Implications of GW searches in the EPTA DR2
arXiv:230616227

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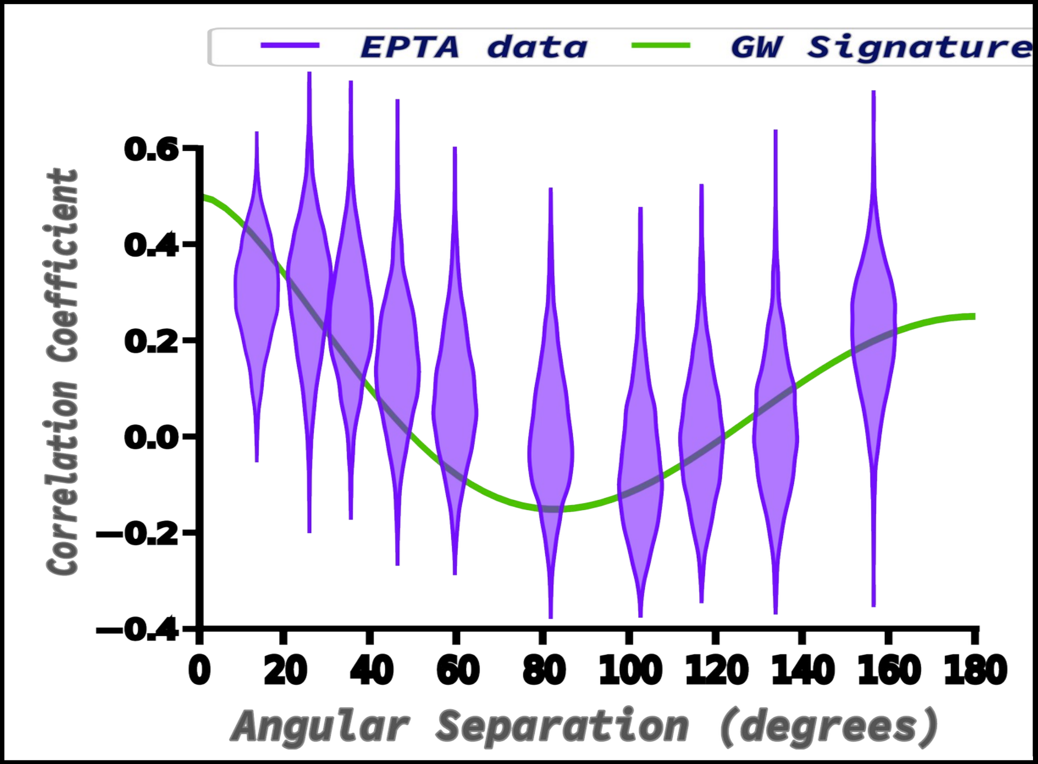
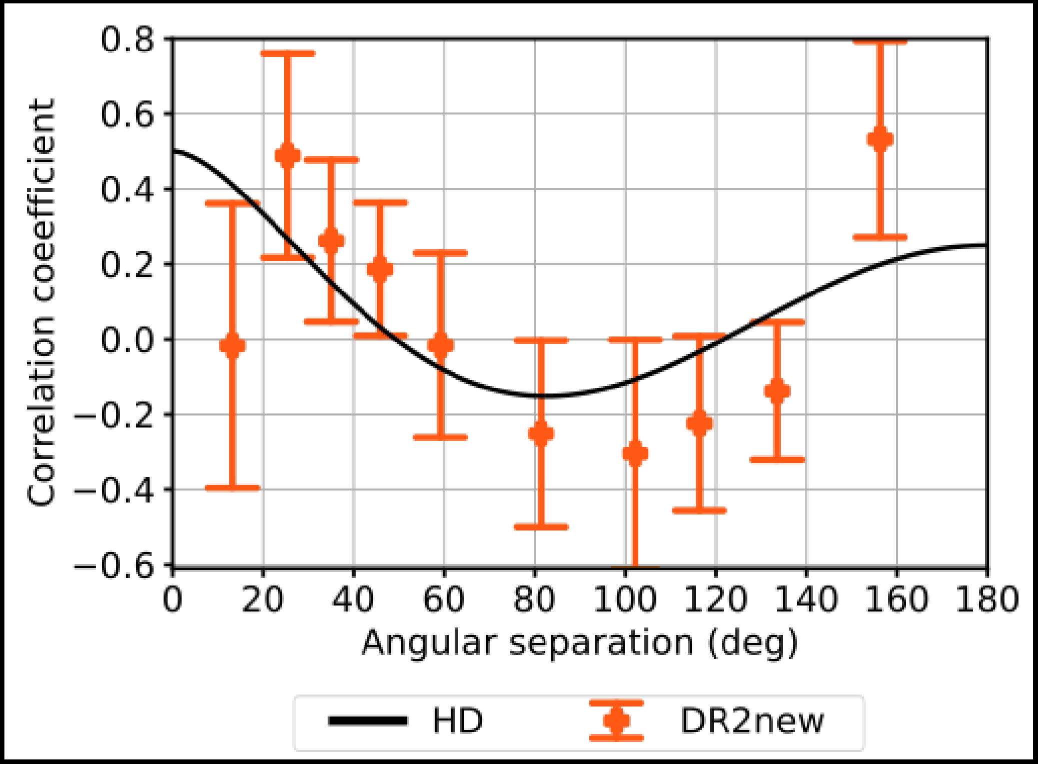
(University of Milano-Bicocca)

-for the European (+Indian) Pulsar Timing Array-



Bayesian analysis

ID	Model	DR2full ENTERPRISE	DR2full FORTYTWO	DR2full+ ENTERPRISE	DR2new ENTERPRISE	DR2new FORTYTWO	DR2new+ ENTERPRISE
1	PSRN + CURN	–	–	–	–	–	–
2	PSRN + GWB	4	5	4	60	62	65
3	PSRN + CLK	< 0.01	< 0.01	< 0.01	0.2	1.2	0.3
4	PSRN + EPH	< 0.01	$\sim 10^{-4}$	< 0.01	0.2	0.2	1.3
5	PSRN + CURN + CLK	2	1	2.7	0.8	2	1.6
6	PSRN + CURN + EPH	1	0.1	1	1	1	1.6
7	PSRN + GWB + CURN	3	3	4	27	13	25
8	PSRN + GWB + CLK	5	12	7	28	35	57
9	PSRN + GWB + EPH	3	3	3.6	33	29	43



Frequentist analysis

	DR2full	DR2full+	DR2new	DR2new+
A^2_{MP}	$4.1^{+5.0}_{-3.9} \times 10^{-31}$	$3.7^{+5.1}_{-4.1} \times 10^{-31}$	$1.5^{+6.7}_{-4.3} \times 10^{-31}$	$4.0^{+7.0}_{-4.6} \times 10^{-31}$
A^2_{DP}	$-1.9^{+4.6}_{-4.1} \times 10^{-31}$	$-0.8^{+5.1}_{-4.3} \times 10^{-31}$	$0.8^{+9.3}_{-5.8} \times 10^{-31}$	$3.9^{+9.1}_{-6.5} \times 10^{-31}$
A^2_{HD}	$2.7^{+3.0}_{-2.5} \times 10^{-30}$	$2.9^{+2.9}_{-2.4} \times 10^{-30}$	$10.0^{+5.1}_{-4.9} \times 10^{-30}$	$11.0^{+4.6}_{-4.4} \times 10^{-30}$
S/N_{MP}	$1.1^{+1.1}_{-1.0}$	$1.0^{+1.1}_{-1.1}$	$0.3^{+1.4}_{-0.9}$	$0.8^{+1.7}_{-1.0}$
S/N_{DP}	$-0.4^{+0.9}_{-0.8}$	$-0.2^{+1.0}_{-0.9}$	$0.1^{+1.5}_{-0.9}$	$0.6^{+1.5}_{-0.9}$
S/N_{HD}	$1.3^{+1.3}_{-1.2}$	$1.4^{+1.2}_{-1.1}$	$3.5^{+2.4}_{-1.7}$	$4.1^{+2.7}_{-1.7}$

Similar results as NANOgrav, PPTA, CPTA

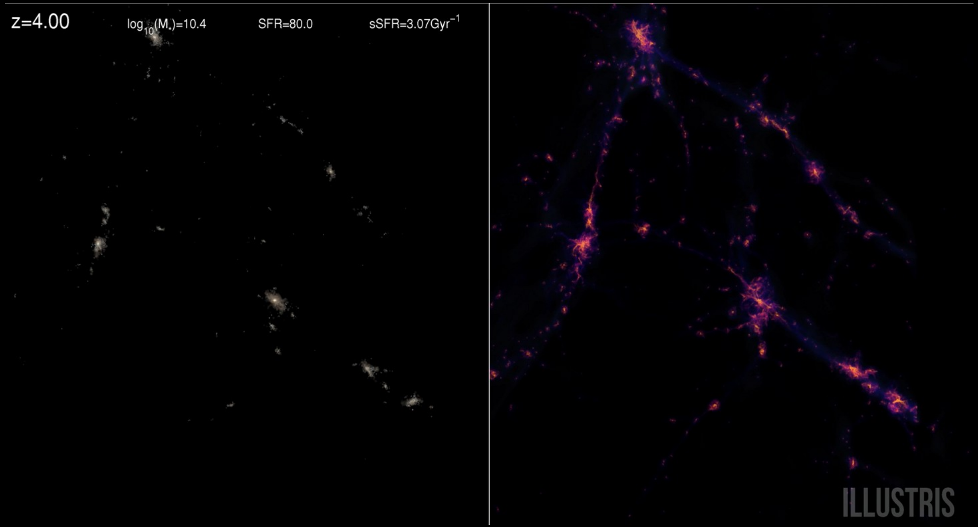
HIERARCHICAL GALAXY & MBH EVOLUTION

GENERAL FRAMEWORK:

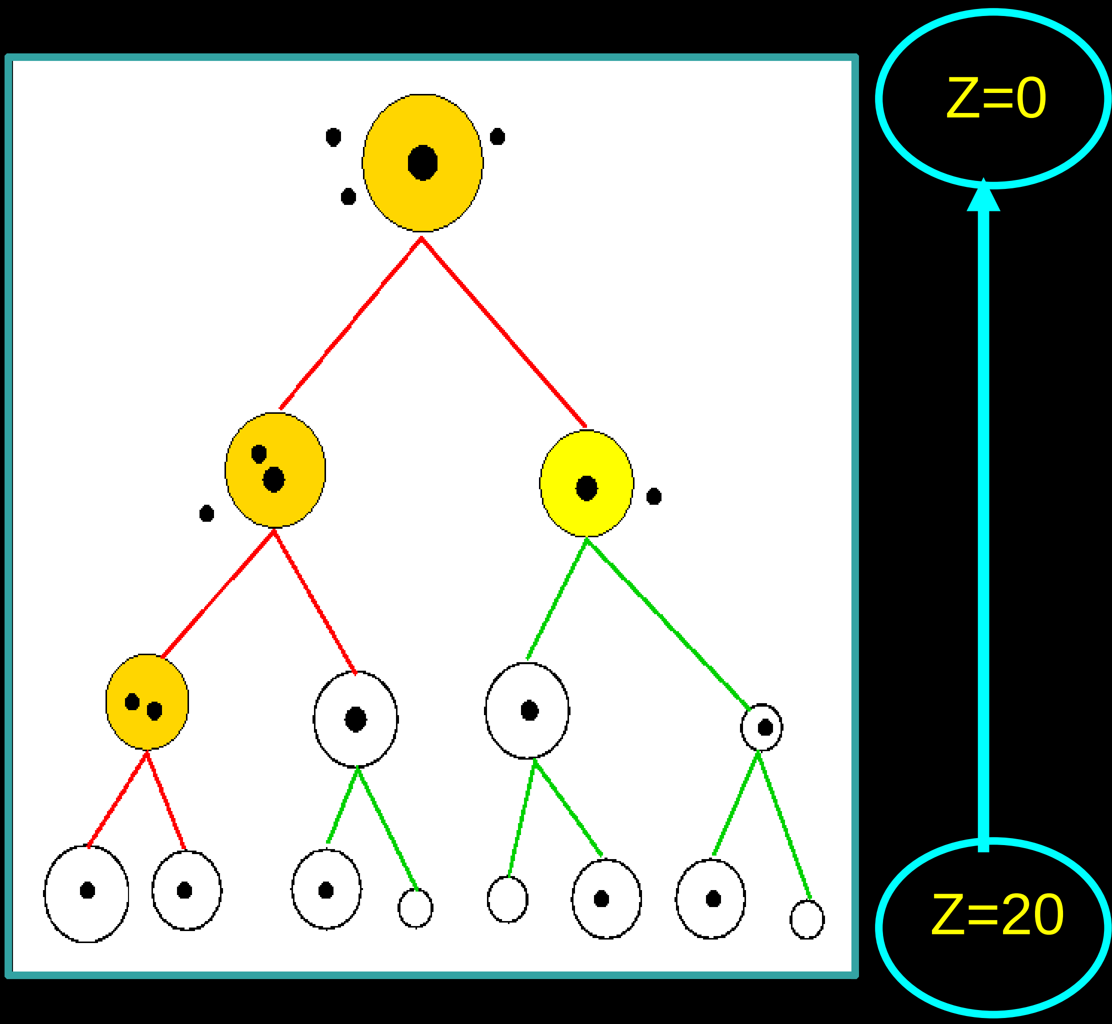
(Volonteri, Haardt & Madau 2003)

Galaxies form hierarchically through a series of mergers and accretion events

Protogalaxies can host seed BH that accrete mass and merge with each other following galaxy mergers

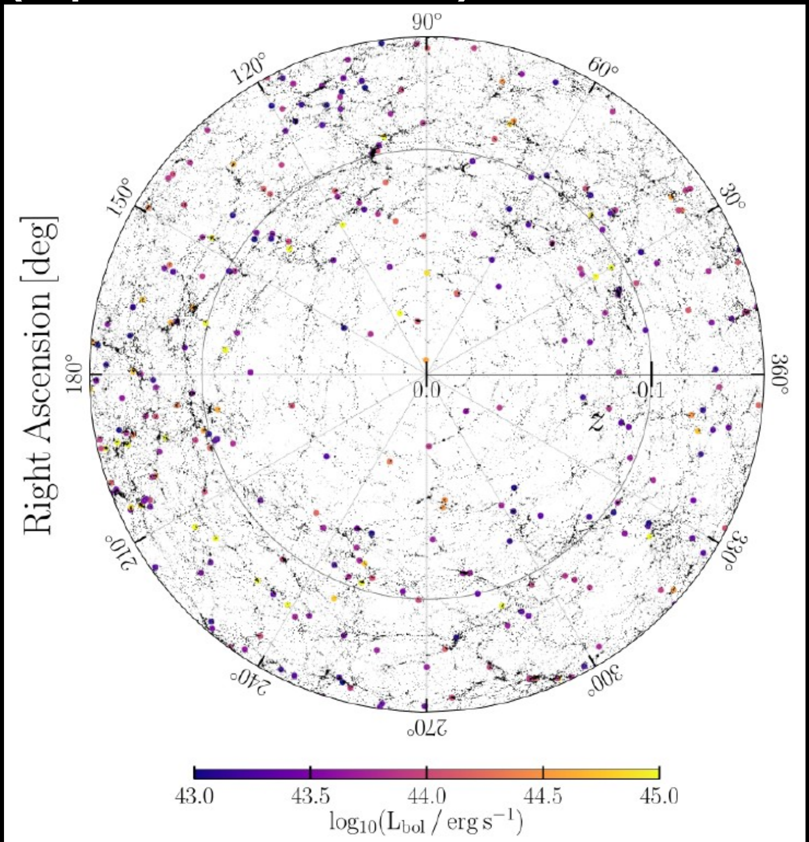


(Illustris simulation)



The expected GW signal in the PTA band

(Izquierdo-Villalba+ 22)



