Measuring the Hubble constant with black sirens

Riccardo Sturani

Instituto de Física Teórica UNESP
International Center for Theoretical Physics-South American Institute for Fundamental Research - São Paulo (Brazil)

H. Leandro, V. Marra, RS, arXiv:2109.07537, Phys.Rev.D 105 (2022) 2, 023523

Aug 23rd, 2022 - Cosmo22 in Rio de Janeiro

Overview

1. Cosmology from standard sirens
2. GWs without z, but “knowing” source population
3. Bayesian inference & Results

GW hits the detector

Each GW detector measures $h = F_+(\alpha,\delta,\psi)h_+ + F_\times(\alpha,\delta,\psi)h_\times$
(α,δ sky position, ψ polarization angle)

$$\nu \equiv m_1 m_2/M^2$$

$$\begin{aligned} h_+ &\sim \frac{1+\cos^2(\theta_{LN})}{2} \quad \nu\frac{Mv^2}{d_c}\cos\phi(t_s/M,\nu,S_i^2/m_i^4,\phi_0,\ldots) \\ h_\times &\sim \cos(\theta_{LN}) \quad \nu\frac{Mv^2}{d_c}\sin\phi(t_s/M,\nu,\ldots) \end{aligned}$$

GW hits the detector

Each GW detector measures $h = F_+(\alpha,\delta,\psi)h_+ + F_\times(\alpha,\delta,\psi)h_\times$
(α,δ sky position, ψ polarization angle)

$\nu \equiv m_1 m_2/M^2$

$$
\begin{aligned}
h_+ &\sim \frac{1+\cos^2(\theta_{LN})}{2} \quad \nu\frac{M(1+z)v^2}{d_c(1+z)}\cos\phi(t_O/(M(1+z)),\nu,S_i^2/m_i^4,\ldots)\\
h_\times &\sim \cos(\theta_{LN}) \quad \nu\frac{M(1+z)v^2}{d_c(1+z)}\sin\phi(t_O/(M(1+z)),\nu,\ldots)
\end{aligned}
$$

$t_O \simeq t_s(1+z)$

See C. Bonvin, C. Caprini, RS, N. Tamanini arXiv:1609.08093 PRD '17 for extact $t_O(t_s)$

GW hits the detector

Each GW detector measures $h = F_+(\alpha,\delta,\psi)h_+ + F_\times(\alpha,\delta,\psi)h_\times$
(α,δ sky position, ψ polarization angle)

$\nu \equiv m_1 m_2/M^2$

$$
\begin{aligned}
h_+ &\sim \frac{1+\cos^2(\theta_{LN})}{2} \quad \nu\frac{\mathcal{M}v^2}{d_L}\cos\phi(t_O/\mathcal{M},\nu,S_i^2/m_i^4,\ldots)\\
h_\times &\sim \cos(\theta_{LN}) \quad \nu\frac{\mathcal{M}v^2}{d_L}\sin\phi(t_O/\mathcal{M},\nu,\ldots)
\end{aligned}
$$

$\mathcal{M} \equiv M(1+z)$, $t_O \simeq t_s(1+z)$

The importance of being modelled: matched-filtering

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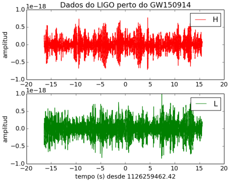

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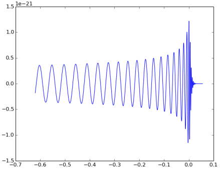

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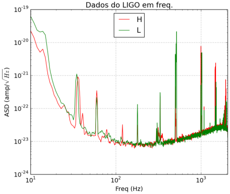

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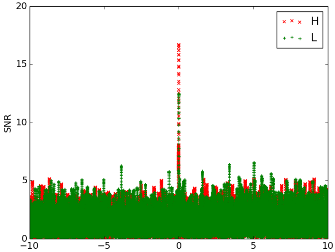


Intrinsic parameters (masses ans spins) determined by signal morphology

Data from https://losc.ligo.org/events/GW150914/

Cosmological Bayesian inference

Aiming at cosmological parameter's posteriors f (for out model: H_0,Ω_m)

$$f(H_0) = p(H_0)p(\Omega_m)p(z|H_0,\Omega_m)\frac{\mathcal{L}(d_L|H_0,\Omega_m,z)}{\mathcal{E}}$$

In absence of a redshift measure, the z prior is crucial

$$p(z|H_0,\Omega_m) = \underbrace{A(H_0,\Omega_m)}_{normalization}\underbrace{R_m^{(\{\theta_i\})}(z)}_{merger\ \ rate}\underbrace{f_{det}(d_C^{(t)}(z))}_{detector}$$

Merger rate $R_m \sim$ star formation rate $\mathcal{R}_f$ + *Poissonian* delay

$$R_m^{(\tau)}(z) = \int_0^z dz_f \frac{dt}{dz_f}\mathcal{R}_f(z_f)\exp\left(-\frac{t(z_f)-t(z)}{\tau}\right)$$

