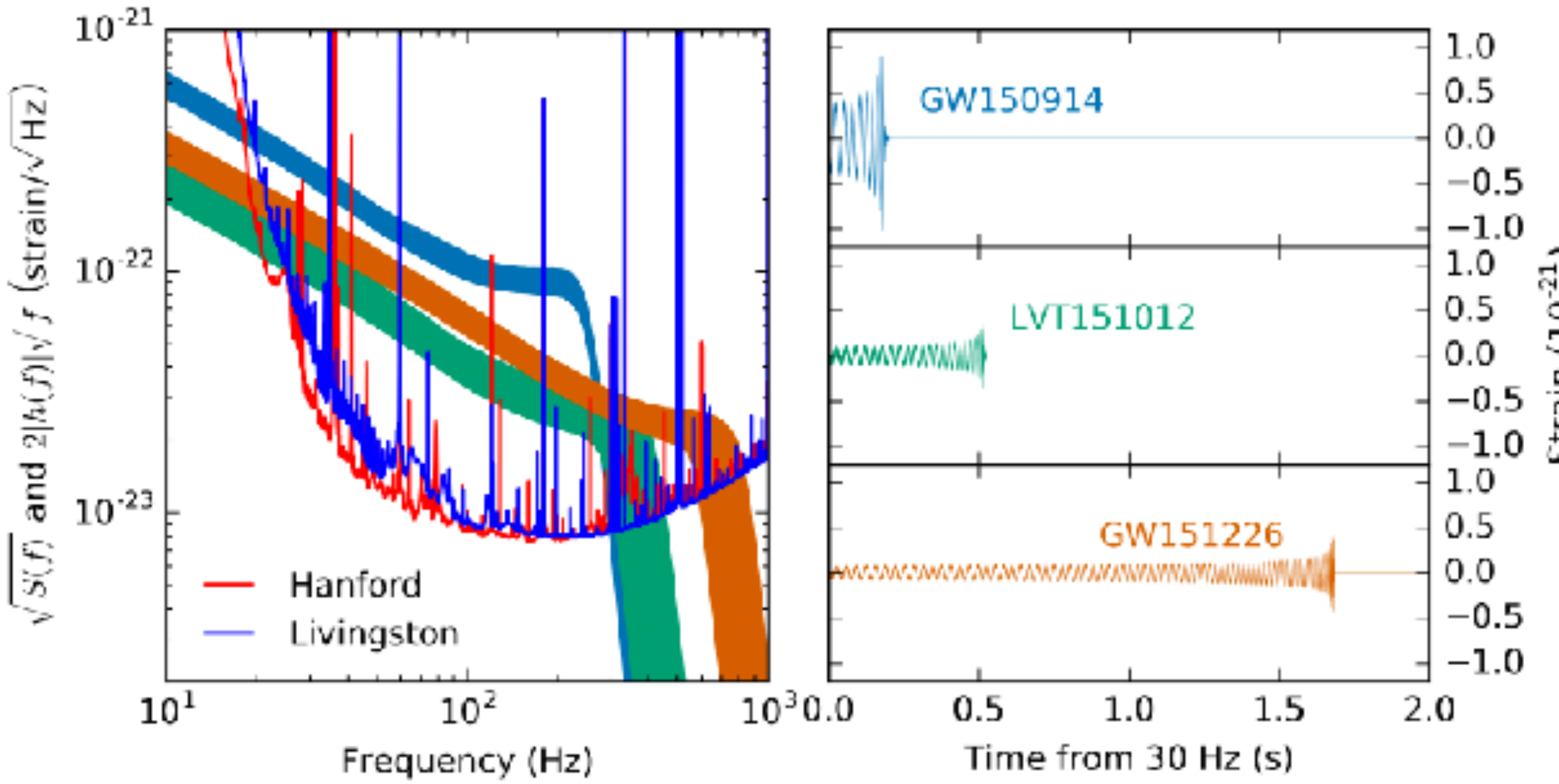
# The 1st Observing Run

- 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

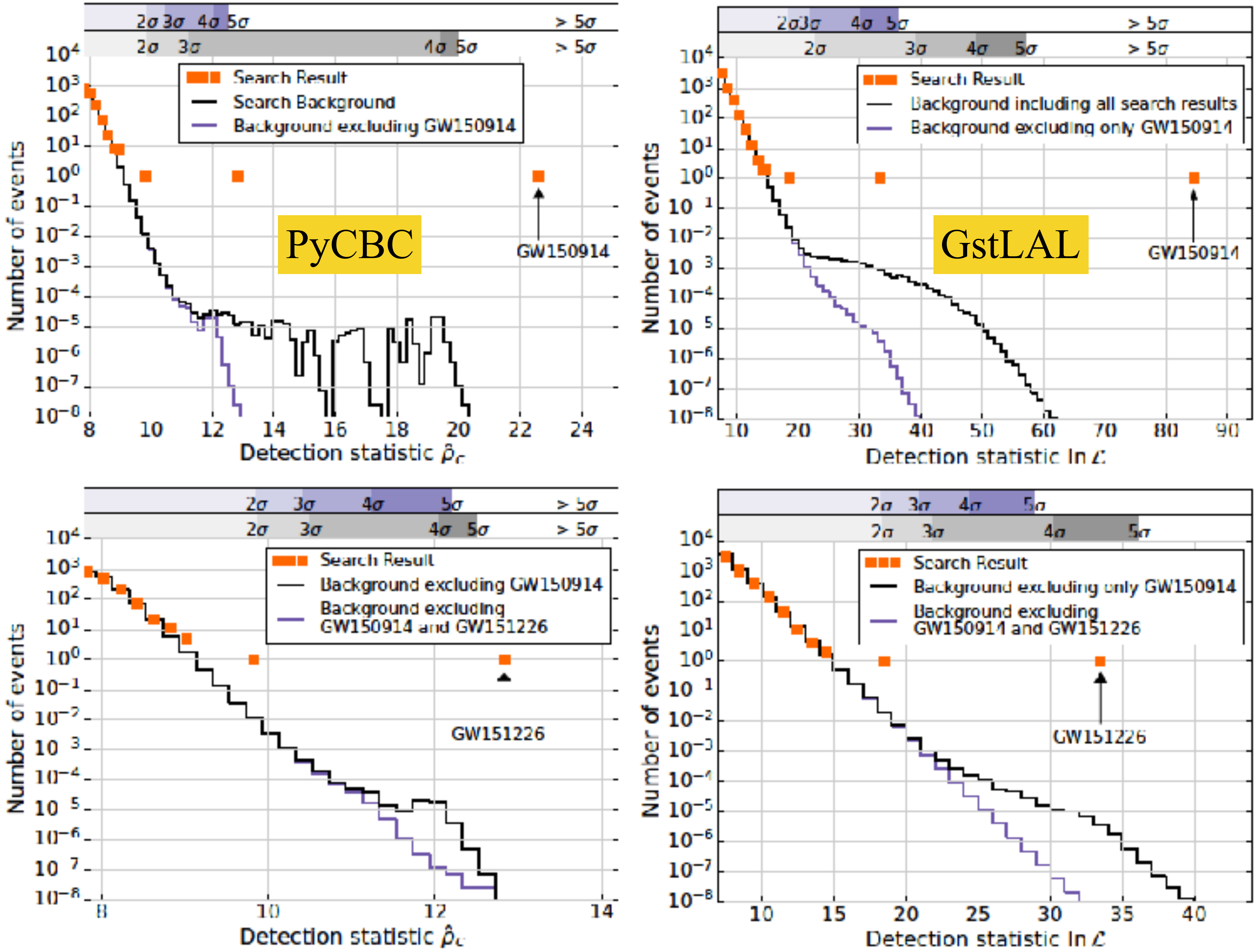
(arXiv1606.0485)