The GW characteristic amplitude coming from a population of circular MBH binaries

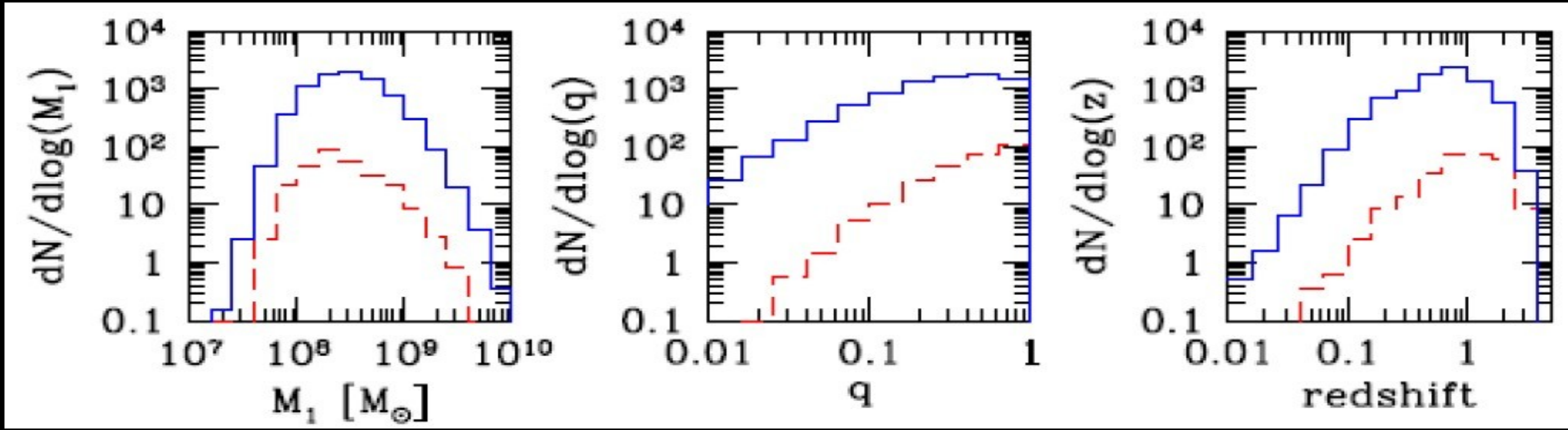
$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^3N}{dz d\mathcal{M} d\ln f_r} h^2(f_r)$$

$$\delta t_{\rm bkg}(f) \approx h_c(f)/(2\pi f)$$

Theoretical spectrum: simple power law

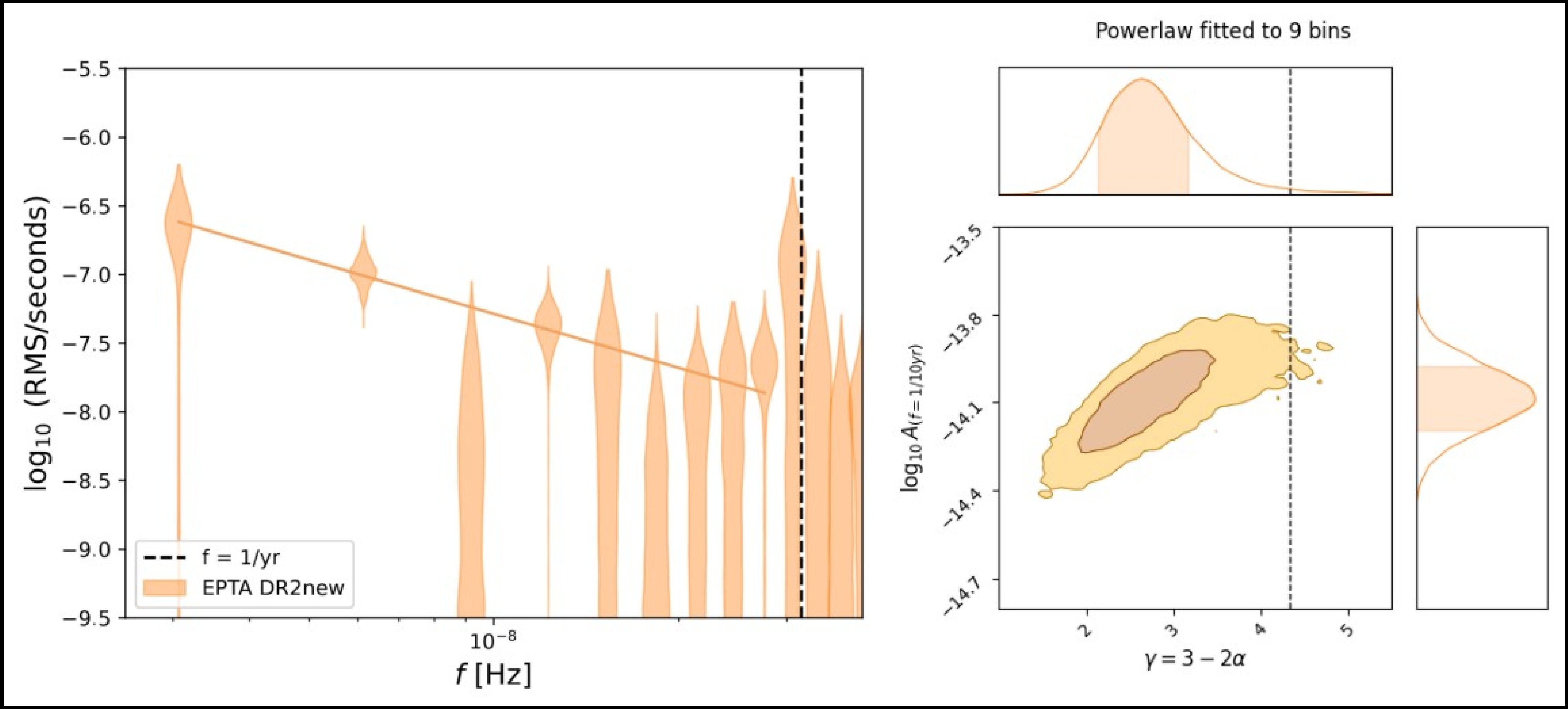
(Phinney 2001)

$$h_c(f) = A \left(\frac{f}{{\rm yr}^{-1}}\right)^{-2/3}$$



The signal is contributed by extremely massive (>$10^8 M_\odot$) relatively low redshift (z<1) MBH binaries (AS et al. 2008, 2012)

Results of EPTA DR2



-4 dataset produced: using DR2new here (only new backend)

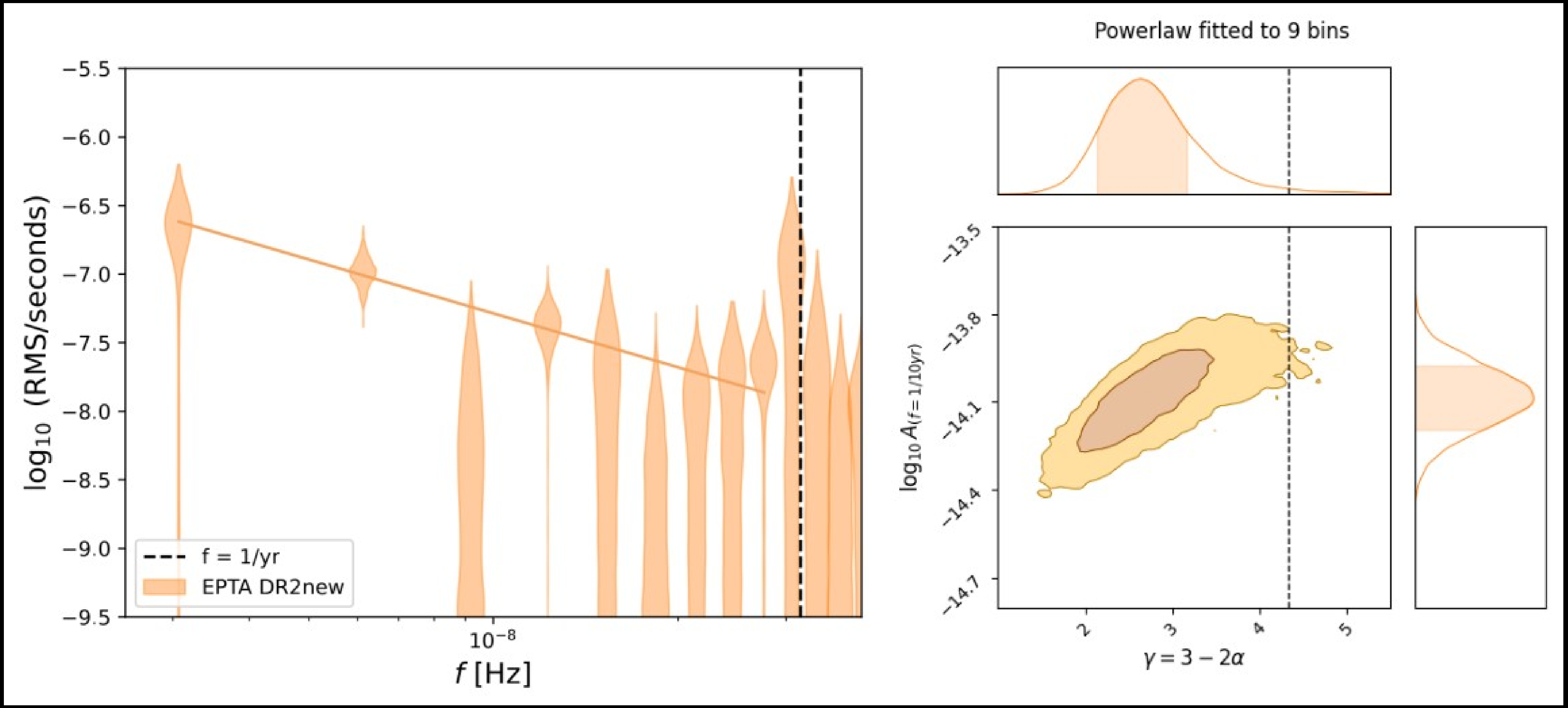
-HD correlated signal favoured with Bayes factor~60

-power constrained in few bins at low freq

-powerlaw fit: γ~2.7 *A*~ -14 [*A*(γ=13/3)~ -14.6]

$$h_c(f) = A \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{-2/3}$$

Results of EPTA DR2



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THINGS YOU HEAR: “too flat for SMBHBs [add your favorite early Universe model that fits the data]”

“Looking at the arxiv, can't help wondering: is there any early-Universe cosmological process that DOES NOT produce the stochastic gravitational-wave background observed by Pulsar-Timing Arrays?”

Yuri Levin

-It’s Inflation!

-It’s phase transitions!

-It’s scalar perturbations!

-It’s topological defects!

-It’s domain walls!

-It’s turbulence induced perturbations!

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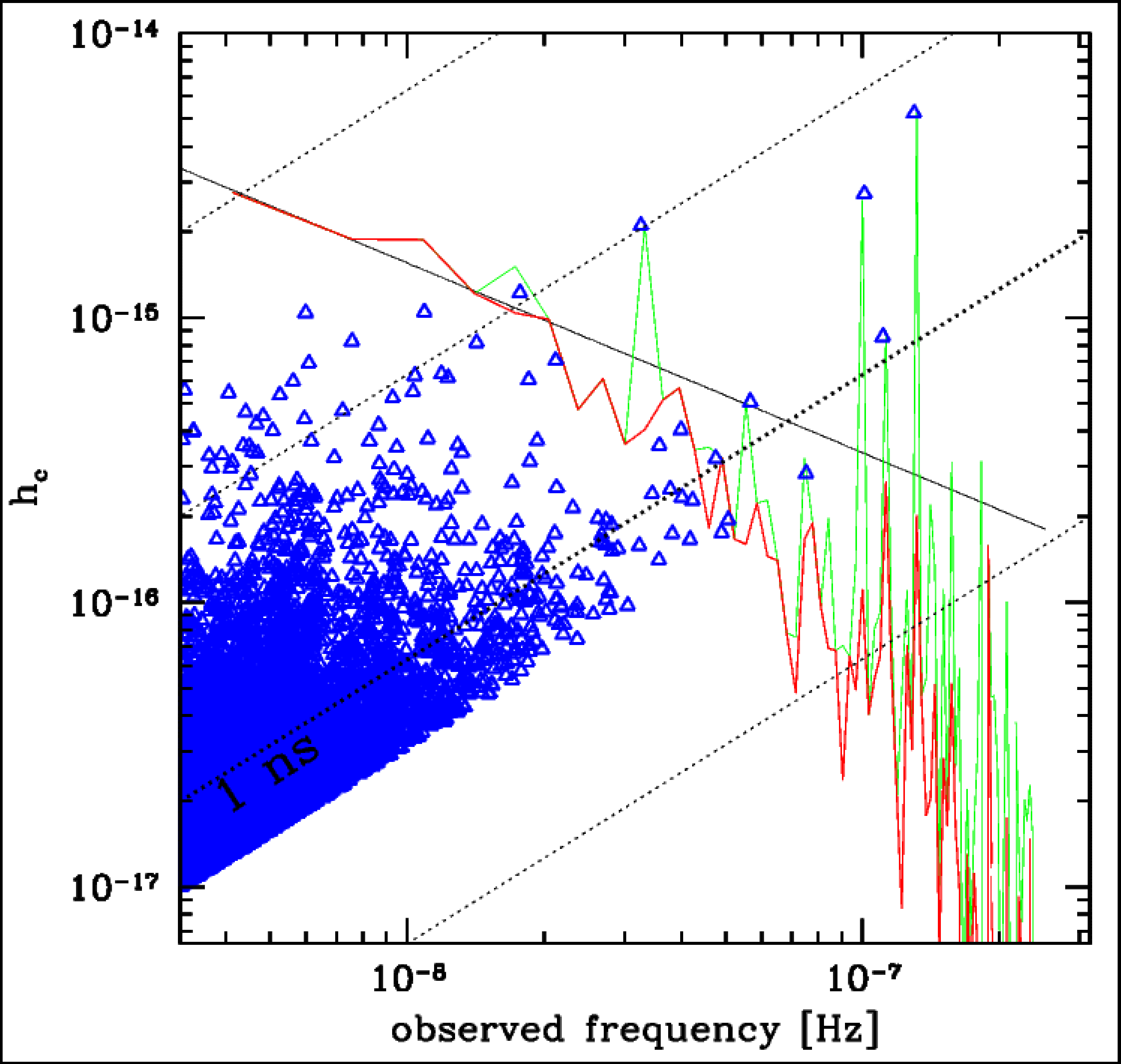


10^{-14}
10^{-15}
10^{-16}
10^{-17}
h_c
1 ns
10^{-8}
10^{-7}
observed frequency [Hz]

The overall GW signal

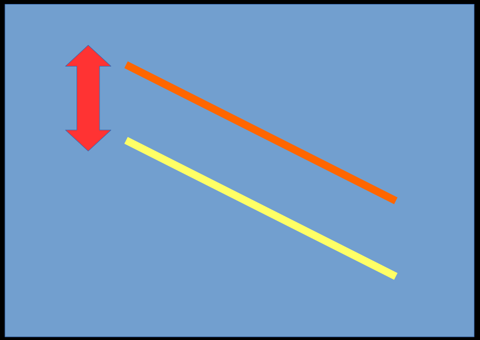
Population parameters

1-Galaxy merger rate <-----> MBHB merger rate

affects the number of sources at each frequency ---> N_0

2-MBH mass – merging galaxy relation

affects the mass of the sources ----> M_c



$$h_c^2(f) = \int_0^\infty dz \int_0^\infty dM_1 \int_0^1 dq \frac{d^4N}{dz\,dM_1\,dq\,dt_r} \frac{dt_r}{d\ln f_{K,r}} \times$$
$$h^2(f_{K,r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{K,r})]}{(n/2)^2} \delta\left[f - \frac{n f_{K,r}}{1+z}\right].$$

$$h_c(f) \propto n_0^{1/2} f^{-\gamma} M_c^{5/6}$$

Local dynamics

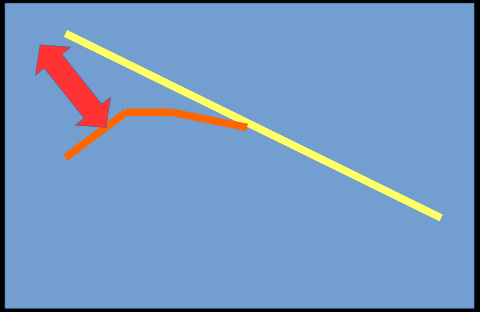
1-Accretion (when? how?)