S.Vitale, W. M. Farr, K. Ng, C. L. Rodriguez, arXiv:1808.00901, APJL '19

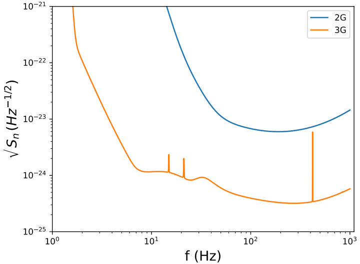
$$\mathcal{R}_f \propto \frac{(1+z)^{2.7}}{1+\frac{1+z}{2.9}^{5.6}}$$

P. Madau, M. Dickinson, arXiv:1403.0007, Ann. Rev. A.A. '14

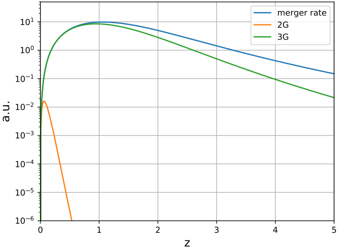
see also X. Ding et al. arXiv:1801.05073 JCAP '19

Detector acceptance

Detector sensitive to $SNR = 2\left(\int_0^\infty \frac{|\tilde{h}(f)|^2}{S_n}\right)^{1/2} \geq 8$



Noise spectral density



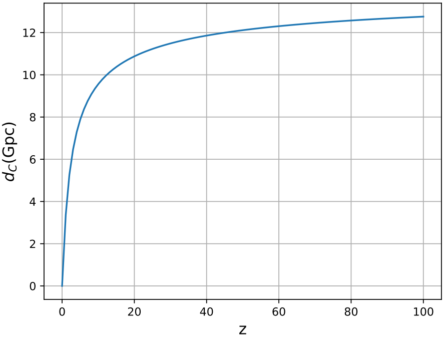
Distribution of detected events ($\tau = 5\,Gyr$)

Typical sources solar mass BHs up to $\sim 10^{2(3)} M_\odot$ for 2(3)G

Exp. cutoff at $d_L \sim$ 320Mpc (2G, $z \sim 0.1$), $d_L \sim 7.9$ Gpc (3G, $z \sim 1.2$)

z-dependence of SNR

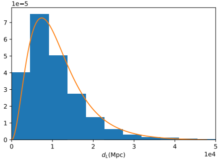
GW amplitude $|\tilde{h}(f)| \sim \frac{(M(1+z))^{5/6} f^{-7/6}}{d_c(1+z)}$

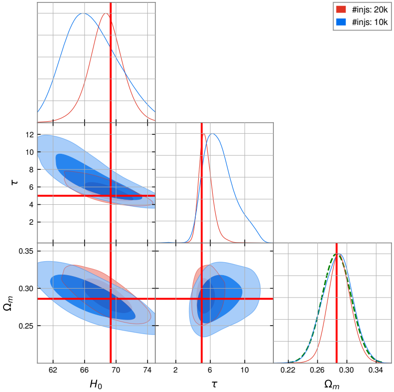


d_c levels off at $\sim 12 Gpc$ ($z \sim 40$), $\implies$ SNR almost independent on z at large distances until signal maximum frequency drops out of the bandwidth

$$f_{max} \sim 20 Hz \left(\frac{M(1+z)}{10^3 M_\odot} \right)^{-1}$$

Result I





Fisher matrix

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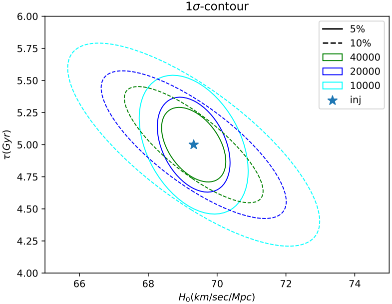
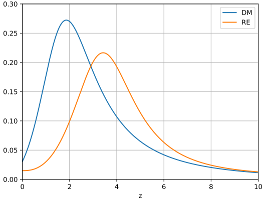


← Montecarlo

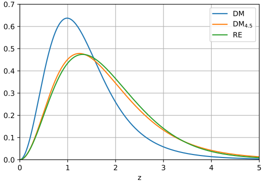
More hyper-parameters

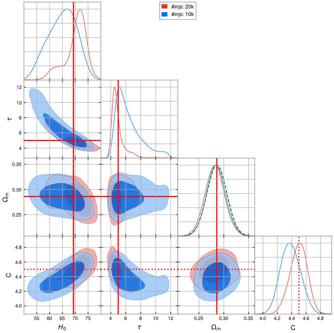
What if underlying merger rate different?



B. Robertson and R. Ellis arXiv:1109.0900 APJ '12

Add a parameter: $\mathcal{R}_f \propto \frac{(1+z)^{2.7}}{1+\left(\frac{1+z}{C}\right)^{5.6}}$





Conclusion

- While 3G standard siren detection rate largely uncertain ($\gtrsim 10^3$/month), surely black sirens will dominate the number of detections, it is worth investigating their impact on cosmological parameter estimation in absence of reliable catalogs
- Fitting population and cosmological parameters *together*