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



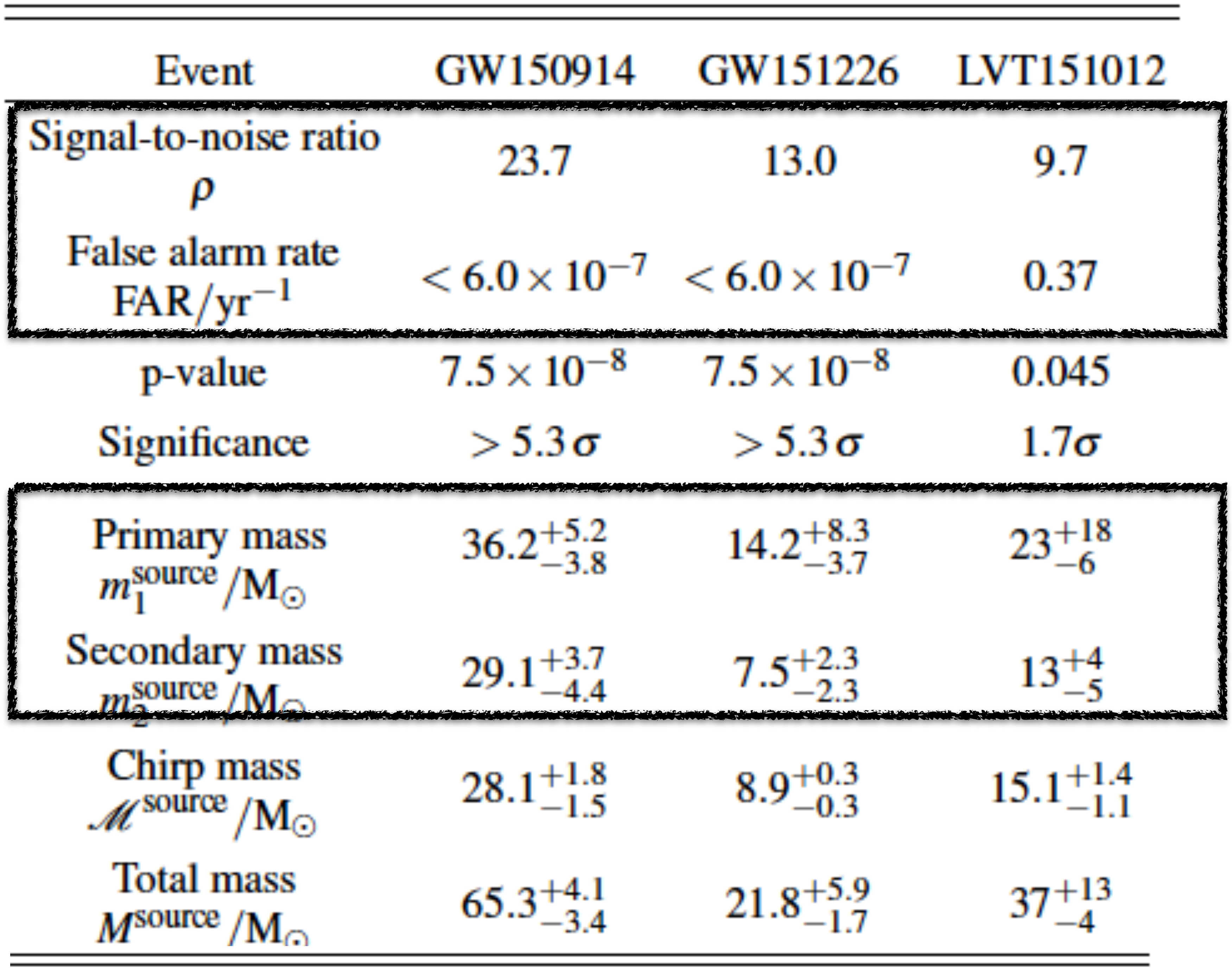
# Significance of the events

Abbott et al., arXiv:1606.04856v1



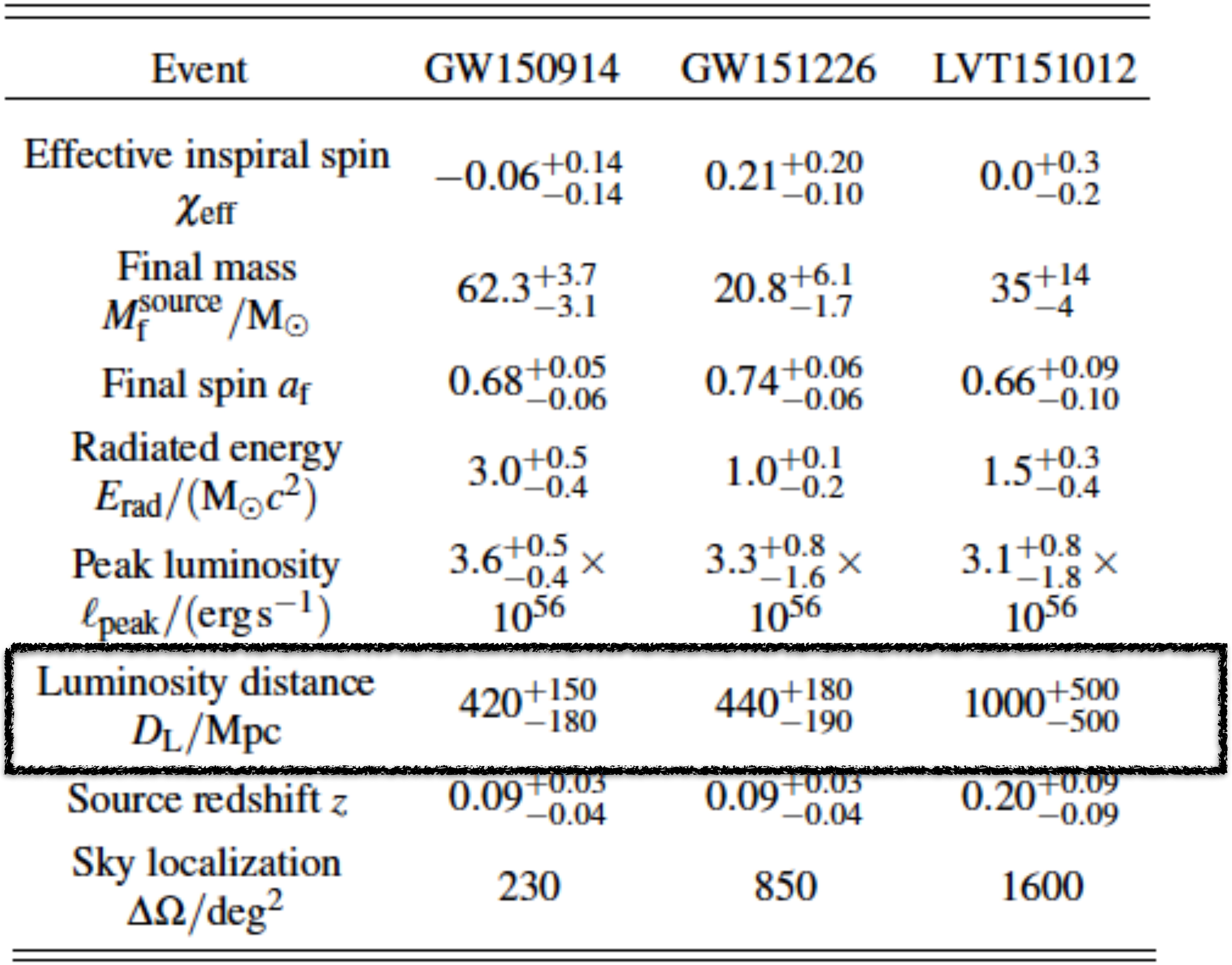
# Derived parameters of the events

Abbott et al., arXiv:1606.04856v1



| Event | GW150914 | GW151226 | LVT151012 |
|---|---|---|---|
| Signal-to-noise ratio $\rho$ | 23.7 | 13.0 | 9.7 |
| False alarm rate $\mathrm{FAR}/\mathrm{yr}^{-1}$ | $< 6.0 \times 10^{-7}$ | $< 6.0 \times 10^{-7}$ | 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 $m_1^{\mathrm{source}}/\mathrm{M}_\odot$ | $36.2^{+5.2}_{-3.8}$ | $14.2^{+8.3}_{-3.7}$ | $23^{+18}_{-6}$ |
| 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 $M^{\mathrm{source}}/\mathrm{M}_\odot$ | $65.3^{+4.1}_{-3.4}$ | $21.8^{+5.9}_{-1.7}$ | $37^{+13}_{-4}$ |

