Constraining galaxy and black hole binary mergers with pulsars

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CEA Seminar
Paris-Saclay, 18th March 2019

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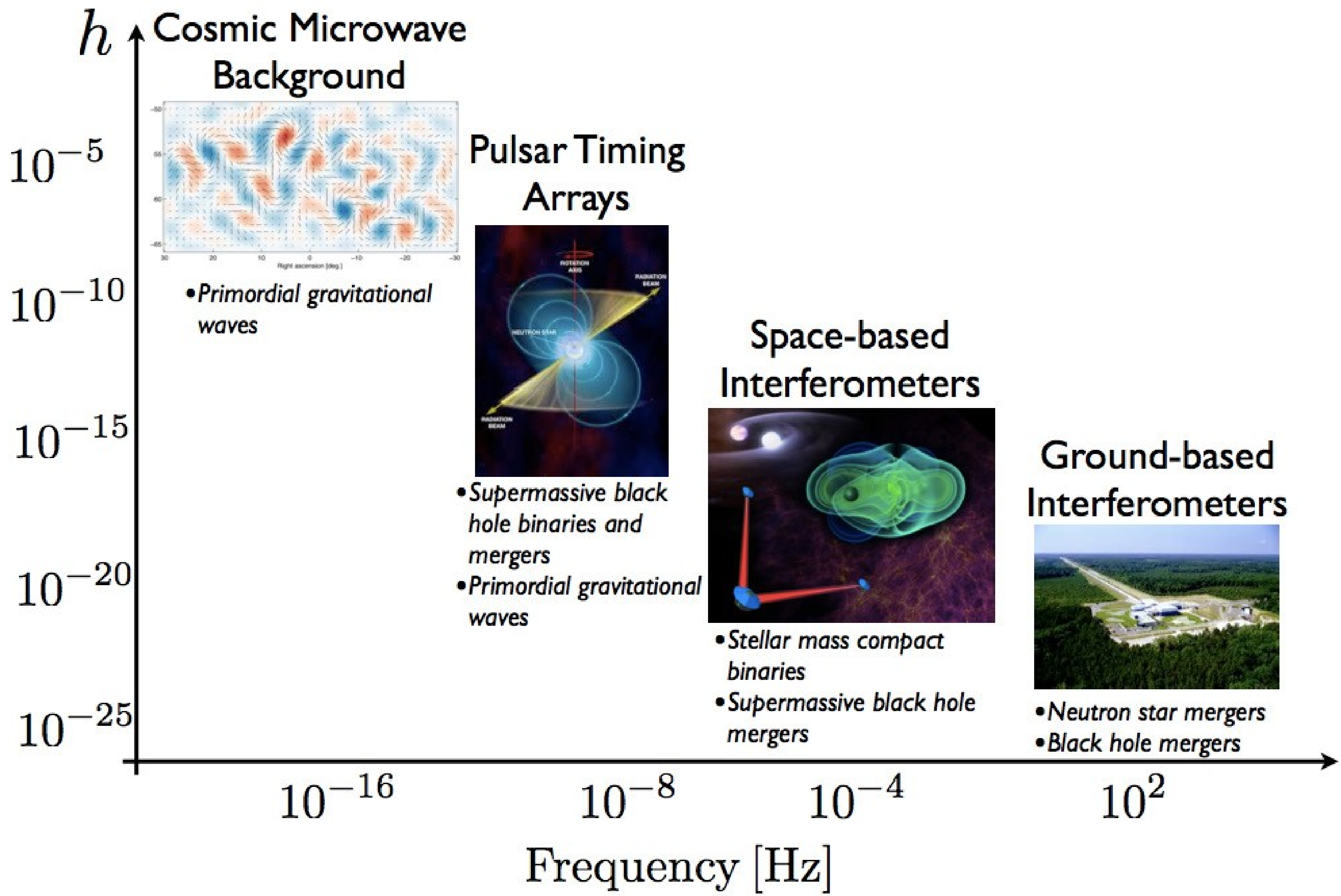
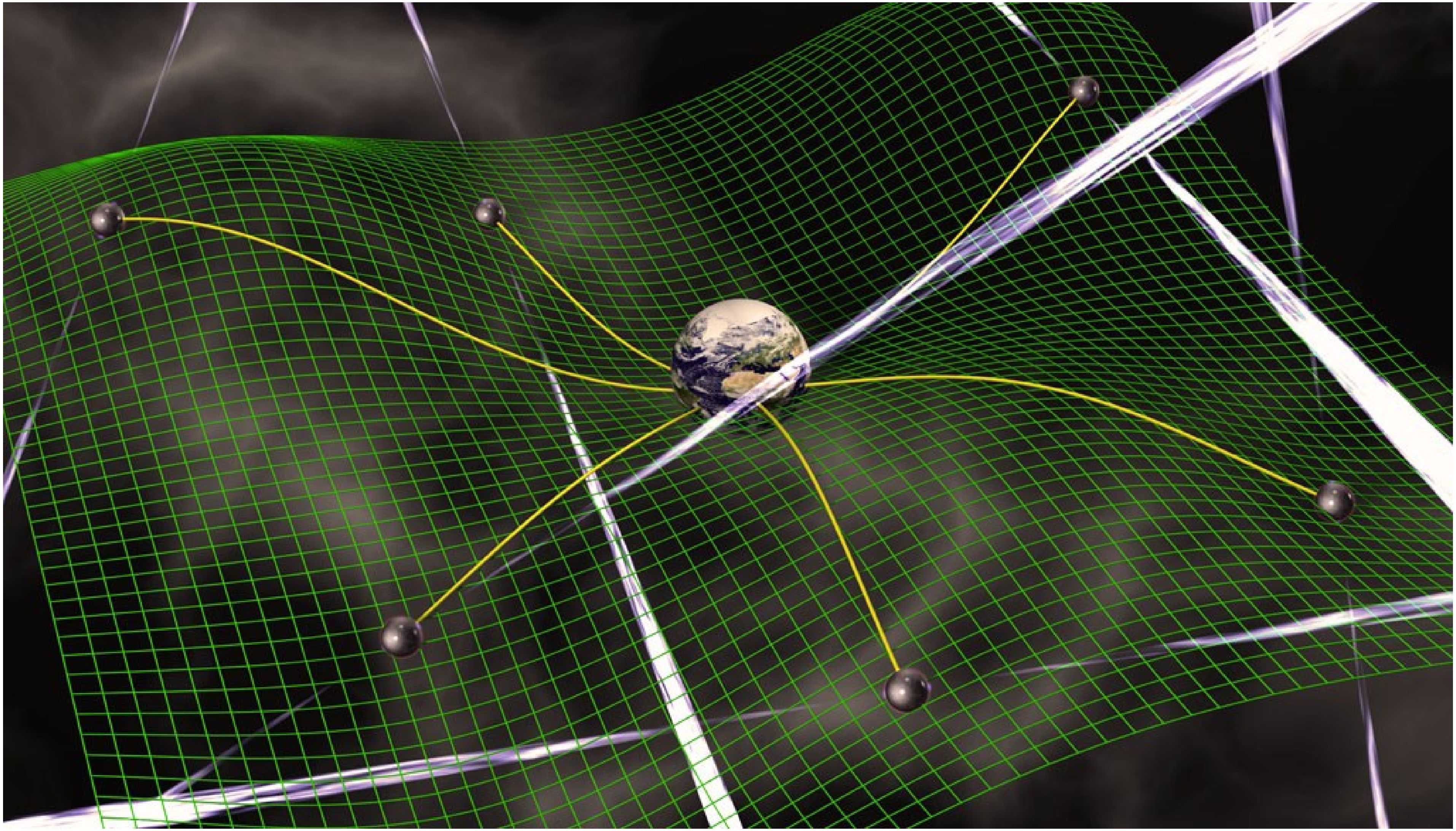
Constraining the astrophysics of galaxy and super massive black hole binary mergers with Pulsar Timing Array (PTA) observations on the Gravitational Wave Background (GWB) emitted by the mergers

