A stochastic gravitational-wave background from binary black hole mergers

Bernard F Whiting (for the LVC), LIGO-G1701173
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Stochastic background sources

- A primordial background of gravitational waves has always been considered a primary focus for stochastic background searches - since it must exist

- A stochastic background of gravitational waves could also arise from a superposition of a large number of unresolved, individual gravitational-wave sources of astrophysical origin

- Advanced LIGO has detected binary black holes at cosmological distances. Sufficiently many such sources, at distances so much greater that they would be individually undetectable, may nevertheless constitute a detectable background of astrophysical origin.

Systematic detection strategy

- Techniques exist for the detection of a background from both isotropic and point source origin - here we focus on the isotropic case

- Although there has been no detection of a stochastic background yet, our approach is both simple and efficient - it involves taking interferometric gravitational wave detectors in pairs, correlating their data and performing what amounts to an all sky average

- Uncorrelated noise should average away over time and any signal should effectively grow as the square root of time, so longer averages are always better, but high sensitivity is key

Background composed of binary black hole sources

- Spectral energy density in gravitational waves characterized by

$$\Omega_{GW}(f) = f/\rho_c \times d\rho_{GW}/df$$

- Binary black hole contribution with parameters θ_k=$(m_1, m_2, \chi_{\rm eff})$

$$\Omega_{GW}(f, \theta_k) = \frac{f}{\rho_c} \int_0^{\sim 20} R_m(z, \theta_k) \frac{dE_{GW}}{df}(\theta_k, (1+z)f) \frac{dz}{4\pi r^2(z)}$$

  - $R_m(z, \theta_k)$ is the merger rate as a function of redshift, z

- Total population gives $\Omega_{GW}(f) = \int d^j \theta_k p(\theta_k) \Omega_{GW}(f, \theta_k)$

  - $p(\theta_k)$ is the probability distribution of parameters

Contribution of binary black holes similar to GW150914

- GW150914 properties: m_1=36M_{sun}, m_2=29M_{sun}, X_{eff}~0, z=0.09, R_0=17$Gpc^{-3}yr^{-1}$ (arXiv:1602.03840)

- GW170104 properties: m_1=31M_{sun}, m_2=19M_{sun}, X_{eff}~-0.12, z=0.18, R_0=32$Gpc^{-3}yr^{-1}$ (arXiv:1706.01812)

- How do black holes with such masses form?

- How often do such binary systems form?

- How frequently do such binaries coalesce?