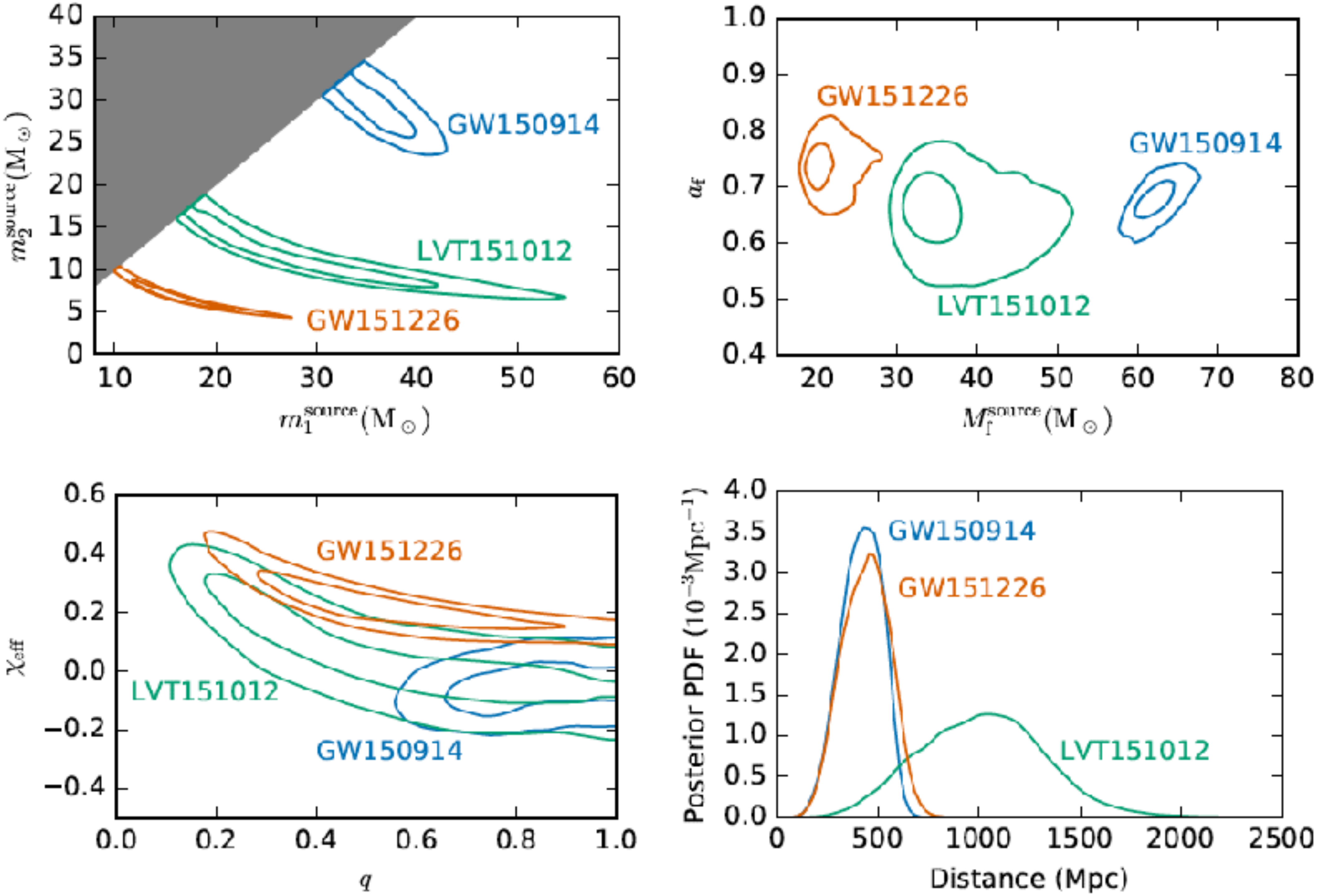
Abbott et al., arXiv:1606.04856v1



| Event | GW150914 | GW151226 | LVT151012 |
|---|---|---|---|
| Effective inspiral spin $\chi_{\mathrm{eff}}$ | $-0.06^{+0.14}_{-0.14}$ | $0.21^{+0.20}_{-0.10}$ | $0.0^{+0.3}_{-0.2}$ |
| 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 $a_{\mathrm{f}}$ | $0.68^{+0.05}_{-0.06}$ | $0.74^{+0.06}_{-0.06}$ | $0.66^{+0.09}_{-0.10}$ |
| 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