Gravitational Wave

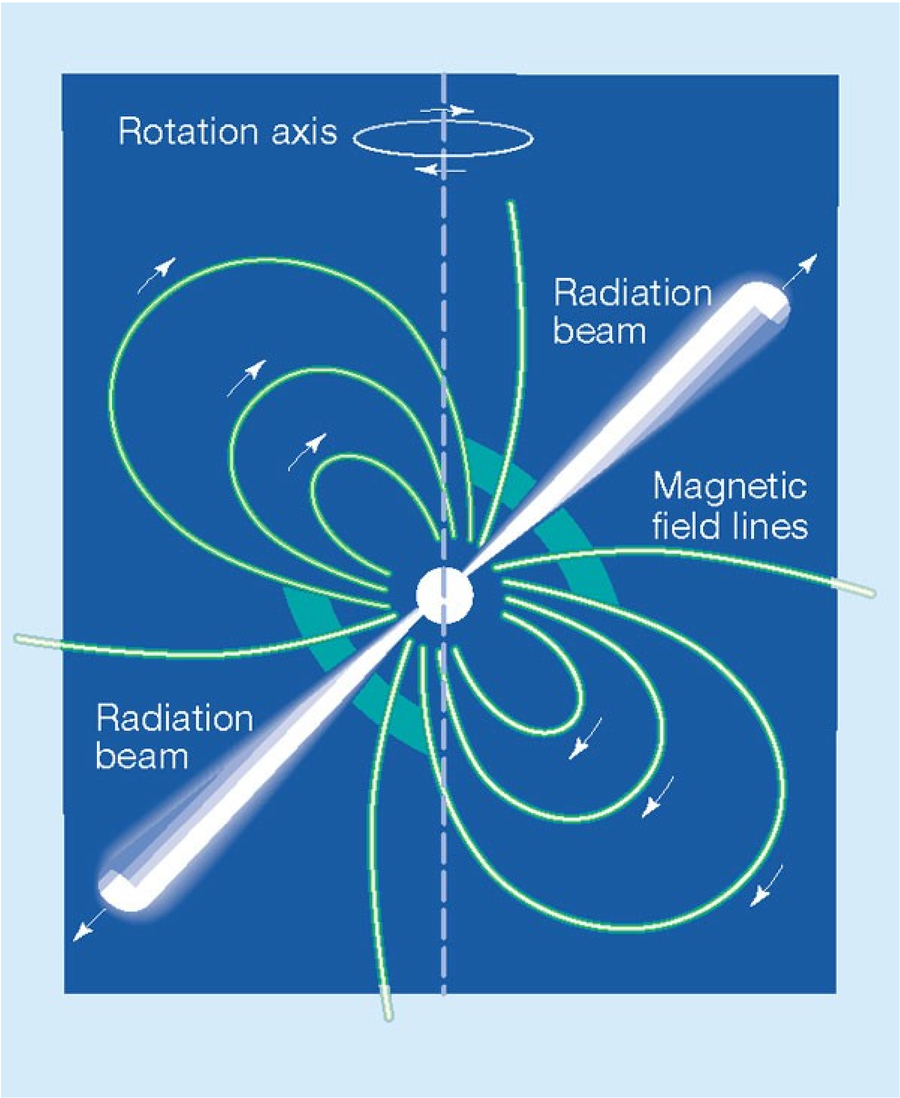


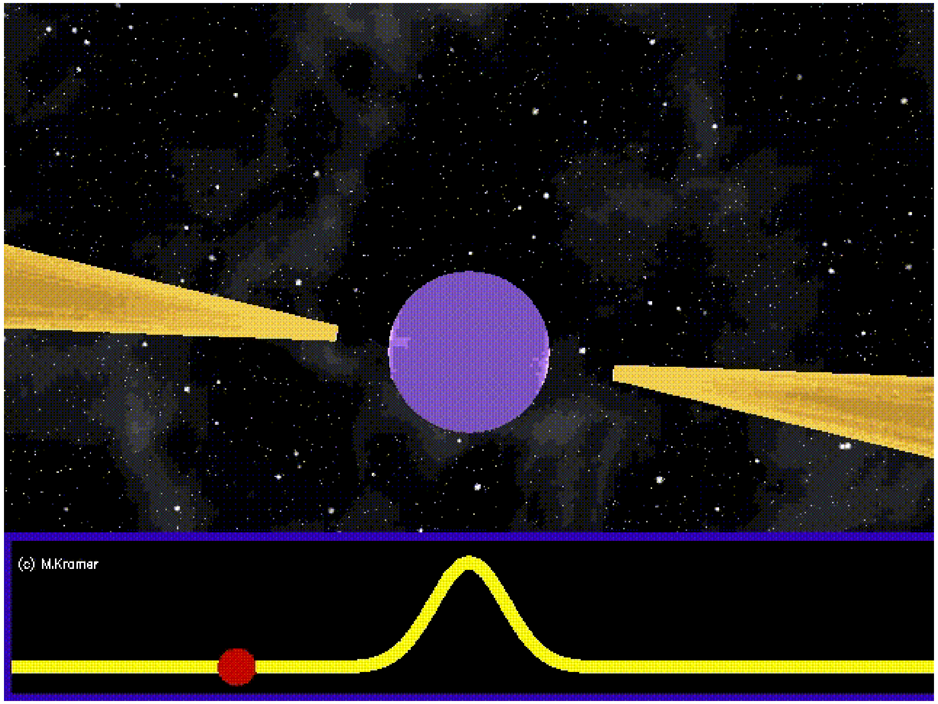
Background



Credits: D. Champion

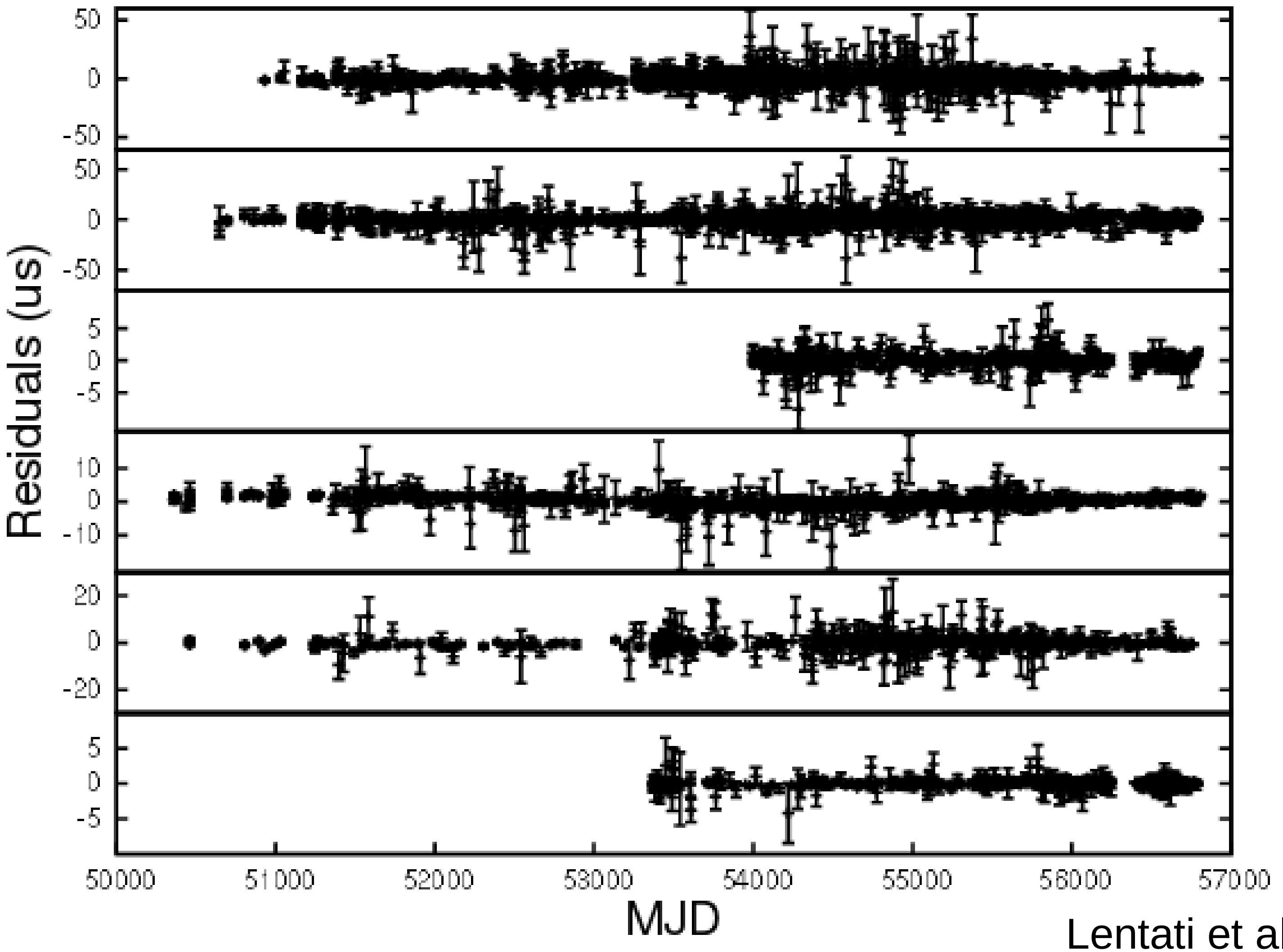
Pulsar





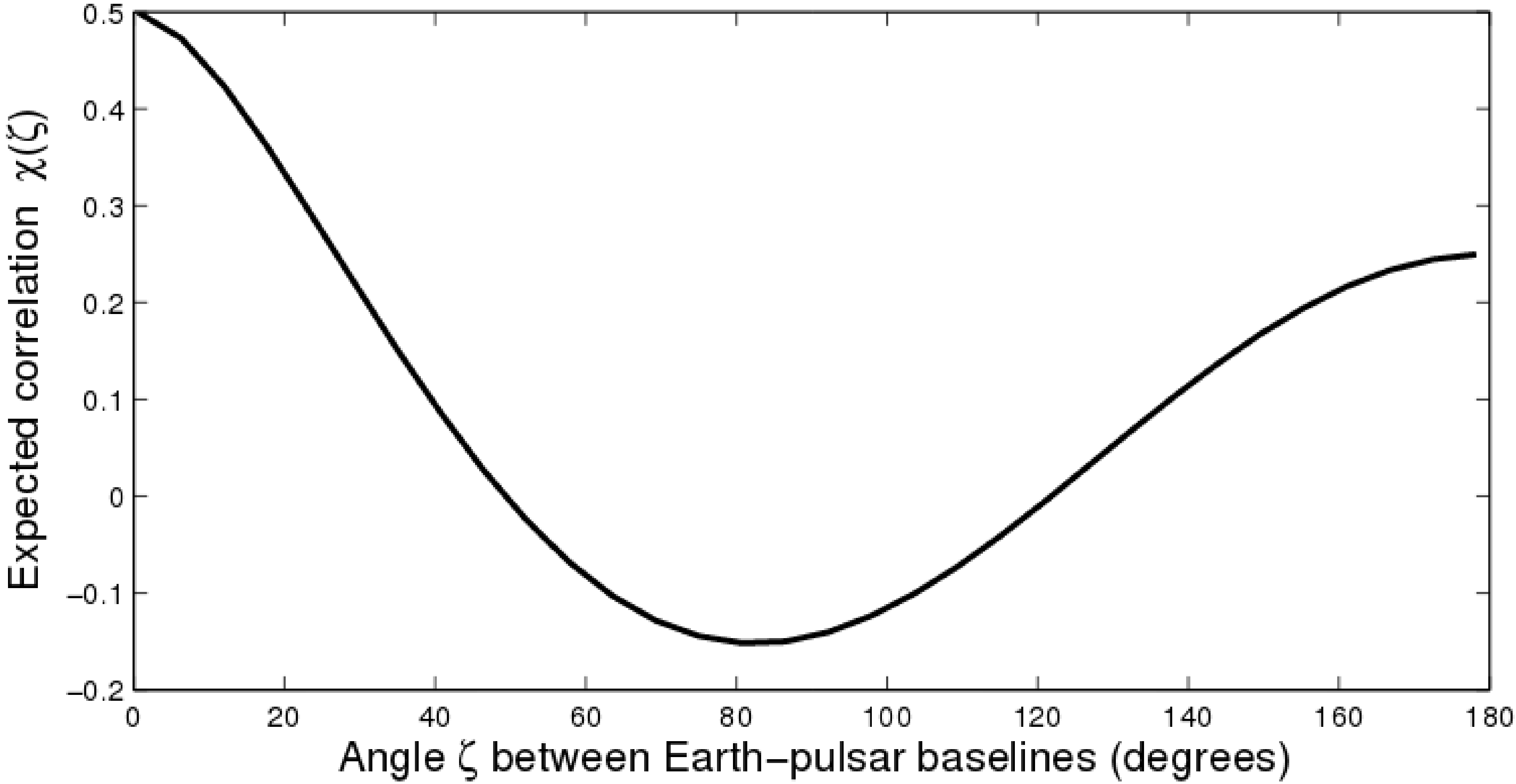
Credits: M. Kramer

Timing

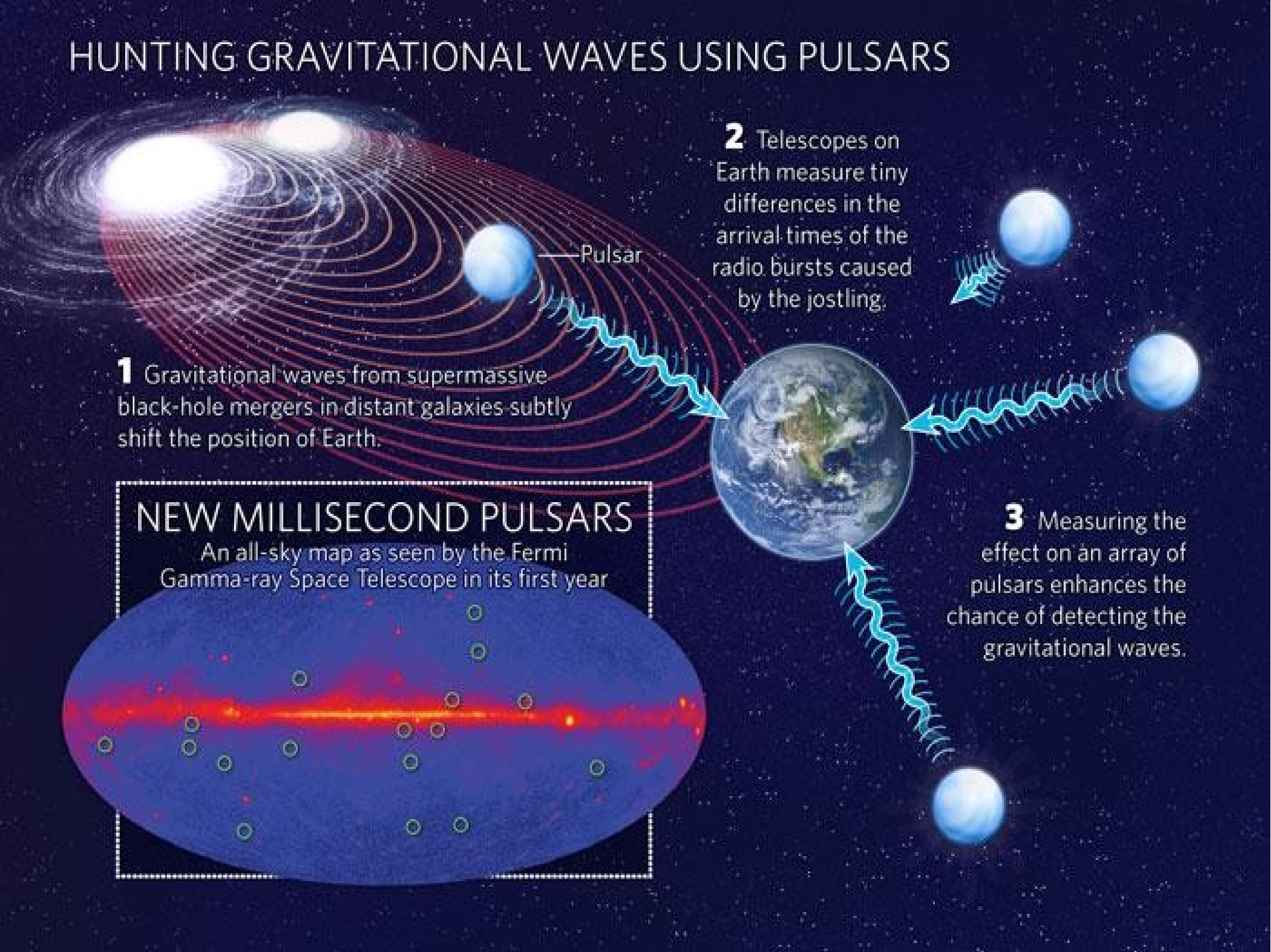


Lentati et al. 2015

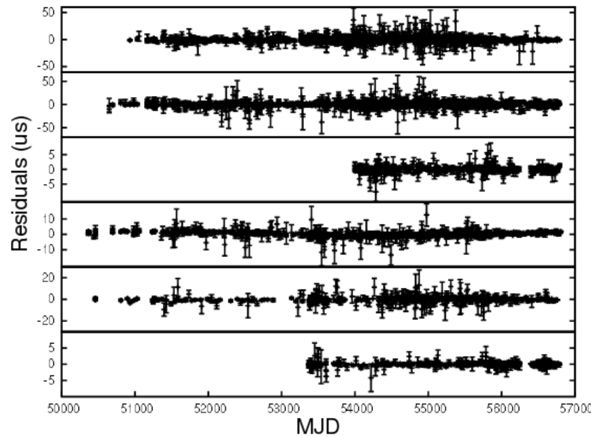
Array



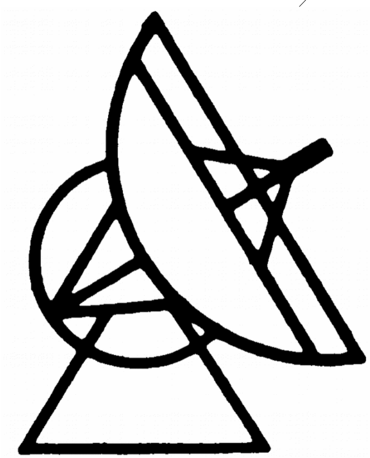
Hellings & Downs 1983

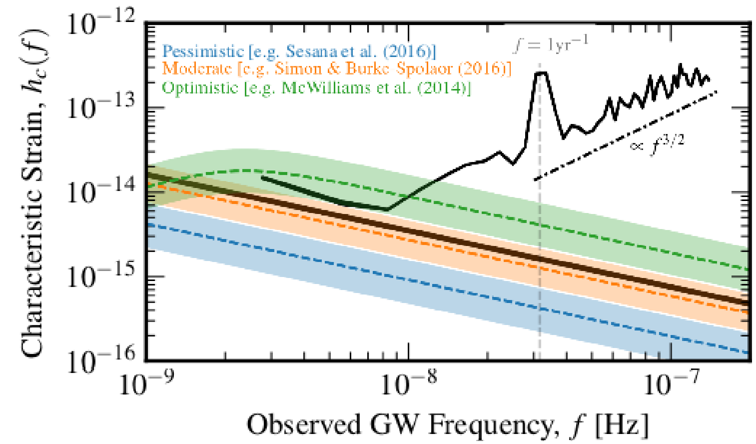

HUNTING GRAVITATIONAL WAVES USING PULSARS
Pulsar
1 Gravitational waves from supermassive black-hole mergers in distant galaxies subtly shift the position of Earth.
