Constraining galaxy and black hole binary mergers with Pulsar Timing Arrays

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HUNTING GRAVITATIONAL WAVES USING PULSARS

Pulsar

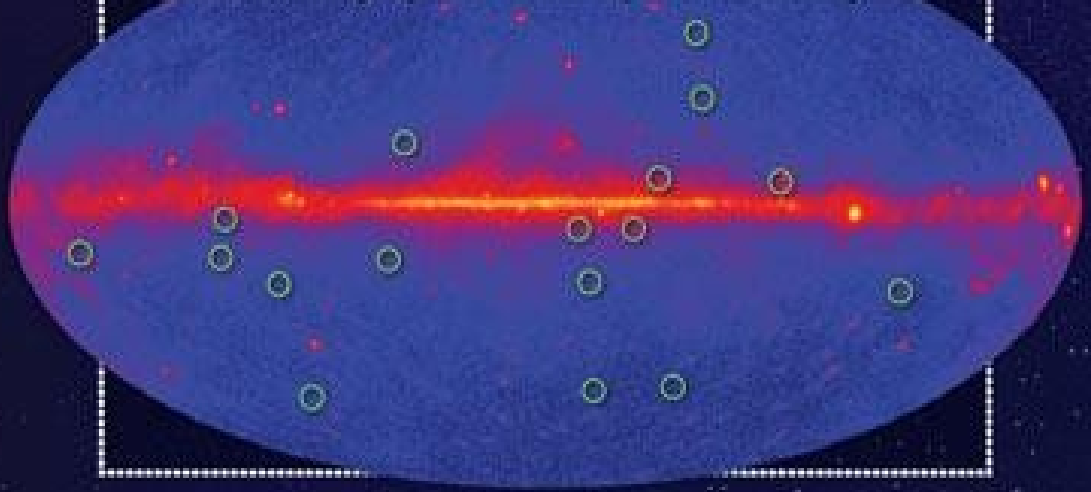
1 Gravitational waves from supermassive black-hole mergers in distant galaxies subtly shift the position of Earth.

2 Telescopes on Earth measure tiny differences in the arrival times of the radio bursts caused by the jostling.

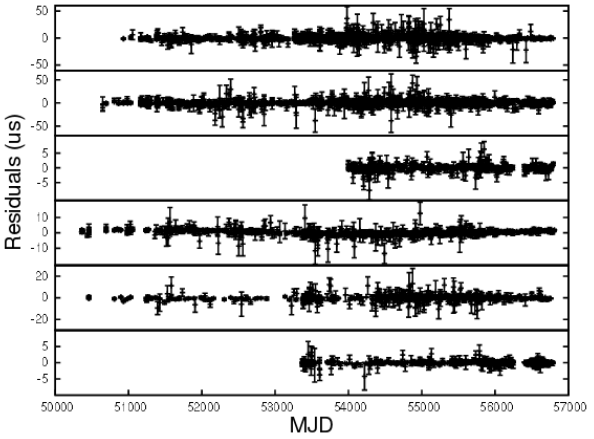
3 Measuring the effect on an array of pulsars enhances the chance of detecting the gravitational waves.

NEW MILLISECOND PULSARS

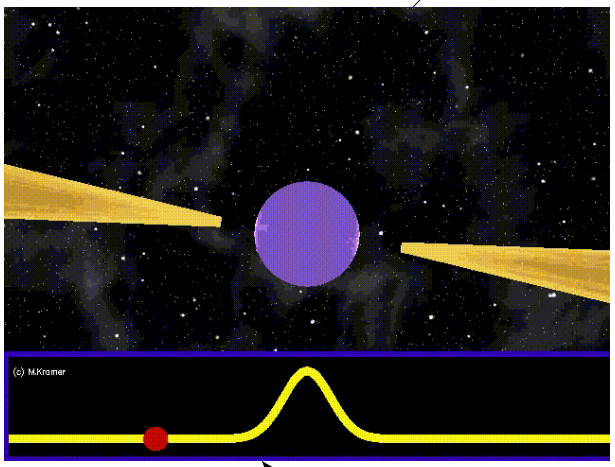
An all-sky map as seen by the Fermi Gamma-ray Space Telescope in its first year

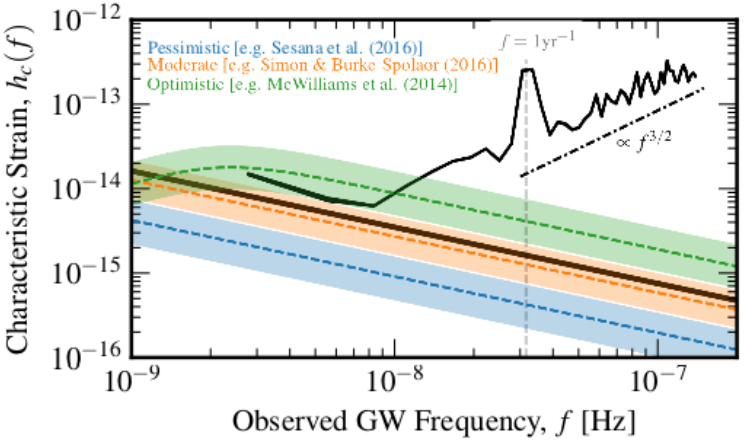


Observation/Timing



Data analysis





Motivation

Interpretation

Constraining astrophysics with pulsars

Using Pulsar Timing Array (PTA) observations on the Gravitational Wave Background (GWB) emitted by a population of super massive black hole binaries (SMBHB)

