Digging deeper: Removal of astrophysical gravitational-wave foreground from black hole and neutron star binaries to reveal the cosmological background

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EPS-HEP, Ghent
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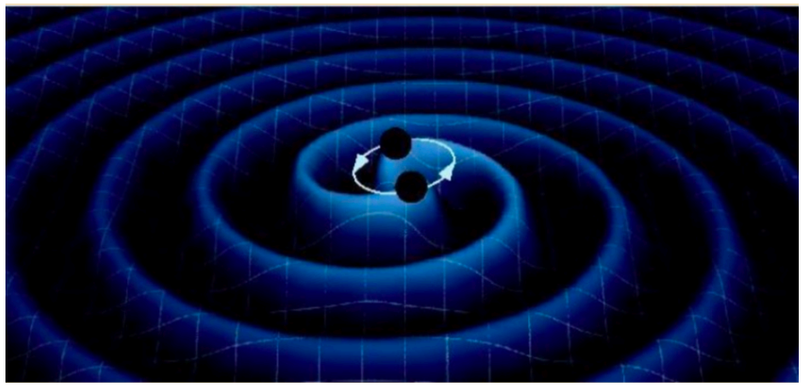
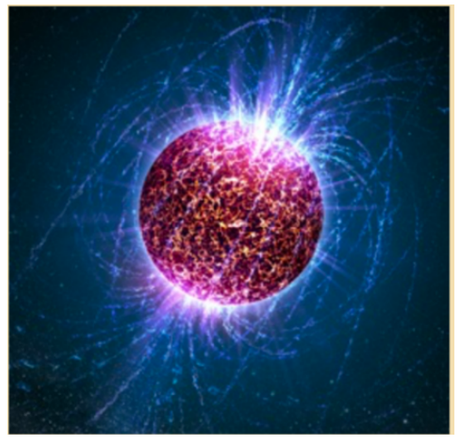
GW: Sources