2 Telescopes on Earth measure tiny differences in the arrival times of the radio bursts caused by the jostling.
3 Measuring the effect on 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

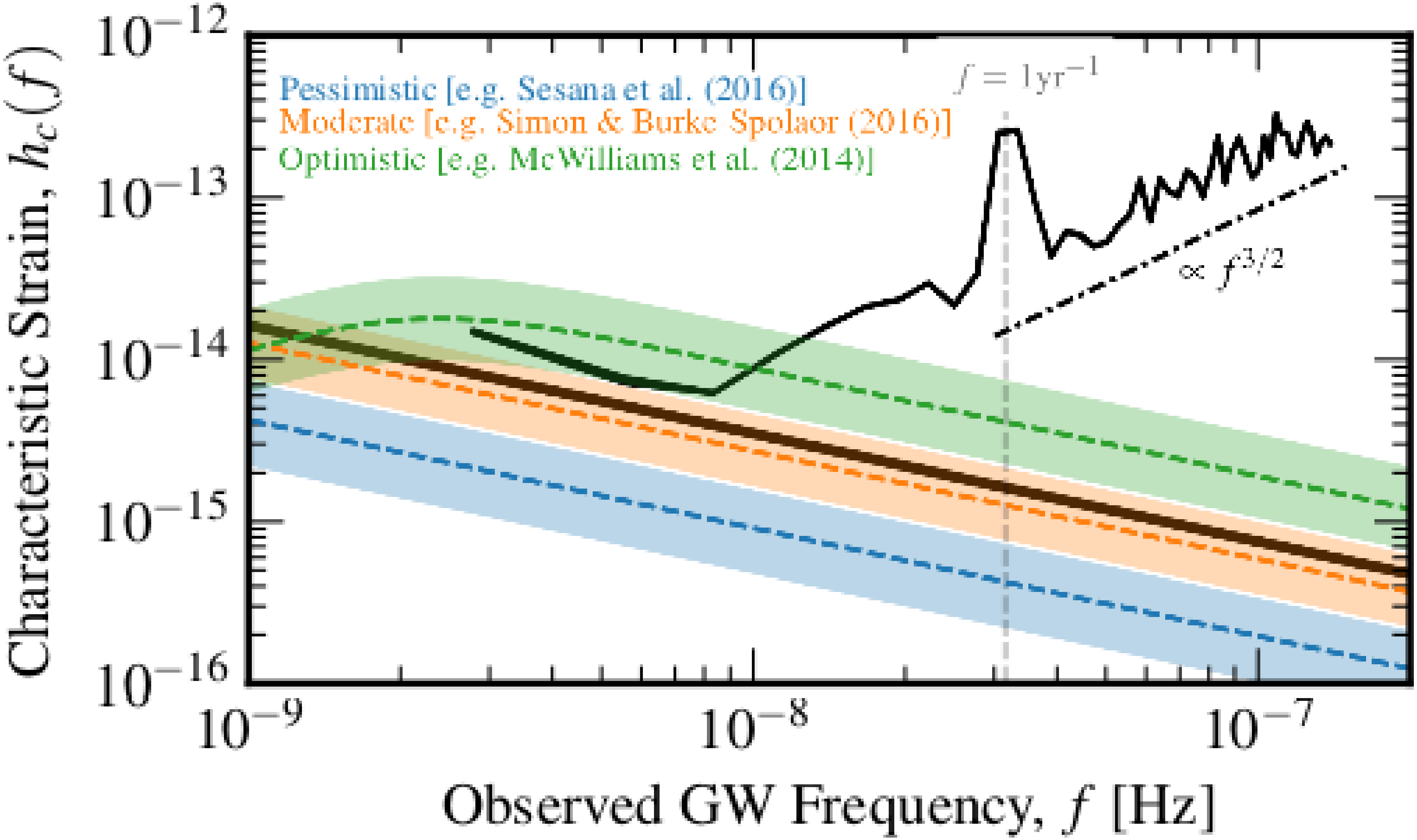
Chen, Sesana, Del Pozzo 2017, MNRAS 470, 1738 – 1749
Chen et al. 2017, MNRAS 468, 404 – 417

Parametric model I

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

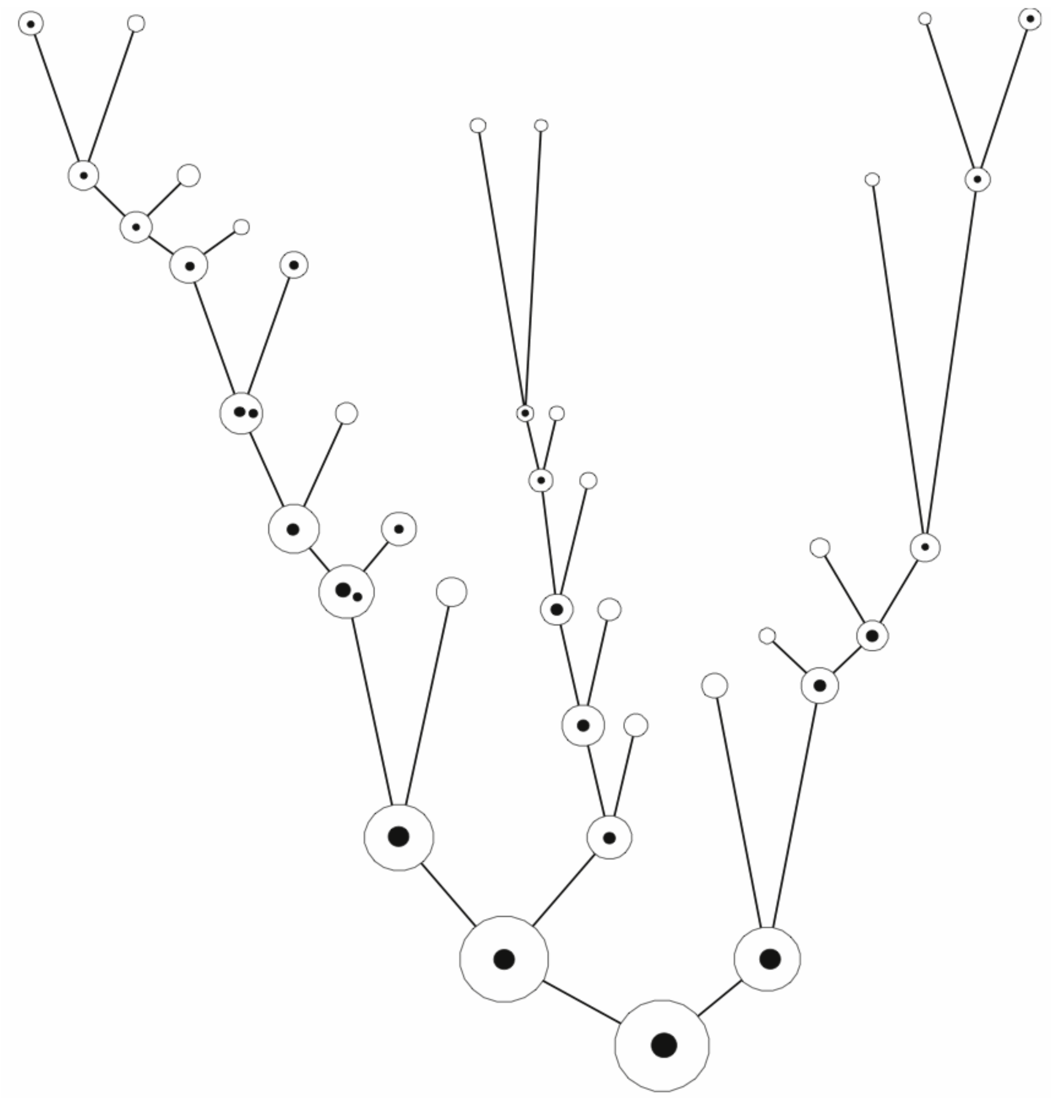
$$h_c^2 = \frac{4G}{\pi c^2 f} \int_0^{\infty} dz \int_0^{\bar{M}} d\mathcal{M} \; n_c(z, \mathcal{M}) \frac{dE}{df}$$