To constrain the properties of the individual binaries

And the parameters of the SMBHB population and galaxy merger rate

Method

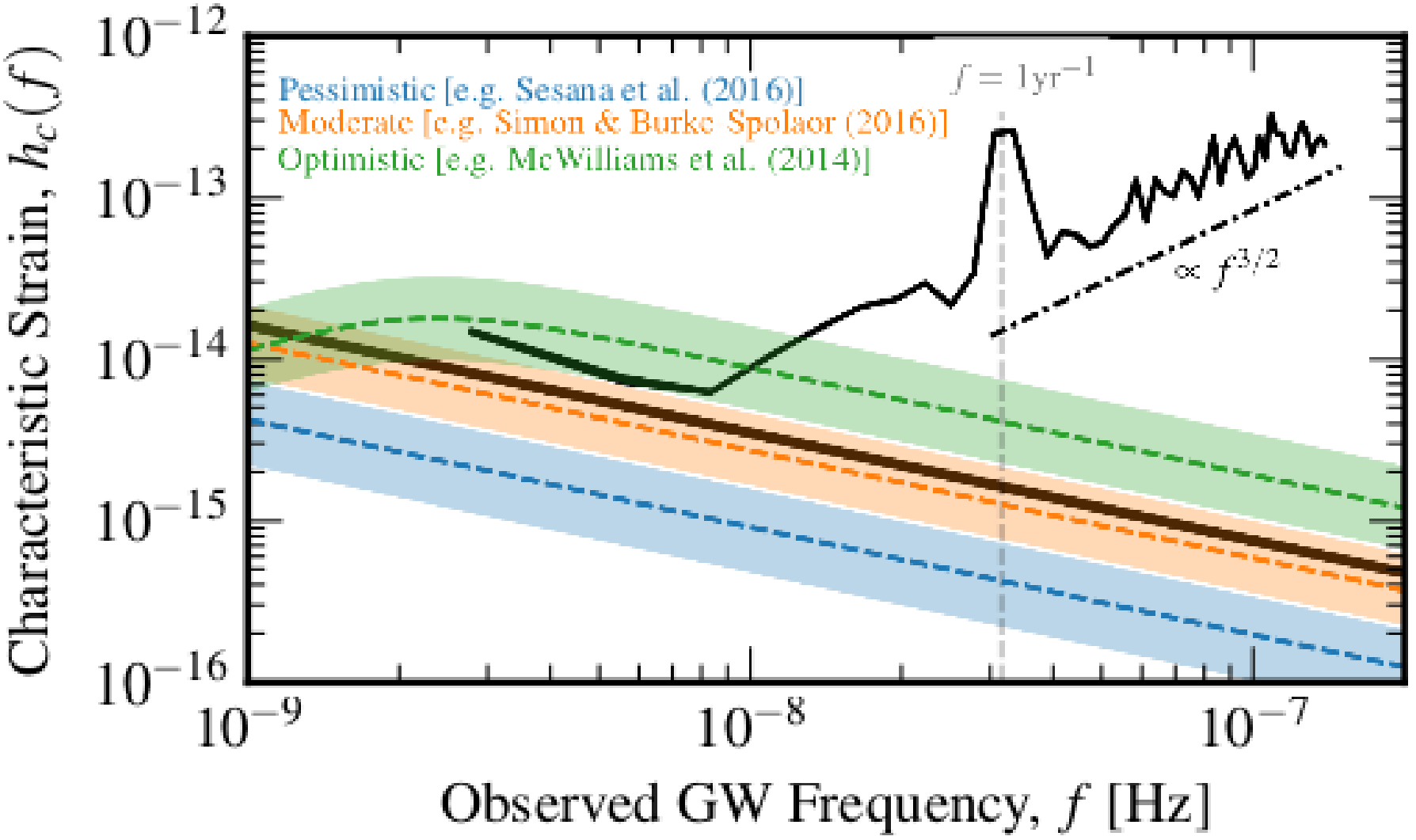
Write a parametric model to compute the GWB

Use PTA upper limits (simulated detections) as likelihood function in a nested sampling algorithm

Get constraints (posteriors) for the parameters and evidences for model comparison

Chen, Sesana, Del Pozzo 2017, MNRAS 470, 1738 – 1749
Chen et al. 2017, MNRAS 468, 404 – 417

GWB Upper Limit



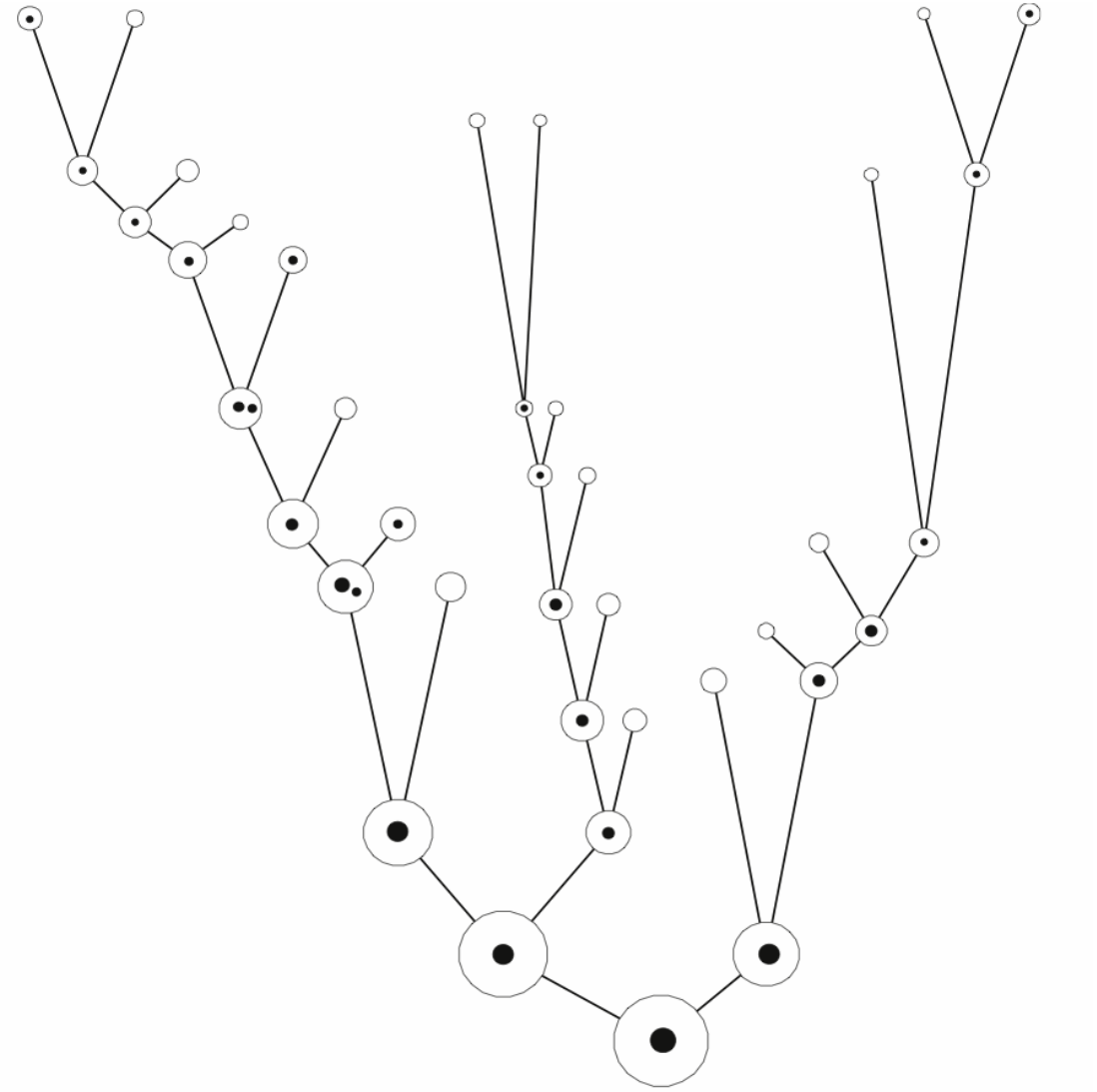
Arzoumanian et al. 2018

Parametric model I

- Population of SMBHB $n_c(z,M)$
- Energy emission of individual binary dE/df

$$h_c^2 = \frac{4G}{\pi c^2 f} \int_0^\infty dz \int_0^{\bar{M}} d\mathcal{M}\; n_c(z,\mathcal{M}) \frac{dE}{df}$$