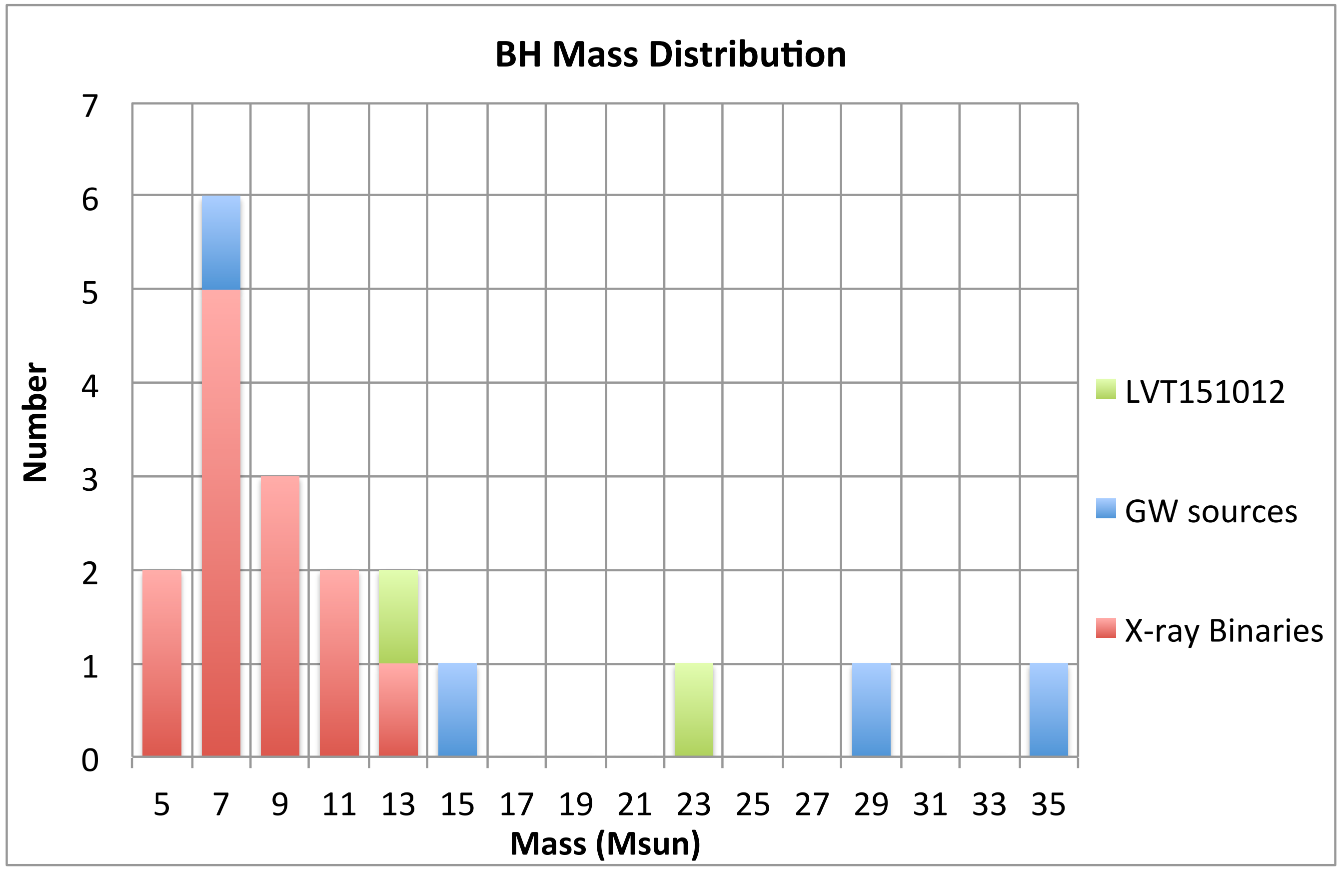
Abbott et al., arXiv:1606.04856v1



# What O1 results tell us?

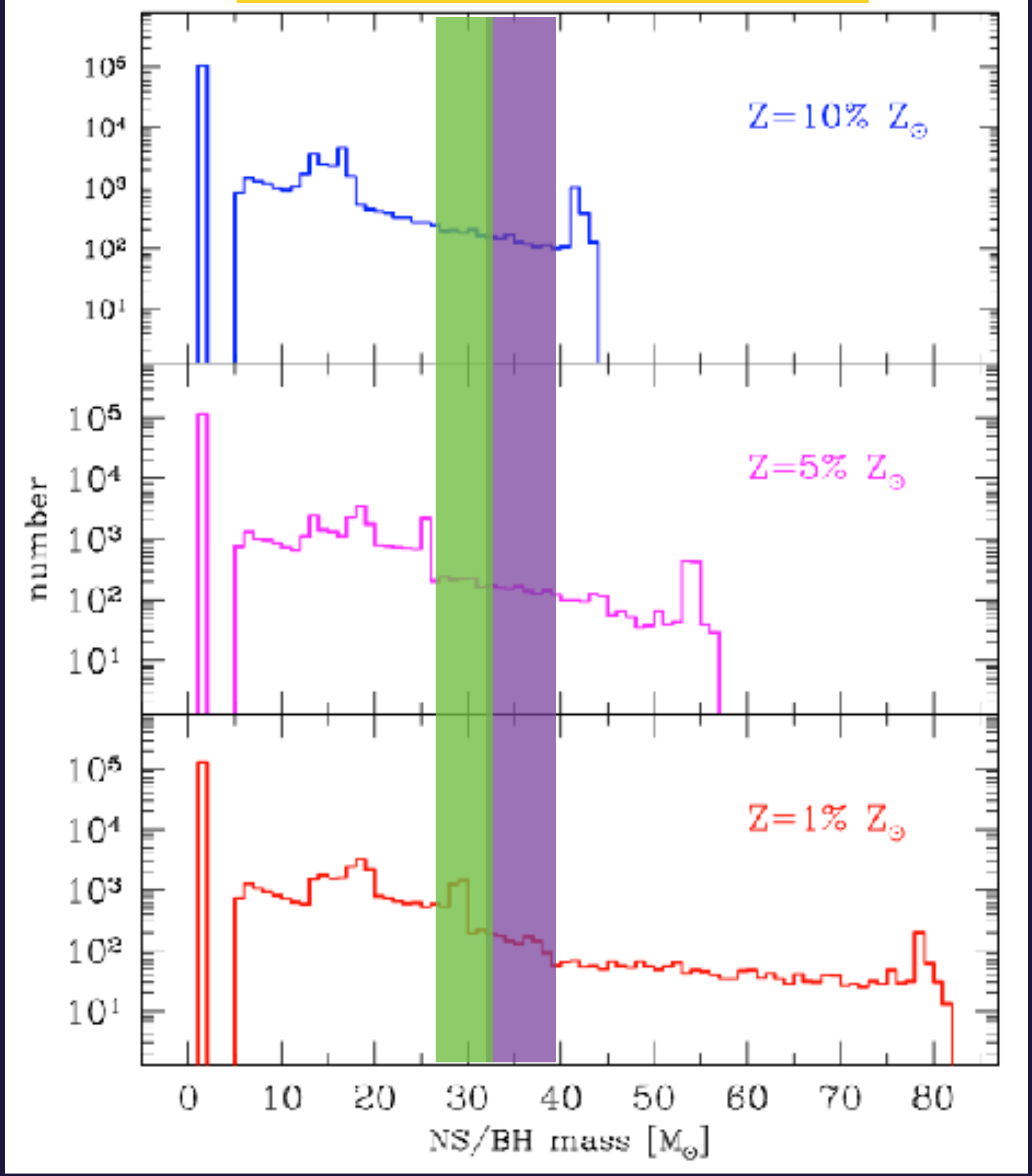
(Abbott et al., 2016, ApJL, 828, L22; Abbott et al., arXiv:1606.04856v1)

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



# Black Hole Masses

- BH mass depends on metallicity
- Maximum mass of BH $\sim 40\ M_\odot$ for $Z<0.1\ Z_\odot$.
- GW150914 could have been formed when the universe was young or in low metallicity galaxies
- Origin:
  - Dynamical (e.g., Bae et al. 2014)
  - Coevolved (e.g., Belczynski et al. 2015,, 2016)



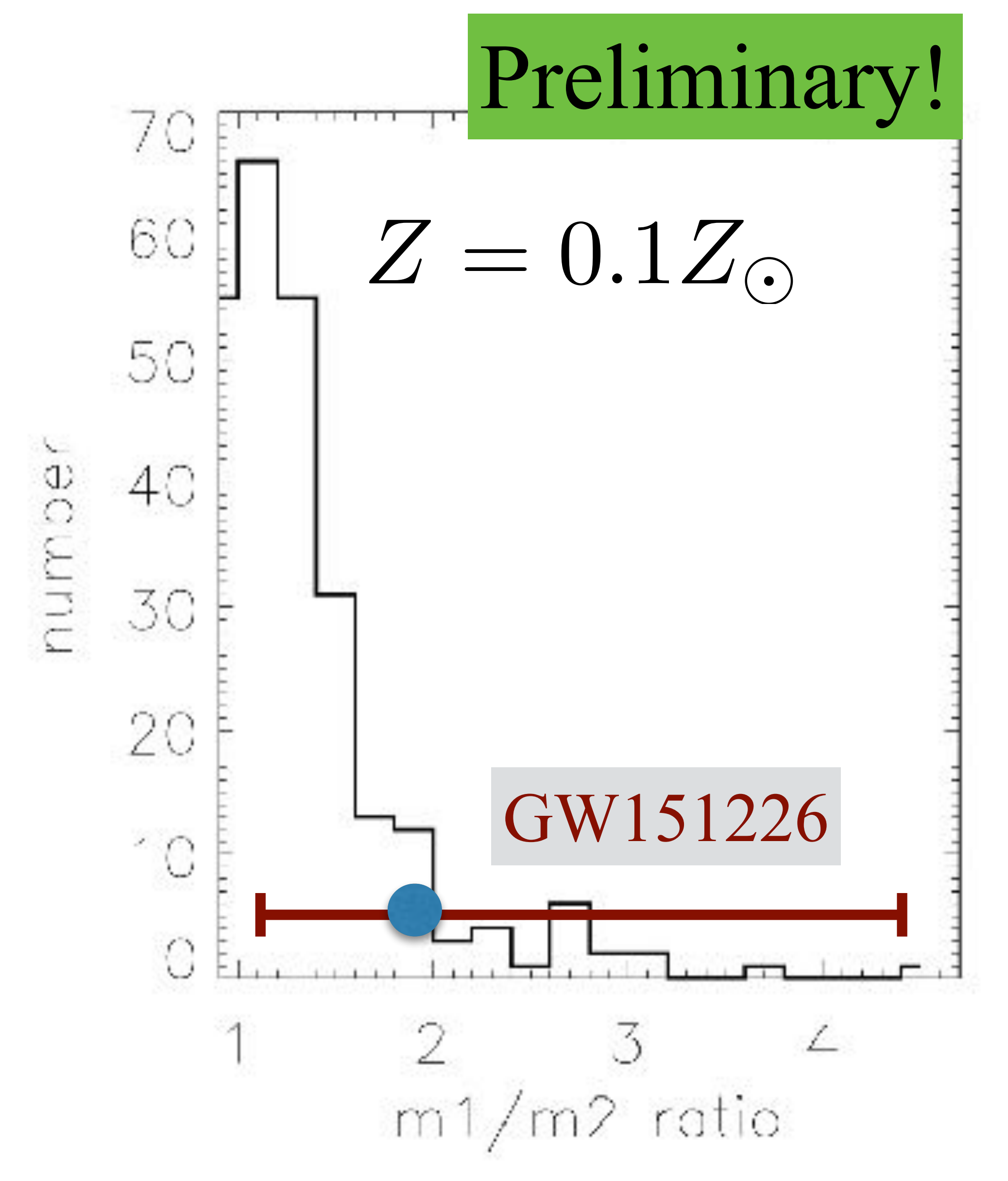
GW150914 masses

Data provided by Belczynski

# Effects of BH Mass Function on Mass Ratios of Dynamical BBH

(Park et al. in preparation)

- Preliminary results with Belczinski's BH mass function
  - Massive BHs sink toward the core first, and form binaries
  - Less massive ones follow sequentially
  - BH mass ratio remain close to 1: most binaries have mass ratio less than 2