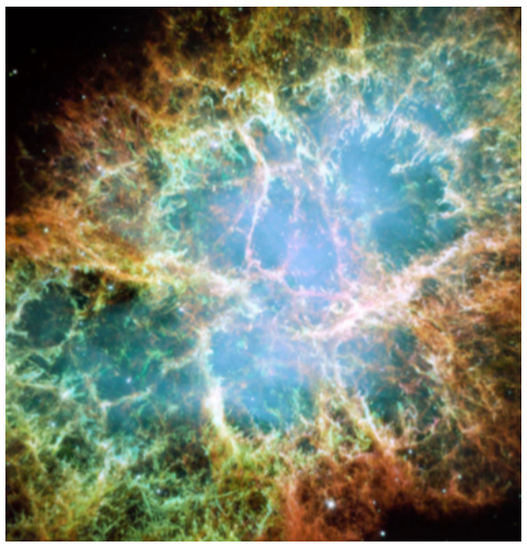
Binary megers

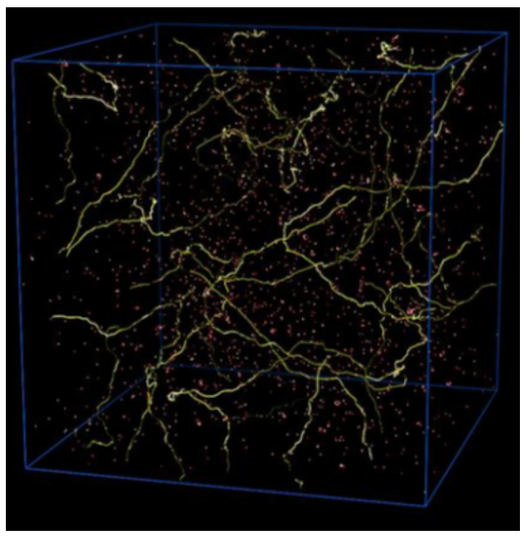


Continuous waves

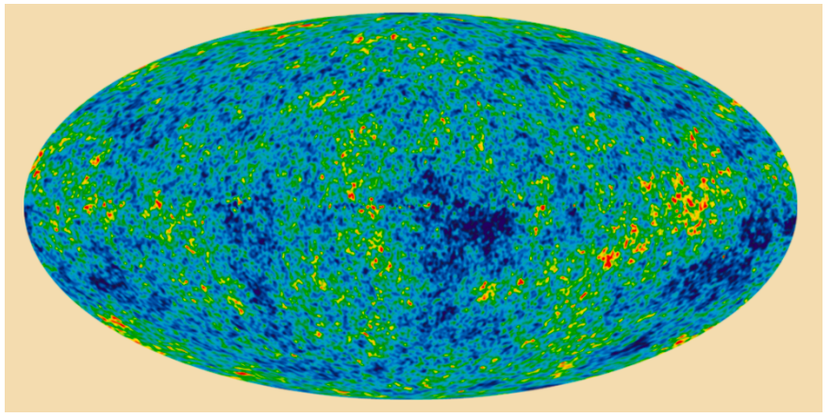


Burst



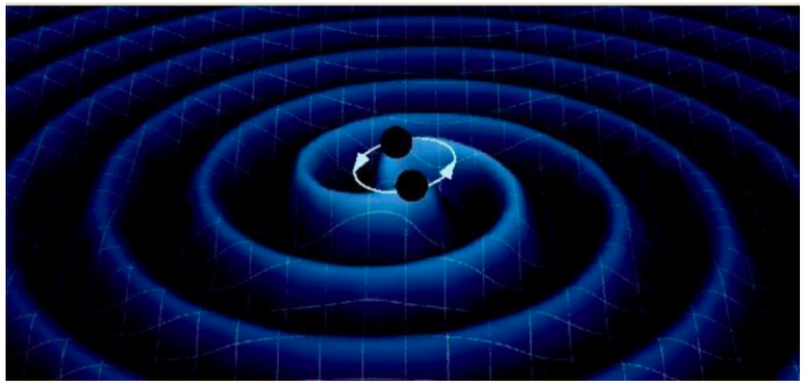


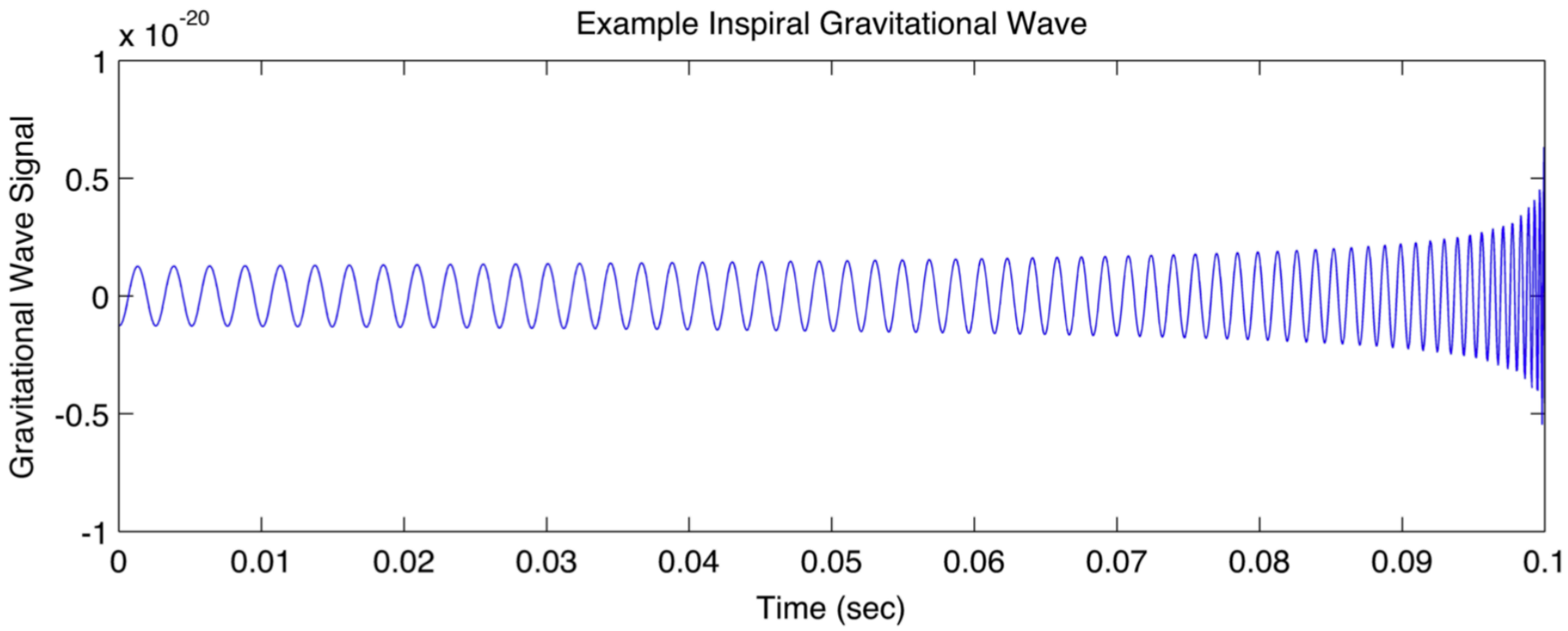
Stochastic



GW: Sources **Binary mergers**

- Radiate GWs as components orbit each other
- Loss of energy/momentum causes orbit to shrink
- Ultimately merge and form a single black hole