Black hole merger tree



Credits: Volonteri

SMBHB – Galaxy Merger

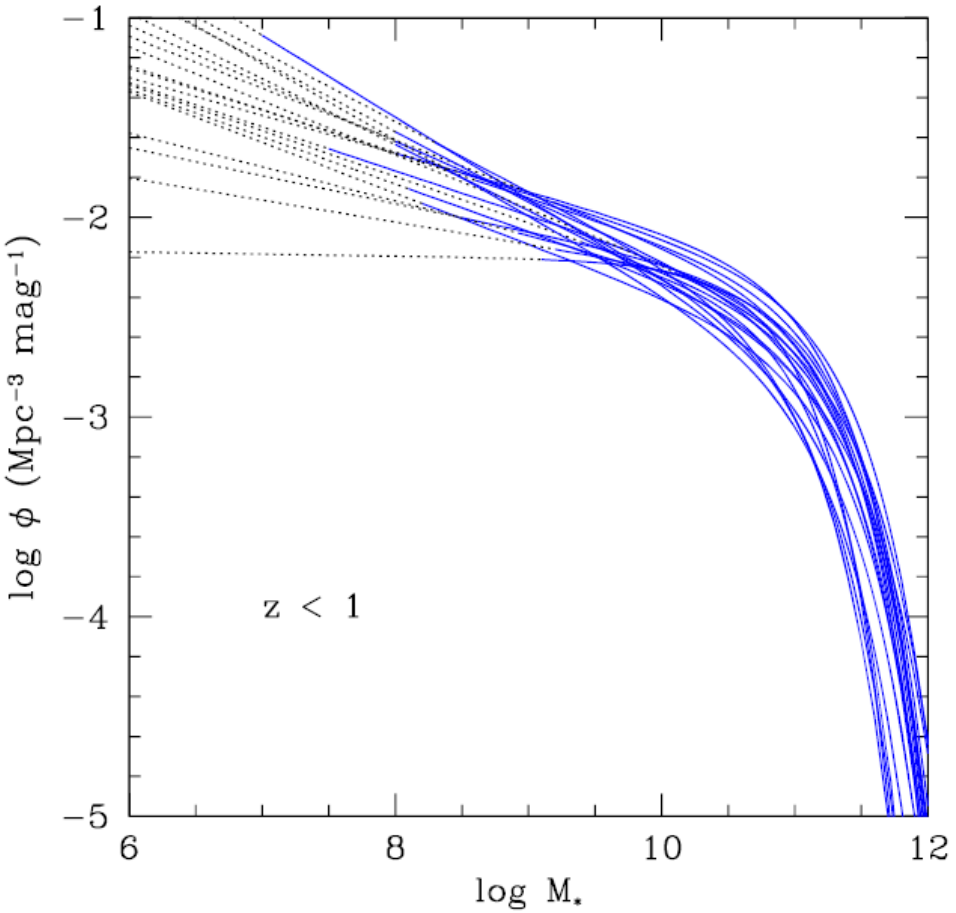
- How many galaxies are there?
- Galaxy Stellar Mass Function

- What fraction of galaxies are in pairs?
- Pair Fraction

- How long does the merger take?
- Merger Time Scale

- What is the relation between a SMBH and its host galaxy?
- $M_G - M_{BH}$ relation

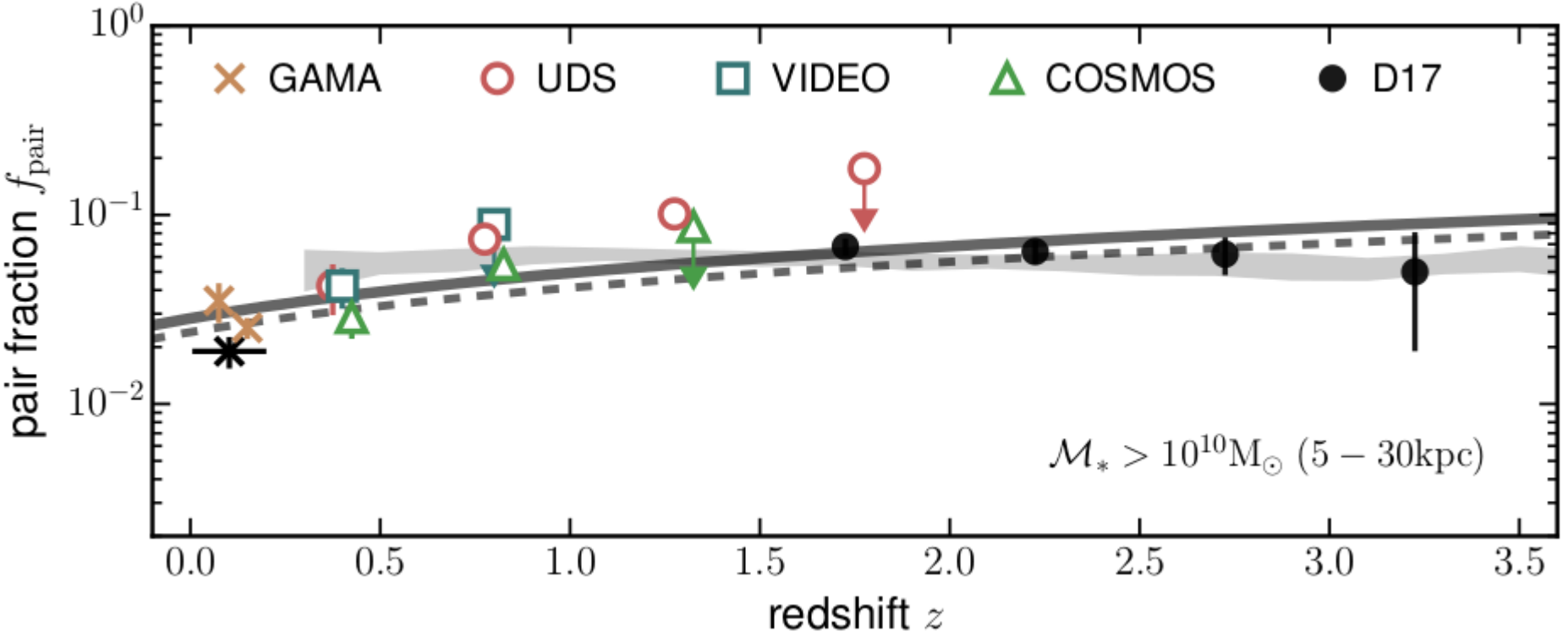
Galaxy stellar mass function



$$\Phi(M_G) = \ln 10\ \Phi_0 \left(\frac{M_G}{M_0}\right)^{1+\alpha} \exp\left(-\frac{M_G}{M_0}\right)$$