# GW background

- Incoherent superposition of merging BH could generate stochastic GW background

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

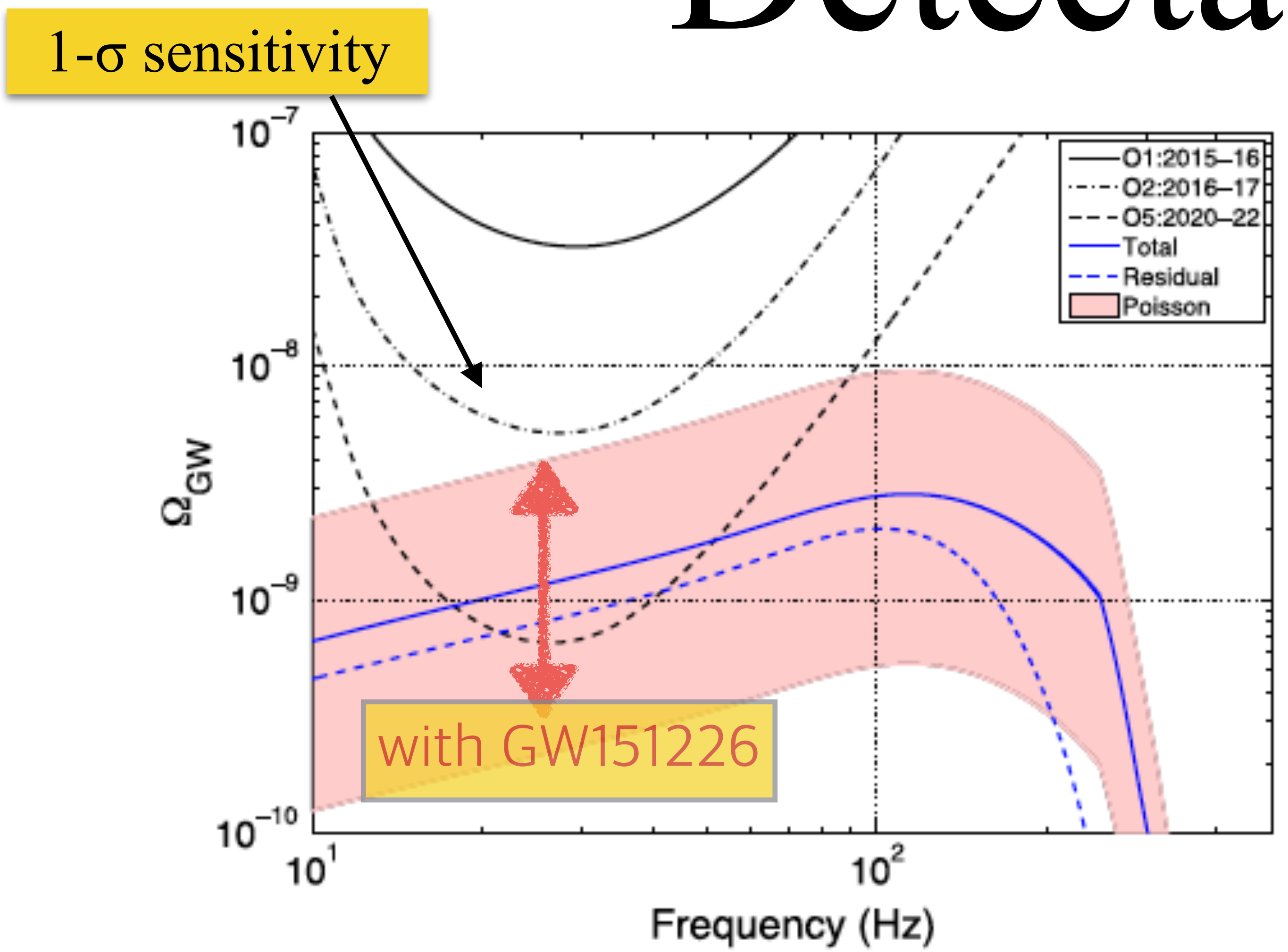
- Consider a BBH of class $k$ with parameters $\theta_k$ merge at a rate $R_m(z; \theta_k)$ per unit comoving volume, then $\Omega_{GW}$ can be obtained by

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

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

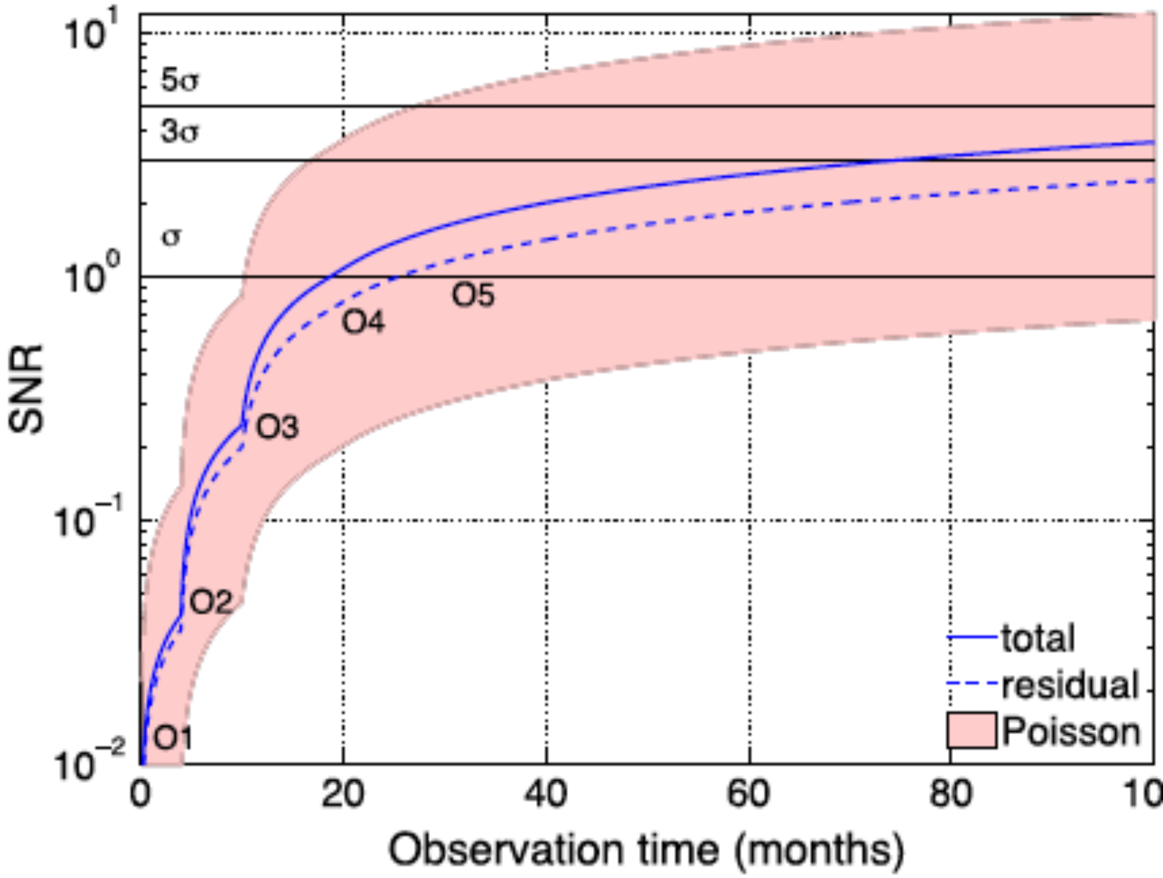
$$R = 16\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