affects the mass of the sources ---> M_c

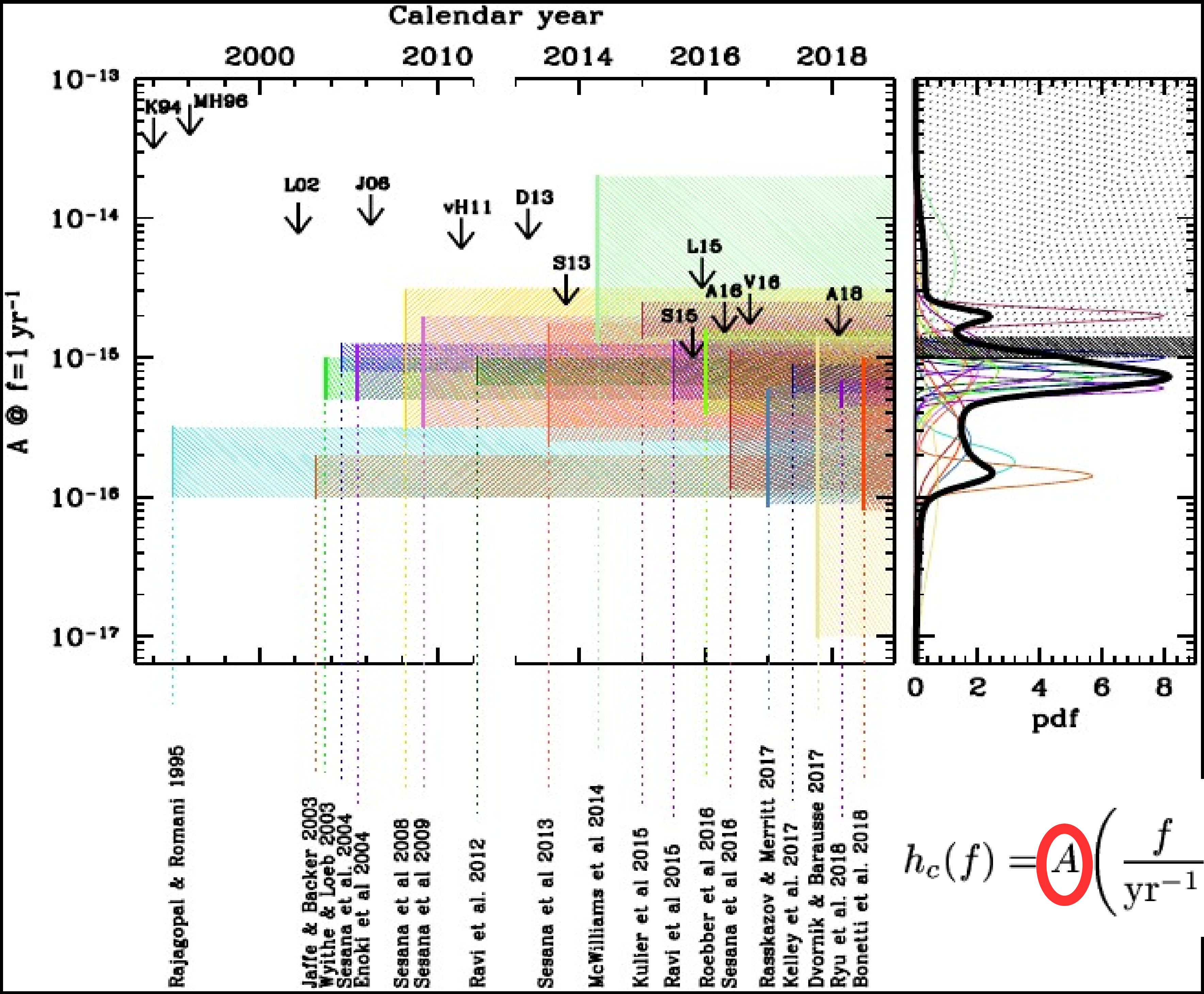
2-MBHB – environment coupling (gas & stars)

affects the chirping rate of the binaries ---> γ

affects the eccentricity ---> chirping rate ----> γ & single source detection

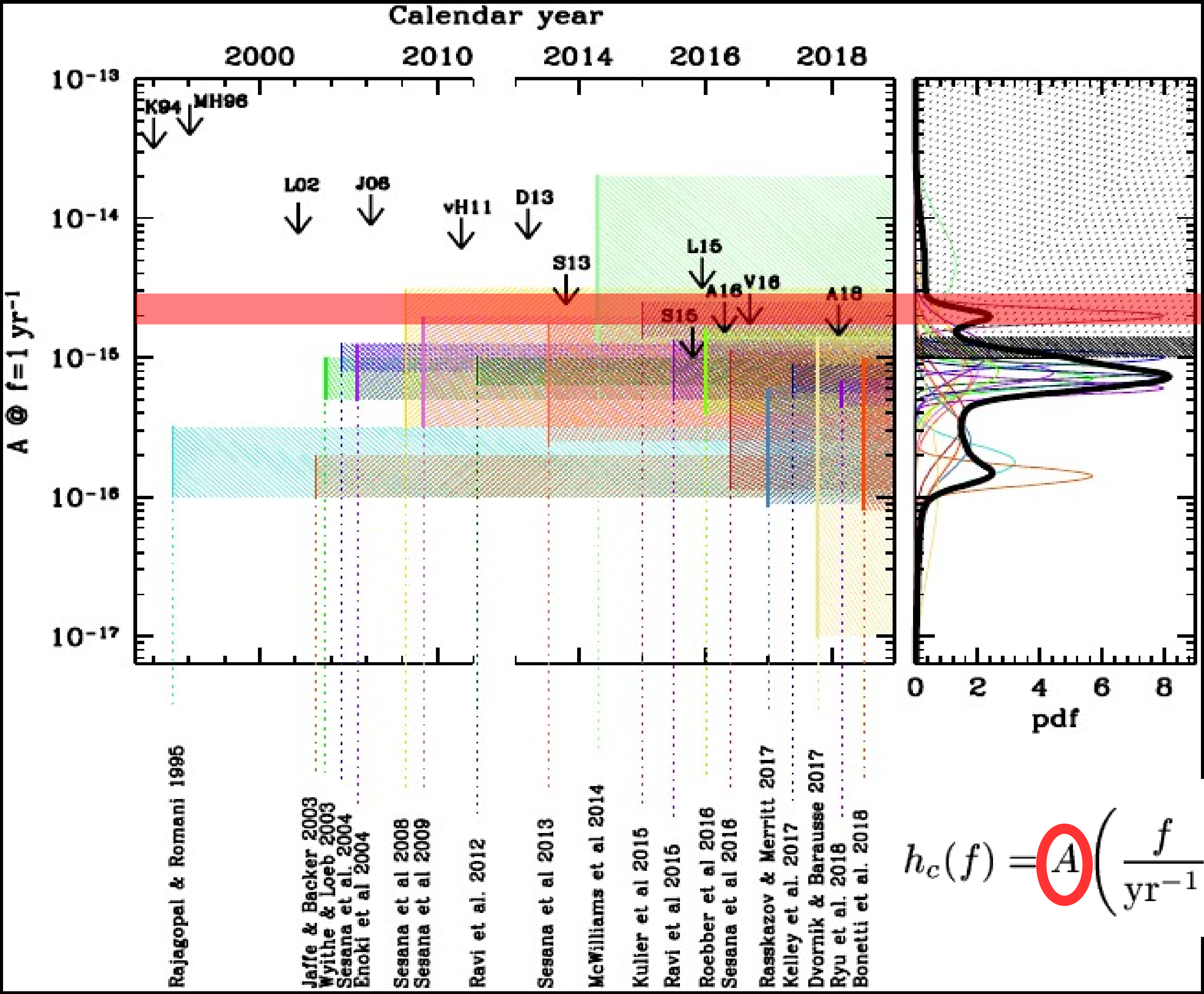


...Some predictions...



$$h_c(f) = A\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-2/3}$$

...Some predictions...



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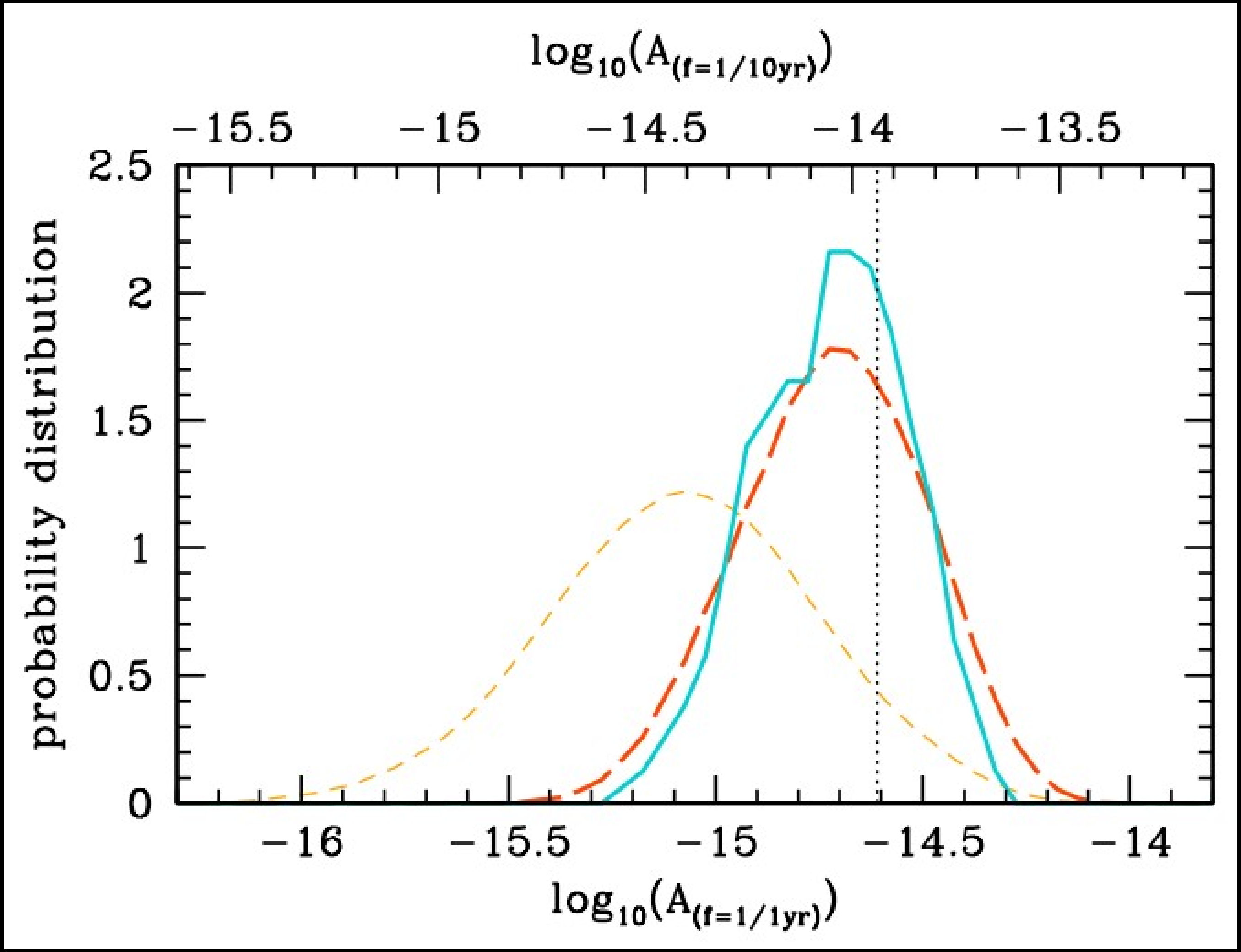
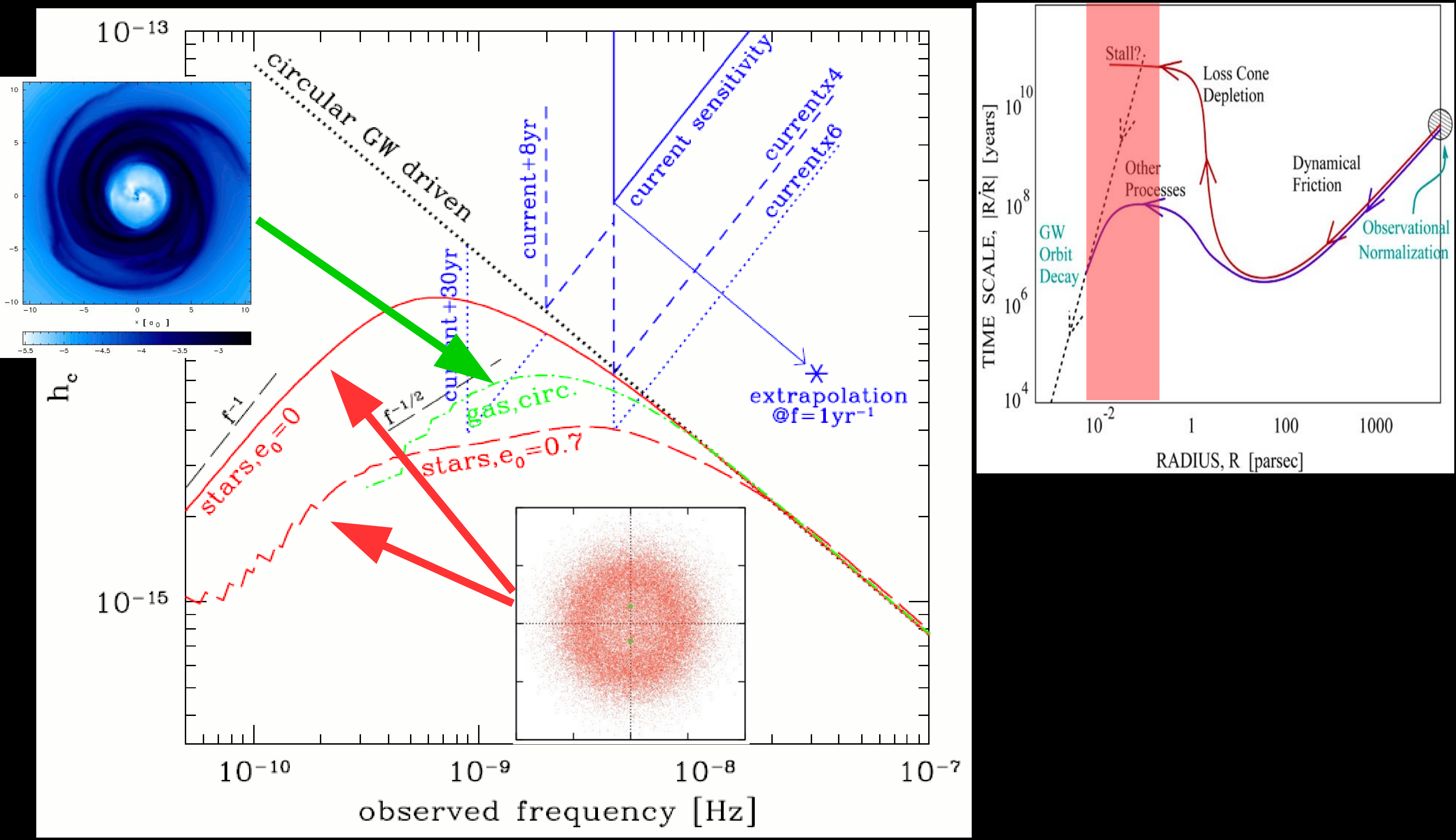