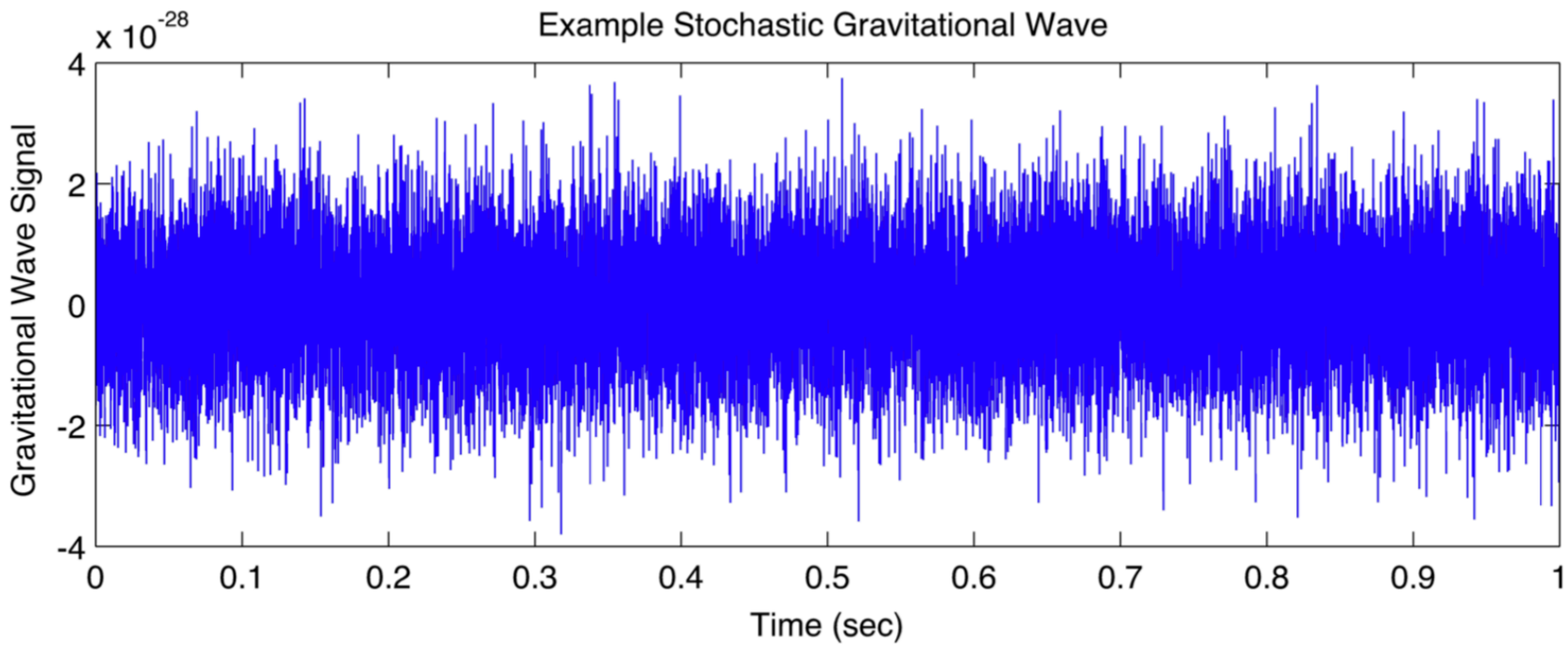


GW: Sources **Stochastic**

- Astrophysical
  - **Black hole and neutron star binaries**
  - Cosmic strings
  - Core collapse supernovae
  - Rotating neutron stars

- Primordial
  - Amplification of vacuum fluctuations during inflation
  - Pre big bang models
  - Phase transitions

Weak emitters, well modeled (statistically), long duration.



Basic Idea

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

$$\rho_C = 3H_0^2/8\pi G$$

$$= \quad 67.8 \pm 0.9 \text{ km/c/Mpc}$$

$$\Omega_{GW} = \Omega_{cbc} + \Omega_{cosmo} + \Omega_{astro}$$

$$\Omega_{GW} = \Omega_{cbc,\,rec} + \Omega_{error} + \Omega_{cbc,\,unres} + \Omega_{cosmo} + \Omega_{astro}$$

$$(\Omega_{error} + \Omega_{cbc,\,unres}) \,?\, \Omega_{cosmo} \,?\, \Omega_{astro}\,.$$

Residual background from CBCs

Basic Idea

Regimbau et al.

arXiv:1611.08943

Population synthesis

$$\Omega_{\rm cbc} = \frac{1}{\rho_c c} f F(f), \qquad F(f) = T^{-1} \frac{\pi c^3}{2G} f^2 \sum_{k=1}^{N} (\tilde{h}^2_{+,k}(f) + \tilde{h}^2_{\times,k}(f)),$$

Fisher matrix

$$\Omega_{\rm error} = \frac{1}{\rho_c c} f F_{\rm error}(f), \qquad F_{\rm error}(f) = T^{-1} \frac{\pi c^3}{2G} f^2 \times$$
$$\times \sum_{k=1}^{N} \left[(\tilde{h}^{\rm true}_{+,k}(f) - \tilde{h}^{\rm rec}_{+,k}(f))^2 + (\tilde{h}^{\rm true}_{\times,k}(f) - \tilde{h}^{\rm rec}_{\times,k}(f))^2 \right].$$

$$(\Omega_{\rm error} + \Omega_{\rm cbc,\ unres}) \ ? \ \Omega_{\rm cosmo} \ ? \ \Omega_{\rm astro} \ .$$