GWB Upper Limit



Arzoumanian et al. 2018

Black hole merger tree



Credits: Volonteri

SMBHB – Galaxy Merger

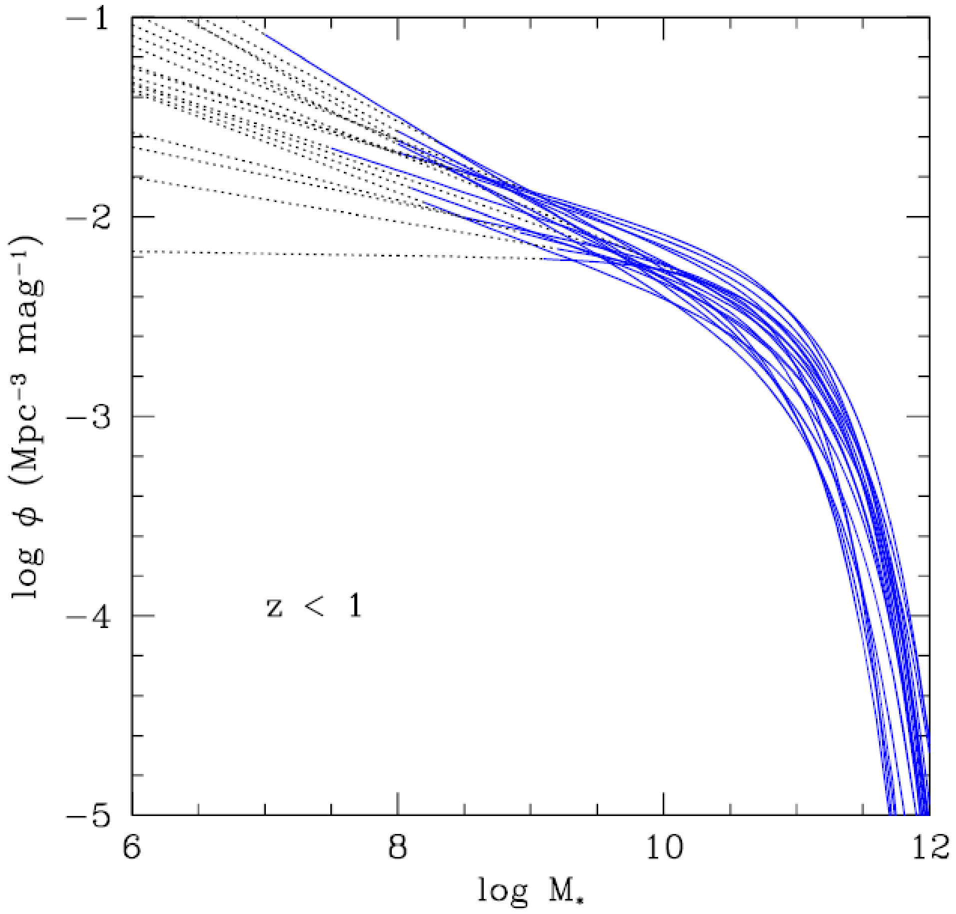
- How many galaxies are there?
- Galaxy Stellar Mass Function