Conselice et al. 2016

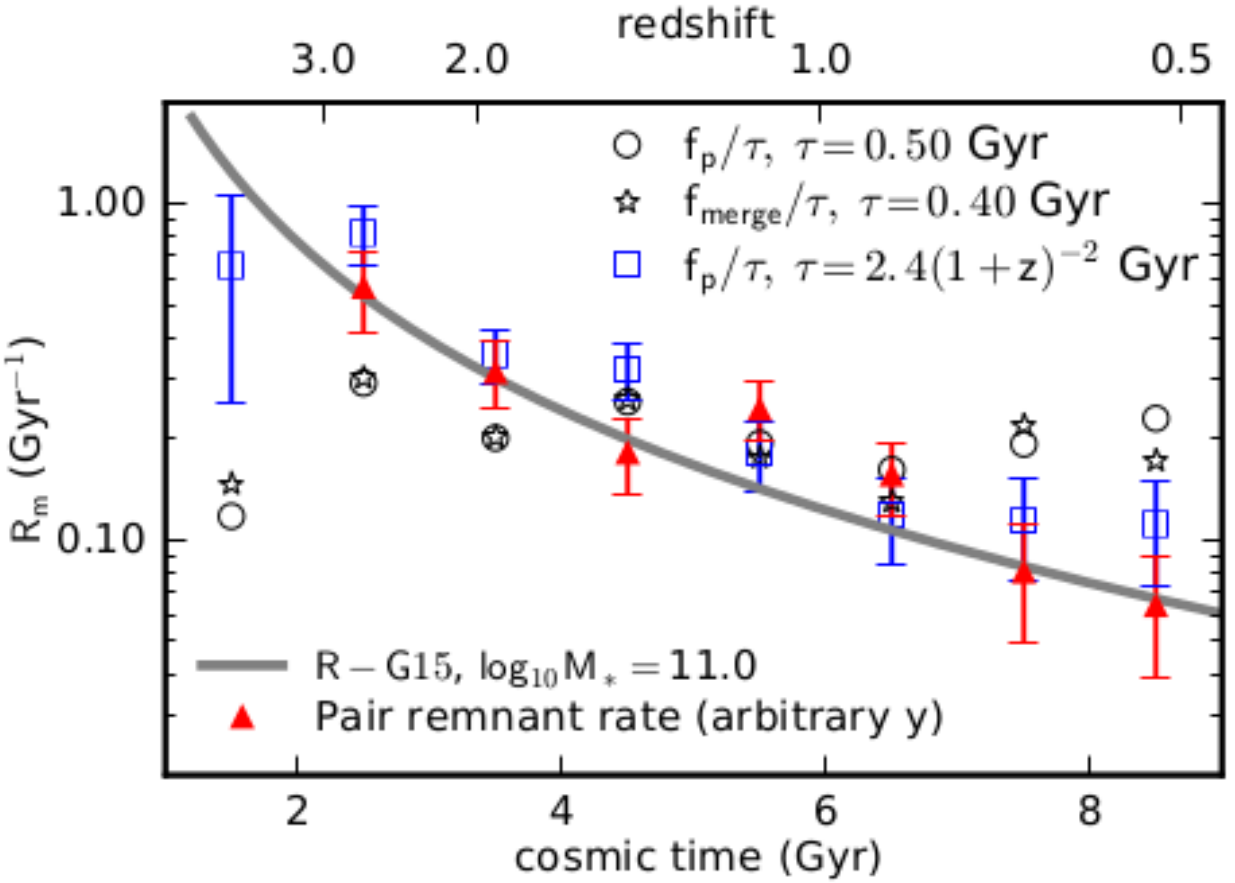
Pair fraction



$$\mathcal{F} = f_0'(1+z)^{\beta}\left(\frac{M_G}{M_0}\right)^{\gamma} q^{\delta}$$

