Predicting the Stochastic Signal from Supermassive Black-Hole Binaries

or

Why my recent PTA papers are not crazy

Sean T. McWilliams
stmcwill@princeton.edu
Princeton University

Physical Applications of MSPs
Aspen Center for Physics

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Overview

- The status of EM observations of “local” galaxies, implications for NANOGrav/PTAs
- A novel (better?) model for the merger history of supermassive black holes
- Implications for gravitational waves in the PTA band from mergers at $z < 1$
- To what extent is our result in tension with other theoretical estimates and observation
- Why we still can be (and think we are) right

MBHBs with PTAs

- PTAs observe SMBHB mergers at 0 < z < ~1
- Galaxies evolve due to mergers, star formation, and mass loss, all were thought to stop at low *z* – *"red and dead"*
- Recent observations question this for Brightest Cluster Galaxies (BCGs)
- We show that the observed evolution of massive galaxies can be matched assuming only mergers drive evolution, detail consequences for PTAs.

MBHBs with PTAs

A BRIGHTEST CLUSTER GALAXY WITH AN EXTREMELY LARGE FLAT CORE

Marc Postman[1], Tod R. Lauer[2], Megan Donahue[3], Genevieve Graves[4], Dan Coe[1], John Moustakas[5,6], Anton Koekemoer[1], Larry Bradley[1], Holland C. Ford[7], Claudio Grillo[8], Adi Zitrin[9], Doron Lemze[7], Tom Broadhurst[10,11], Leonidas Moustakas[12], Begoña Ascaso[13], Elinor Medezinski[7], and Daniel Kelson[14]

The Astrophysical Journal, 756:159 (10pp), 2012 September 10

DISENTANGLING THE CIRCUMNUCLEAR ENVIRONS OF CENTAURUS A: GASEOUS SPIRAL ARMS IN A GIANT ELLIPTICAL GALAXY

D. Espada[1,2,3], S. Matsushita[3,4], A. B. Peck[4,5], C. Henkel[6,7], F. Israel[8], and D. Iono[9]

The Astrophysical Journal Letters, 756:L10 (5pp), 2012 September 1

HST/WFC3 Confirmation of the Inside-Out Growth of Massive Galaxies at 0<z<2 and Identification of their Star Forming Progenitors at z~3

Shannon G. Patel, Pieter G. van Dokkum, Marijn Franx, Ryan F. Quadri, Adam Muzzin, Danilo Marchesini, Rik J. Williams, Bradford P. Holden, Mauro Stefanon

(Submitted on 1 Aug 2012)

The Astrophysical Journal > Volume 761 > Number 1

Xiaoxia Zhang *et al.* 2012 *ApJ* **761** 5 doi:10.1088/0004-637X/761/1/5

THE COSMIC EVOLUTION OF MASSIVE BLACK HOLES AND GALAXY SPHEROIDS: GLOBAL CONSTRAINTS AT REDSHIFT $z \lesssim 1.2$

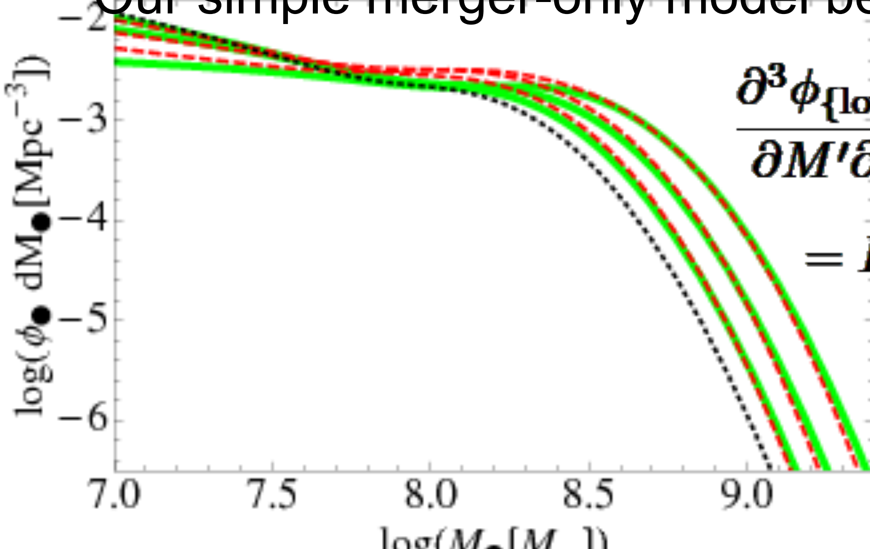
Xiaoxia Zhang[1], Youjun Lu[1], and Qingjuan Yu[2]