# Detectability



1-σ sensitivity

with GW151226

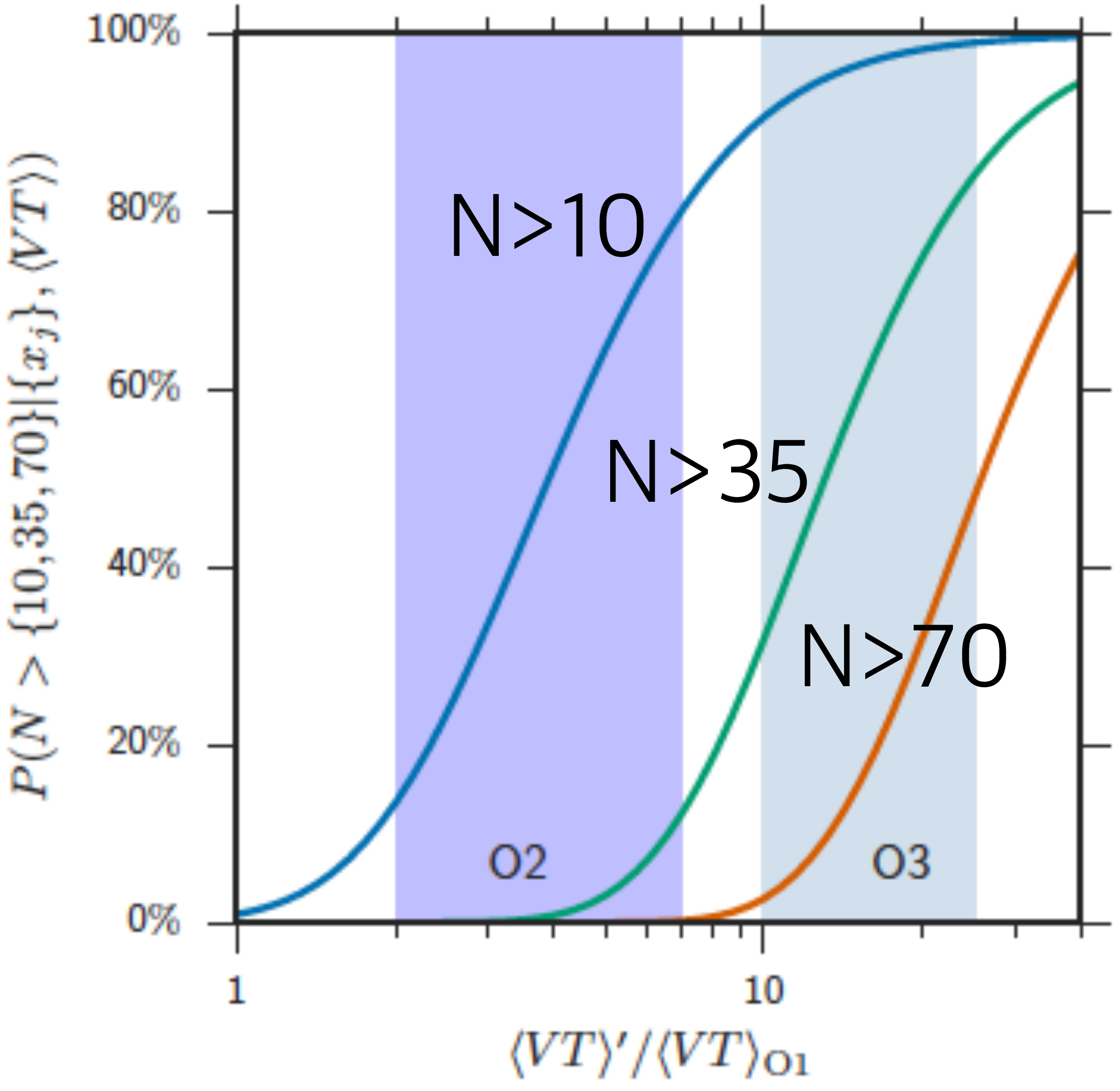


Abbott et al. 2016, PRL, 116, 131102 , GW150914 only

- 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 $\Omega_{GW}$ does not change significantly with GW151226.

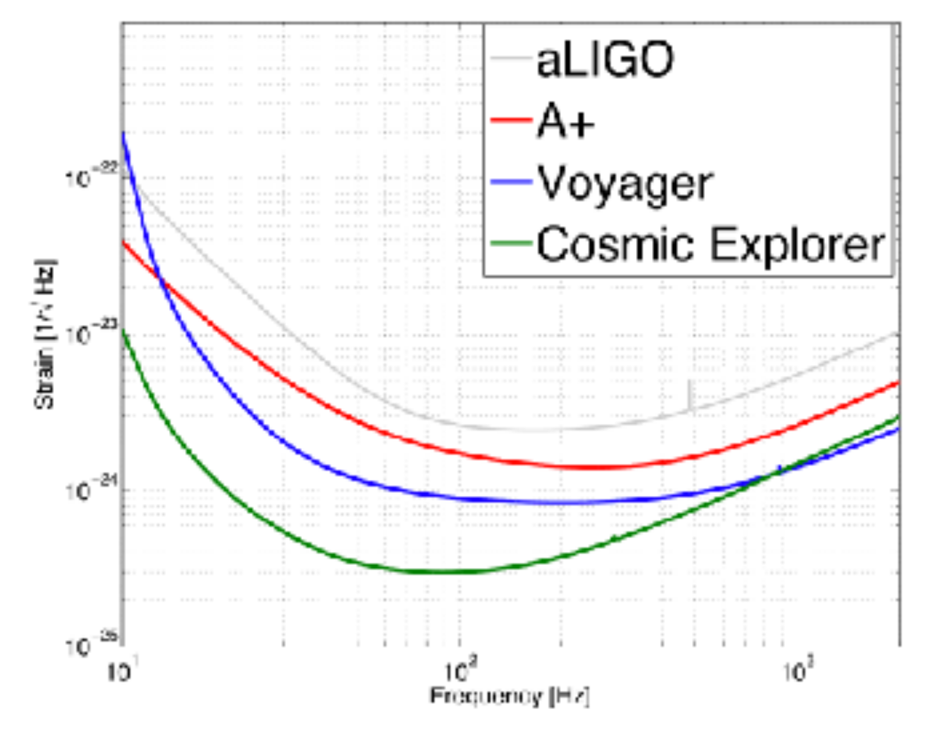
# Prospects

- O2 (from November 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, etc.
- We may be able to detect GW background in the near future.