Residual background from CBCs

Simulation Model

Mass distribution

BBH - $p(m_1) \propto m_1^{-2.35}$

$m_1, m_2 : 5 - 100 M_\odot$

BNS - uniform

$m_1, m_2 : 1 - 2 M_\odot$

Simulation Model

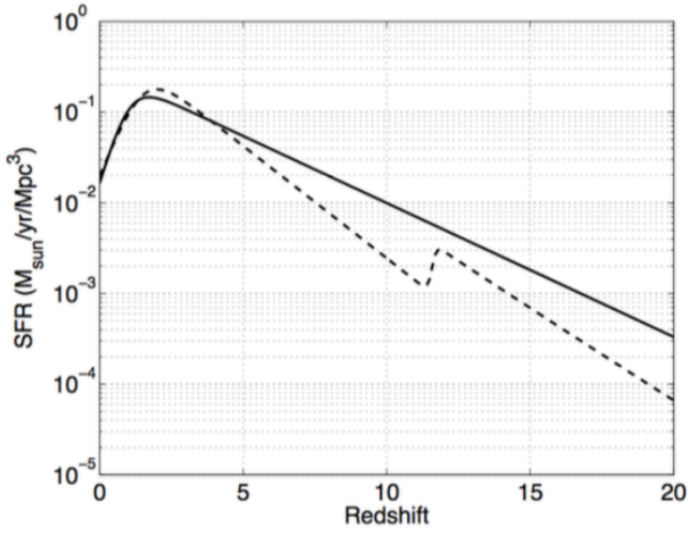
Redshift distribution

Merger rate in observer frame

$$p(z) = \frac{R_z(z)}{\int_0^{10} R_z(z)dz}$$

Merger rate per comoving volume element in the source frame

$$R_z(z) = \int \frac{R_m(z)}{1+z}\frac{dV}{dz}(z)dz$$

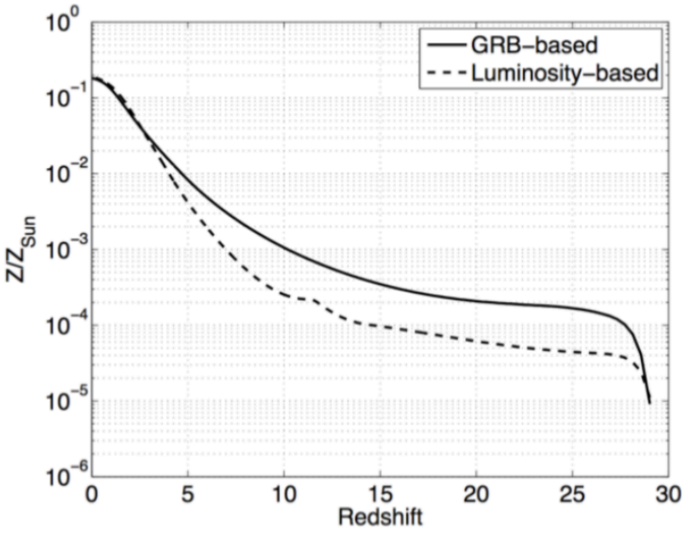


$$R_m(z) = \int_{t_{\min}}^{t_{\max}} R_f(z_f)P(t_d)dt_d$$

Binary formation rate given a redshift at the formation time

Time delay distribution between formation and merger

$$p(t_d) \propto 1/t_d \qquad t_{\min} < t_d < t_{\max}$$



Vangioni et al. 2015
Figure from Krocker et al. 2015

Black hole and neutron star binaries

76,107 BBH, 1,438,835 BNS in the population

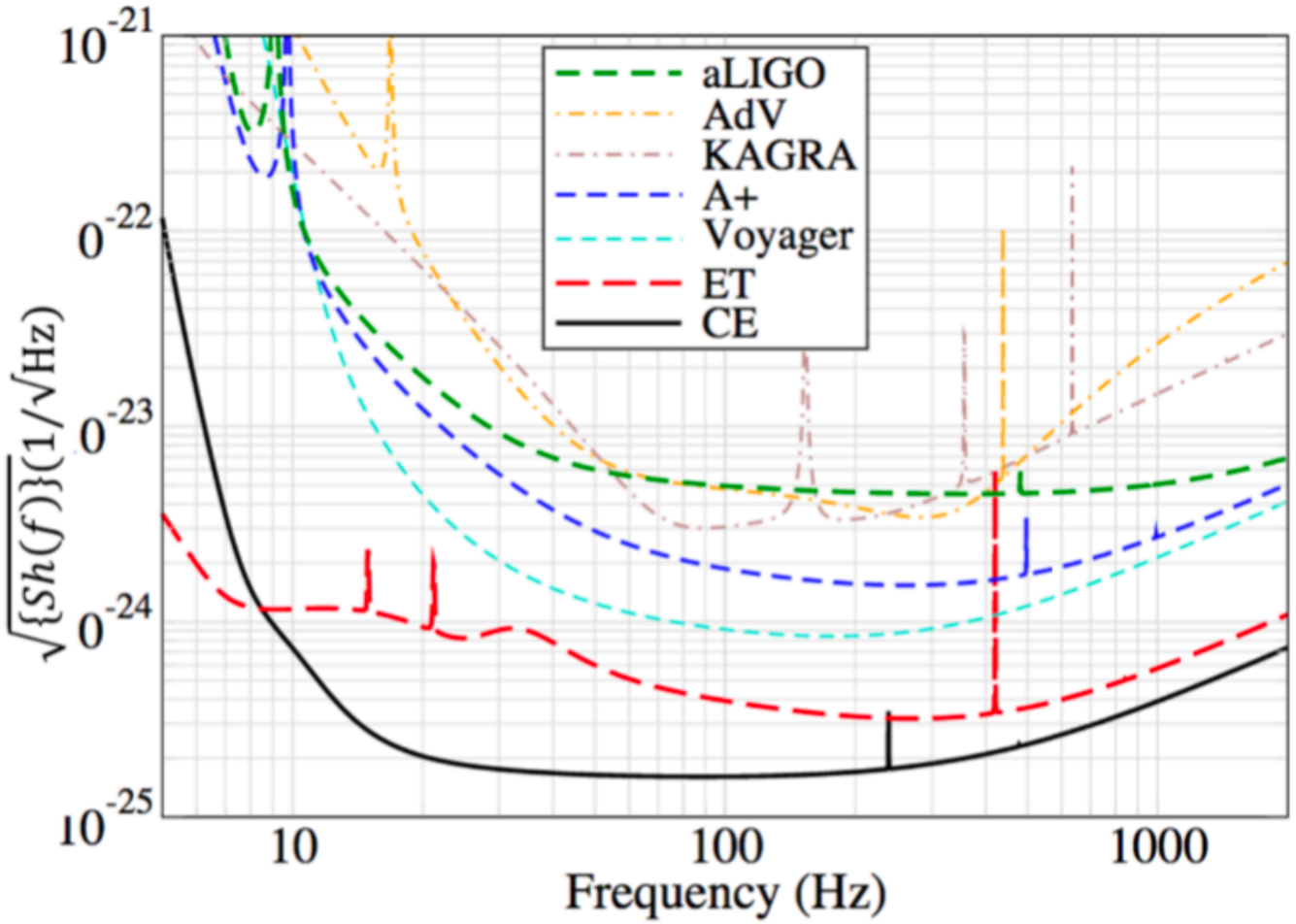
So far:
O1 - 3 BBHs
O2 - 7 BBHs, 1 BNS
O3 - 18 unretracted triggers

3-network 3 G detectors:

51.3% BNS with SNR >= 12.0
98.6% BBH with SNR >= 12.0

5-network 3 G detectors:

75.3% BNS with SNR >= 12.0
99.9% BBH with SNR >= 12.0



Parameter recovery: using Fisher matrices

$$\tilde{h}(f) = \mathcal{A} f^{-7/6} e^{i\Psi(f)}$$

$$\Psi(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\eta\nu^5}\sum_{k=0}^{N}\alpha_k \nu^k$$