Evolution of the Mass Function

- Number density of galaxies vs. mass is well-described by the Schechter function at $z > 1$, and for most galaxies at $z < 1$
- However, at $z < 1$, very massive galaxies (i.e. BCGs) deviate, appear to double there mass in $0 < z < 1$ despite being red and dead:

$$\phi(M)\,dM \equiv (\phi_{\rm low} + \phi_{\rm BCG})\,dM = \varphi\, M^{\alpha}\,\exp(-M)\,dM + \varphi \exp\left[-\frac{1}{2}\left(\frac{2.5\log M}{\sigma_M}\right)^2 - 1\right] dM$$

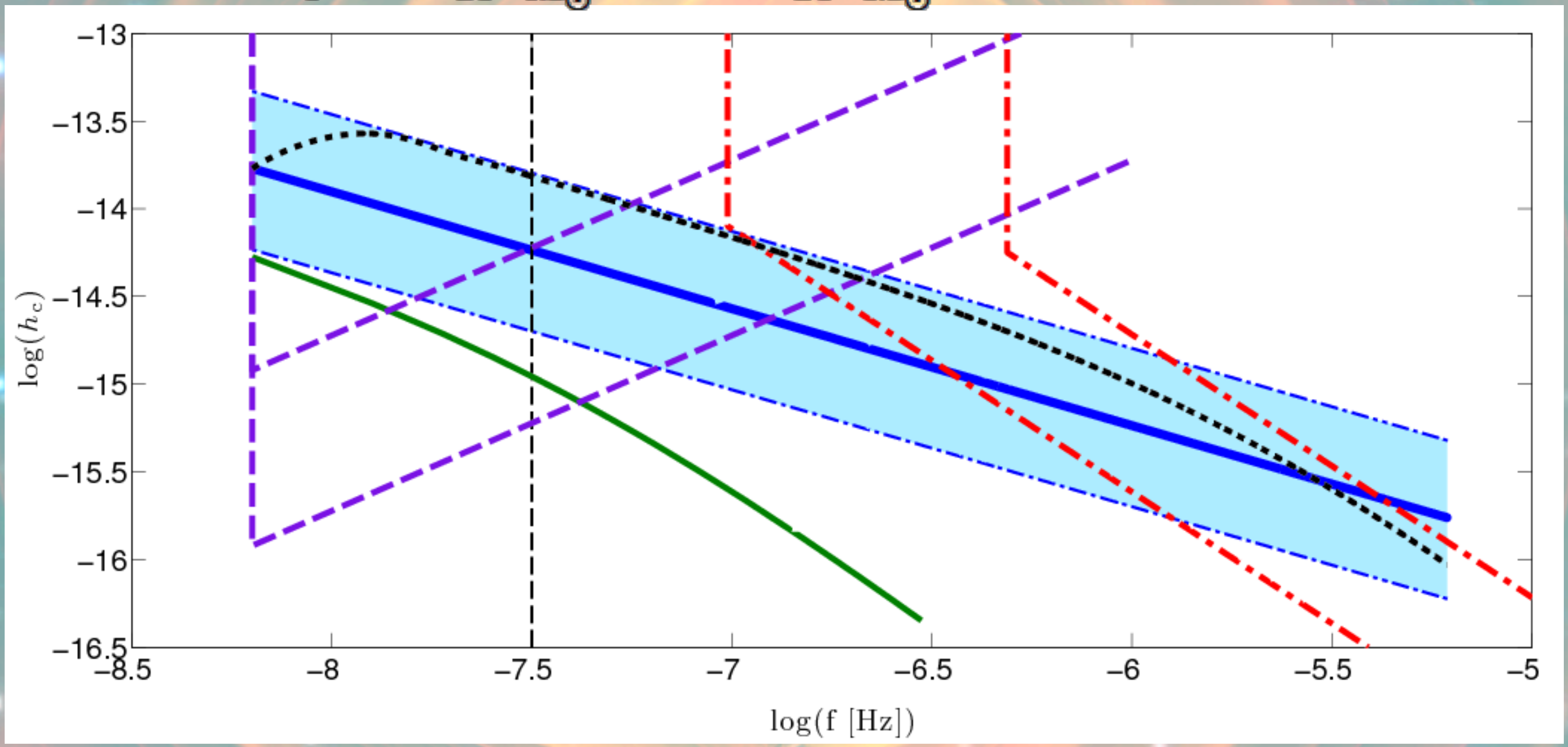
- BCGs grow by comparable mass (~4:1) mergers based on observations. Our simple merger-only model bears this out and duplicates observations.