- 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

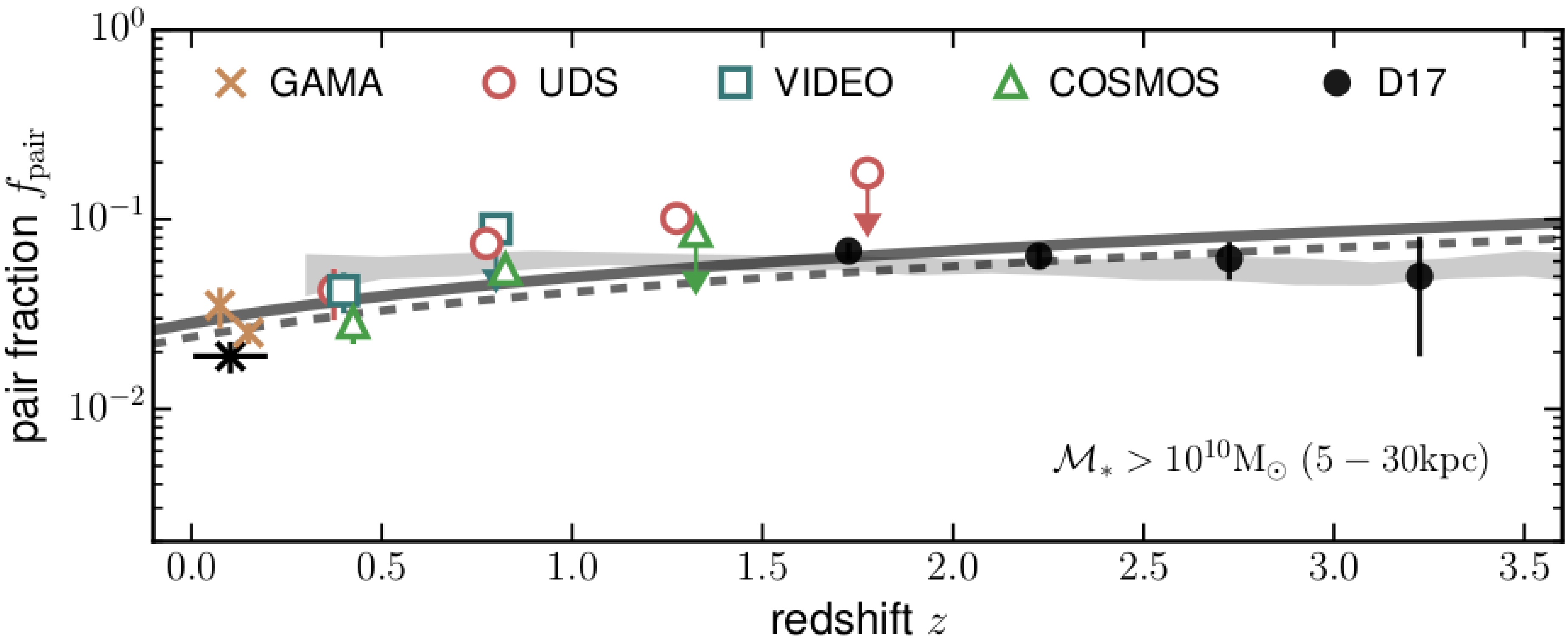
Galaxy stellar mass function



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

Conselice et al. 2016

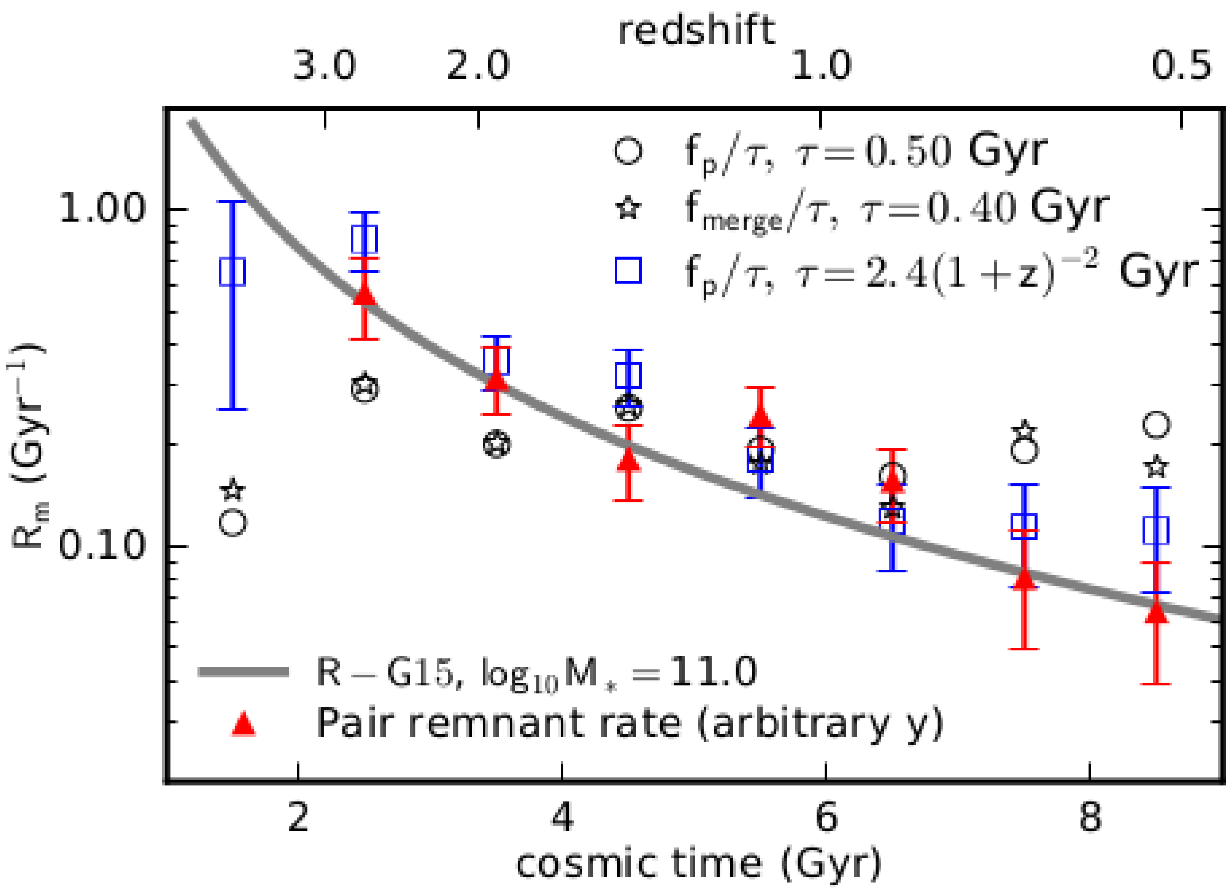
Pair fraction



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

Mundy et al. 2017

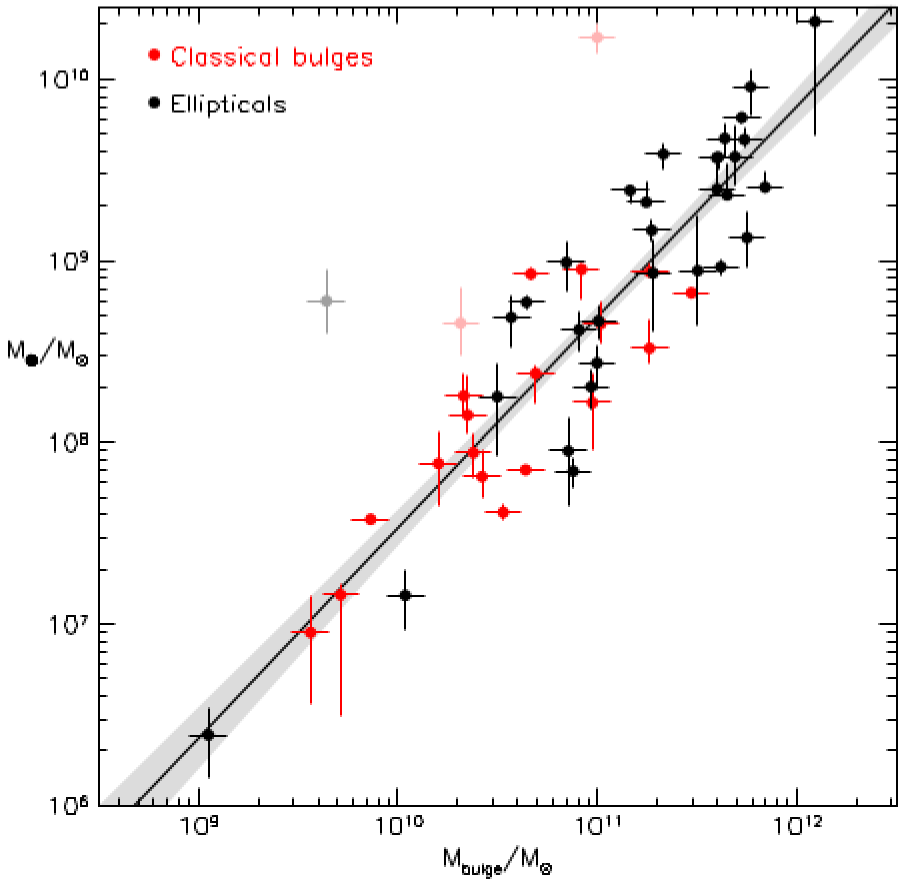
Merger time scale



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

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

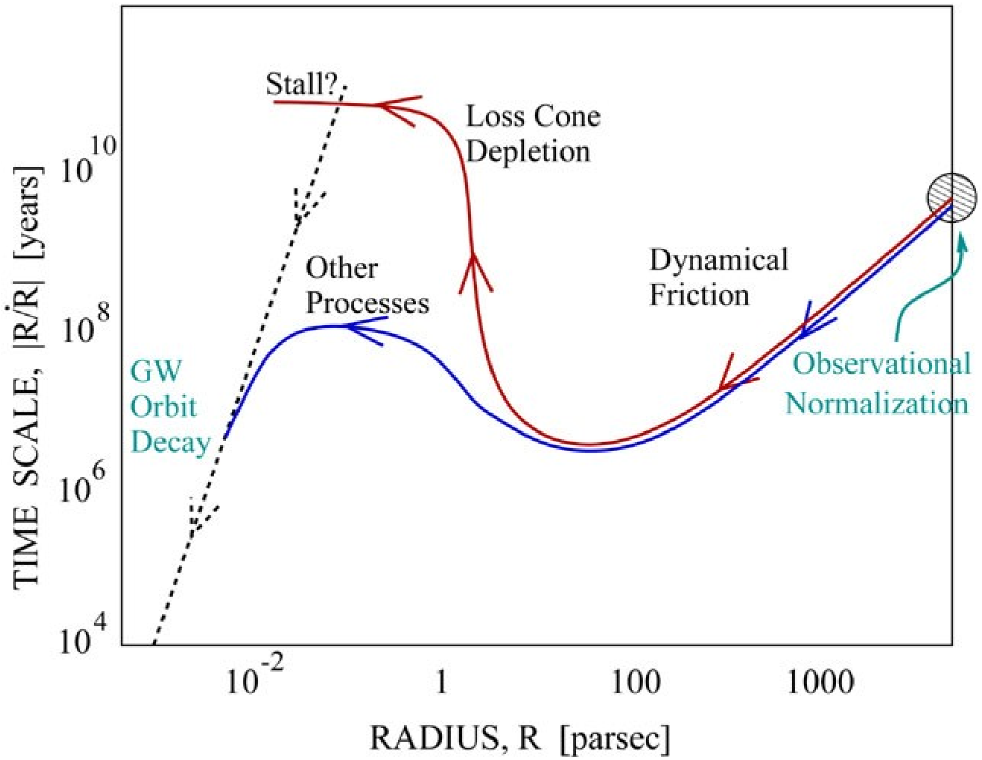
- Galaxy Stellar Mass Function
- Pair Fraction

$$n_c(z, \mathcal{M}) \approx n_1 \left(\frac{M_G}{M_0}\right)^{\alpha_1} e^{-M_G/M_0} (1+z)^{\beta_1} q^{\gamma_1} \frac{dM_G}{dM_{BH}}$$

- Merger Time Scale
- M_G – M_BH relation

Binary evolution

- Binary evolution transition from driven by the environment to gravitational waves
- Assign each binary the same initial e_t at the turnover frequency f_t



$$\left(\frac{df}{dt}\right)_{env} = \frac{3}{2(2\pi)^{2/3}}\frac{H\rho_i}{\sigma}G^{4/3}(2.5\mathcal{M})^{1/3}f^{1/3}$$

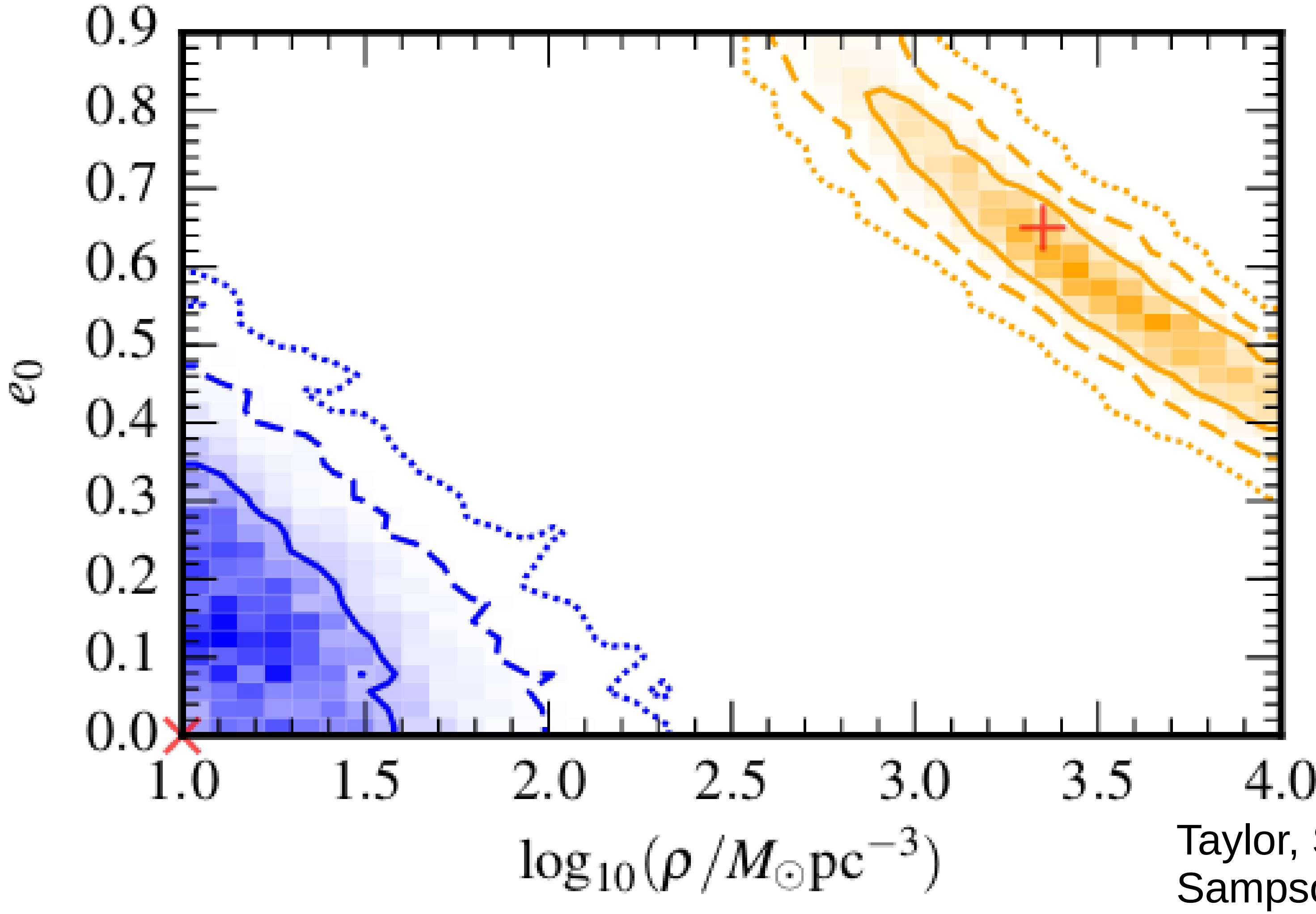
Vasiliev et al. 2015

$$\left(\frac{df}{dt}\right)_{gw} = \frac{96}{5}(\pi)^{8/3}\frac{G^{5/3}}{c^5}\mathcal{M}^{5/3}f^{11/3}F(e)$$

Peters and Matthews 1963

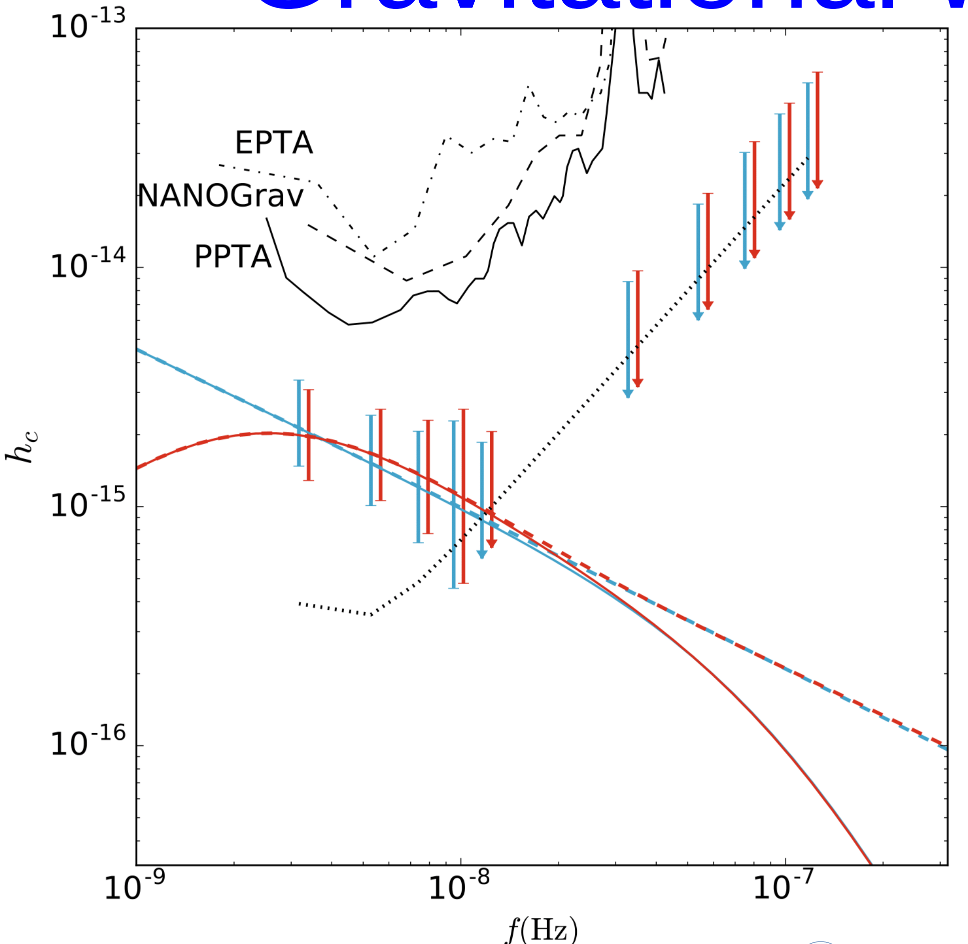
Include parameter for stellar density around the SMBHB