This is not a first principle calculation, there's a lot of 'freedom'
Most notably:

-MBH-galaxy relations (and their redshift evolution, e.g. Simon 2023

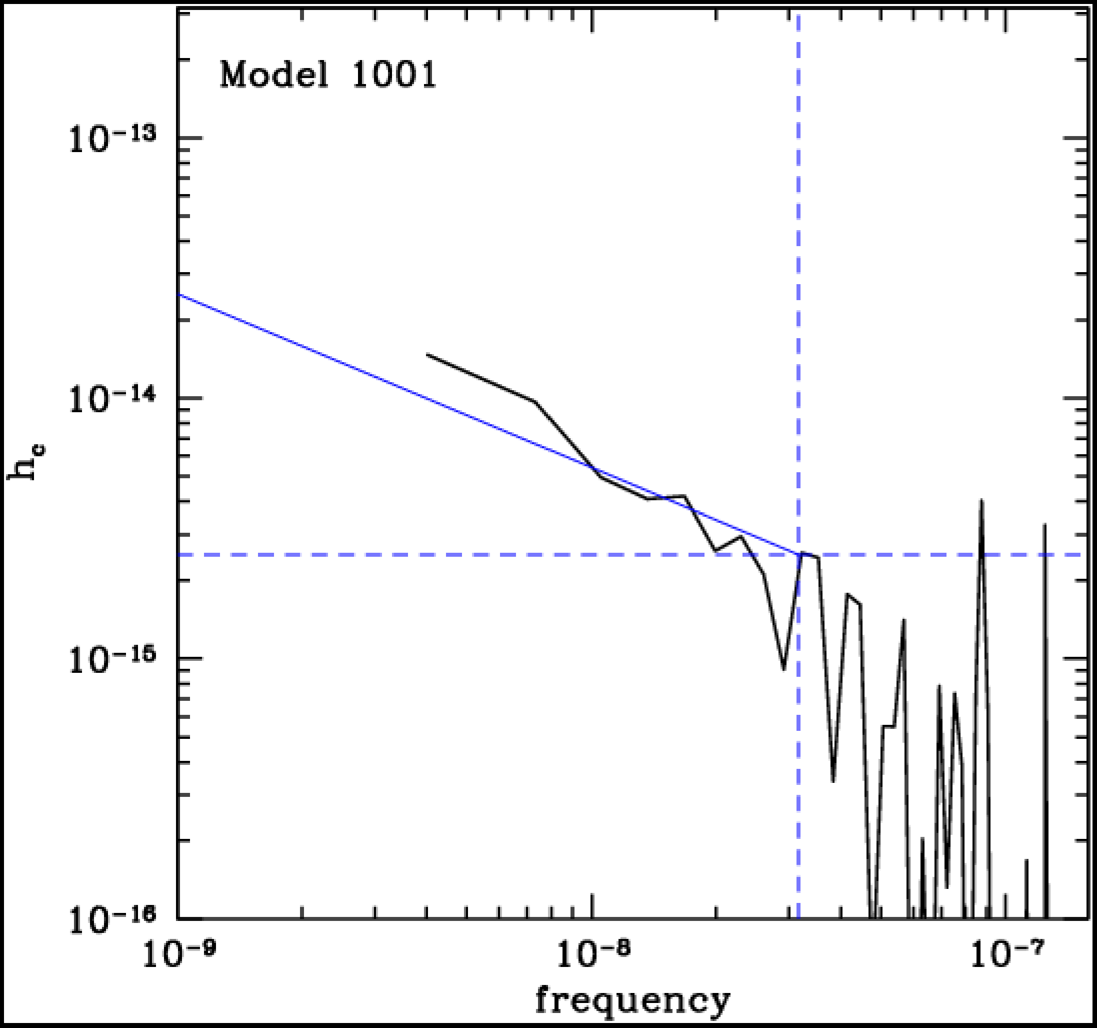
-accretion during mergers (Before? After? Onto the primary? Secondary?)

Uncertainty in the GW background shape



(Kocsis & AS 2011, AS 2013, Ravi et al. 2014, McWilliams et al. 2014)

Qualitative comparison with empirical models



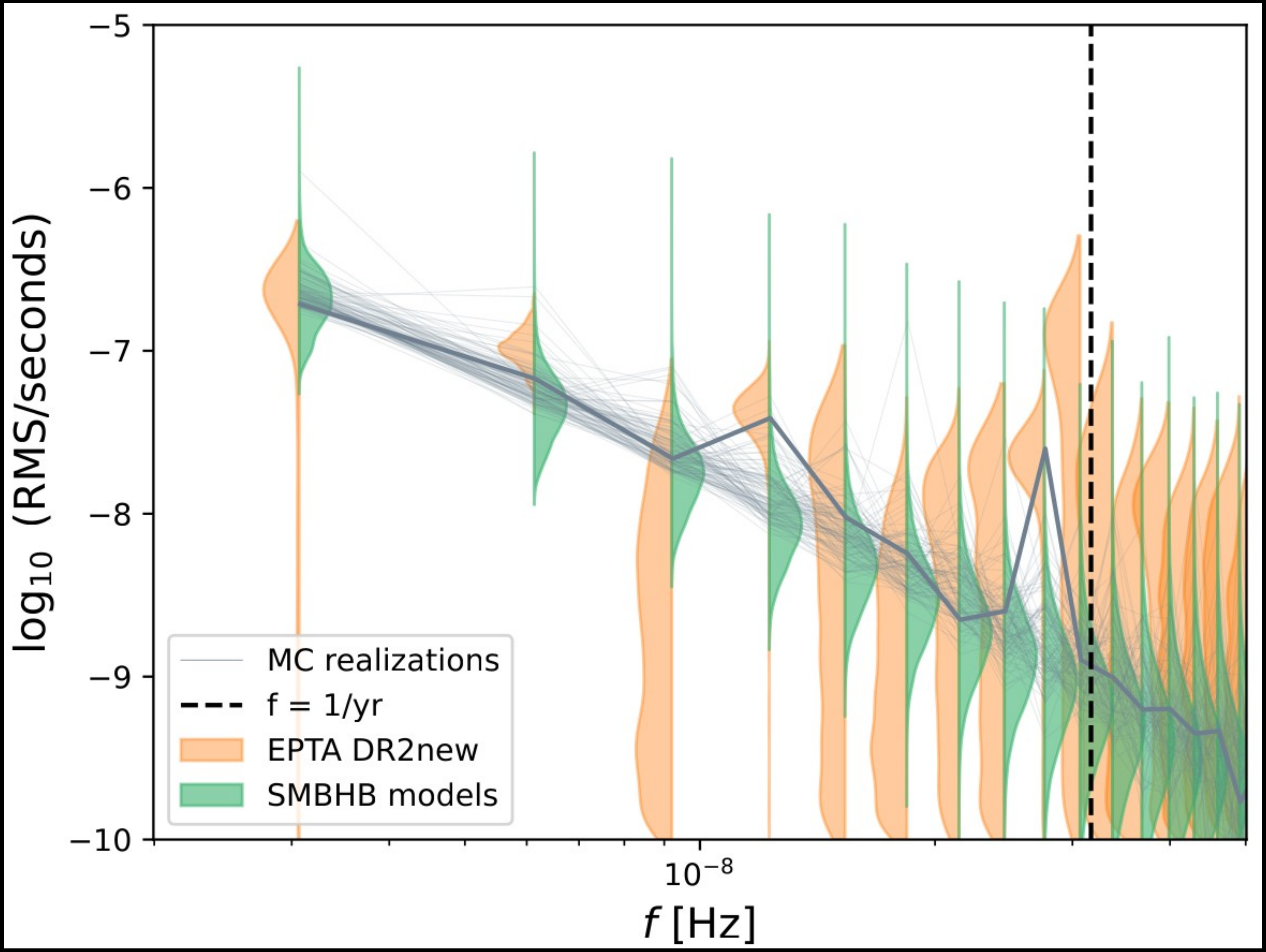
Qualtitative comparison with Rosado+15 models

-Merger rate determined observationally (S13) via galaxy mass function, pair fraction, merger time etc etc...

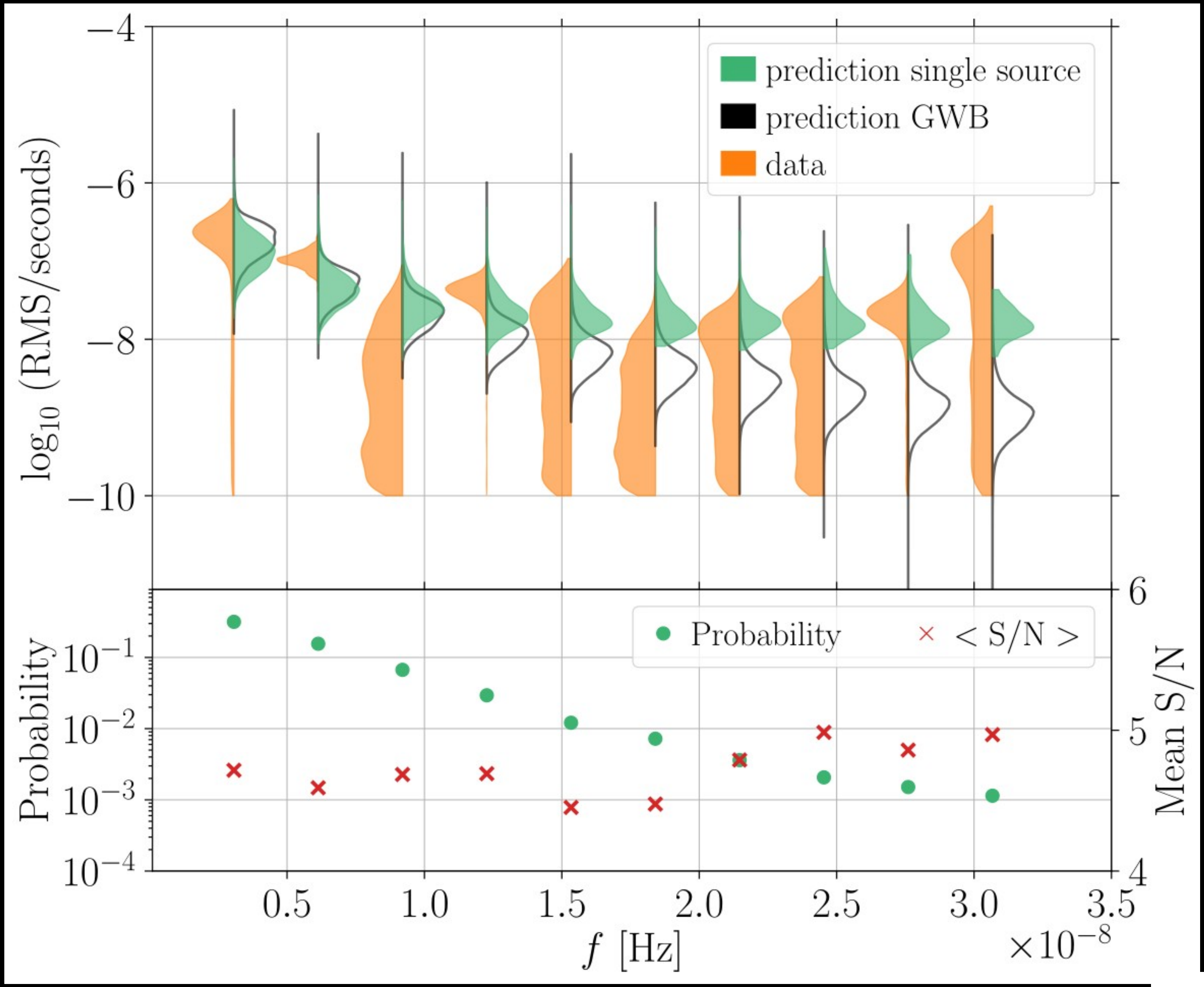
-constrained by observations

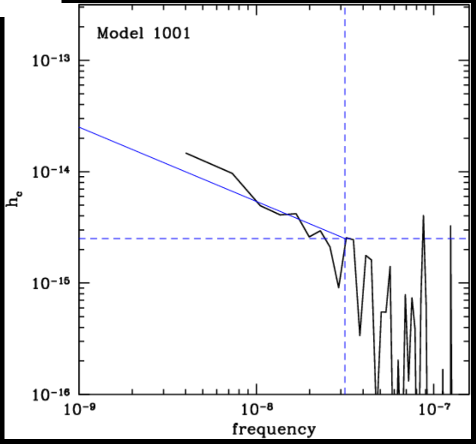
-adding hardening via stars and eccentricity (S10)

324k MC realizations
-captures signal variance
-capture resolvable sources



Free spectrum in good agreement with measurements (9 bins)
Excess power measured at the 9th bin (flat γ~3)