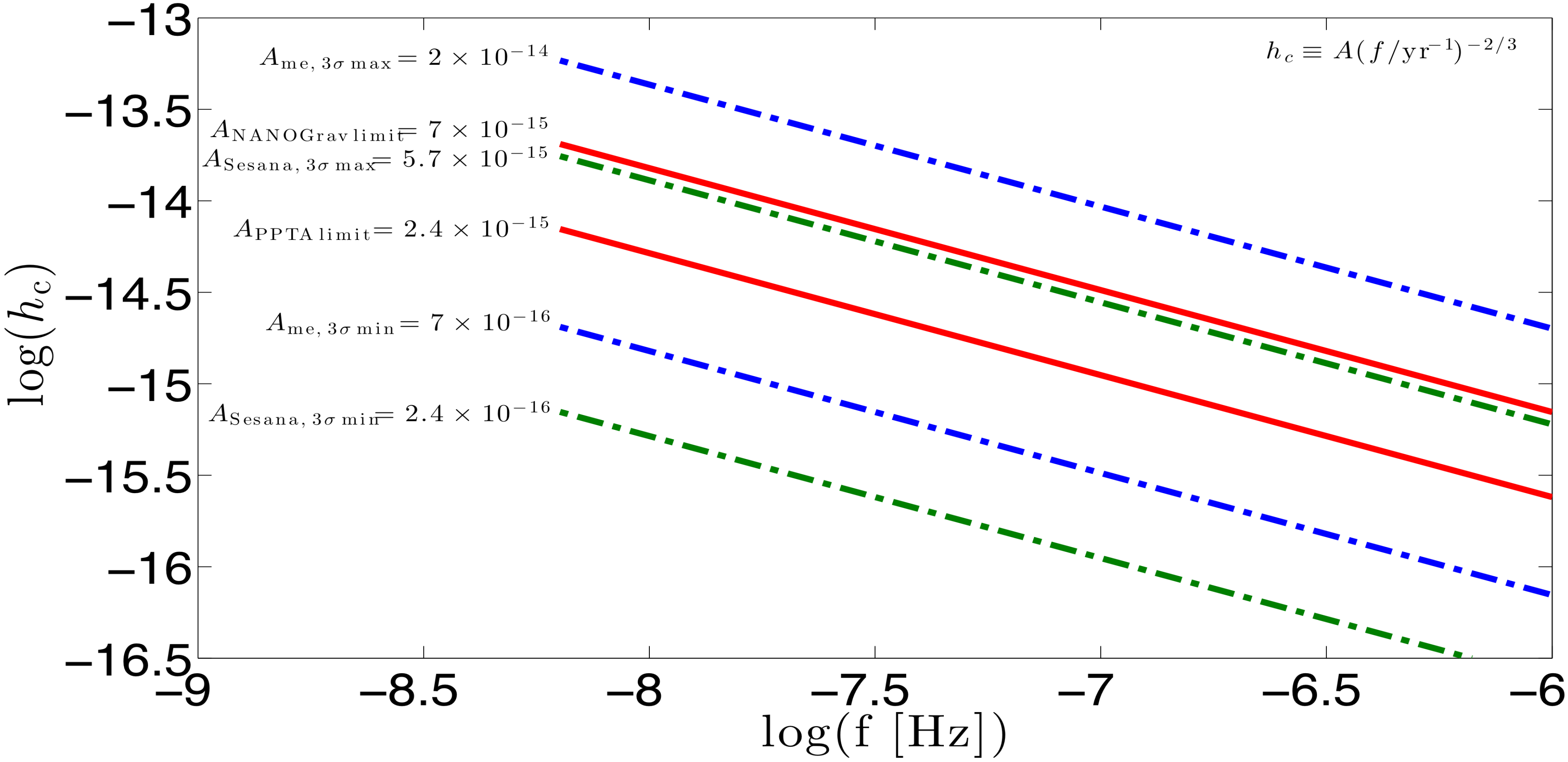
$$\frac{\partial^3 \phi_{\{\rm low,\,BCG\}}}{\partial M' \partial M'' \partial z} dM' dM'' dz = P(z)dz\, \phi_{\{\rm tot,\,BCG\}}(M')\,dM'\,\phi_{\{\rm tot,\,low\}}(M'')\,dM''$$