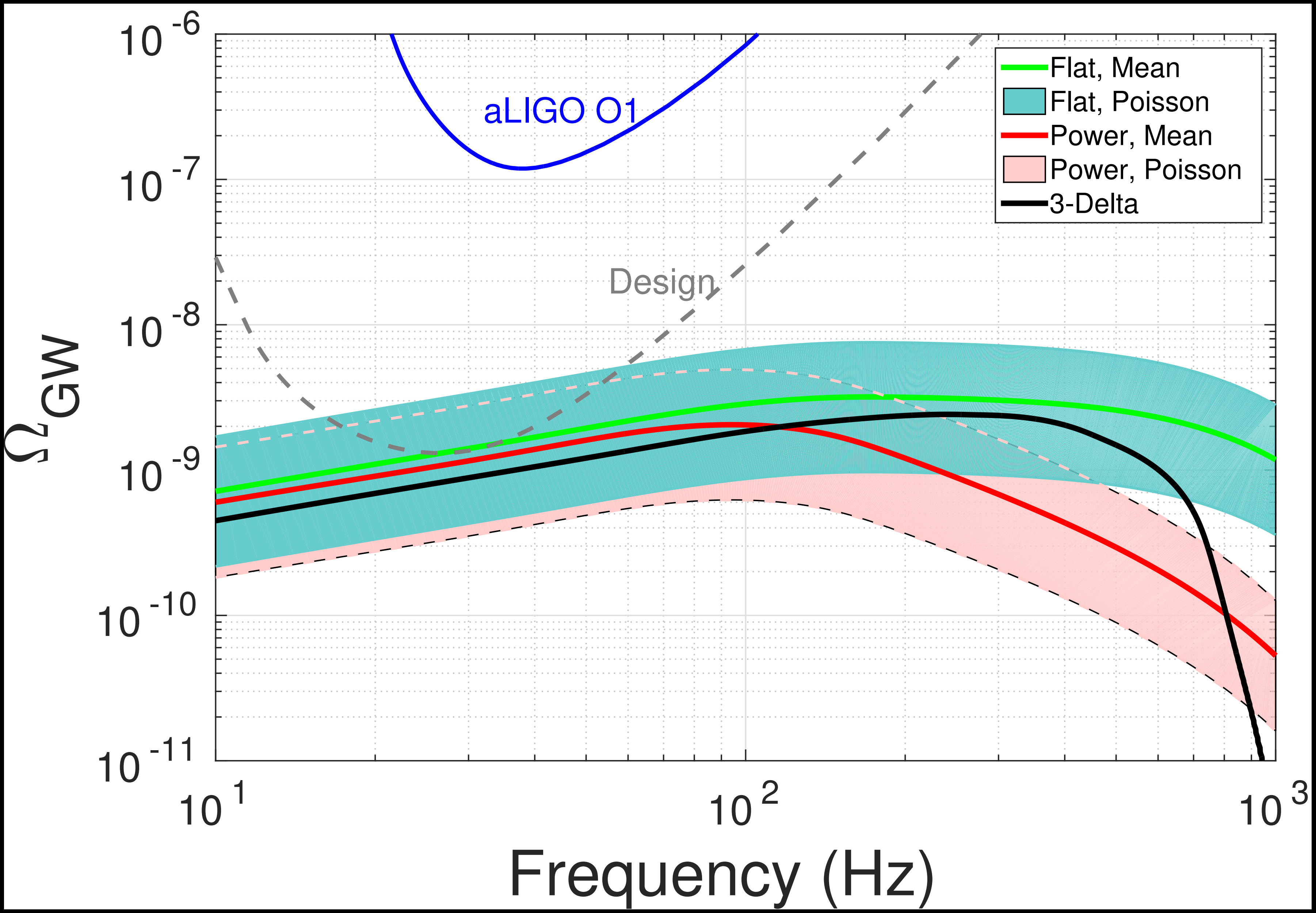
$$R_m(z, \theta_k) = \int_{t_{\min}}^{t_{\max}} R_f(z, \theta_k) p(t_d, \theta_k) dt_d$$

Model parameters investigated

- Raw star formation rates
- Merger rate independent of redshift
- Constant and inverse power for delay
    - dependent on time of formation
- Formation in dense clusters or otherwise
- ISM metallicity at time of star formation
- Low mass origin of proto-collapsing stars
- **All uncertainties smaller than statistical fluctuations**

Fiducial model

- O1 observations (GW150914, LVT151012 , GW151226 & GW170104) consistent with both dynamical and field formation channels
- Fiducial model inspired by population synthesis studies of field binaries. Assumptions:
  - Binary black hole formation rate proportional to star formation rate at metallicity less than half solar metallicity
  - Star formation rate based on gamma ray burst rate
  - Metallicity-redshift relation adopted from Madau and Dickinson (2014), rescaled to account for local observations
  - Metallicity is log-normally distributed (σ=0.5) at each redshift
  - $p(t_d) \sim 1/t_d$ for $t_d > 50$ Myr, and $t_d < t_{Hubble}$.
- Find: $\Omega_{\rm GW}(25{\rm Hz}) = (1.1-1.3)^{+1.8}_{-0.8} \times 10^{-9}$ and $\Omega_{\rm GW}(f < 100{\rm Hz}) \propto M_c^{5/3} f^{2/3}$
- where: $M_c = (m_1 m_2)^{3/5}(m_1+m_2)^{-1/5}$ ($28M_{sun}$ for GW150914, $21M_{sun}$ for GW170104)