Eccentricity – Stellar density



Taylor, Simon, Sampson 2017

Gravitational wave spectrum



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

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

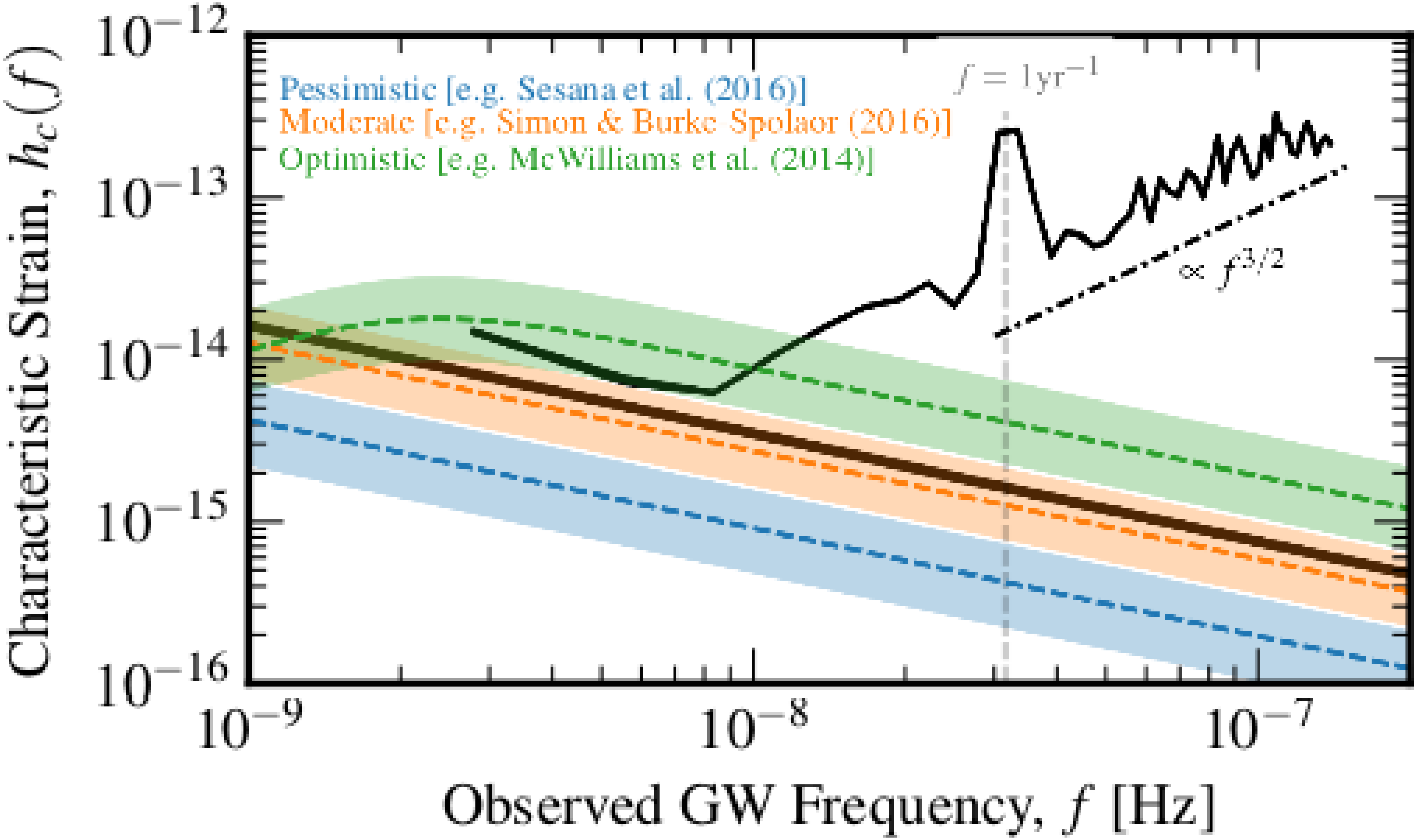
Chen, Sesana, Del Pozzo 2017

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

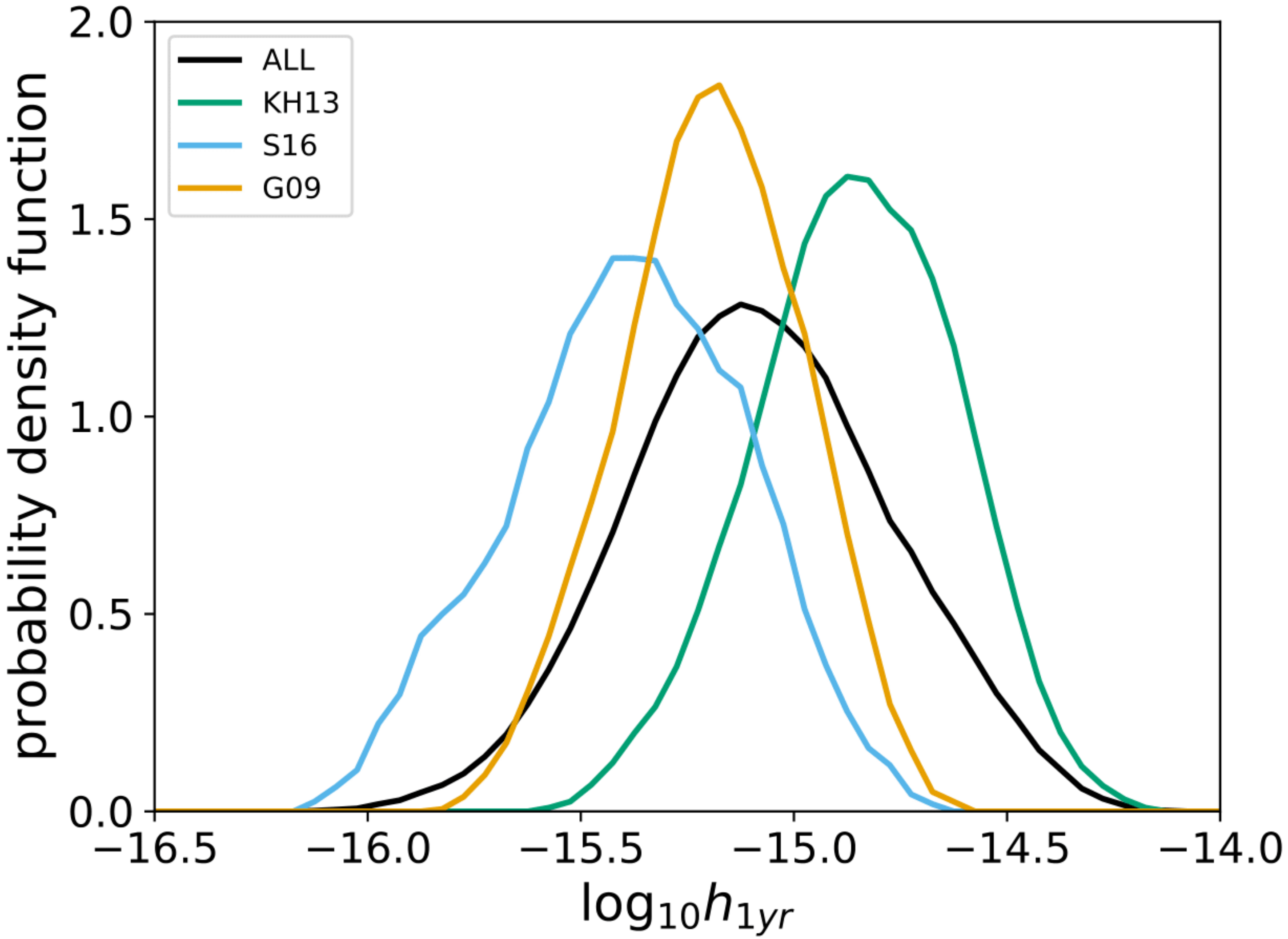
$$h_c^2 = \frac{4G}{\pi c^2 f} \int_0^{\infty} dz \int_0^{\bar{M}} d\mathcal{M} \; n_c(z, \mathcal{M}) \frac{dE}{df}$$