Gravitational wave signature

$$h_c^2(f) = \int_0^1 dz \int_{10^6\,\mathrm{M}_\odot}^{10^{11}\,\mathrm{M}_\odot} dM_2 \int_{10^6\,\mathrm{M}_\odot}^{M_2} dM_1 N h^2 \frac{d^4 p}{dM_1 dM_2 dz\, df}$$



$$h_{\rm fit} \equiv h_{\rm o} \exp\left[\left(\frac{f}{f_{\rm DF}}\right)^{\beta}\right] \left(\frac{f}{f_{\rm o}}\right)^{-2/3} \left(1 + \frac{f}{f_{\rm o}}\right)^{\gamma}$$



"me": STM, Ostriker, and Pretorius, http://arxiv.org/abs/1211.5377
"Sesana": Sesana, http://arxiv.org/abs/1211.5375
"PPTA": Talk by Ryan Shannon

Why do we differ with Sesana? Part I

- We assume mergers dominate galaxy evolution for $z < 1$, evolve the mass function numerically.
- Sesana combines the observed mass function and pair fraction, doesn't evolve.
- If you try to evolve the Sesana mass function using the Sesana merger rate self-consistently, you can't.
- Sesana requires that a) galaxies only grow by ~30% through mergers since $z = 1$ and b) star formation is as important as mergers for BCGs since $z = 1$
- Ok, but why are our merger rates so different?