We truncate the series at k = 0.

K.G. Arun et al.

arXiv:gr-qc/0411146

Parameters for Fisher matrix,

$$\theta = (f_0 t_c, \phi_c, ln\mathcal{M})$$

In terms of these,

$$\Psi(f) = 2\pi\frac{f}{f_0}\theta_1 - \theta_2 - \frac{\pi}{4} + \frac{3}{128}\left(\frac{\pi e^{\theta_3} f G M_{sun}}{c^3}\right)^{-5/3}$$

Parameter recovery: using Fisher matrices

The fisher matrix elements are given by,

$$\Gamma_{ij} = 2\int_{f_L}^{f_H} \frac{\tilde{h}^*_{\theta_i}(f)\tilde{h}_{\theta_j}(f) + \tilde{h}_{\theta_i}(f)\tilde{h}^*_{\theta_j}(f)}{S_n(f)}\mathrm{d}f,$$

where,

$$\tilde{h}_{\theta_i}(f) = \frac{\partial}{\partial\theta_i}(\tilde{h}(f)),$$

Parameter recovery: using Fisher matrices

$$\tilde{h}_{\theta_1}(f) = \frac{2\pi f A}{f_0} f^{-7/6} e^{i(\Psi(f)+\pi/2)},$$

$$\tilde{h}_{\theta_2}(f) = A f^{-7/6} e^{i(\Psi(f)-\pi/2)},$$

and,

$$\tilde{h}_{\theta_3}(f) = A f^{-7/6} e^{i(\Psi(f)-\pi/2)} \frac{5}{128} (\frac{\pi e^{\theta_3} f G}{c^3})^{-5/3}.$$

Parameter recovery: using Fisher matrices

Fisher matrix for a detector-network,

$$\Gamma_{ij}^{\rm net} = \sum_{\rm det} \Gamma_{ij}^{\rm det}.$$

Variance-covariance matrix,

$$\Sigma_{ij} = (\Gamma^{-1})_{ij}.$$

Bias in parameter estimation

$$\mathbf{R} = [\Delta\theta_1, \Delta\theta_2, \Delta\theta_3] = \mathbf{pO} - \mathbf{pT},$$