GWB Upper Limit



Arzoumanian et al. 2018

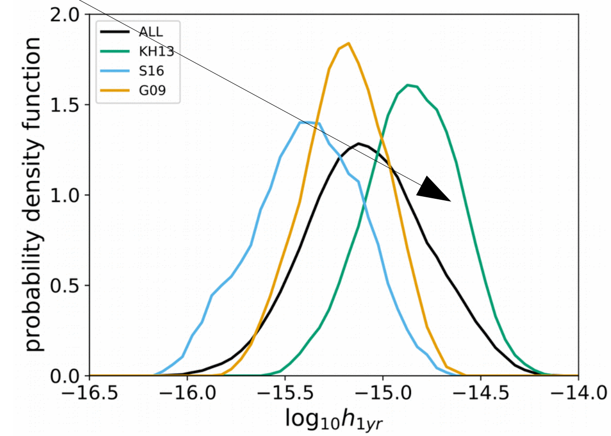
Characteristic strain

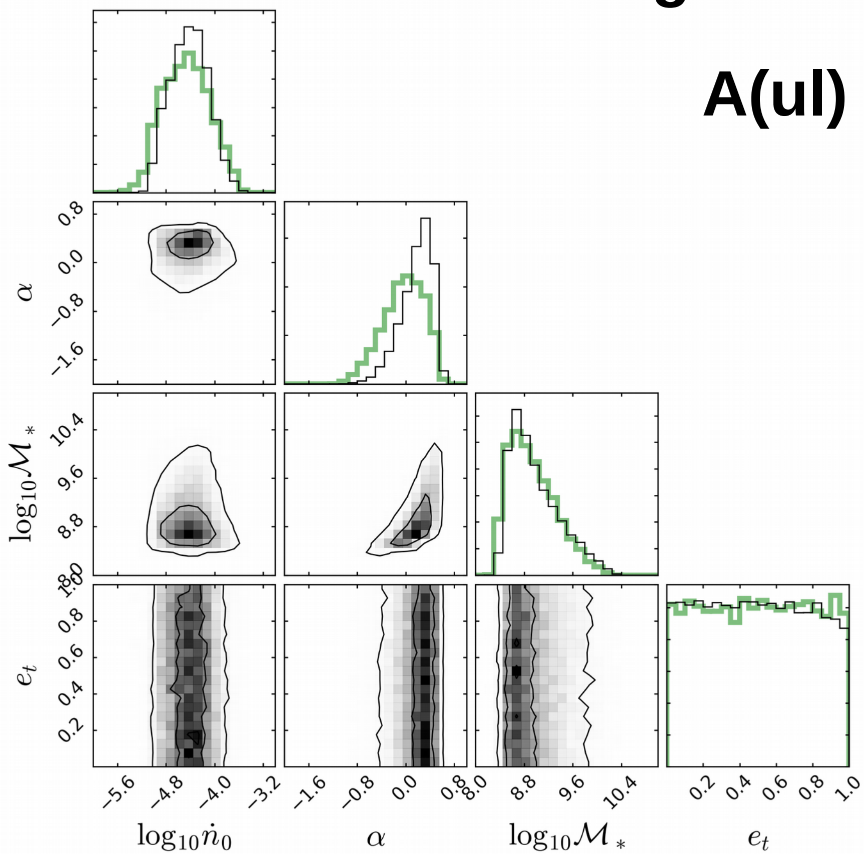


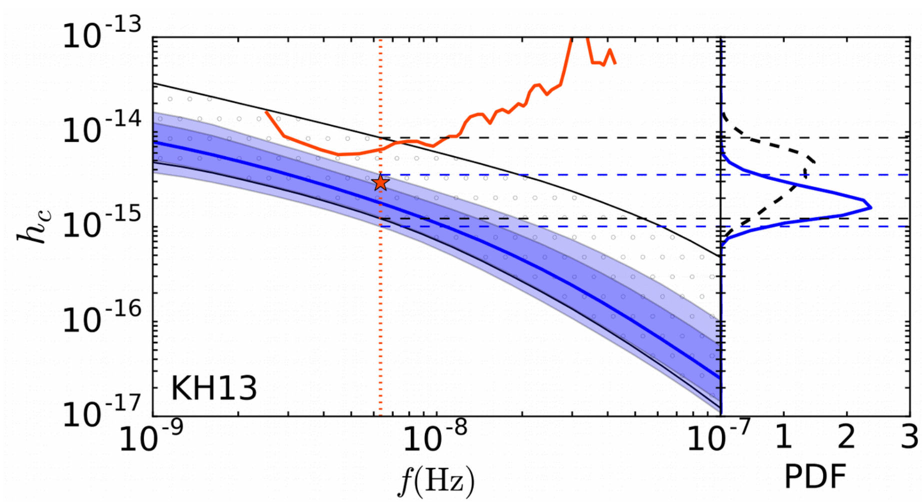
Results KH13

Log Evidence = -2.36

A(ul) = 1e-15







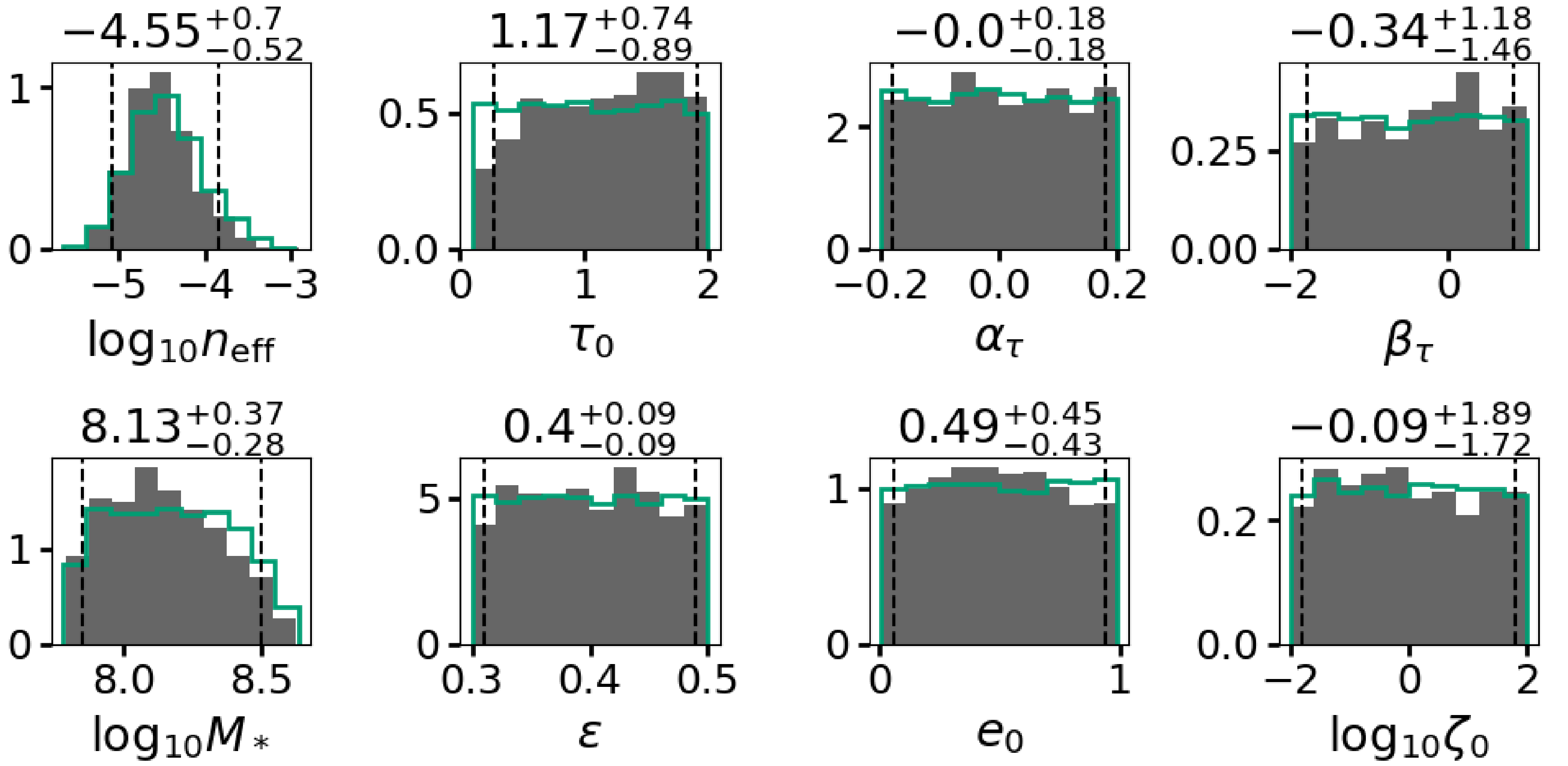
Middleton et al. 2018

Summary

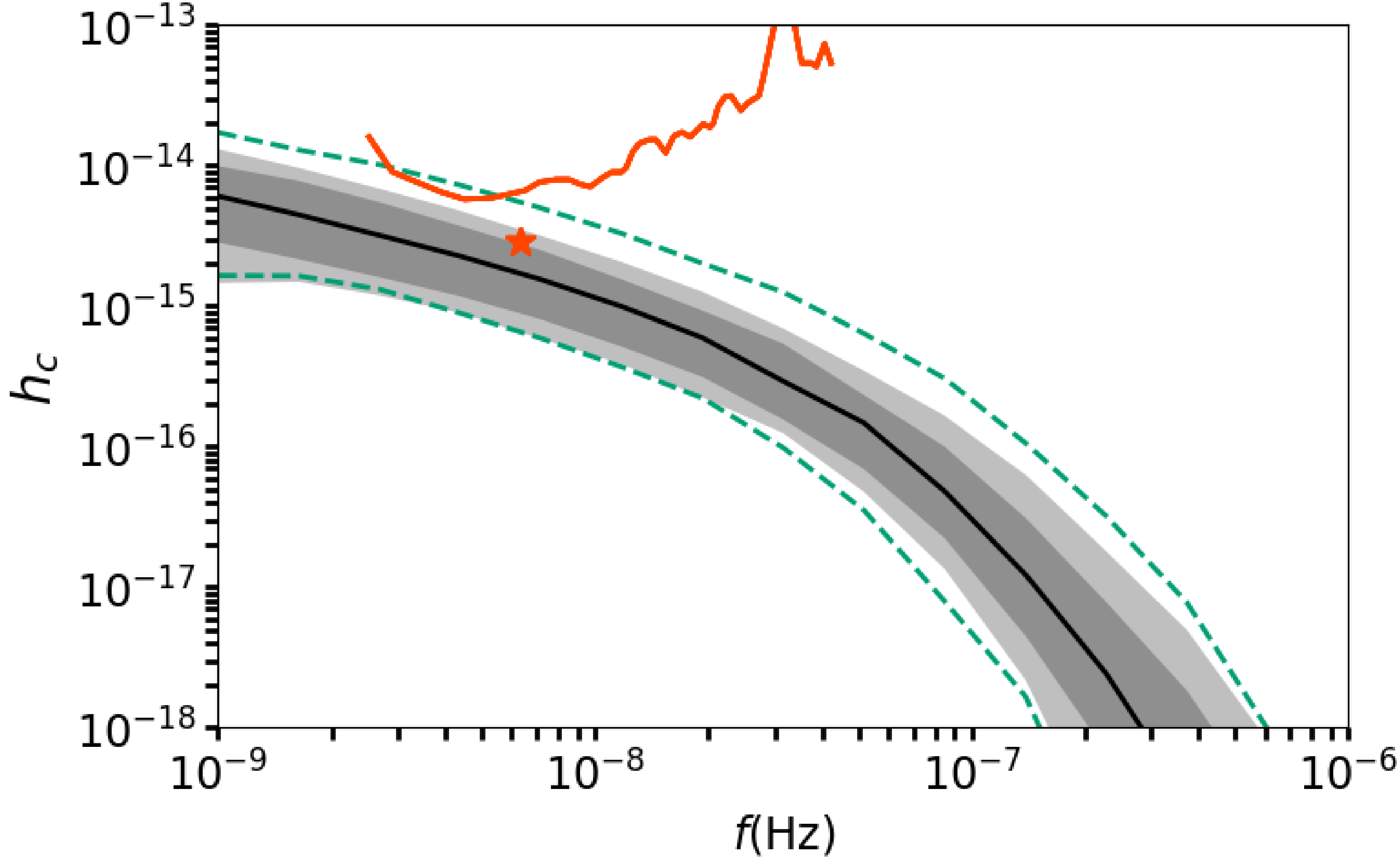
	MAX	S16	G09	ALL	KH13
MAX	1 : 1	1 : 1.8	1 : 3.3	1 : 3.4	1 : 10.6
S16		1 : 1	1 : 1.8	1 : 1.9	1 : 5.8
G09			1 : 1	1 : 1.03	1 : 3.2
ALL				1 : 1	1 : 3.1
KH13					1 : 1

- Models predicting a higher strain than PTA upper limits are slightly disfavoured against models with lower amplitudes
- No tension between assembly models of SMBHB and pulsar observations, Middleton et al. 2018, NatComms, 9, 573