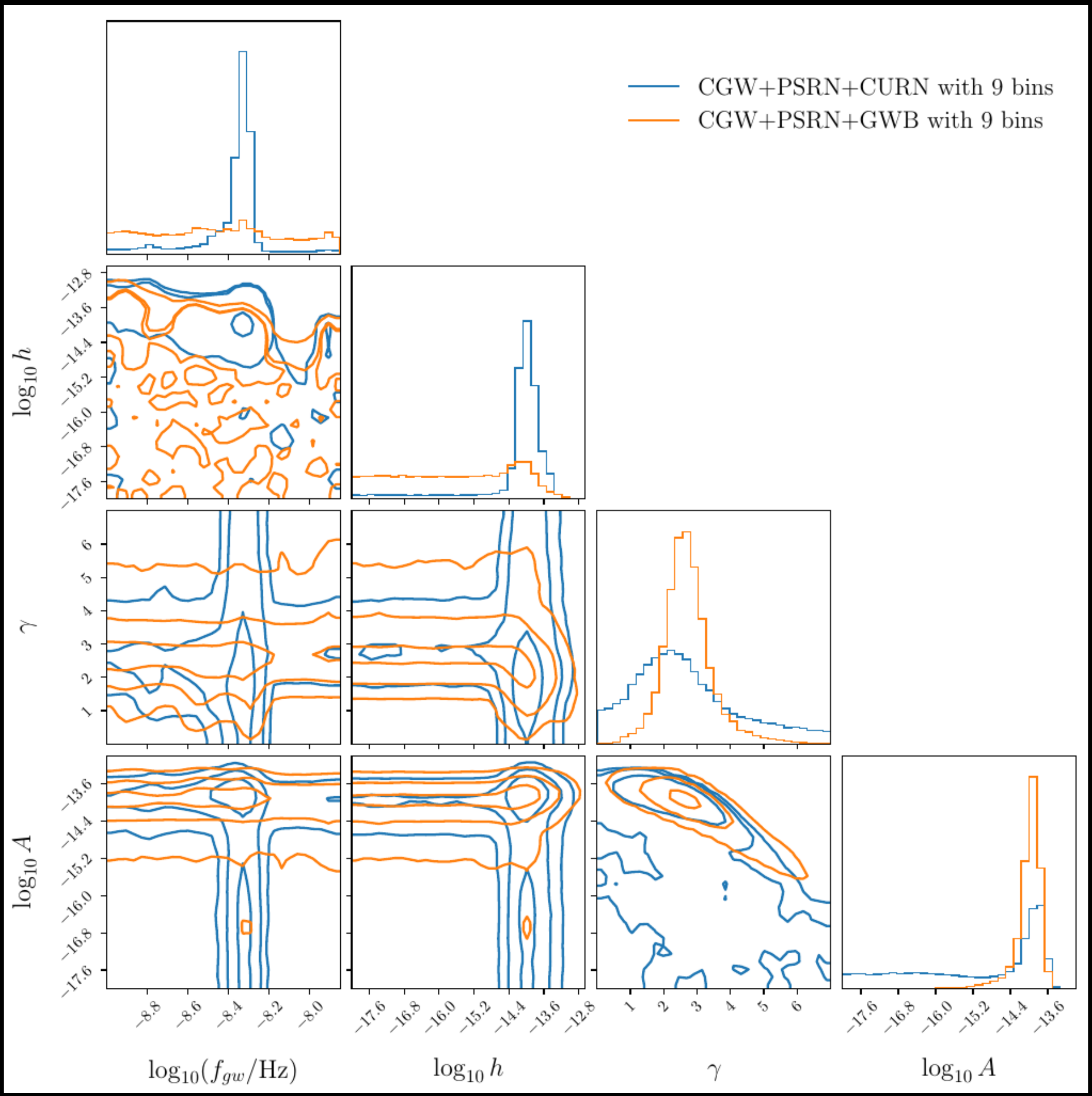


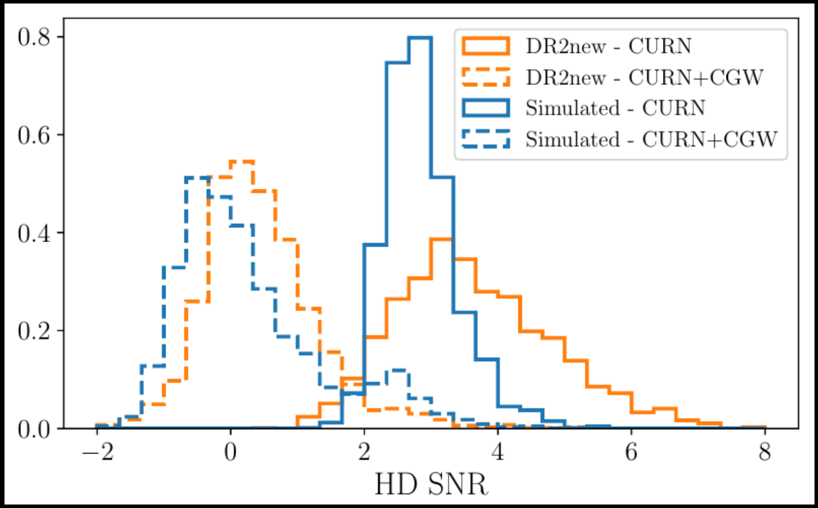


Models allow to compute CGW detection statistics (circular, SNR>3)

~50% probability to have at least a CGW (mostly at the lowest frequency) **(higher than Becsy+2022, but lower SNR threshold)**

Assessing the type of signal is NOT trivial





Data can be fit by an individual continuous GW (CGW)

Strongly preferred over common noise….

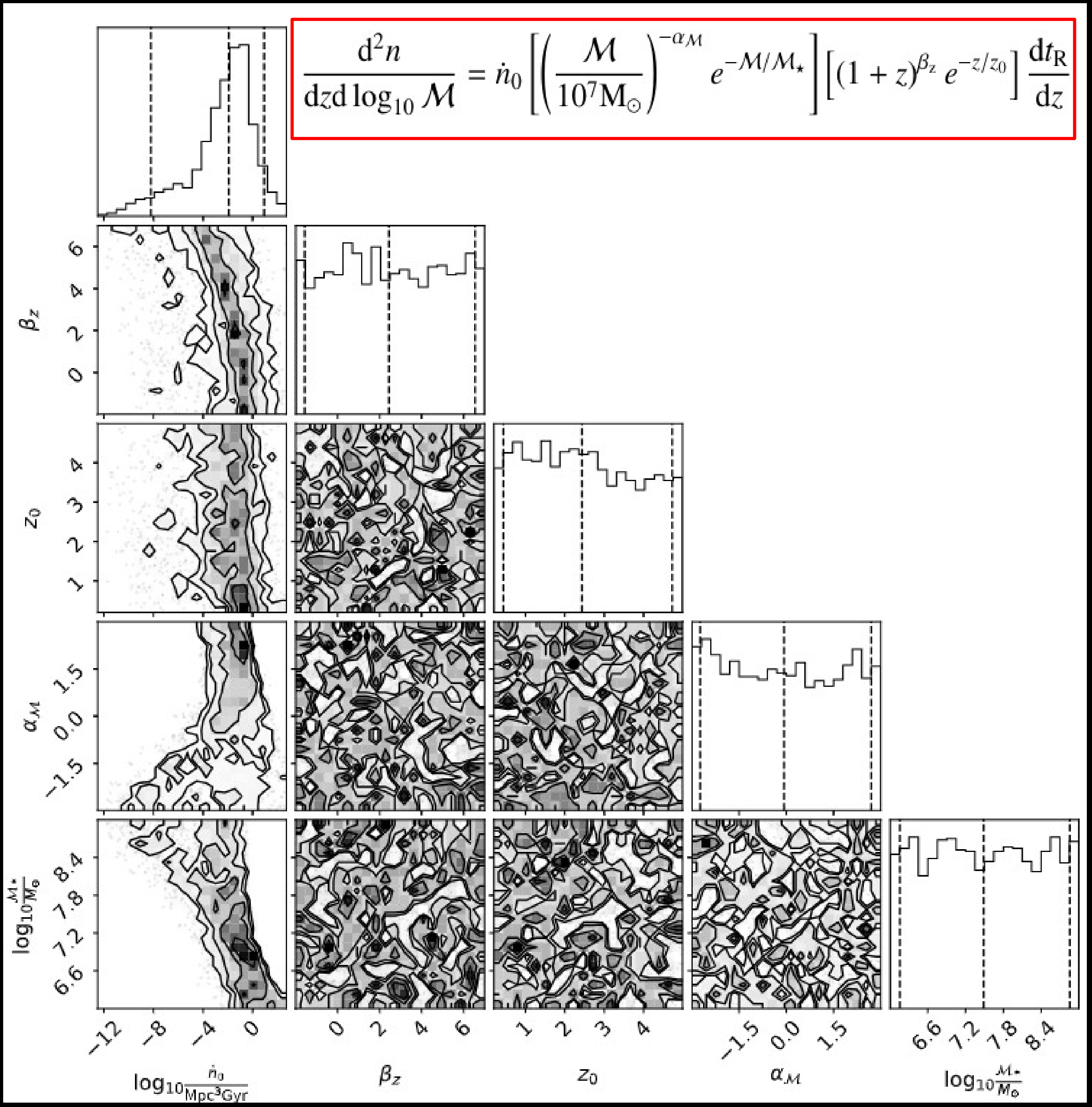
...but absorbed by the GWB

Simulations show that it can be difficult to discriminate between CGW and GWB at this stage

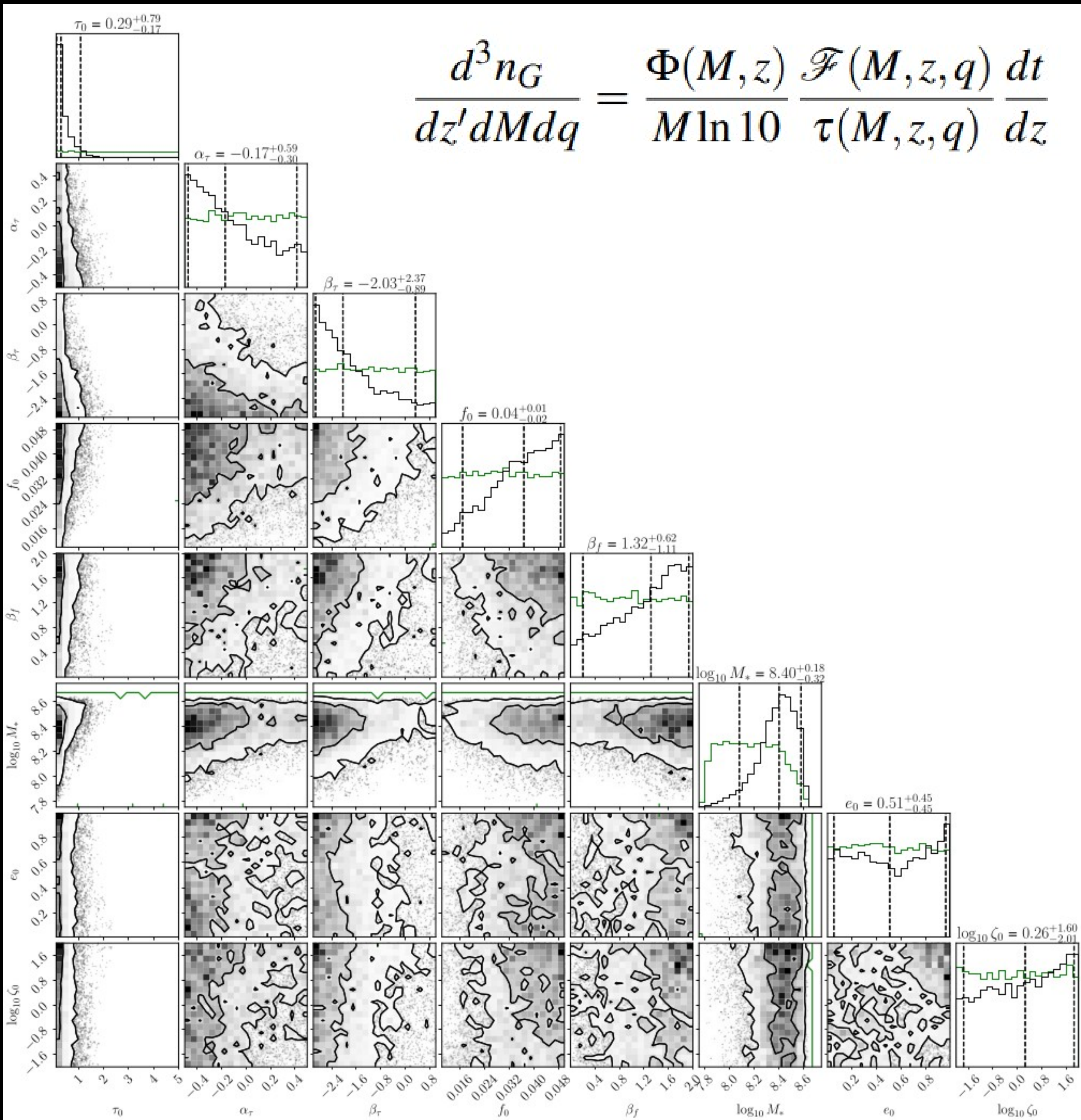
SMBHB inference from the data

Agnostic models
(Middleton+16)
-general mass function
(Schechter + z dependence)
-no other constraints
-circular binary

Only constrain: SMBHB merger density



$$\frac{d^3 n_G}{dz' dM dq} = \frac{\Phi(M,z)}{M \ln 10} \frac{\mathscr{F}(M,z,q)}{\tau(M,z,q)} \frac{dt}{dz}$$



Astro constrained models

(Chen+19)

-generalization of Rosado+15

-informed by observations:

-Galaxy mass function

-Galaxy pair fraction

$$f_{\rm pair} = f_0 \left(\frac{M}{10^{11}{\rm M}_\odot}\right)^{\alpha_f} (1+z)^{\beta_f}$$

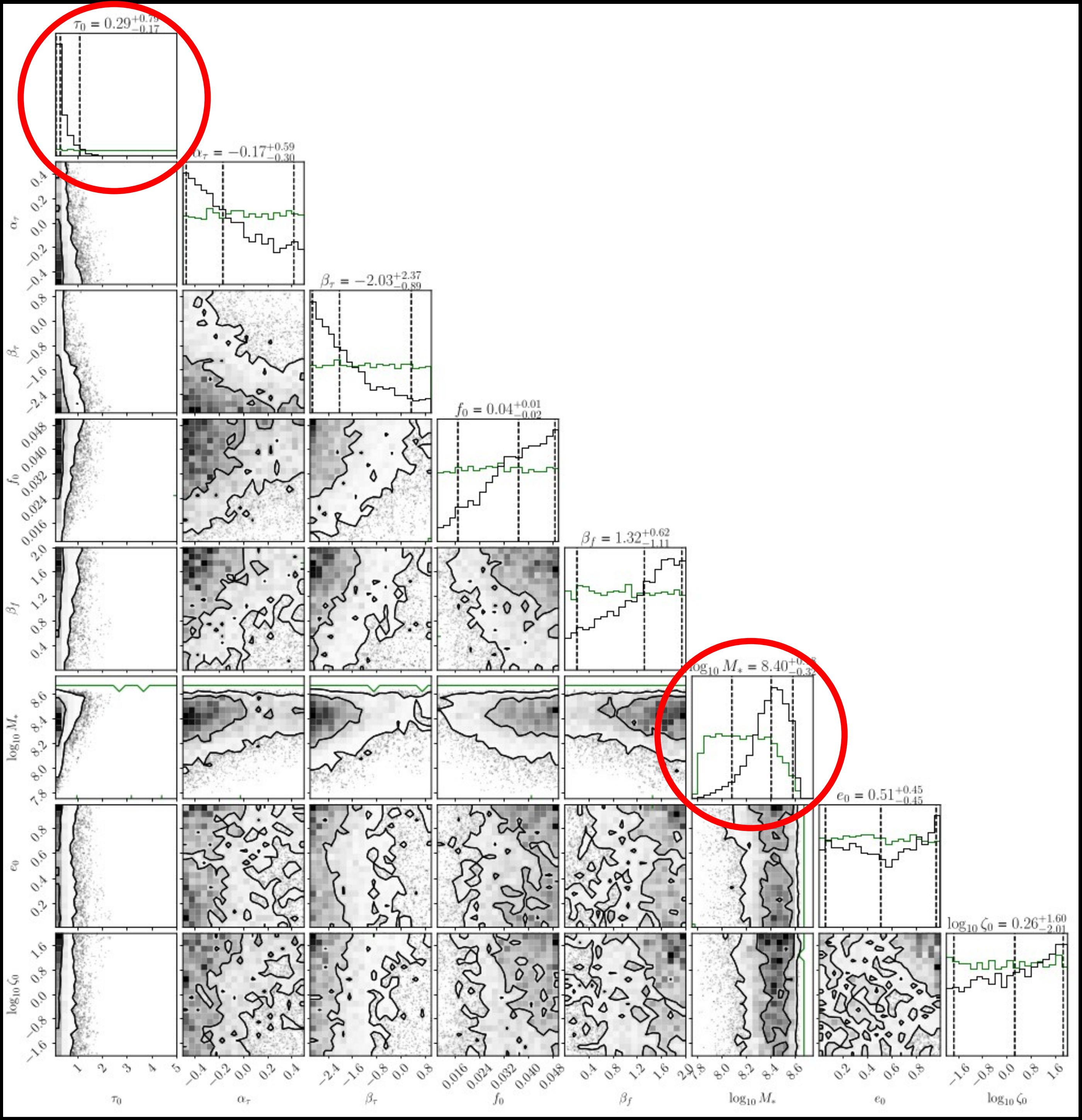
-SMBHB merger timescale

$$\tau = \tau_0 \left(\frac{M}{10^{11}{\rm M}_\odot}\right)^{\alpha_\tau} (1+z)^{\beta_\tau} q^{\gamma_\tau}$$

-SMBH-galaxy relation

$$m = \mathcal{N}\left\{M_* \left(\frac{M_b}{10^{11}{\rm M}_\odot}\right)^{\alpha_*}, \epsilon\right\}$$