Why do we differ with Sesana? Part II

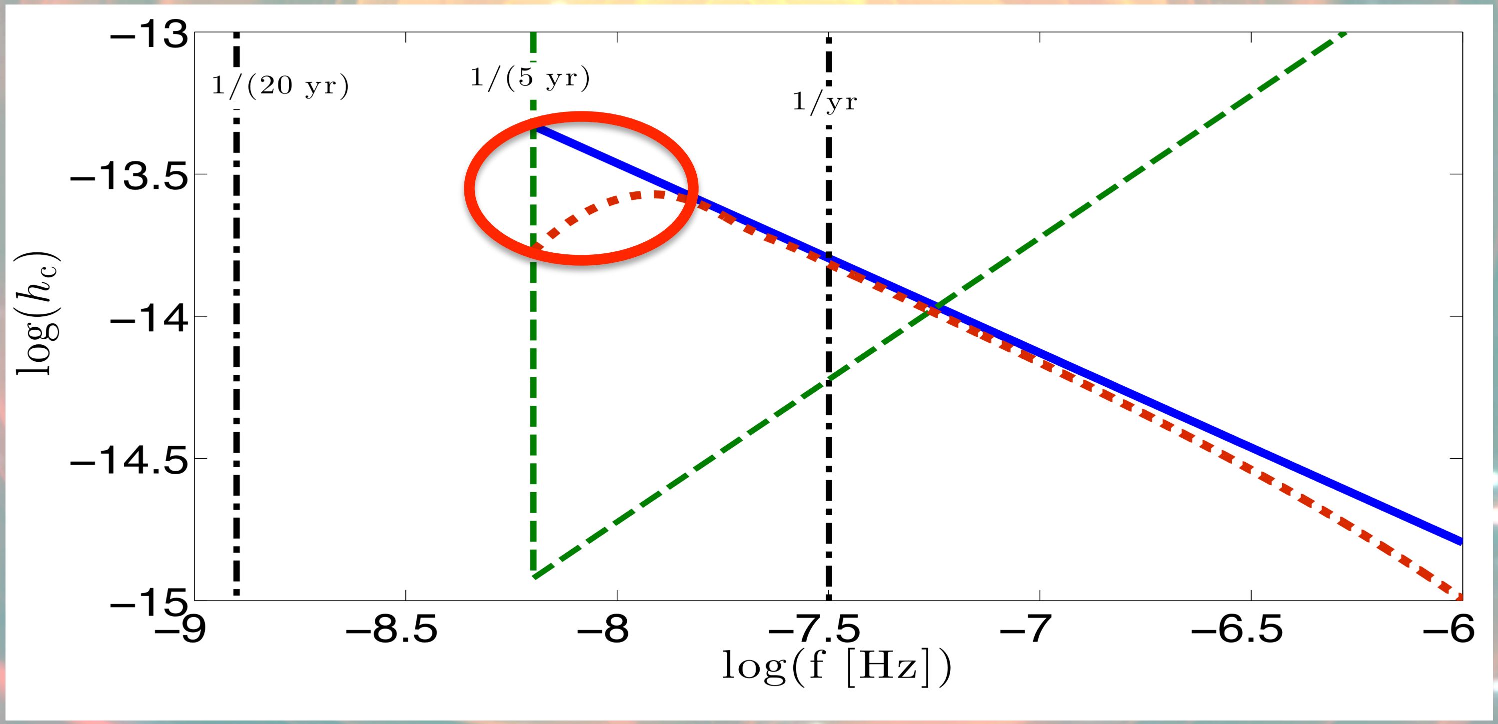
- Pre-2010 papers favored ~30-40% mass growth for BCGs at $z < 1$ (though still without star formation).
- More recent observations (and simulations **with baryons**) strongly suggest mass doubling since z = 1.
- Sesana (and everyone else) uses the Millenium simulation - N-body with semi-analytic inclusion of some baryonic physics, but not baryonic mass
- Baryonic mass can make a HUGE difference:

$$\frac{R_{df,DM+baryons}}{R_{df,DM}} = \frac{t_{df,DM}}{t_{df,DM+baryons}} \propto \left(1 + \frac{M_{baryons}}{M_{DM}}\right)^{\beta}$$

- If $\beta = 9$ (NFW) and $M_{baryons} \sim M_{DM}$, $\frac{R_{df,DM+baryons}}{R_{df,DM}} \approx 500$

Why are we (sort of) in tension with PPTA?

- Technically (i.e. statistically), we're not
- Nontrivial behavior at low frequencies - unclear how to translate our model to a bound, but it *may* only improve as $T_{obs}^{1/2}$
- Constraint depends disproportionately on $f \sim 1/T_{obs}$, not the $f =$ yr^{-1} that is always referenced. We actually quoted $A(f = \text{yr}^{-1})$.



Why don't others see this dip at low frequency?