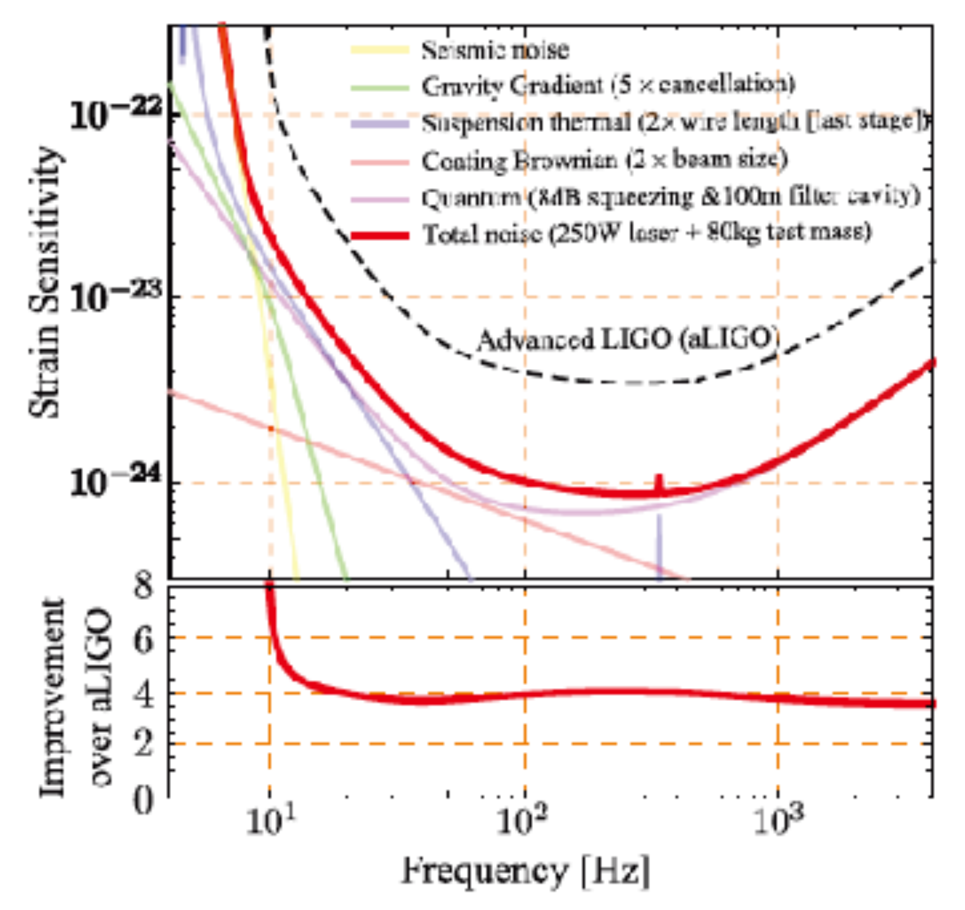


Abbott et al., arXiv:1606.04856v1

# More Sensitive Detectors



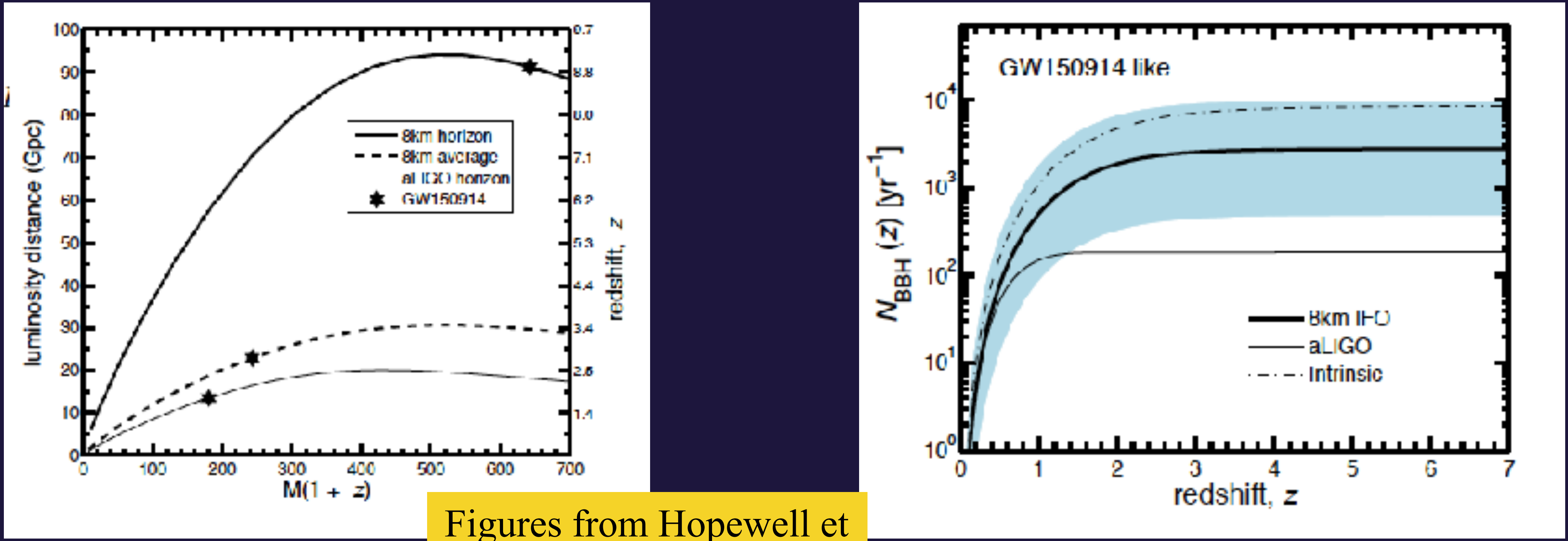
LIGO Upgrade Plan (LIGO-T1400316)



8km Advanced Detector concept
(Blair et al. 2015)

- LIGO sensitivity can increase x 1.5 with moderate upgrade (A+)
- Factor of 3 increase will require major upgrade (Voyager)
- Order of magnitude upgrade will require a new detector (Cosmic explorer)
- Recently a new detector with 8km in Australia with existing technologies was proposed (Blair et al. 2015, Hopewell et al. 2016

# With 8 km detector



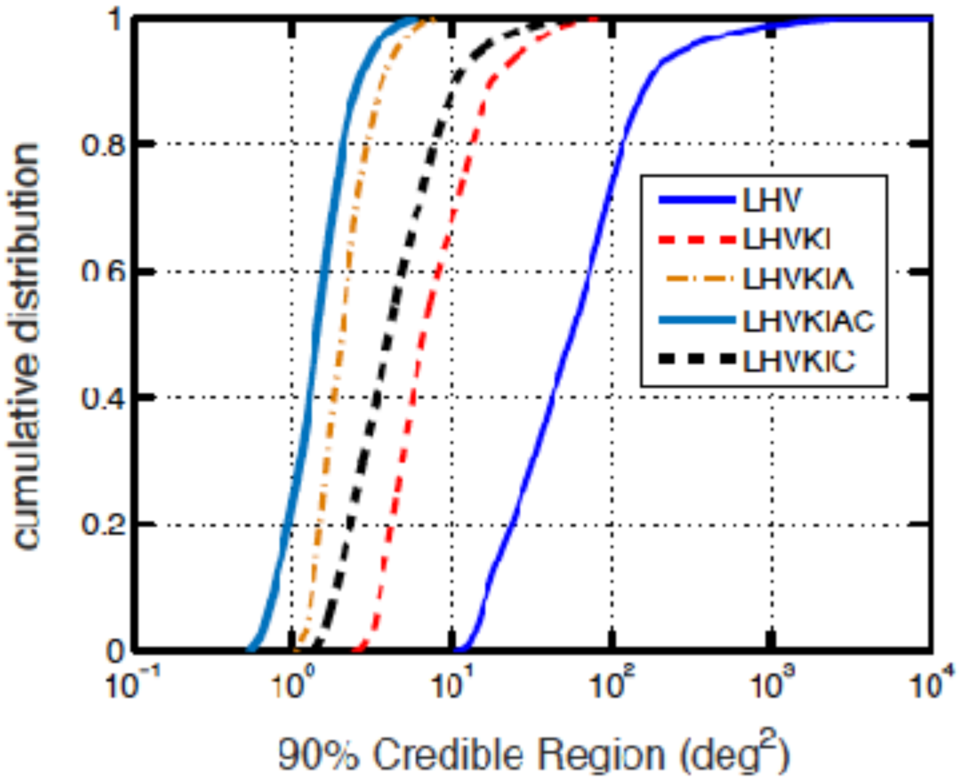
Figures from Hopewell et al., in prep.

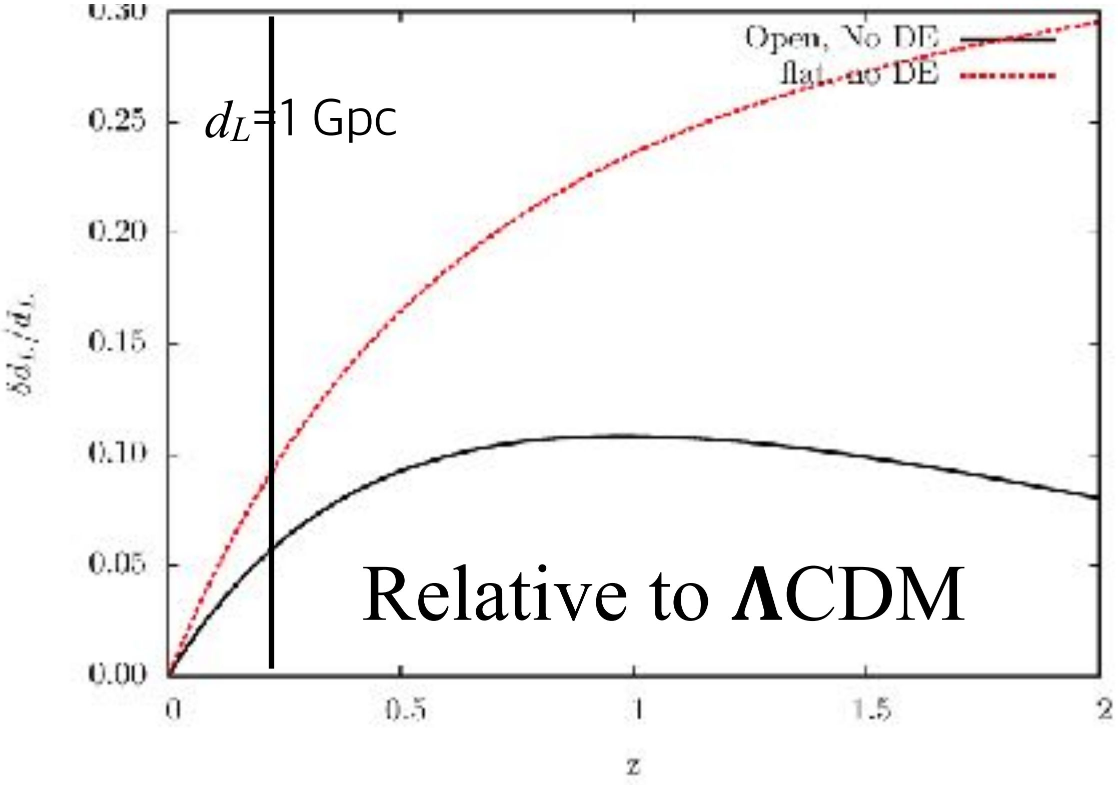
- Horizon distance will increase ~x 4
- Detection rate will increase x 64: ~a few 1000 per year

# Cosmology with GW

- Luminosity distance can be determined with GW data alone.
- If host galaxy is identified, we can derive $z$-$d_L$ relation.
- Within $d_L$~0.4 Gpc (z~0.09), more than 20% source can be localized within 0.1 sq. deg.
  - There would be ~ 3 Milky-like galaxies within the error circle.
  - Number of galaxies grows with $z^4$ within error circle: distant GW sources are increasingly difficult to localize.
- How about Neutron star mergers?
  - EM followup will enable us to identify host galaxies more easily
  - Horizon would be ~ 1 Gpc with 8km detector