-eccentricity and environment



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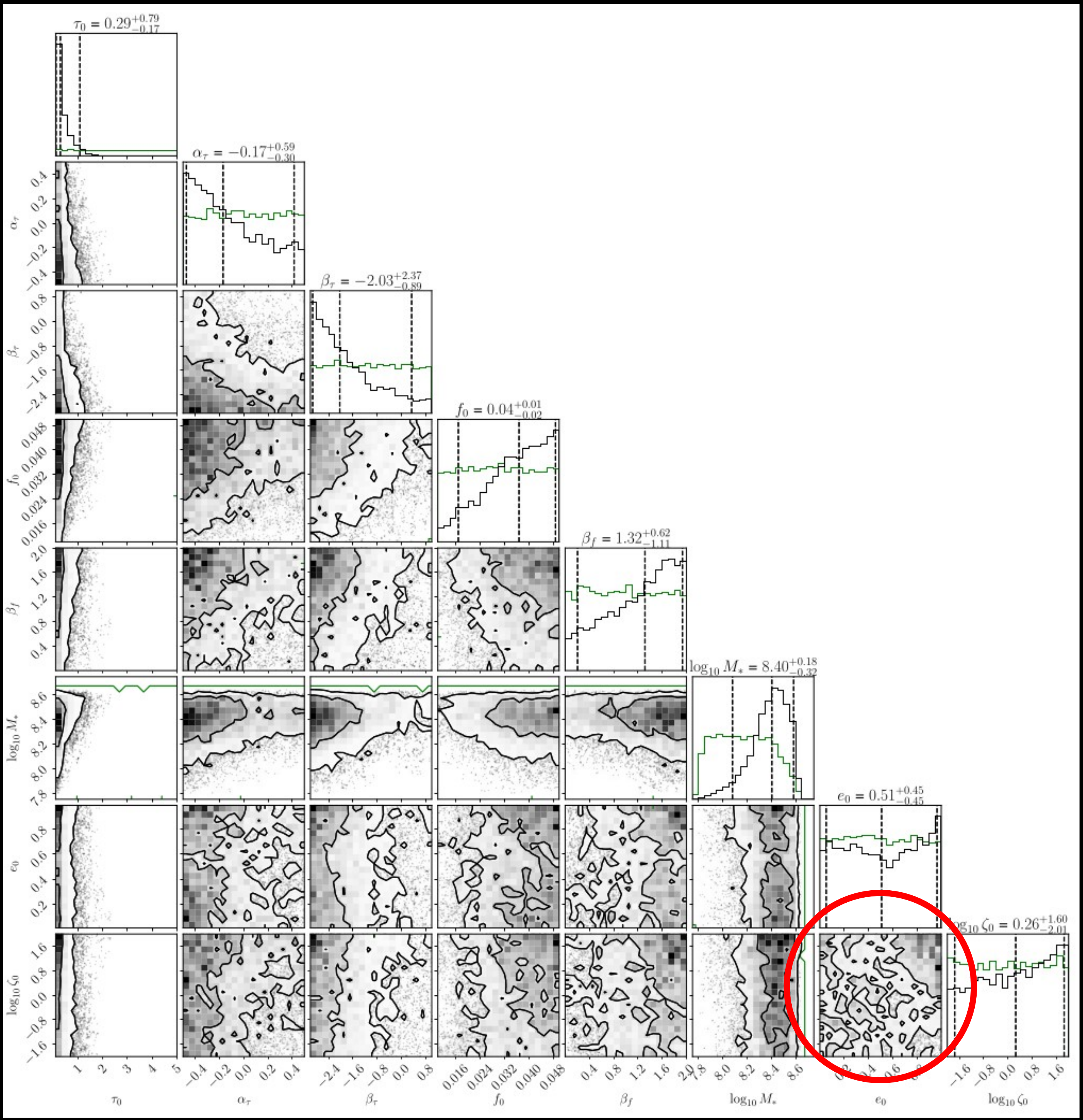
Best constrains:

-SMBHB time to merger

-SMBH – M_* relation

SMBHB are massive and merge frequently



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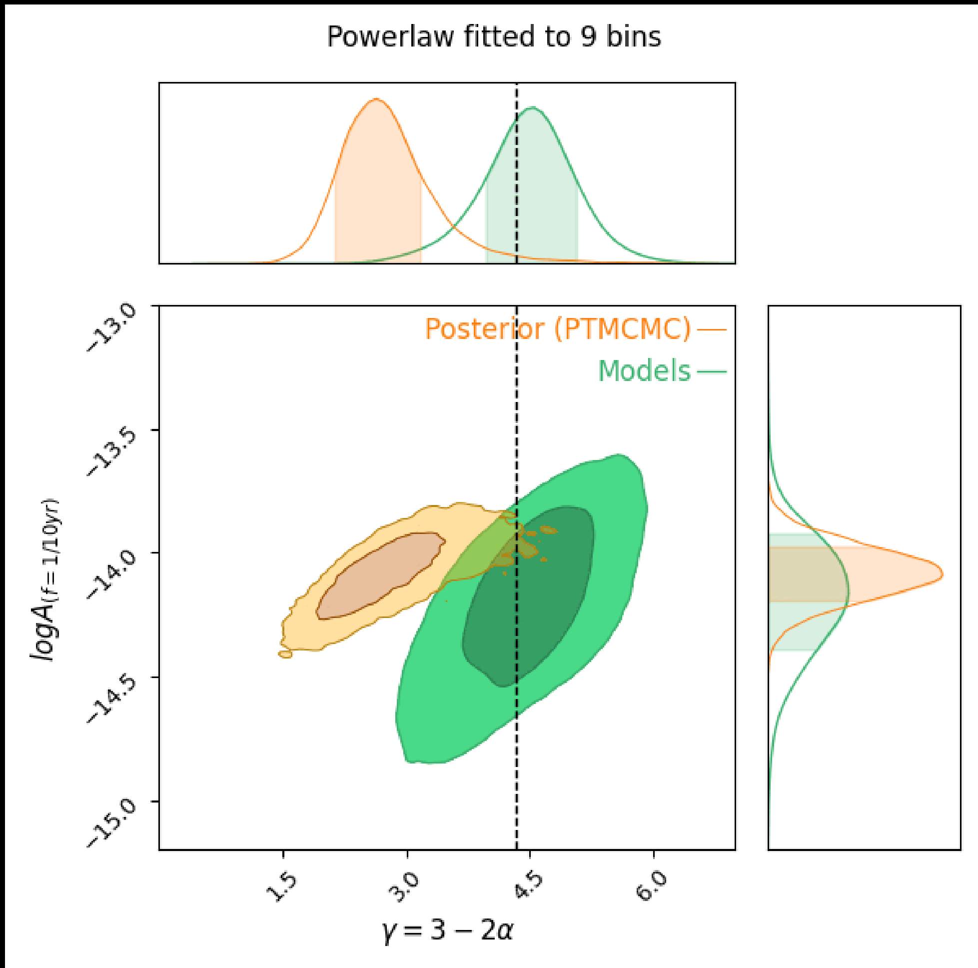
Best constrains:

-SMBHB time to merger

-SMBH – M_* relation

-Slight preference for eccentric/dense environments



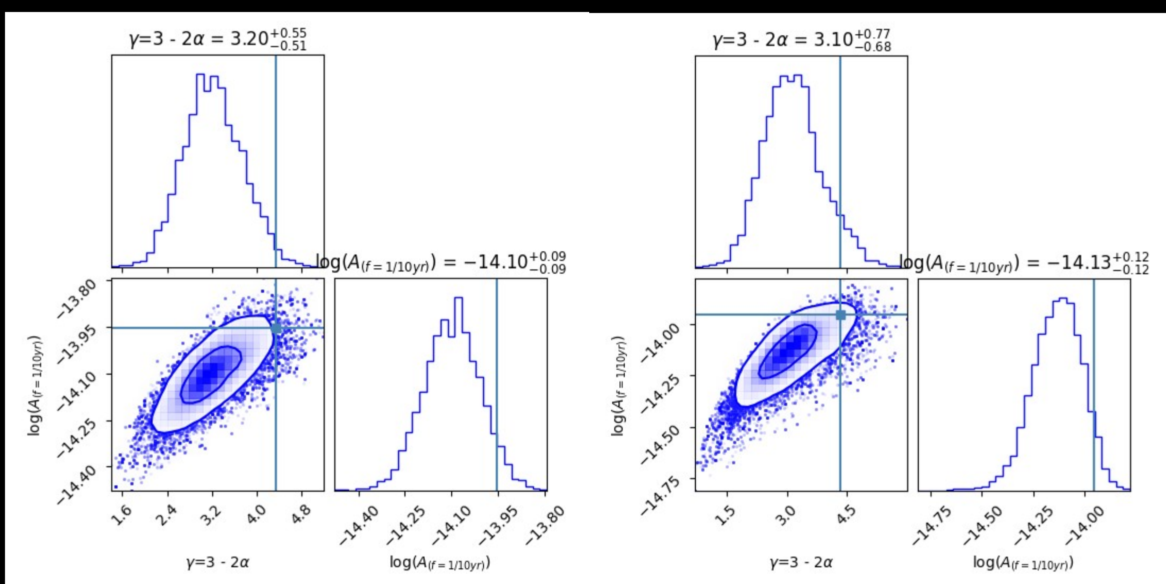
A- gamma plots broadly consistent

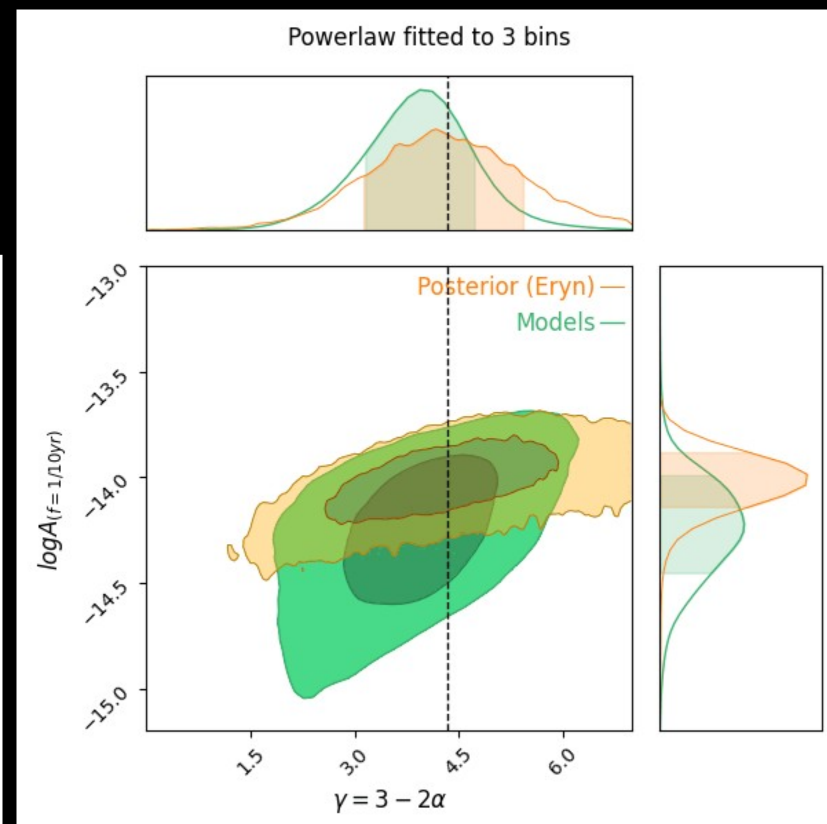
A normalized @1/10yr

Warning:

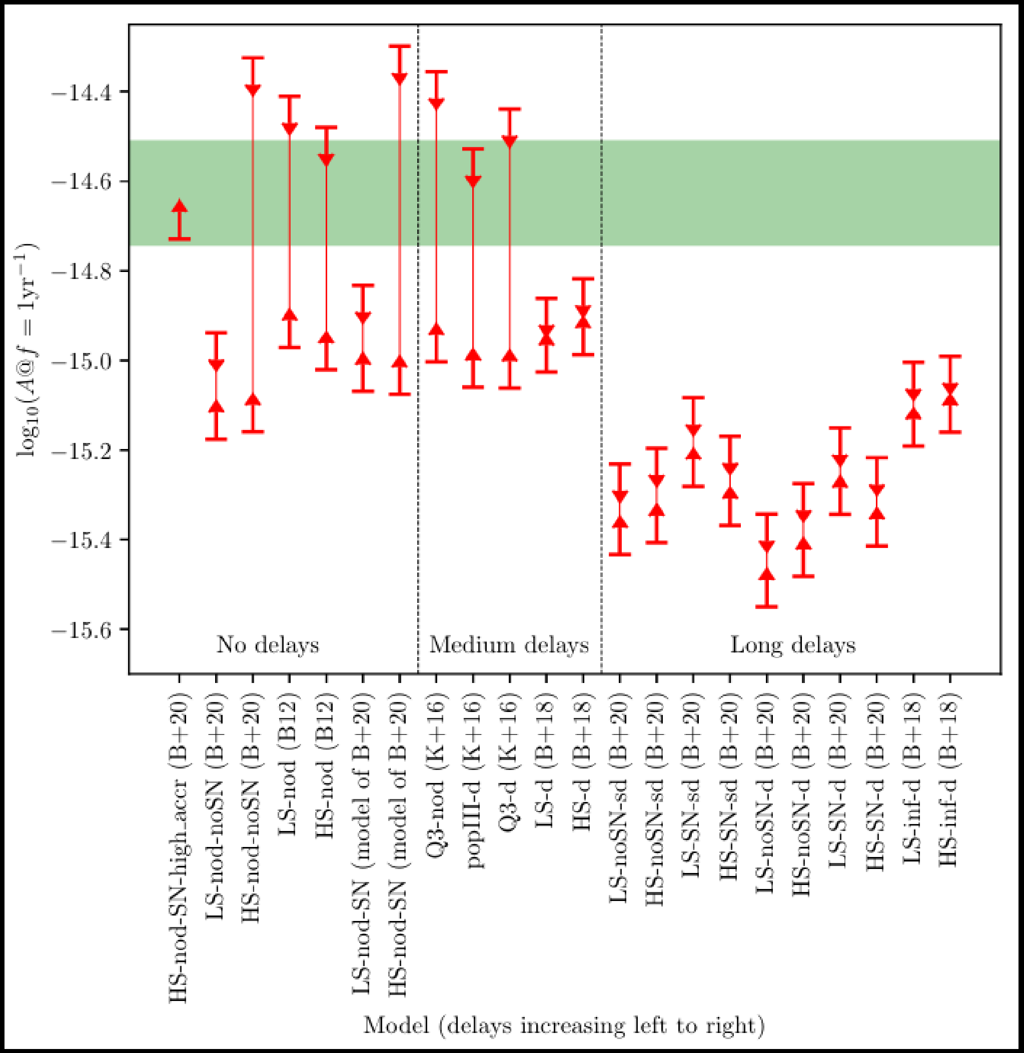
-fits and mesurements depend on numbers of bin