Mundy et al. 2017

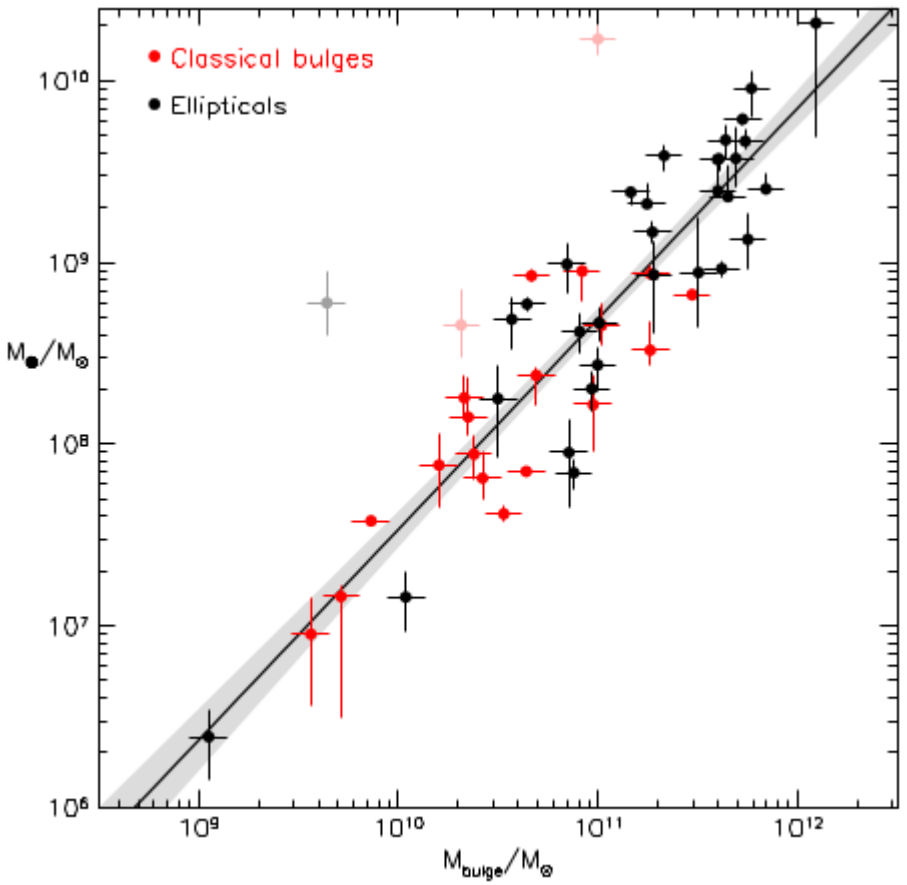
Merger time scale



$$\tau = t_0 \left(\frac{M_G}{M_0} \right)^{\epsilon} (1+z)^{\zeta} q^{\eta}$$

Snyder et al. 2016

$M_G - M_{BH}$ relation

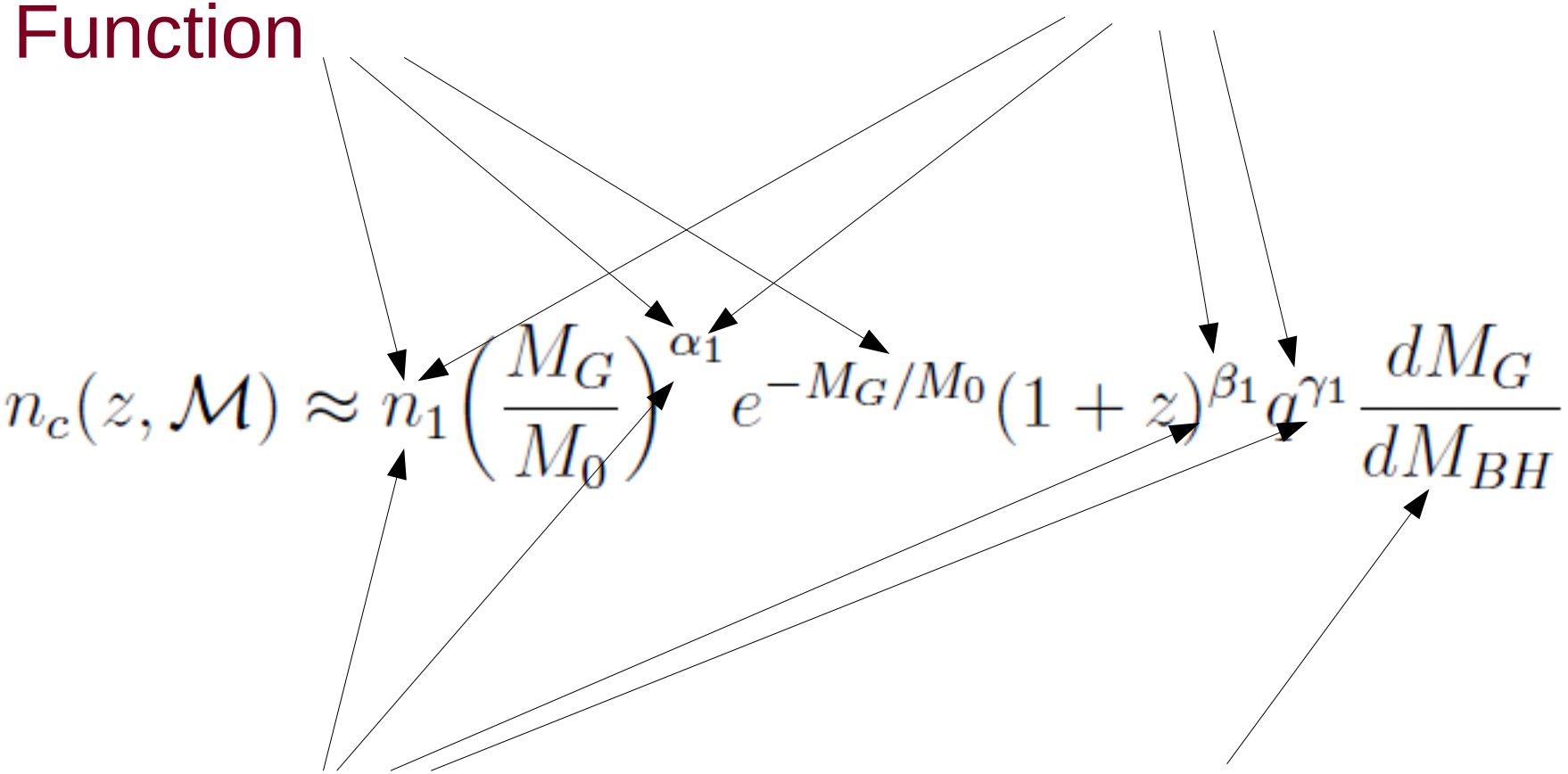


$$M_{BH} = M_* \left(\frac{M_G}{10^{11} M_\odot} \right)^{\theta} * \text{scatter}$$

Kormendy and Ho 2013

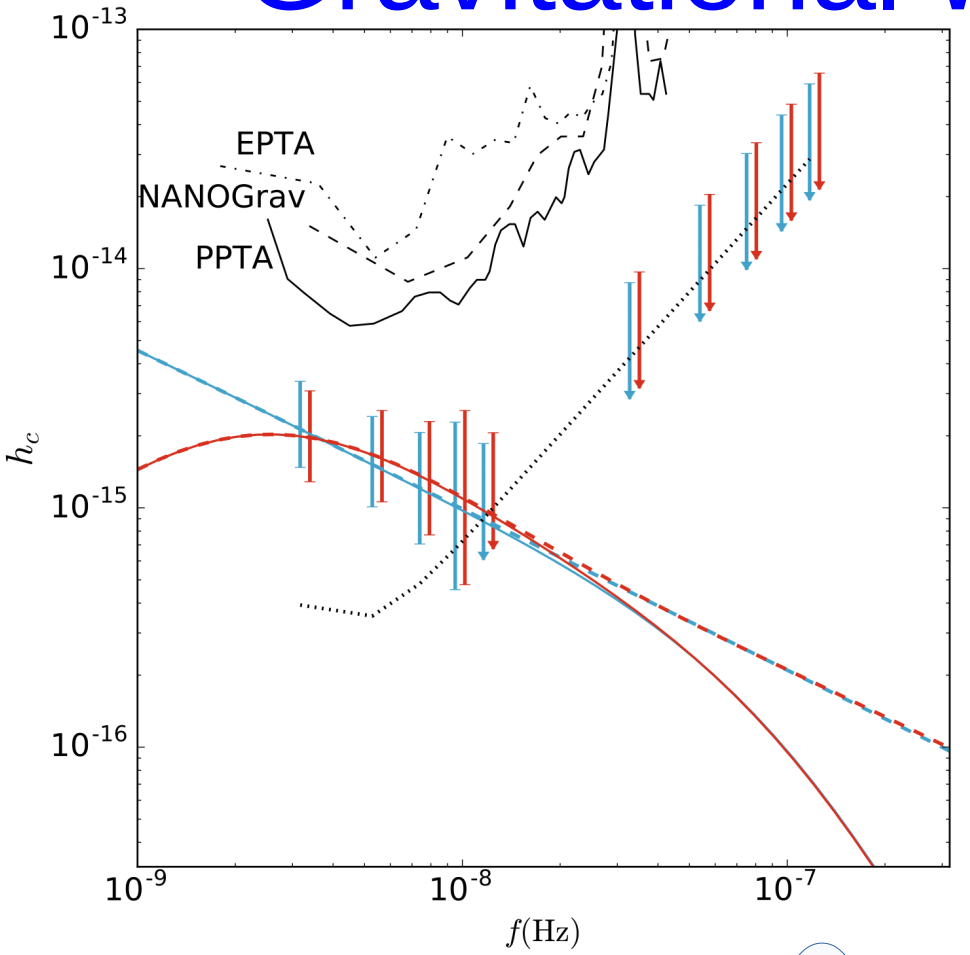
Galaxy Merger – SMBHB

- Galaxy Stellar Mass Function
- Pair Fraction



- Merger Time Scale
- M_G – M_{BH} relation

Gravitational wave spectrum



$$\int_{f-\Delta f}^{f+\Delta f}\int_0^\infty\int_{\bar{M}}^\infty \frac{d^3N}{df\,dz\,d\log_{10}\mathcal{M}} = 1$$