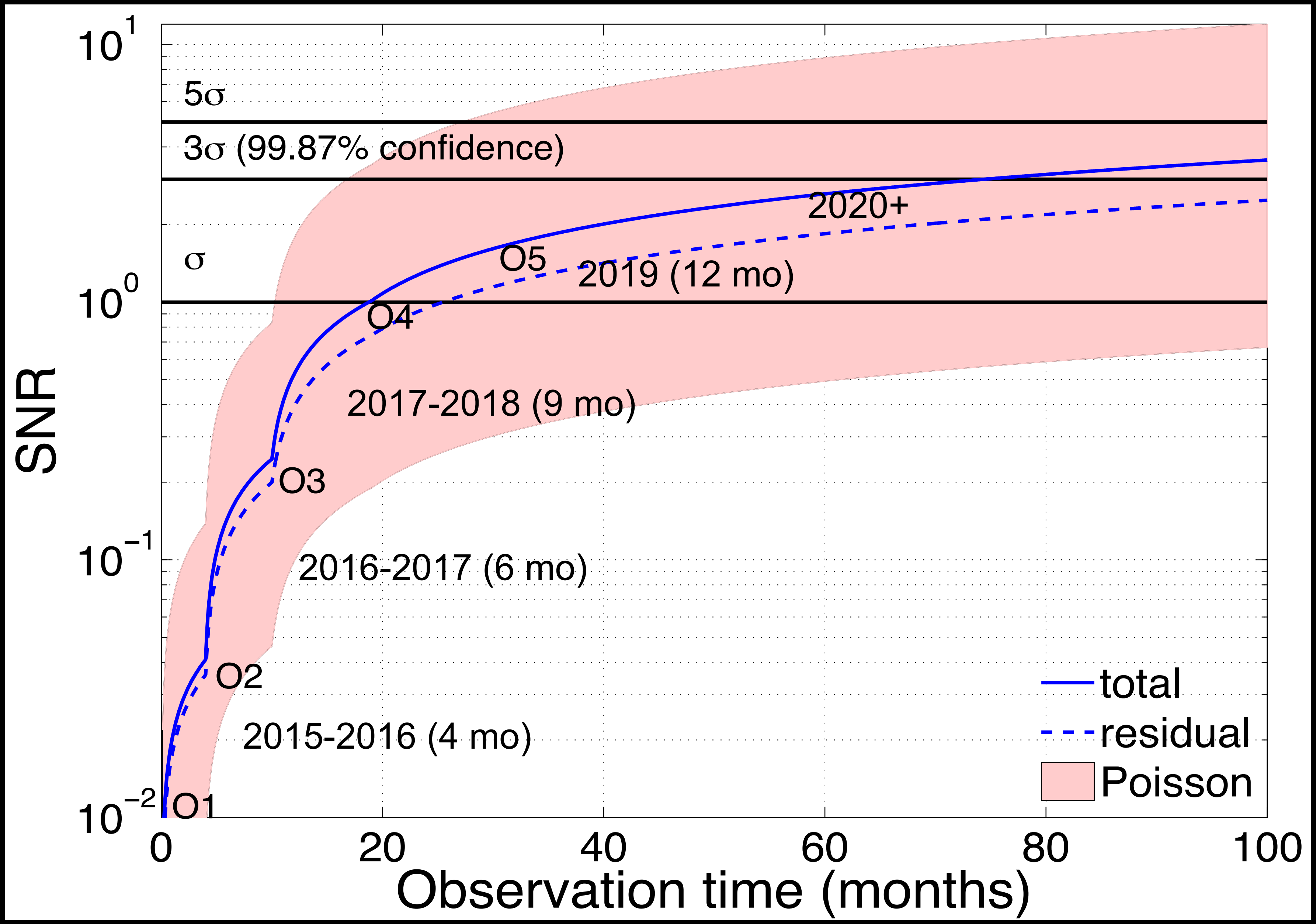


Results for a fiducial model

Detection may be possible before design sensitivity reached. See Phys.Rev.Lett. **118**, 121101 (2017) for details.

Detection strategy details

- Could easily confound a stochastic background with detector noise
- Seek to measure the stochastic background by cross-correlating, over very long periods of time, data streams from pairs detectors
- Account for non-alignment and spatial distance between detectors
- Different filters to optimize the search for different spectral indices
- Signal to noise ratio accumulates over time
- $$\mathrm{SNR} = \frac{3H_o^2}{10\pi^2}\sqrt{2T}\left[\int_0^\infty \sum_{i=1}^{n}\sum_{j>i} \frac{\gamma_{ij}^2(f)\Omega_{\mathrm{GW}}^2(f)}{f^6 P_i(f) P_j(f)} df\right]^{1/2}$$



Evolution of SNR with time

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Conclusion

- Stochastic background from astrophysical sources is expected to be at the high end of previous predictions
- This background could possibly be measured by the Advanced LIGO and Virgo instruments operating at or near their design sensitivity
- Current statistical uncertainties greater than differences between many formation and coalescence models
- Complementarity between signals detected, at low and high redshift, regarding source origin identification