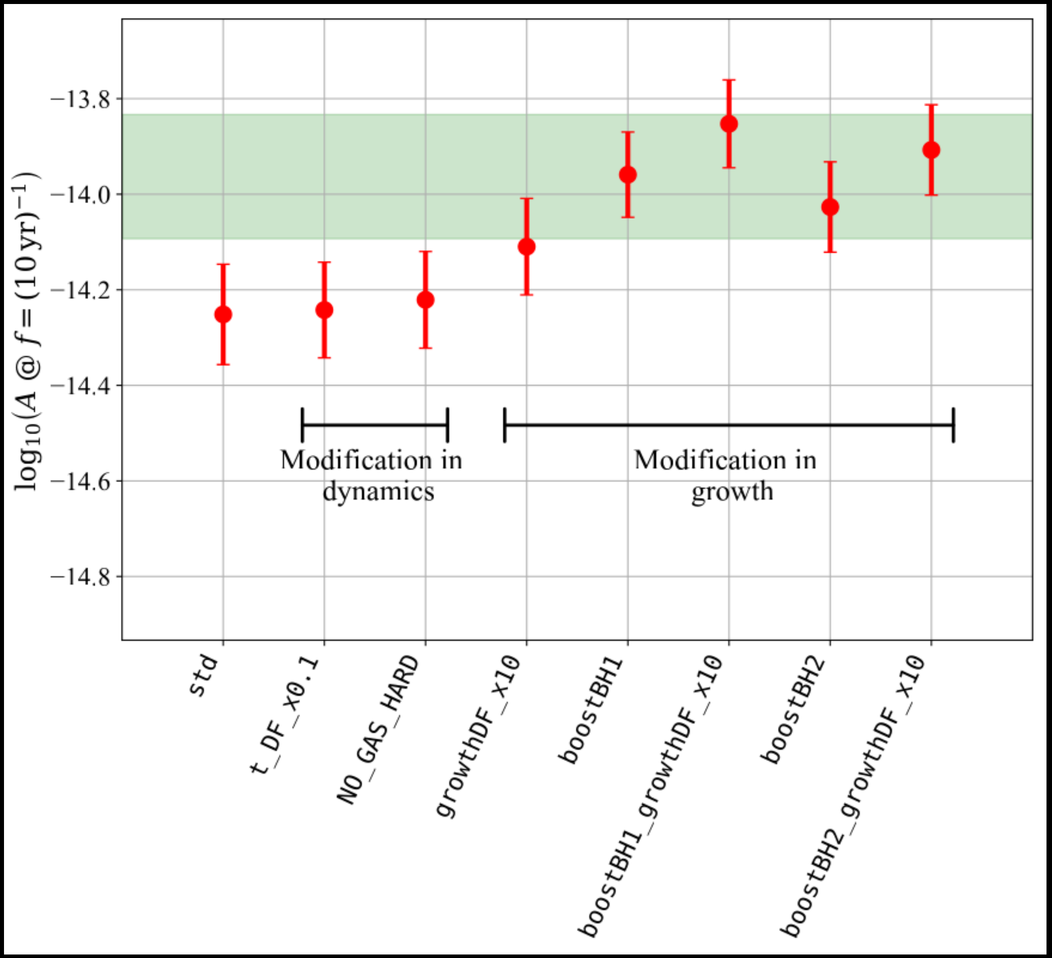
-mesured flat value could be due to low SNR





Comparison with semianalitic models





Barausse12

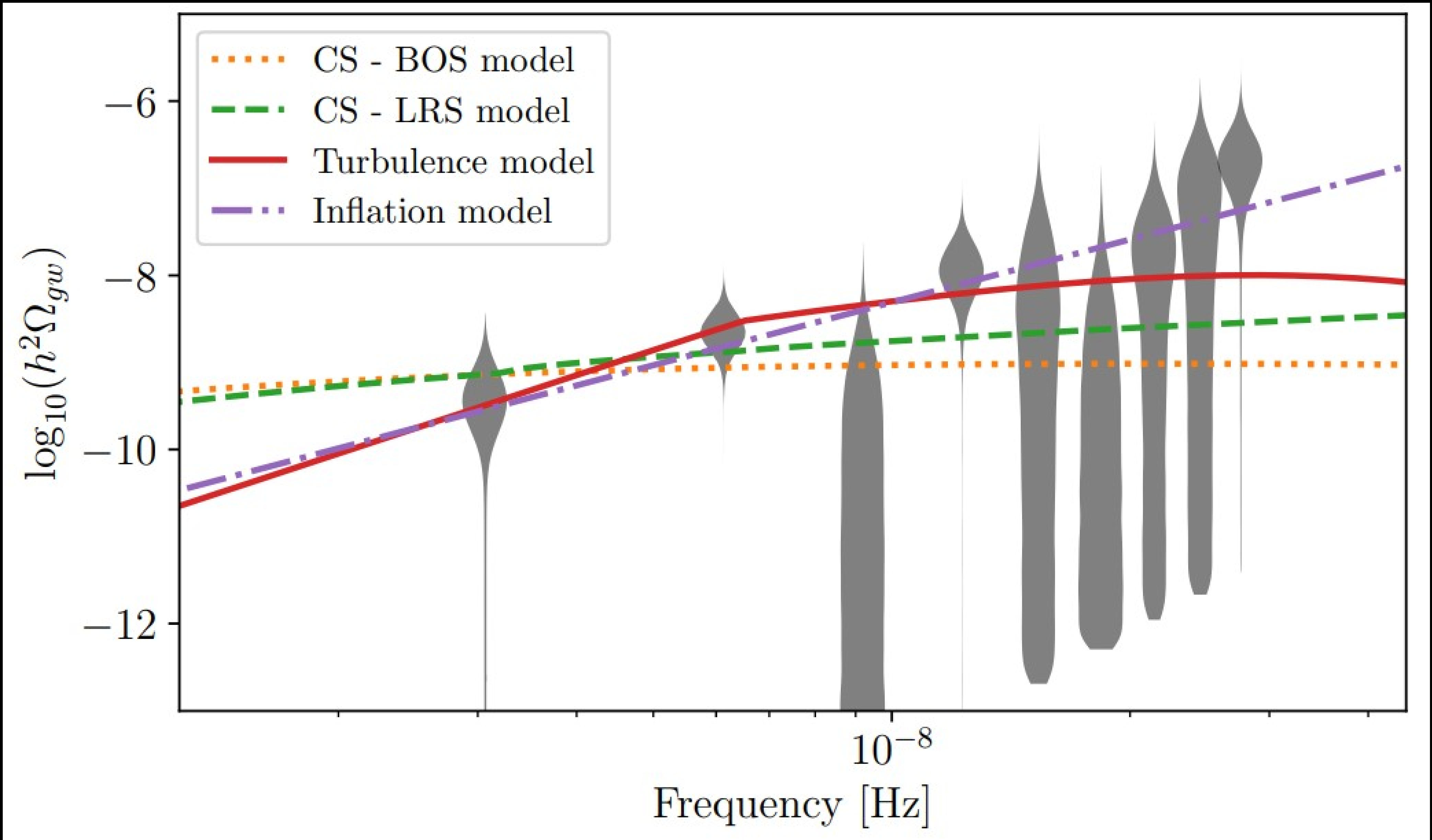
- hard to reproduce the observed amplitude
- higher resolution can help
- short delays favoured

L-Galaxies

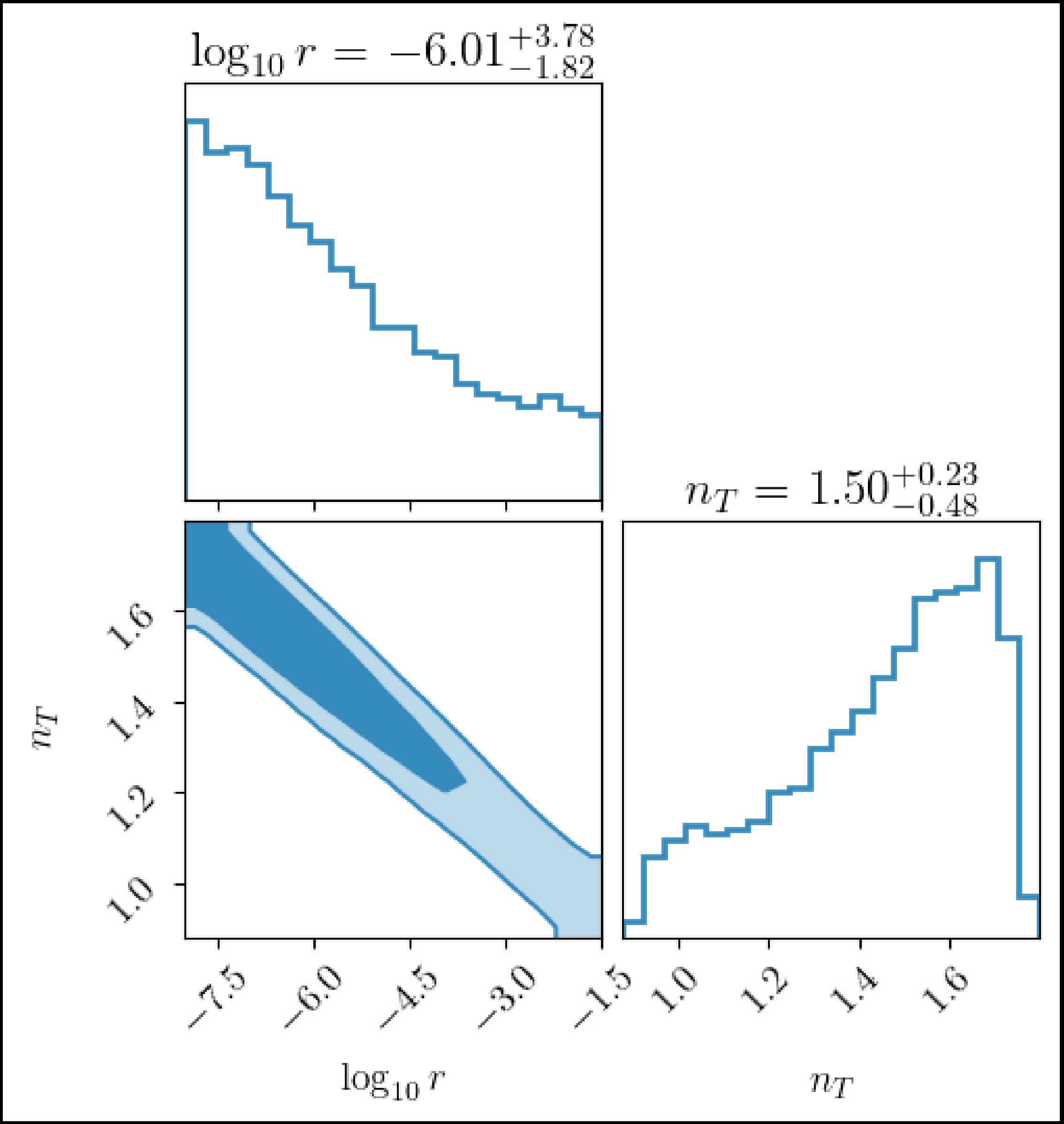
- hard to reproduce the observed amplitude
- needs boosting of the SMBH growth
- might run into problems with quasar L func

Non trivial constraints to SAMs

Early Universe



Early Universe: I. Inflation



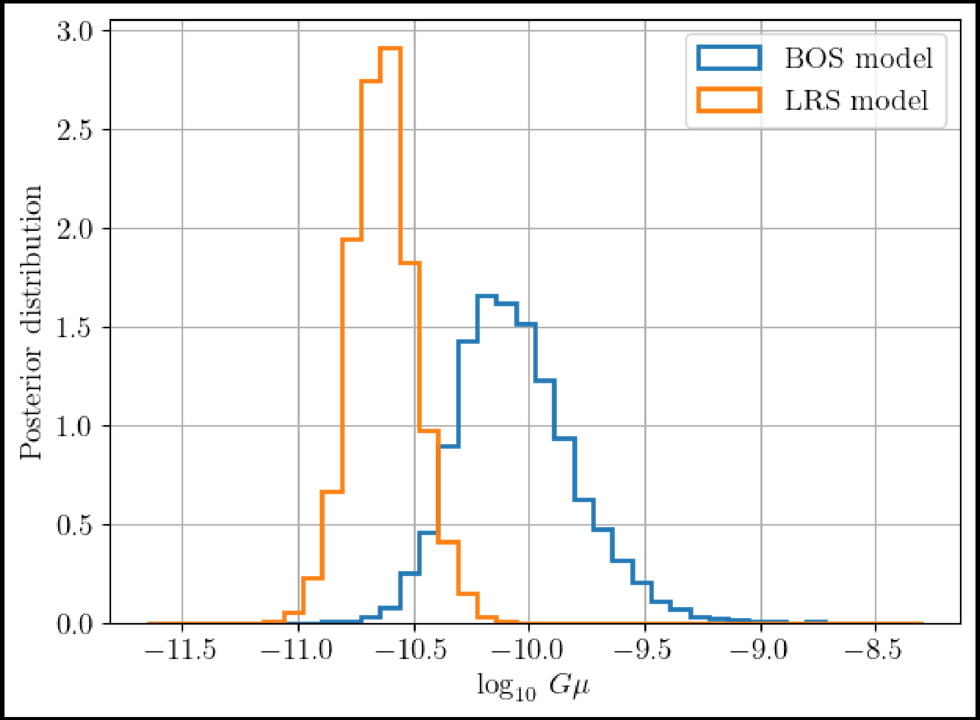
Ingredient of the standard cosmological model

Occurs shortly after the Big Bang

Strong correlation n_T -r

Inflation interpretation implies n_T>1 and $\log_{10} r$ < -4

Early Universe: II. Cosmic strings

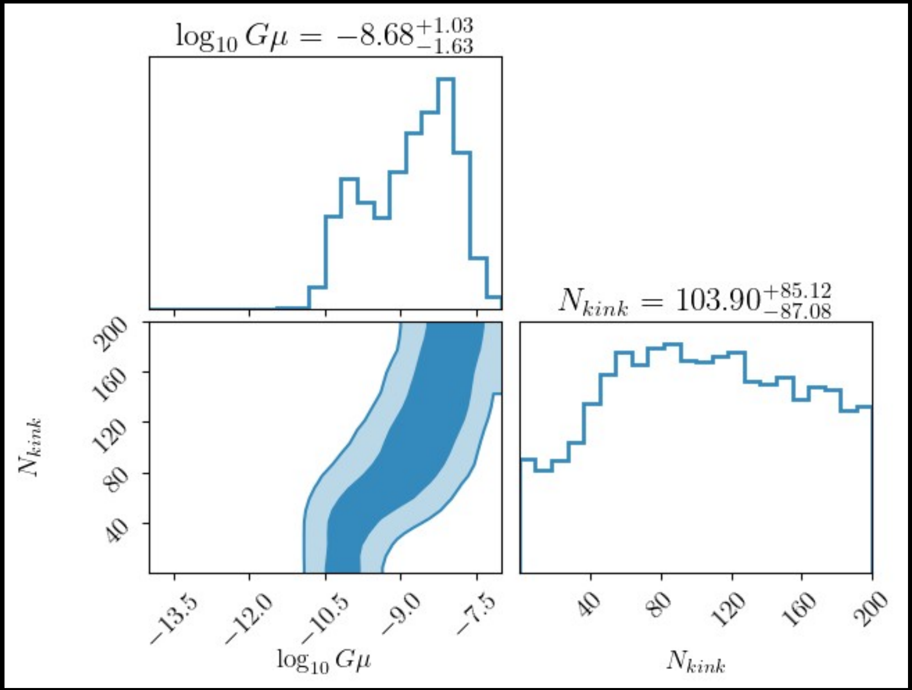


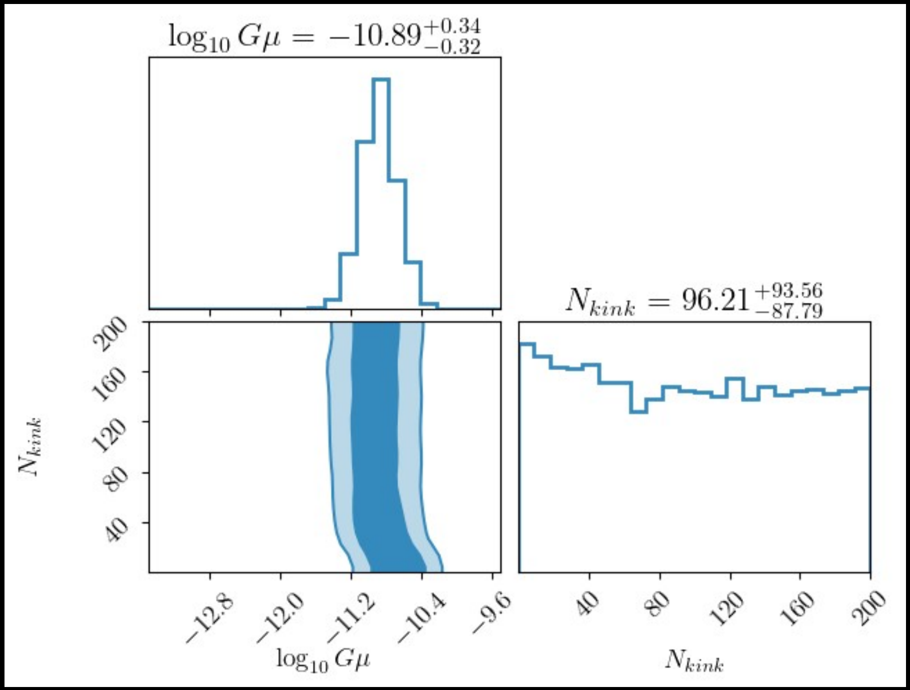
Produce GWs through decay of loops and kinks.