Upper mass limit:
Sesana, Vecchio, Colacino 2008

Sum of harmonics

$$h_c^2 = \frac{4G}{\pi c^2 f}\int_0^\infty dz \int_0^{\bar{M}} d\mathcal{M}\, n_c(z,\mathcal{M})\frac{dE}{df} = \frac{4G}{\pi c^2 f}\int_0^\infty dz \int_0^{\bar{M}} d\mathcal{M}\, n_c(z,\mathcal{M})\sum_{n=1}^{\infty}\frac{1}{n}\frac{dE_n}{dt}\frac{dt}{de}\frac{de}{df_n}$$

Population function

Spectrum of individual binary

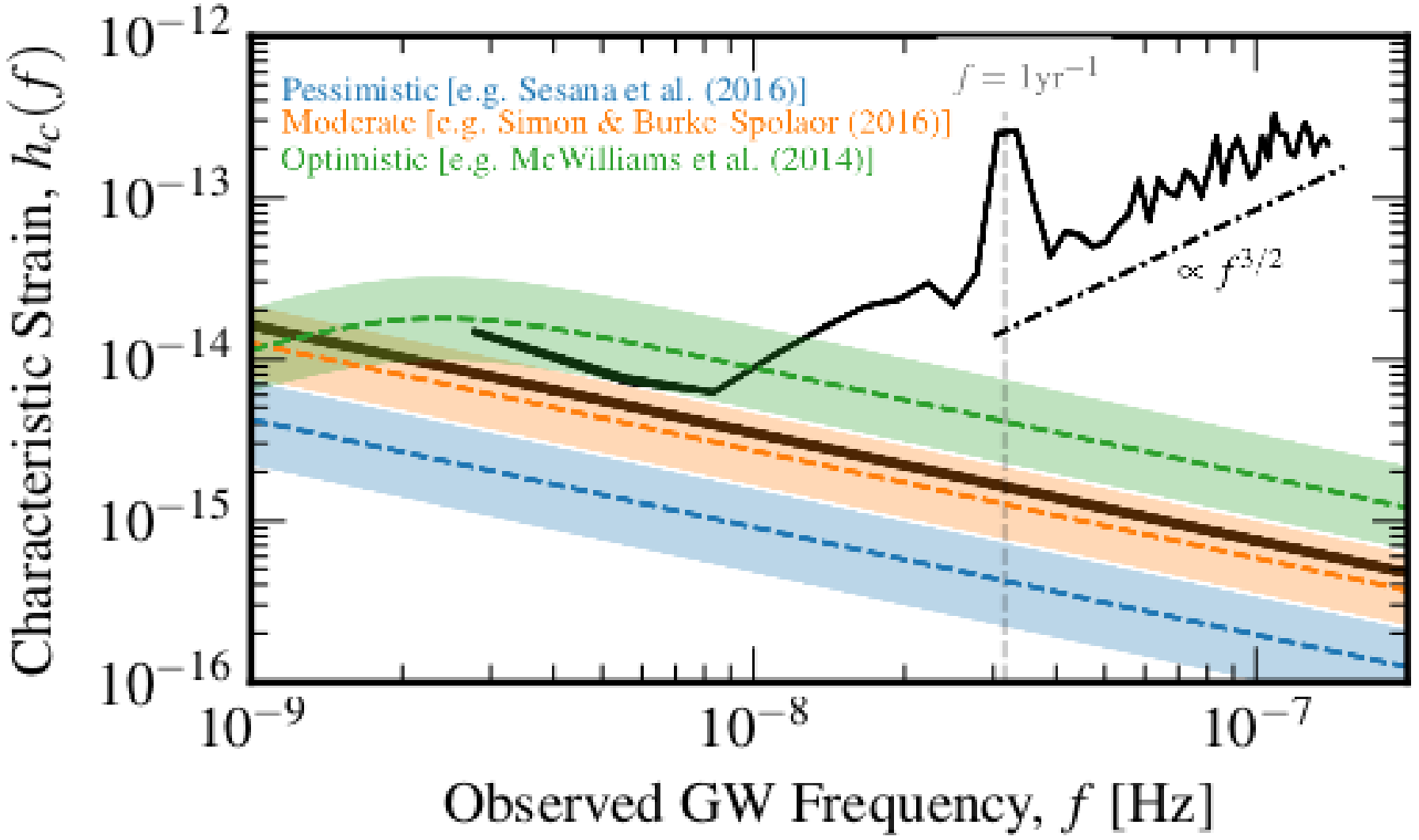
Chen, Sesana,
Del Pozzo 2017

Parametric model II

- Population of SMBHB $n_c(z,M)$
- Analytic description with 16 / 5 eff + 3 parameters
- Energy emission of individual binary *dE/df*
- Eccentricity, stellar density

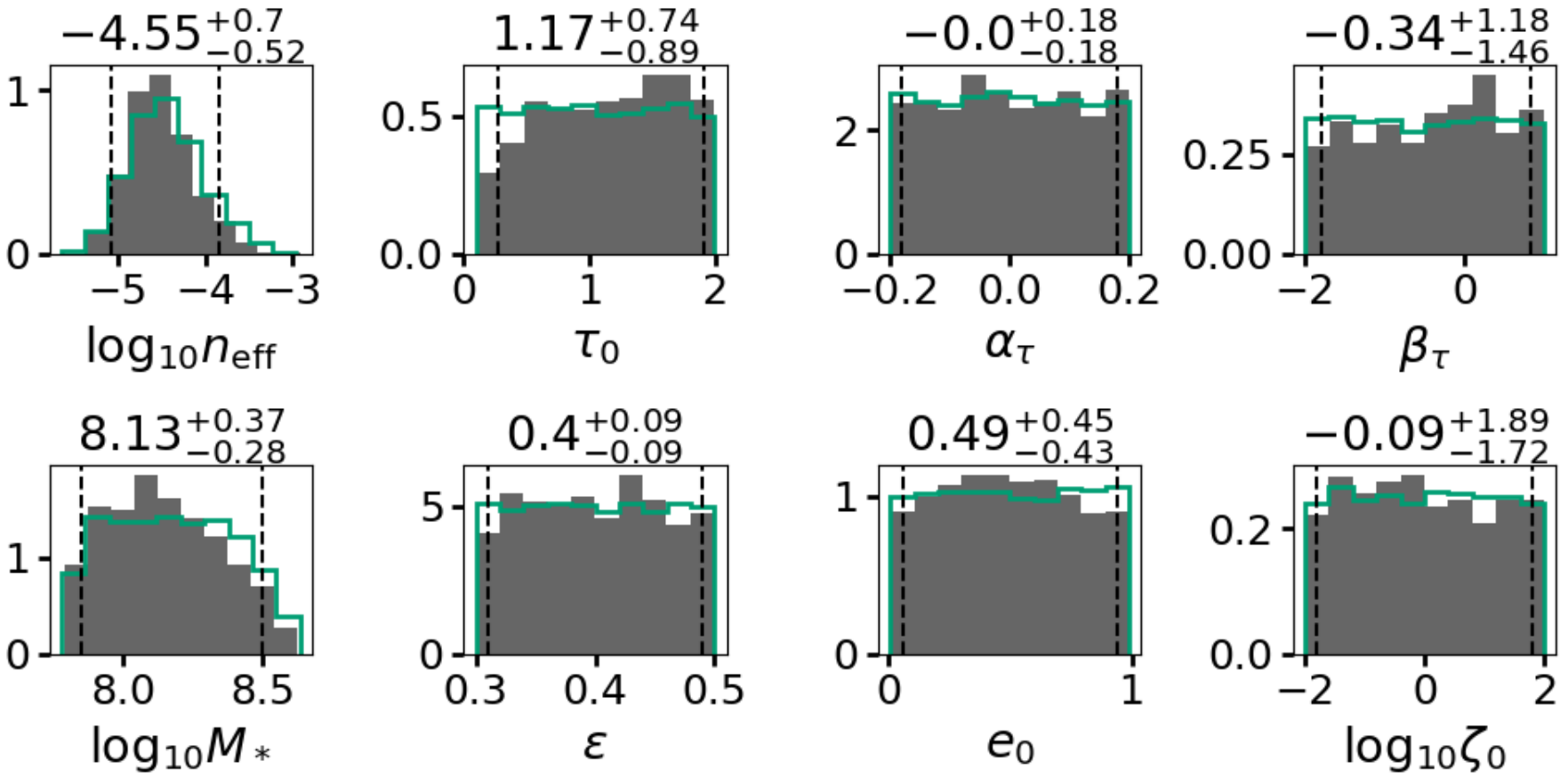
$$h_c^2 = \frac{4G}{\pi c^2 f} \int_0^\infty dz \int_0^{\bar{M}} d\mathcal{M}\; n_c(z,\mathcal{M}) \frac{dE}{df}$$