Assuming 8km detector in Australia, GW150914-like source
(Hopewell et al. in preparation)

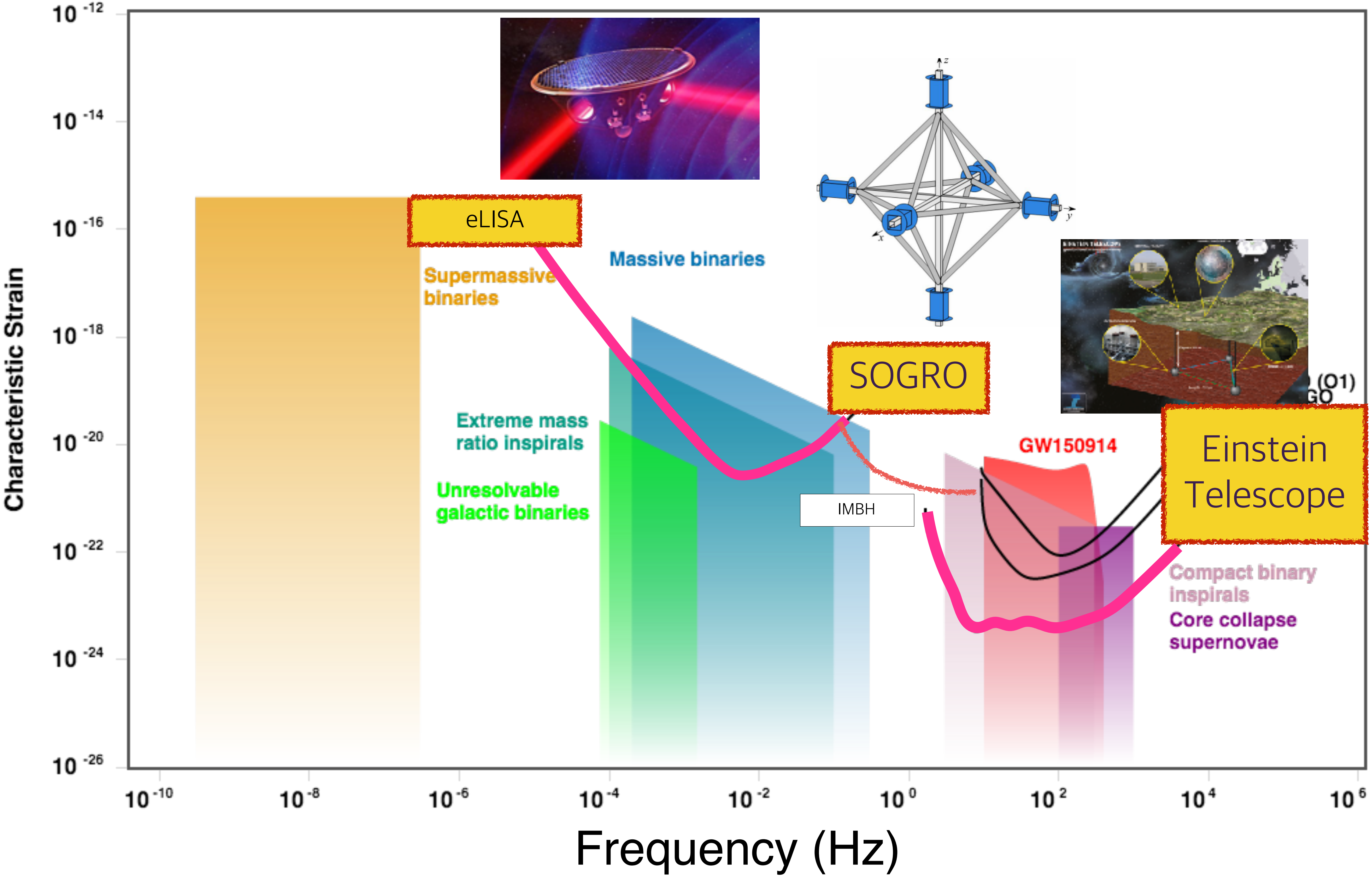




$d_L$=1 Gpc

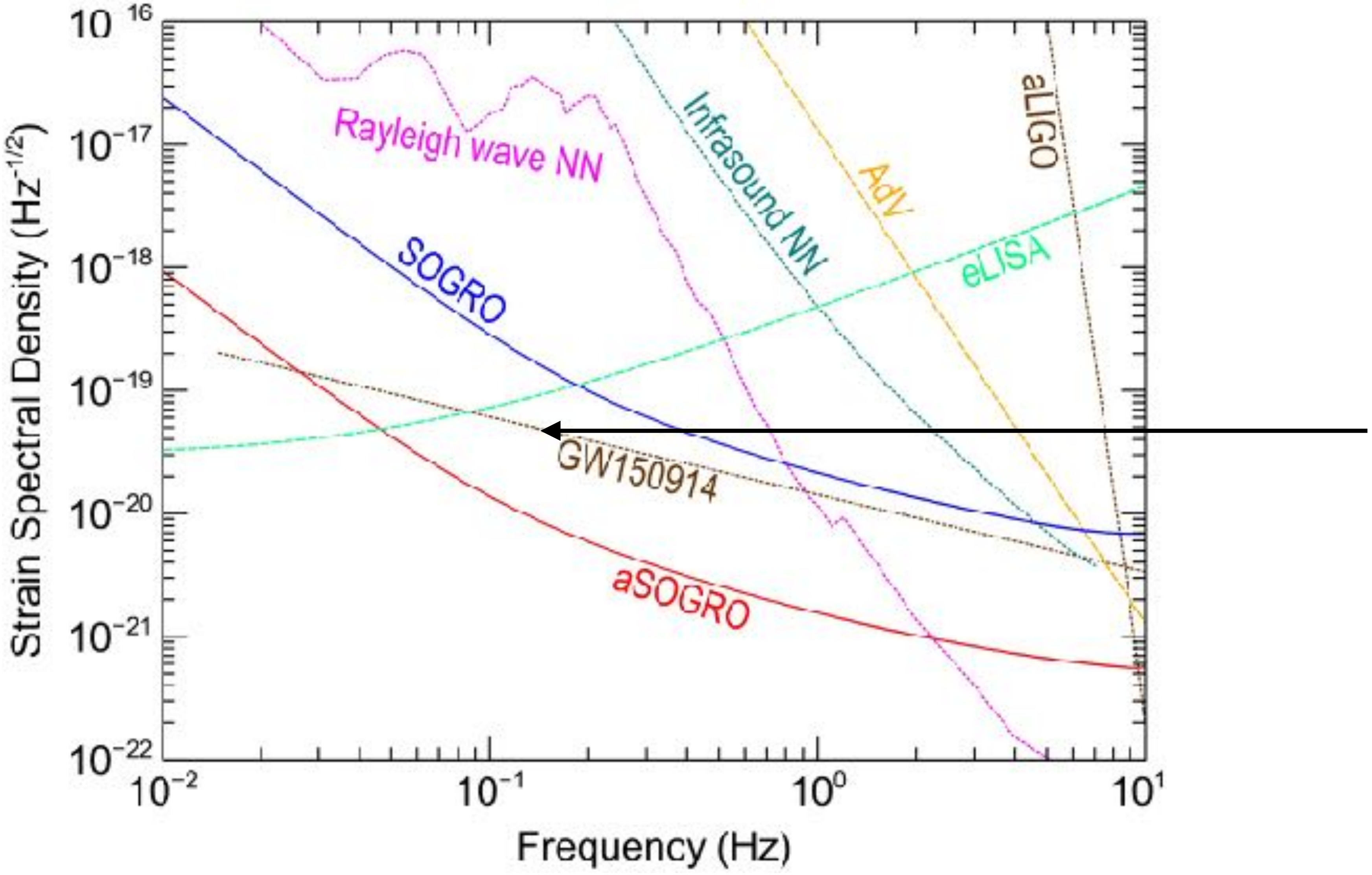
Relative to ΛCDM

# Detectors and Sources at other frequency bands



http://rhcole.com/apps/GWplotter/

# 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
  - Coevolved or dynamical?: Cannot be constrained yet
- Prospects
  - Frequent detections are expected with forthcoming observing runs
  - Sensitive detectors in the near future will enable us to observe more distant sources
  - Low frequency GW detectors will enable us to observe more massive black holes