GWB at low frequency can constrain the string tension parameter.

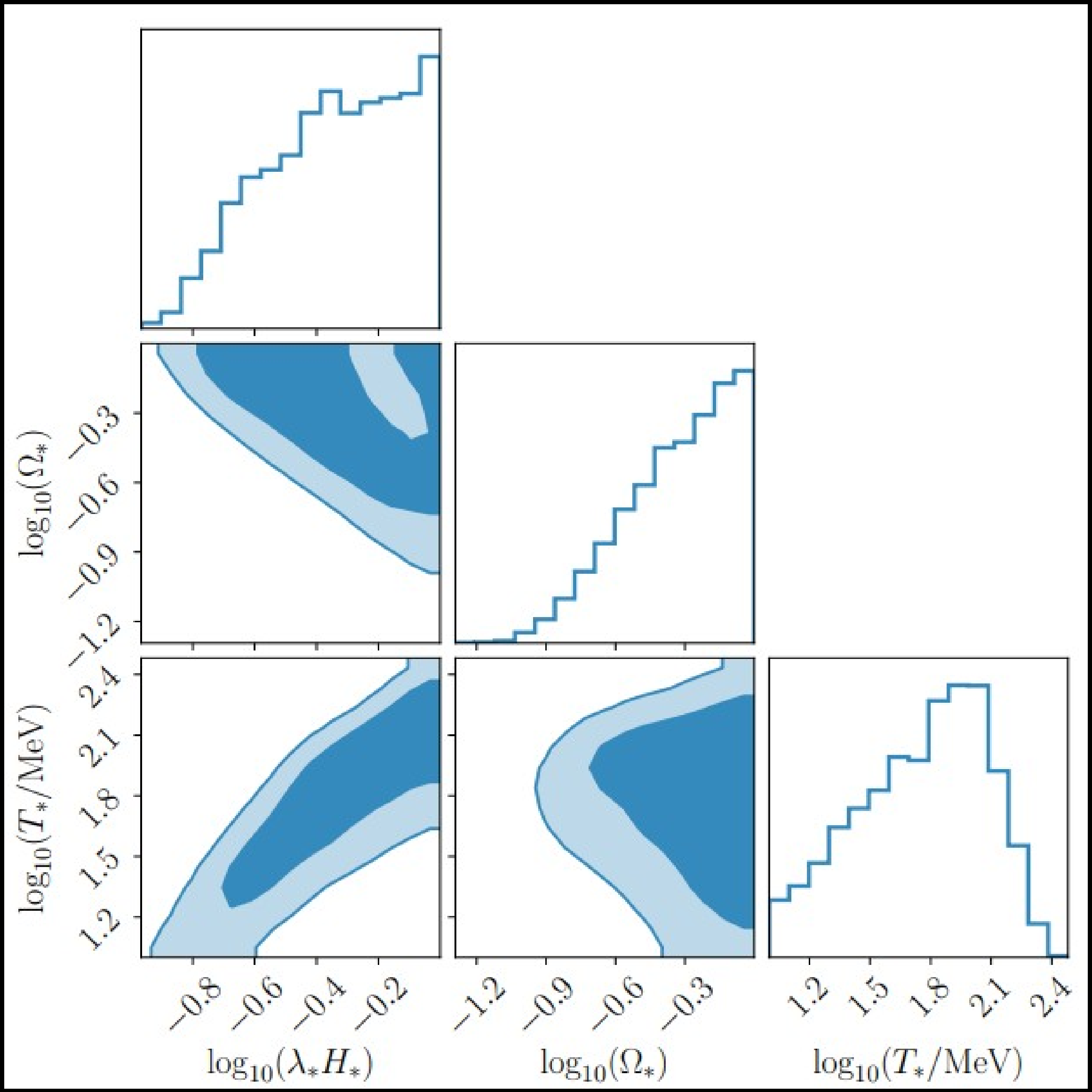
DR2 measrurment consistent with -11 < $\log_{10} G\mu$ < -9.5

Kinks unconstrained





Early Universe: III. 1st order QCD phase transitions



-T_* : temperature at which the GW spectrum is originated

-$\lambda_* H_*$: characteristic length scale of the magnetic energy spectrum

-Ω_M : magnetic energy density

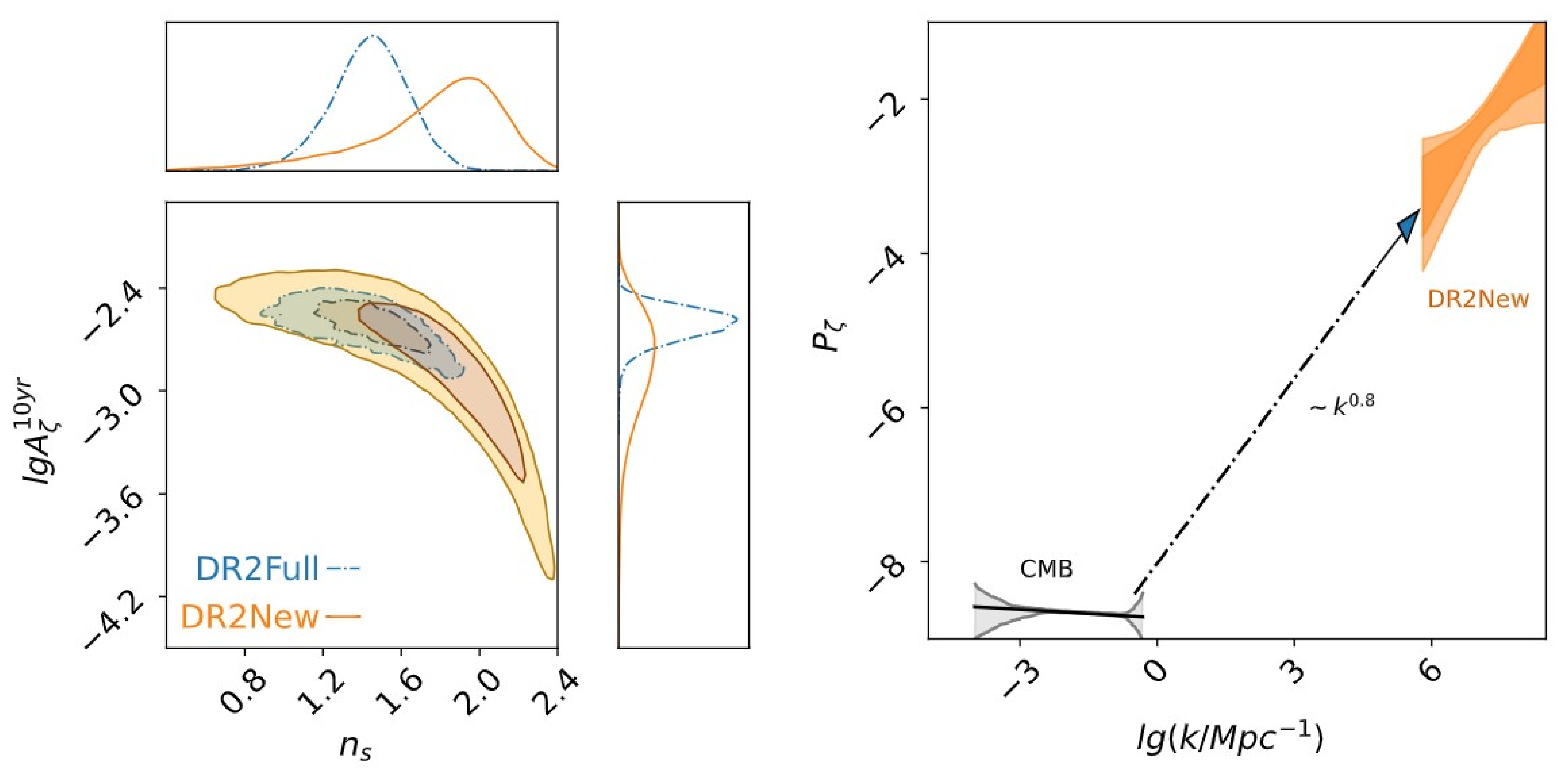
Early Universe: IV. Curvature perturbations

-Scalar perturbations in the early Universe seen in the CMB

-Can source GWs at second order

We assume a Power Law spectrum $P_\zeta = A_\zeta^{10\mathrm{yr}} \left(\frac{k}{k_{10\mathrm{yr}}} \right)^{(n_s - 1)}$

Excess at small scale must be invoked to not violate CMB constraints



Constraints on Ultra Light Dark Matter

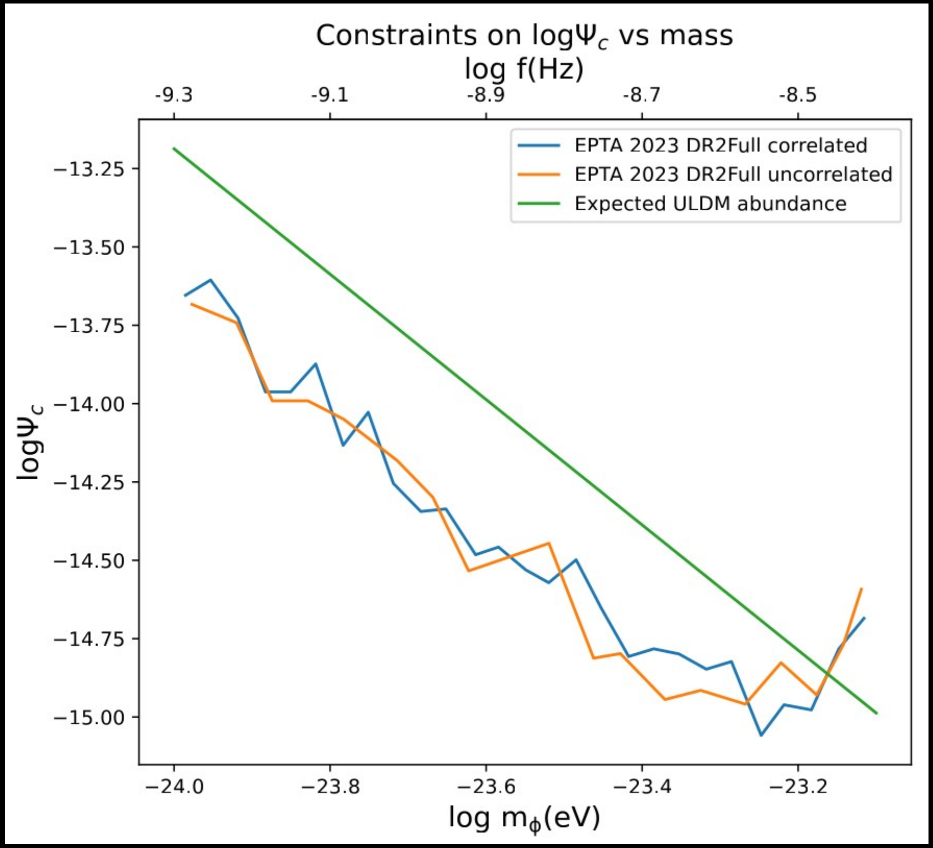
- -Appealing dark matter candidate.
- -Produces oscillations of the gravitational potential affecting the TOAs
- -Effect depends on scalar field mass

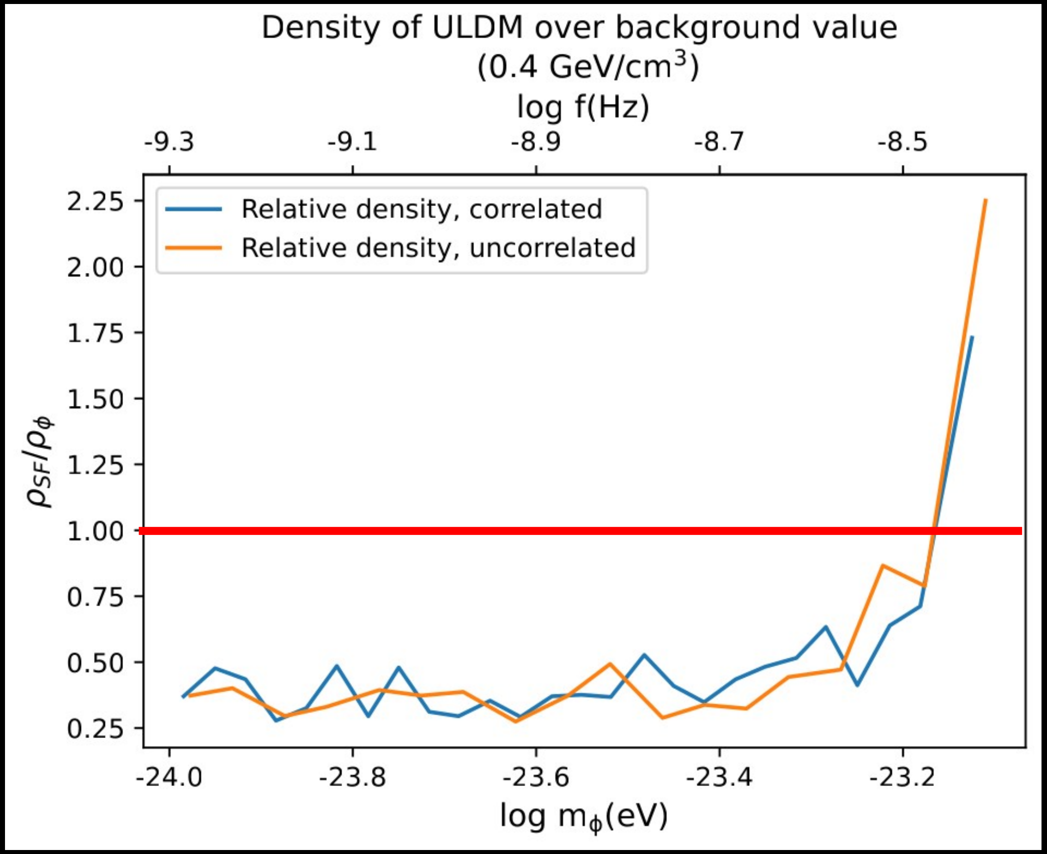
$$\delta t = \frac{\Psi_c(\vec{x})}{2m_\phi}[\hat{\phi}_E^2 \sin(2m_\phi + \gamma_E) - \hat{\phi}_P^2 \sin(2m_\phi + \gamma_P)], \quad (3)$$

where

$$\frac{\Psi_c(\vec{x})}{10^{-18}} \approx 6.52 \left(\frac{10^{-22}\ \mathrm{eV}}{m_\phi}\right)^2 \left(\frac{\rho_\phi}{0.4\ \mathrm{GeV/cm^3}}\right) \quad (4)$$

-24 < m < -23.2 ruled out as DM in the solar neighborhood





DOGGYBAG

-EPTA DR2 show a signal consistent with a GW origin (HD correlation)

-Hard to separate CGW from GWB

-signal broadly consistent with SMBHB origin

-SMBHB are massive and merge quickly

-Signal informative for galaxy formation models

-There's a number of processes in the Early Universe that can fit the data.

-First PTA constraints on fuzzy DM at some mass scale


Nectaria Gizani
shantanudesai
ESTINTORE