GWB Upper Limit

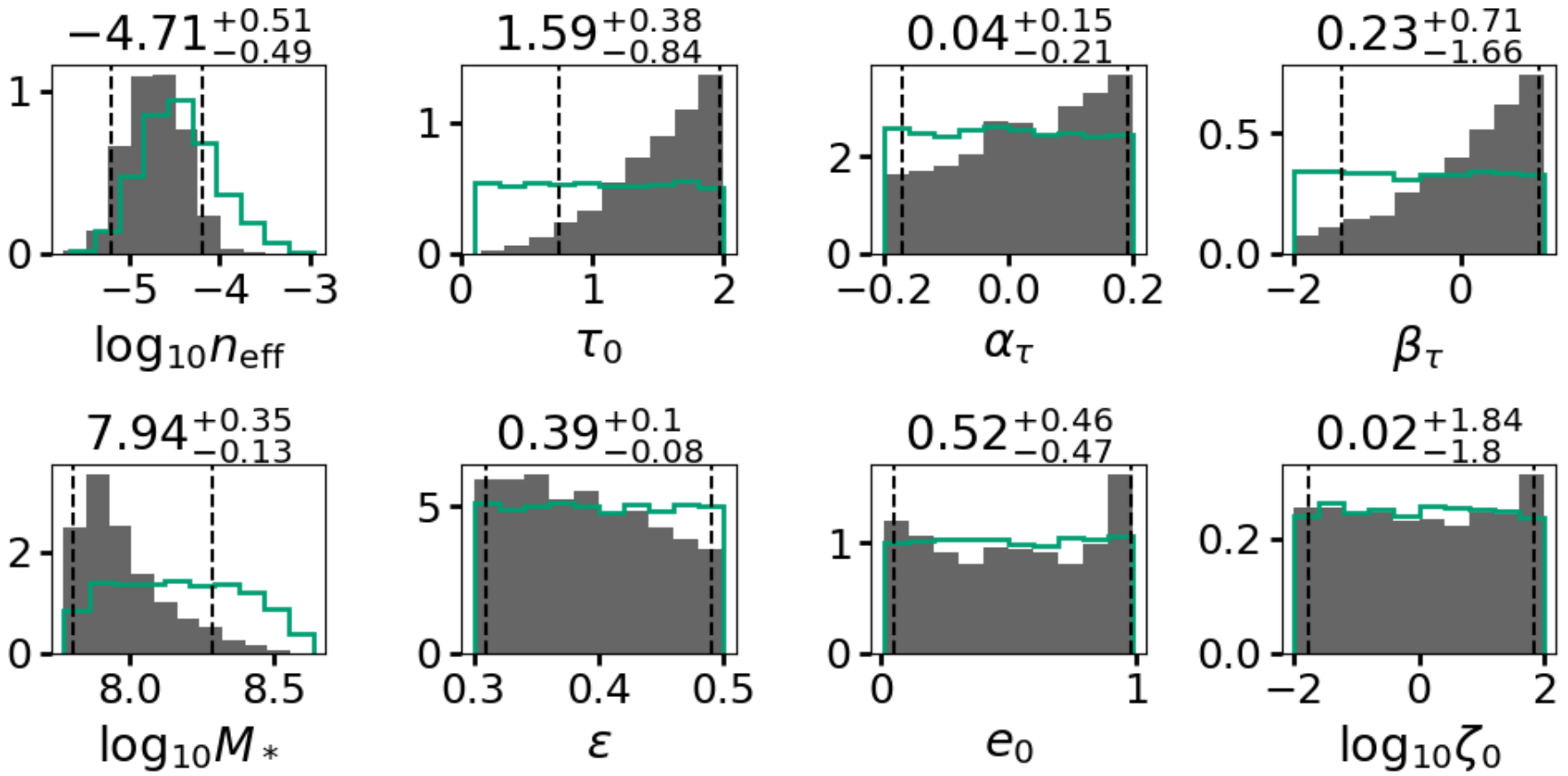


Arzoumanian et al. 2018

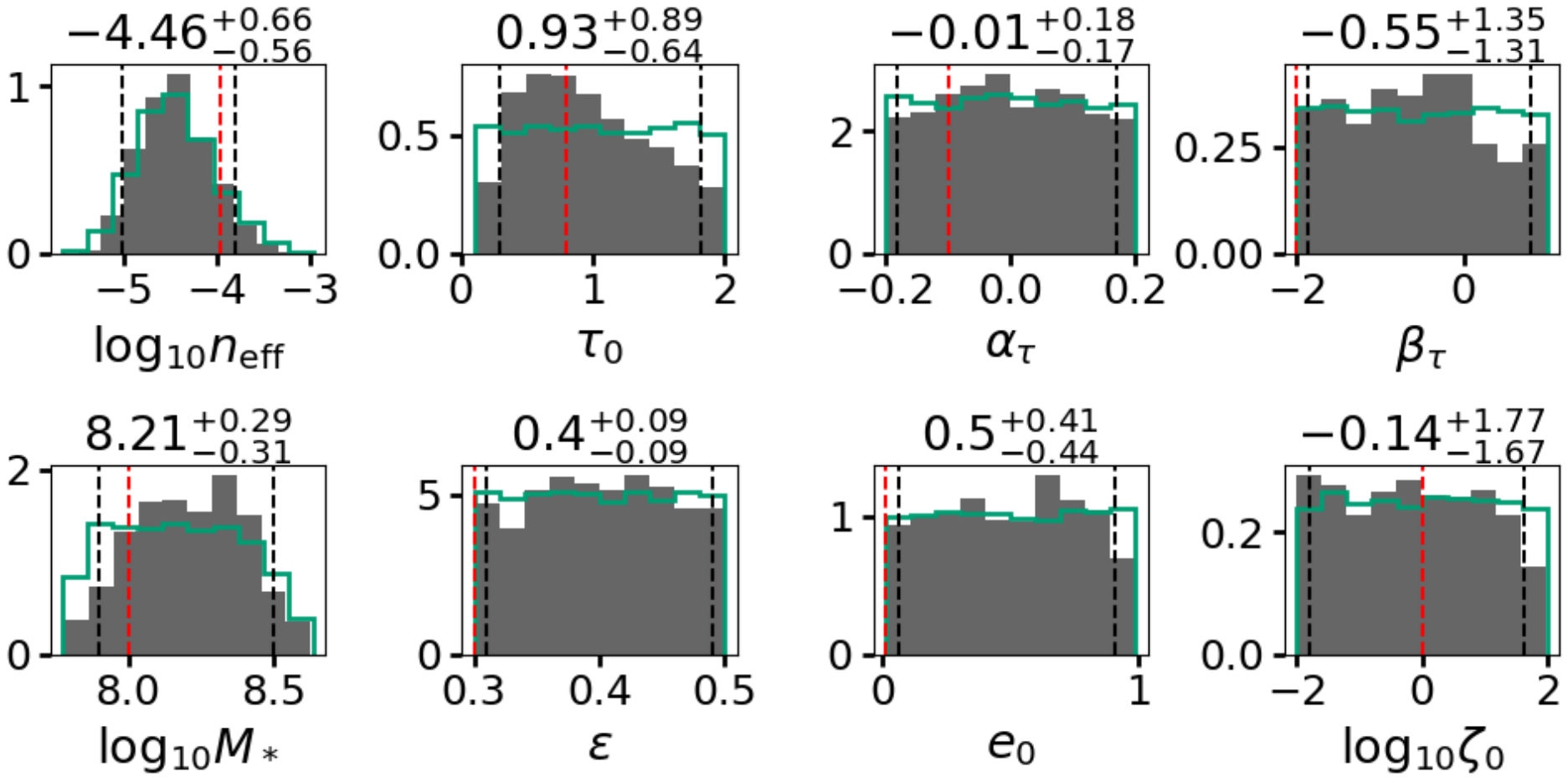
Results – Current Upper Limit



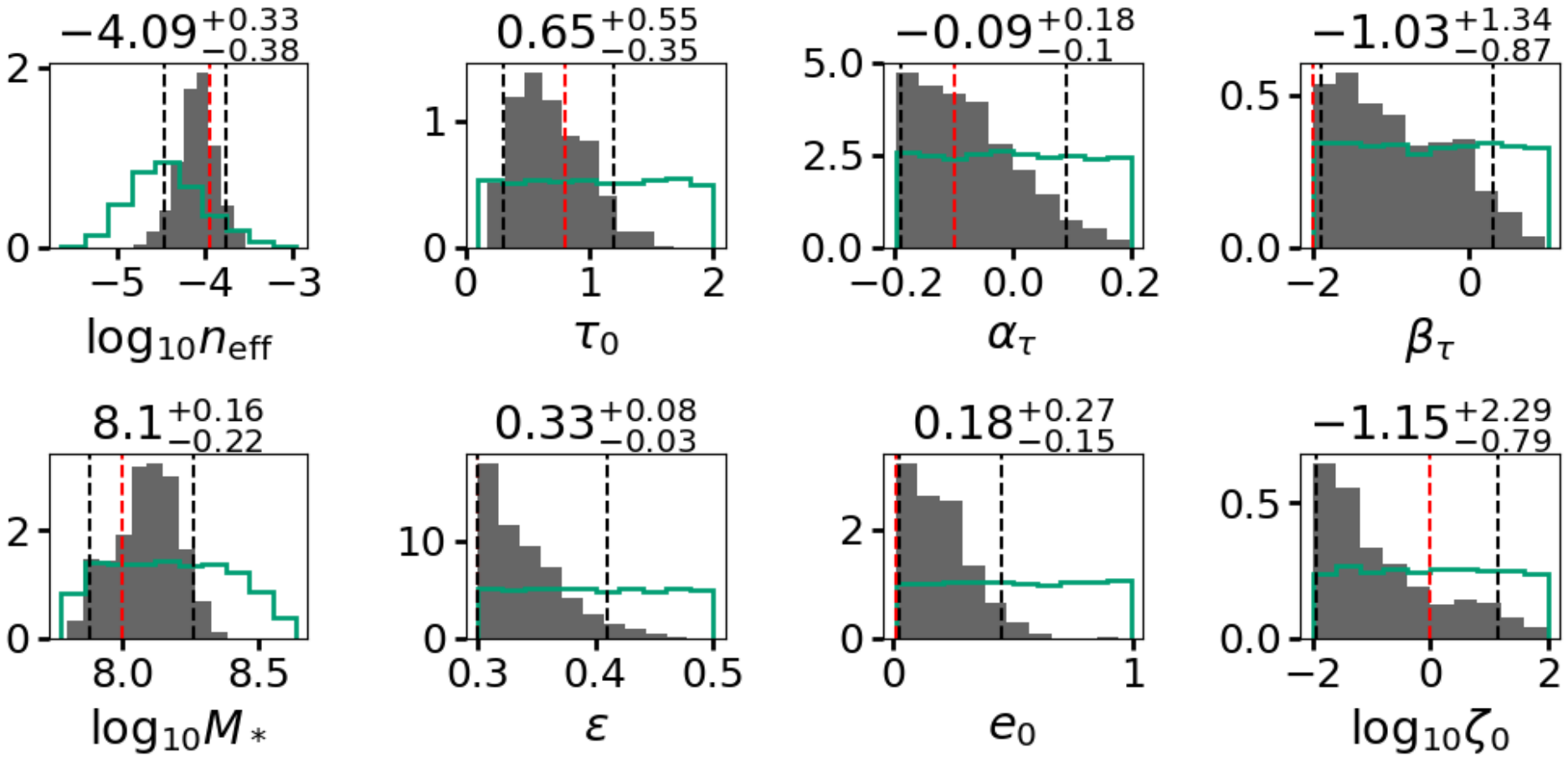
Results – Future Upper Limit



Posterior distributions – Initial detection



Posterior distributions – Ideal detection



Conclusions

1) PTA upper limits (detections) can be used to constrain the underlying SMBHB population and the properties of the binaries
2) Parametrized model of the GWB and priors from astrophysical observations
3) Nested sampling gives constraints on the parameters and provides evidences for model comparison
4) https://arxiv.org/abs/1810.04184