STM, Ostriker, and Pretorius,
http://arxiv.org/abs/1211.5377

use the well-known expression for the dynamical friction timescale (Chandrasekhar 1943; Tremaine et al. 1975) in a convenient form (Eq. 8.12 in Binney & Tremaine (1987)),

$$t_{\rm DF} = \frac{19{\rm Gyr}}{\ln(1+M_\star^h/M_\bullet^s)}\left(\frac{R_e}{5{\rm kpc}}\right)^2 \frac{\sigma(R_e)}{200{\rm km/s}}\frac{10^8{\rm M}_\odot}{M_s}$$
$$\approx \frac{4.5{\rm Gyr}}{q(6.9-\ln q)}\left(\frac{M_\bullet^h}{10^8{\rm M}_\odot}\right)^{2/3}(1+z)^{-3/2}, \qquad (12)$$

where R_e is the half-light radius of the host galaxy and σ is the local velocity dispersion, for which we use

$$R_e = 2.5\,{\rm kpc}\left(\frac{M_\bullet}{10^8\,{\rm M}_\odot}\right)^{0.73}(1+z)^{-1.44}\ \text{and}$$
$$\sigma(R_e) = 190\,{\rm km/s}\left(\frac{M_\bullet}{10^8\,{\rm M}_\odot}\right)^{0.2}(1+z)^{0.44}, \qquad (13)$$

where the mass-dependence comes from fits to Sloan Digital Sky Survey (SDSS) data (Nipoti et al. 2009), and the redshift dependence comes from fits to simulation results which were shown to be consistent with various surveys in Oser et al. (2010) within the redshift range we consider.

Volonteri, Haardt, and Madau,
ApJ 582 559 (2003)

$$t_{\rm df} = 1.17\frac{r_{\rm circ}^2 V_c}{G M_s \ln\Lambda}\epsilon^\alpha = 1.65\frac{1+P}{P}\frac{1}{H\sqrt{\Delta_{\rm vir}}\ln\Lambda}\Theta \quad (9)$$

(Lacey & Cole 1993; Binney & Tremaine 1987), where V_c is the circular velocity of the satellite in the new halo of mass $M+M_s$ and virial radius $r_{\rm vir}$, $r_{\rm circ}$ is the radius of the circular orbit having the same energy as the actual orbit, the "circularity" ϵ is the ratio between the orbital angular momentum and that of the circular orbit having the same energy, H is the Hubble parameter, $P = M_s/M$ is the (total) mass ratio of the progenitors, and the Coulomb logarithm is taken to be $\ln\Lambda \approx \ln(1+P)$. The dependence of this timescale on the orbital parameters is contained in the term

$$\Theta = \epsilon^\alpha (r_{\rm circ}/r_{\rm vir})^2\,. \qquad (10)$$

The most likely orbits occurring in cosmological CDM simulations of structure formation have circularity $\epsilon = 0.5$ and $r_{\rm circ}/r_{\rm vir} = 0.6$ (e.g., Tormen 1997; Ghigna et al. 1998). With these initial orbital parameters, recent numerical investigations by van den Bosch et al. (1999) and Colpi, Mayer, & Governato (1999) suggest a value $\alpha = 0.4$–0.5 for the exponent in equation (10). Here we assume $\Theta = 0.3$, but we note that the merger timescale computed in this way does not include the increase in the orbital decay timescale due to tidal stripping of the satellite (Colpi et al. 1999). Satellites will merge with the central galaxy on timescales shorter than the then Hubble time only in the case of major mergers, $P \gtrsim 0.3$. In minor mergers, tidal stripping may leave the satellite BH almost "naked" of its dark halo, too far from the center of the remnant for the formation of a BH binary.

- They used a mass-independent t_{df}
- Most recent paper from Sesana uses the pair fraction catalog combined with essentially my eq. 12, so he should now see the same dip (he doesn't show his raw strain in his new paper).

Conclusions

- We've estimated the stochastic signal strength, and find it is ~2x – 5x higher than previous estimates at $f = yr^{-1}$
- NB: Our model should be fully in tension with constraints by ~2016 **iff nature picks a realization with little or no dip at low frequencies** – otherwise, our model still predicts a 2x – 5x stronger signal at $f = yr^{-1}$, but a much weaker signal overall, with sensitivity perhaps only improving as $\sim T_{obs}^{1/2}$
- If a null result persists until ~2020, either Sesana's low merger rate is right, or there's a dip (eventually, we'll know which)
- If a null result persists beyond ~2022, then we don't understand the massive BH mass function and/or we don't understand how BHs merge once their galaxies merge
  - Dynamical friction
  - Last parsec problem