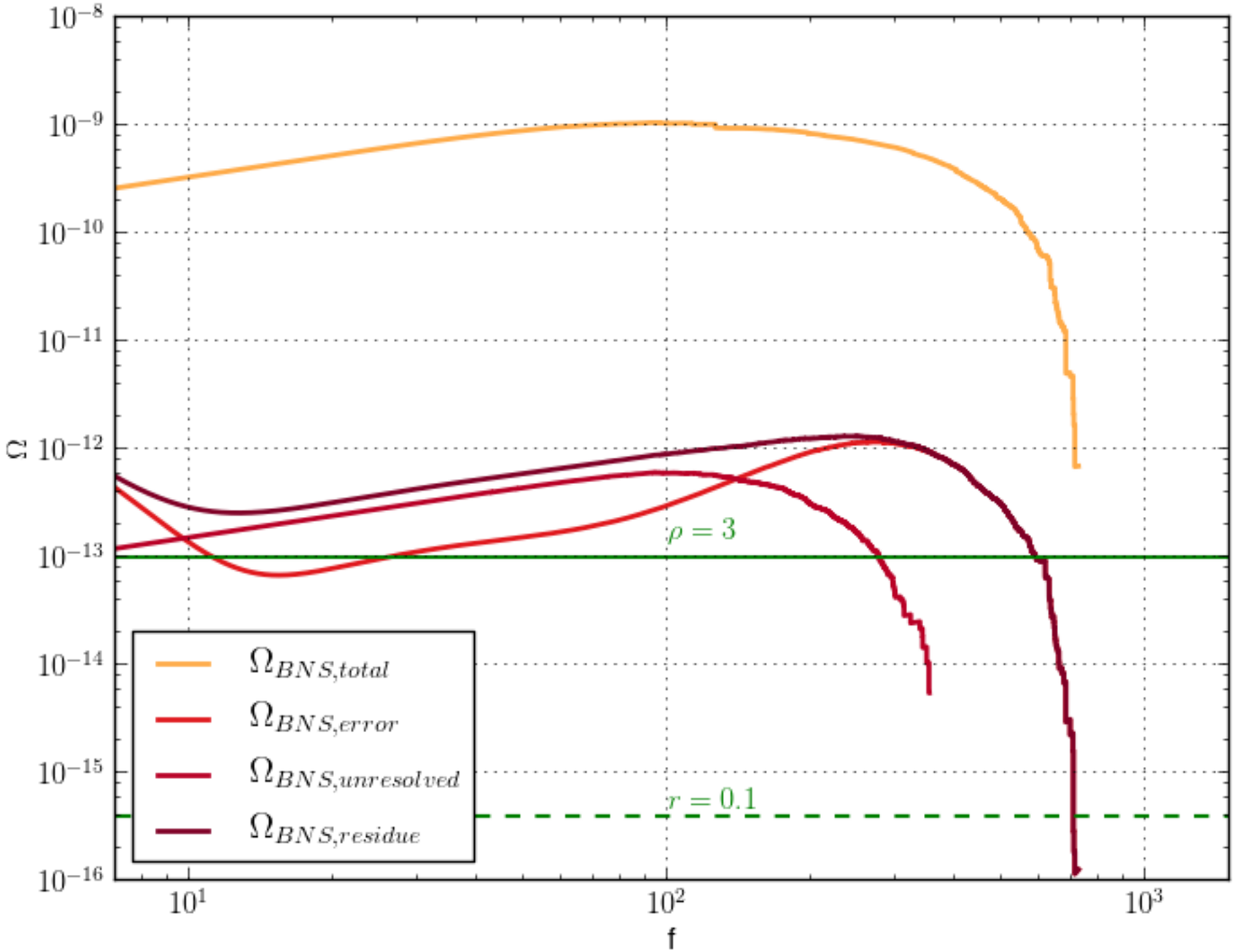
$$\Delta t_c = \frac{\Delta\theta_1}{f_0},$$