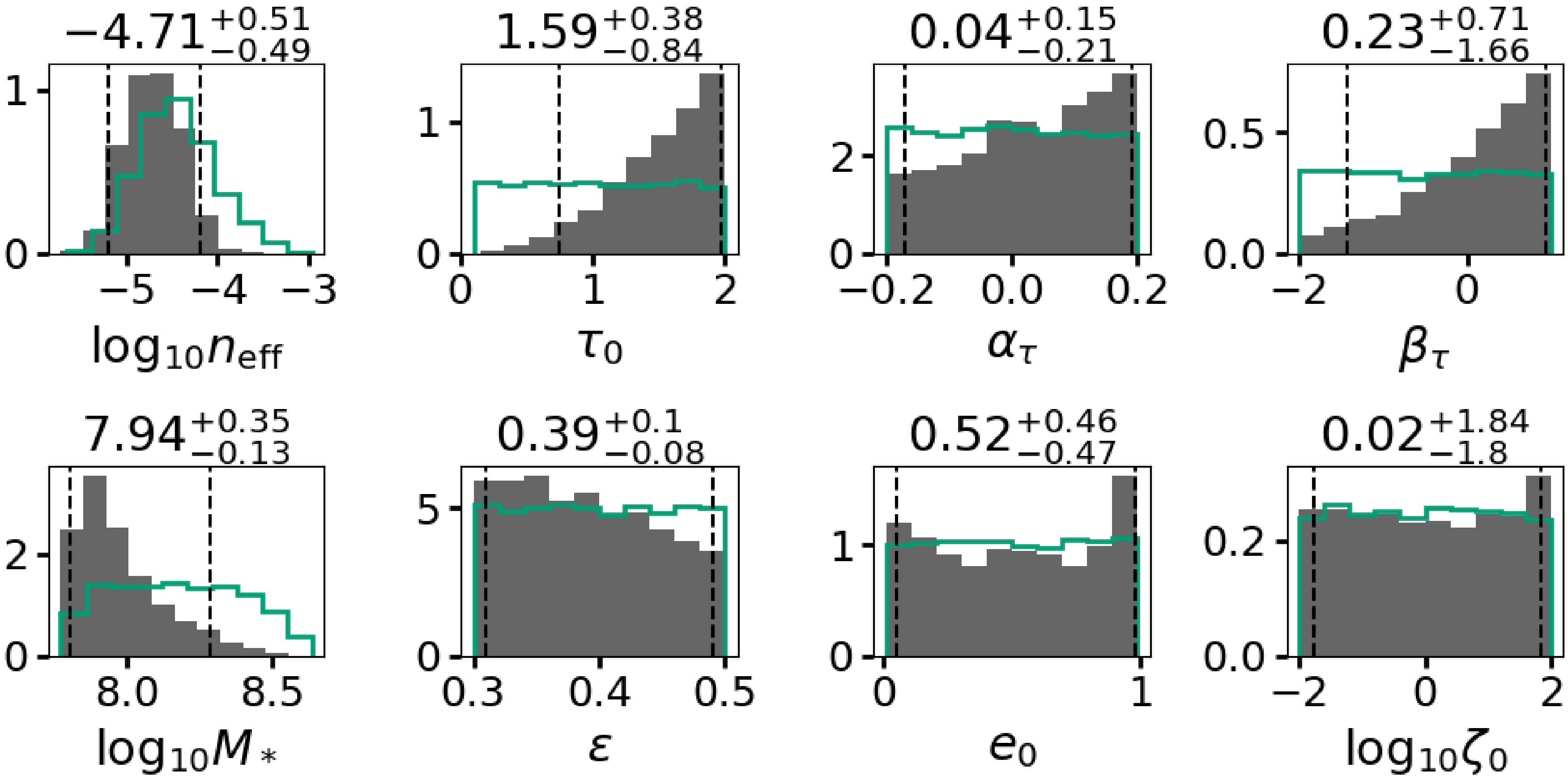
Results – Current Upper Limit



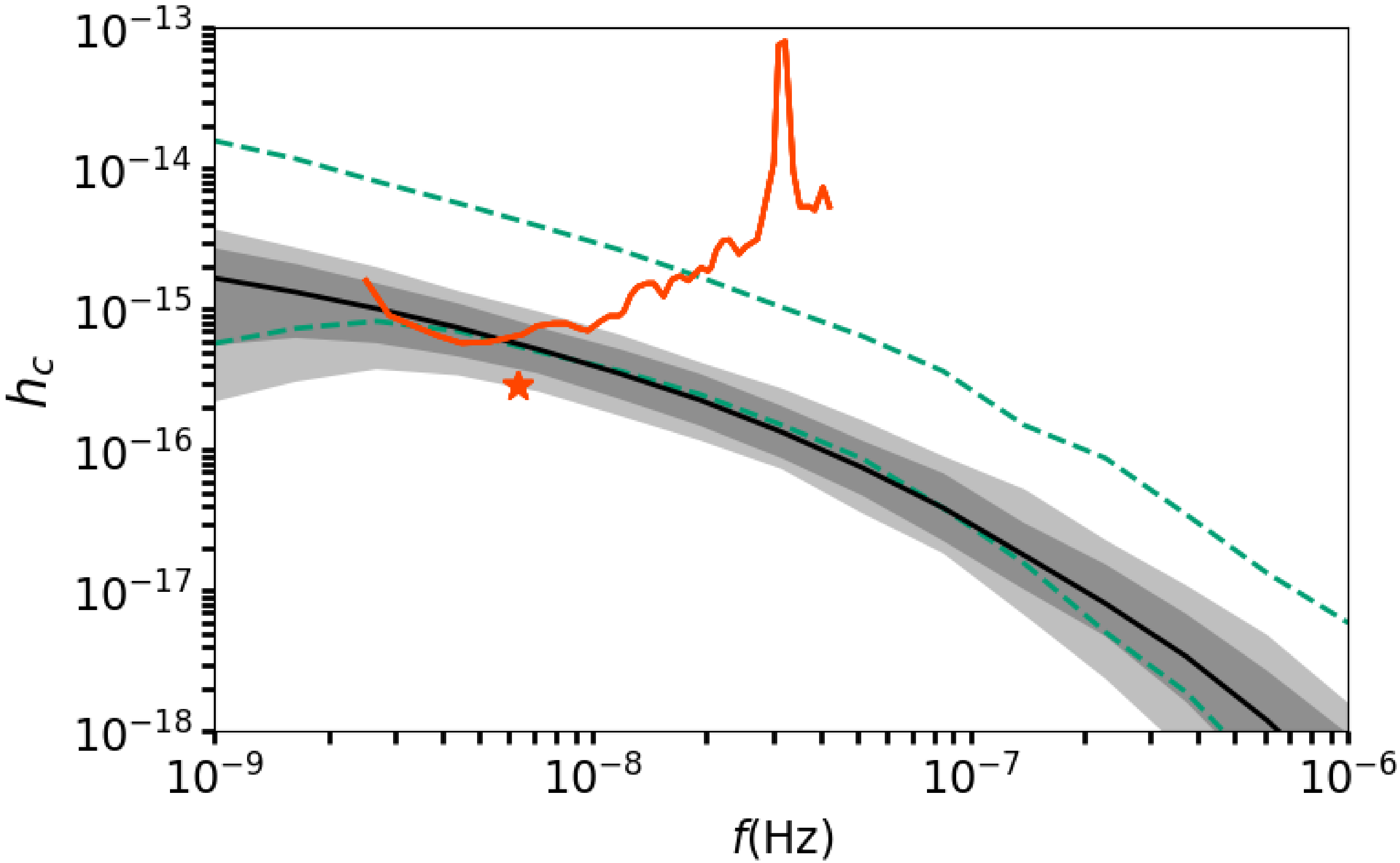
Results – Current Upper Limit



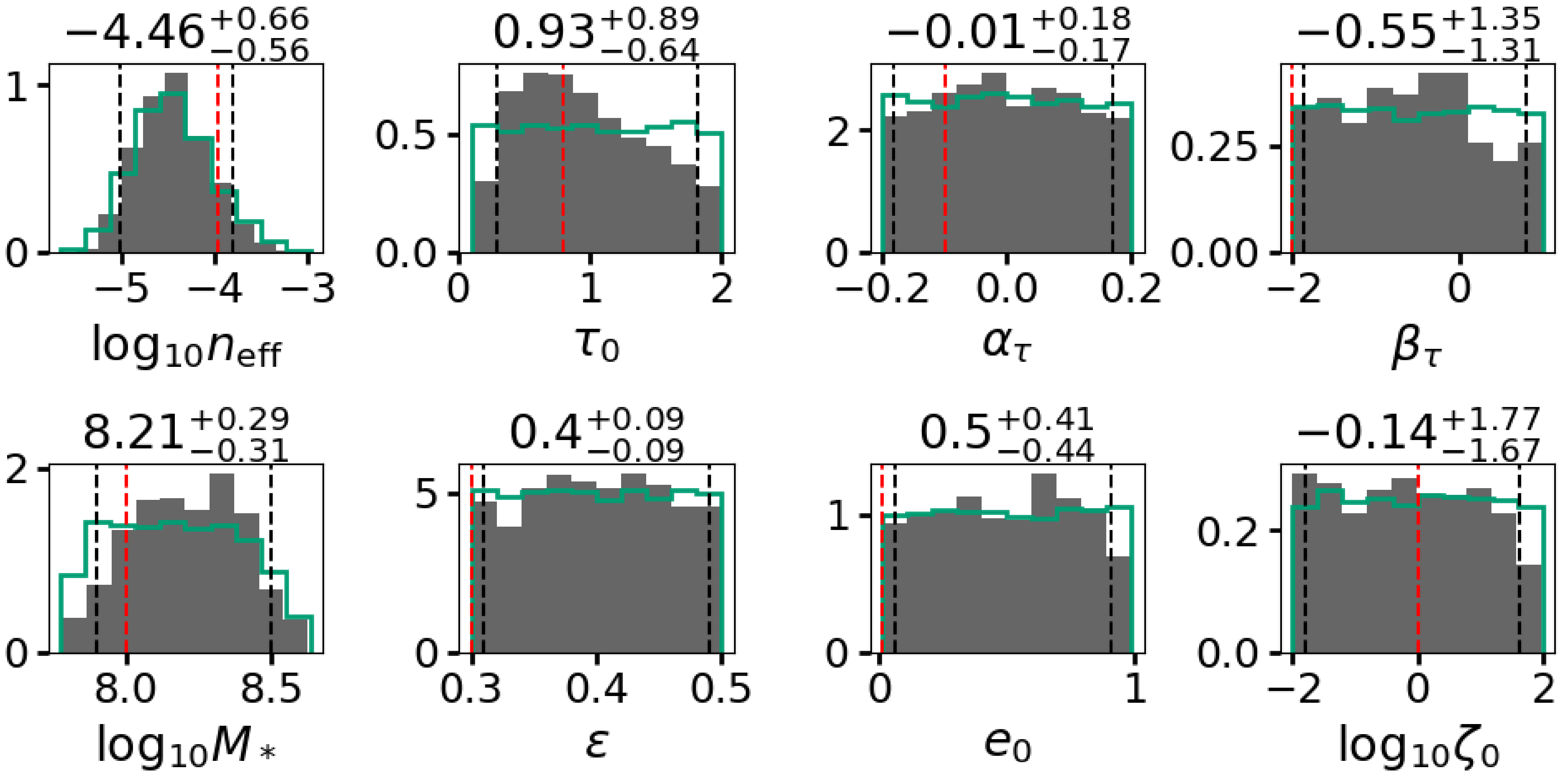
Results – Future Upper Limit



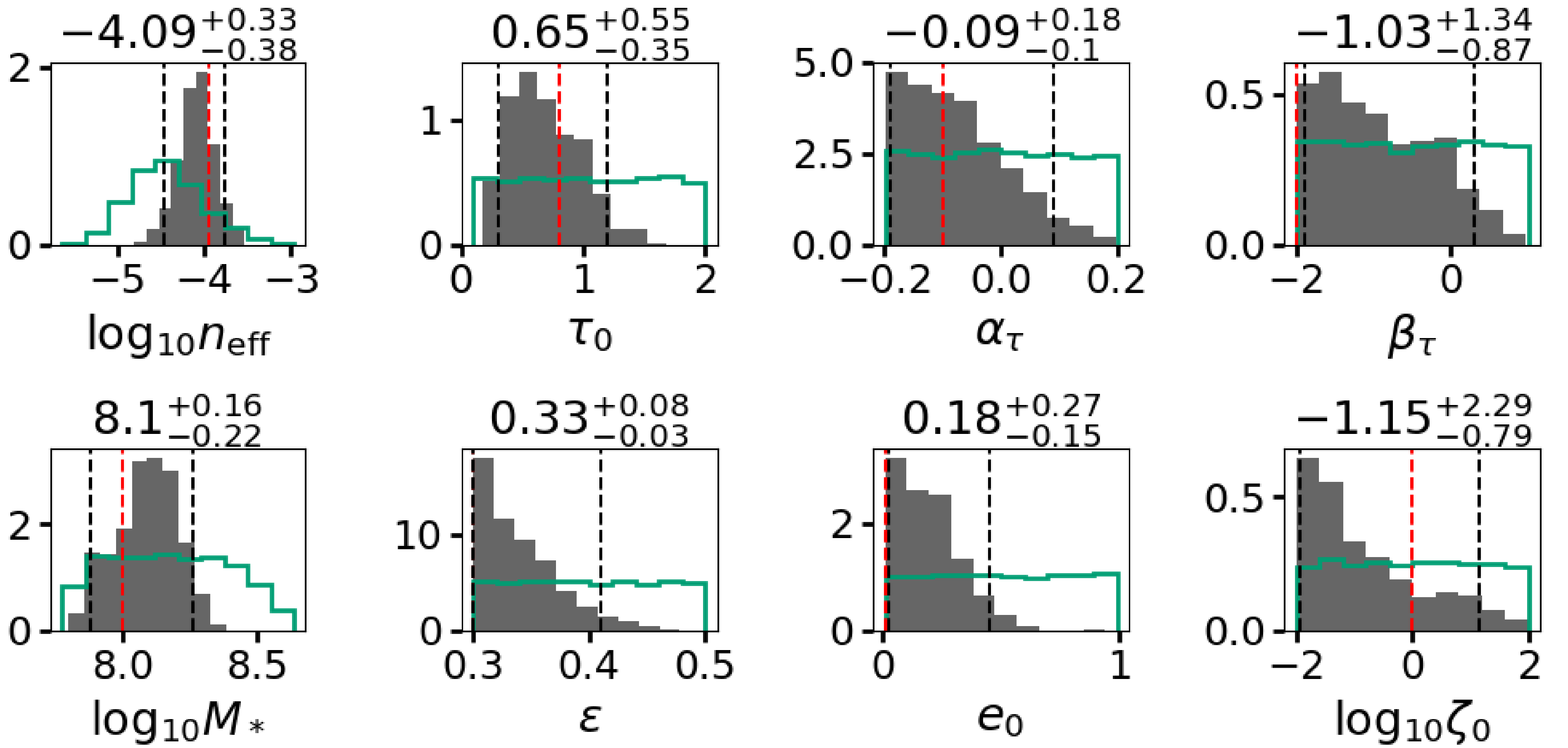
Results – Future Upper Limit



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

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