$$\Delta\phi_c = \Delta\theta_2,$$

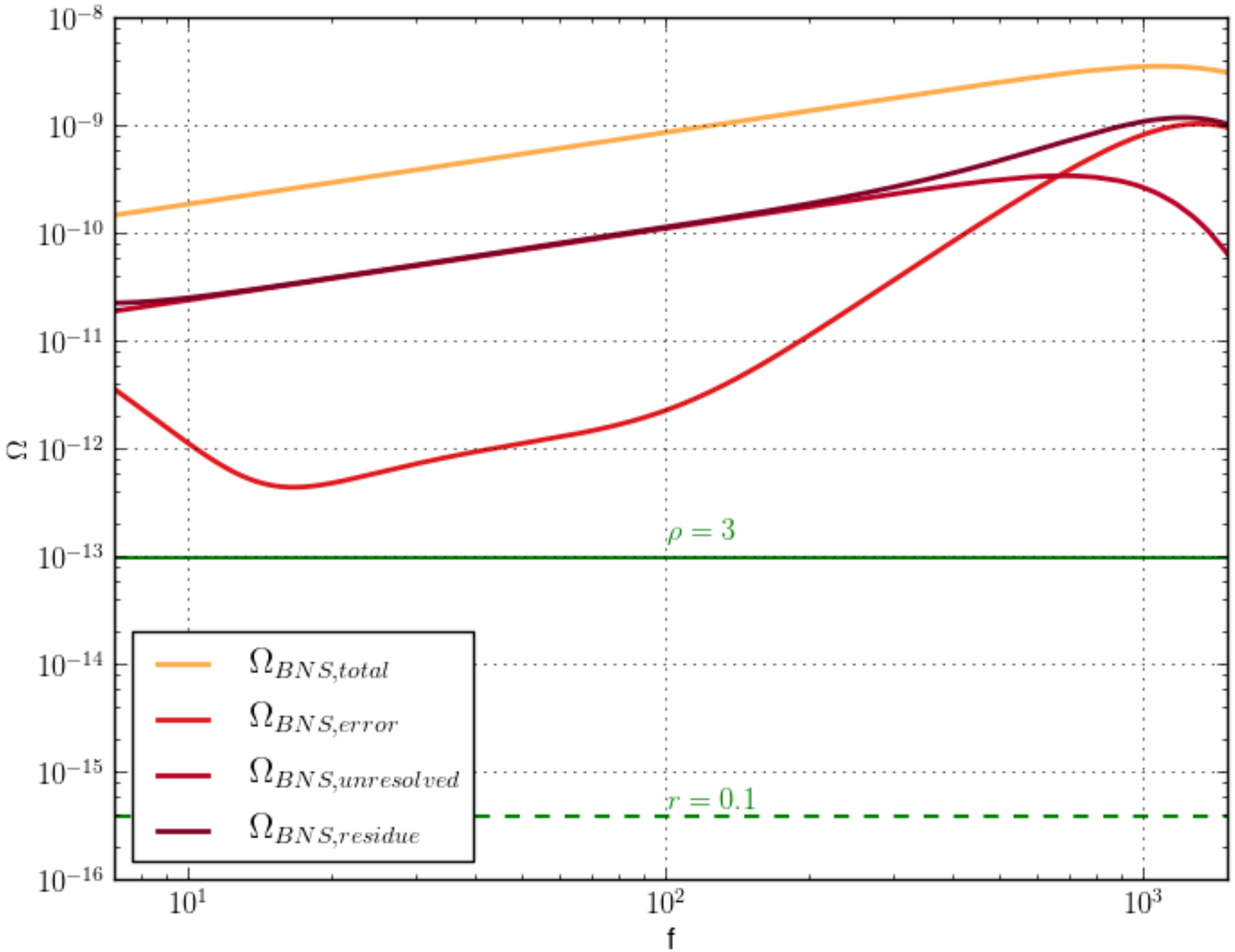
and

$$\Delta\mathcal{M} = \mathcal{M}\Delta\theta_3.$$

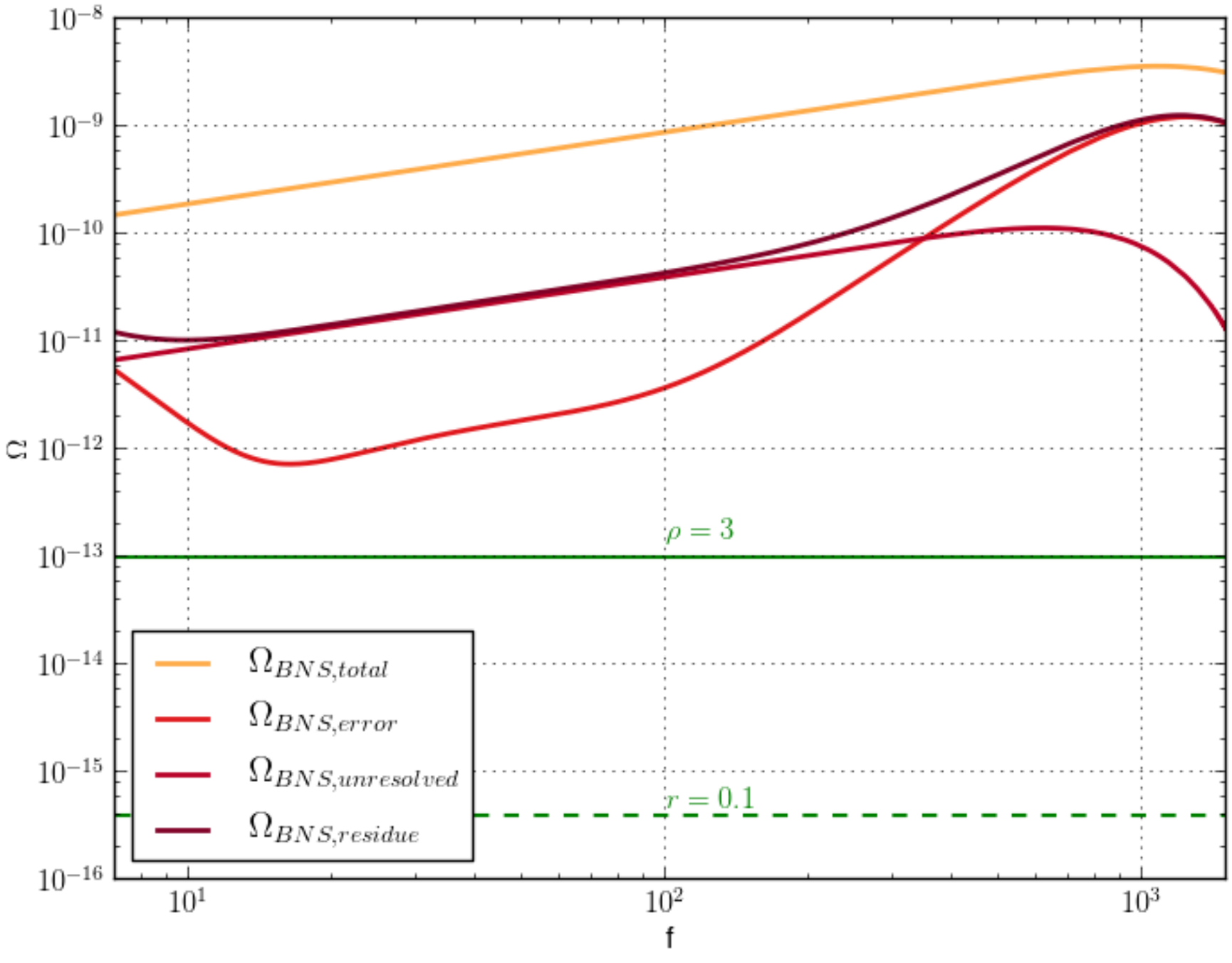
Results: BBH


10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Ω
10^{1}
10^{2}
10^{3}
f
$\rho = 3$
$r = 0.1$
$\Omega_{BNS,total}$
$\Omega_{BNS,error}$
$\Omega_{BNS,unresolved}$
$\Omega_{BNS,residue}$

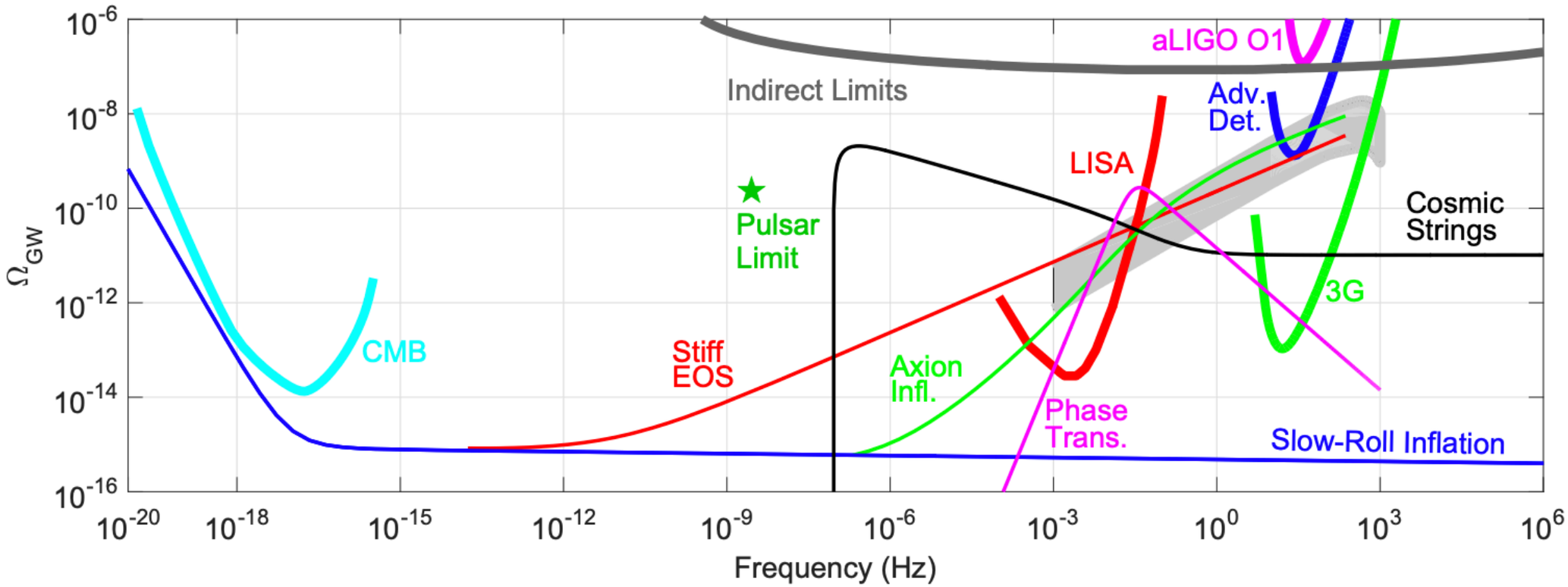
Results: BNS


10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Ω
10^{1}
10^{2}
10^{3}
f
$\rho = 3$
$r = 0.1$
$\Omega_{BNS,total}$
$\Omega_{BNS,error}$
$\Omega_{BNS,unresolved}$
$\Omega_{BNS,residue}$

Results: BNS, snr threshold 8



Proposed backgrounds



arXiv: 1903.09260

Conclusions and Future Work

- The residual background for BBH is dominated by bias in parameter recovery
- The residual background for BNS is dominated by unresolved sources
- There is still a lot of uncertainty in population model, especially local BNS merger rate

Thank you 😊