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Constraining Supermassive Black Hole Binary Dynamics Using Pulsar Timing Data

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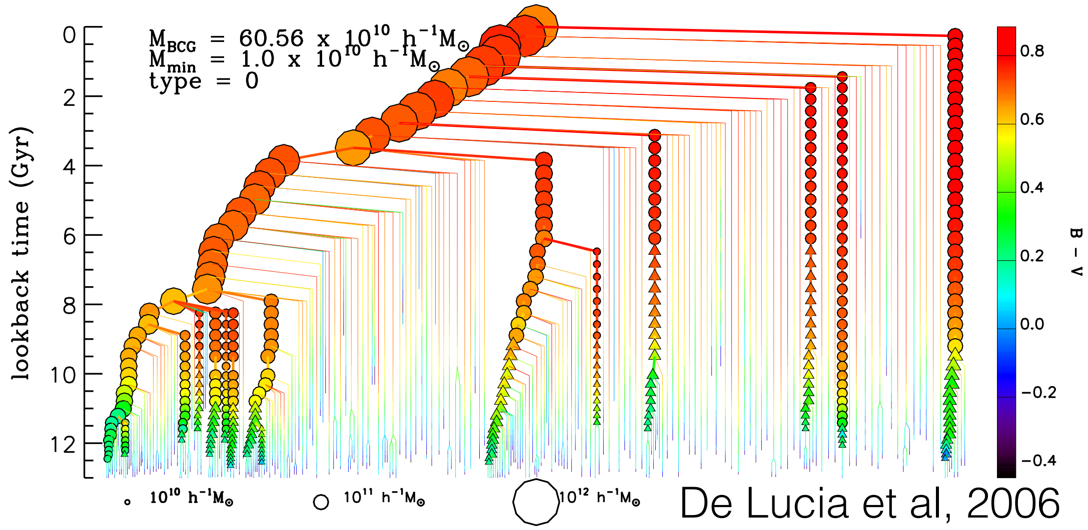
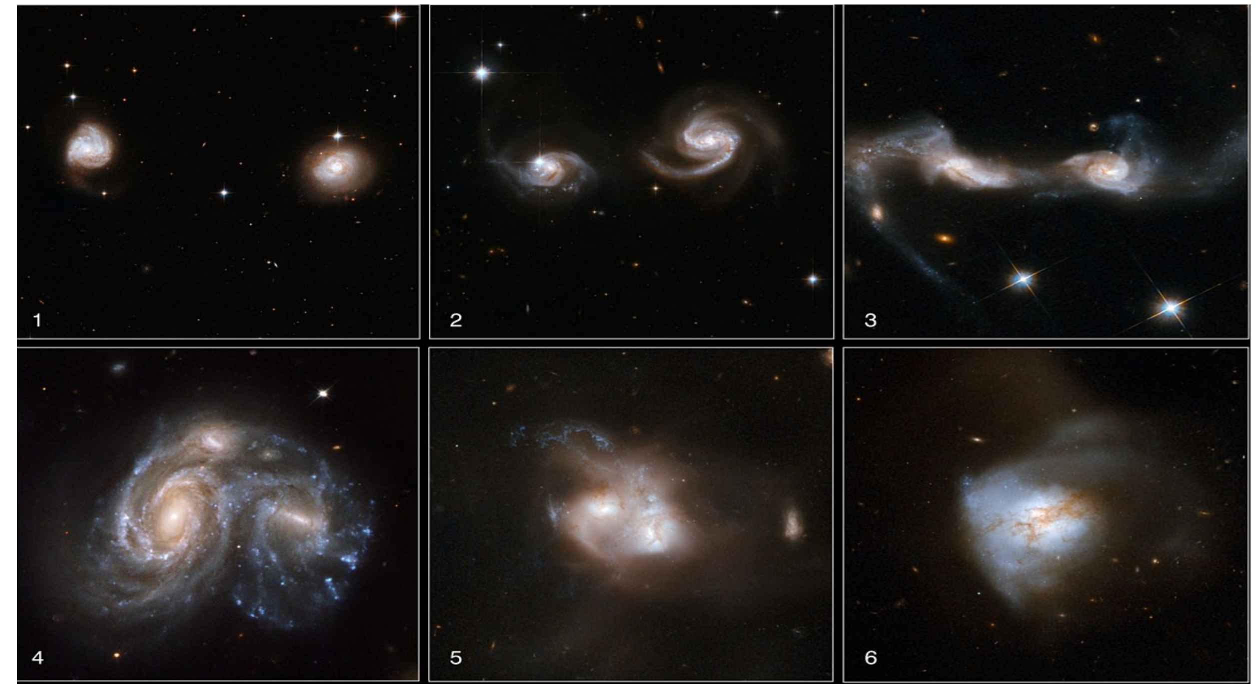
Outline

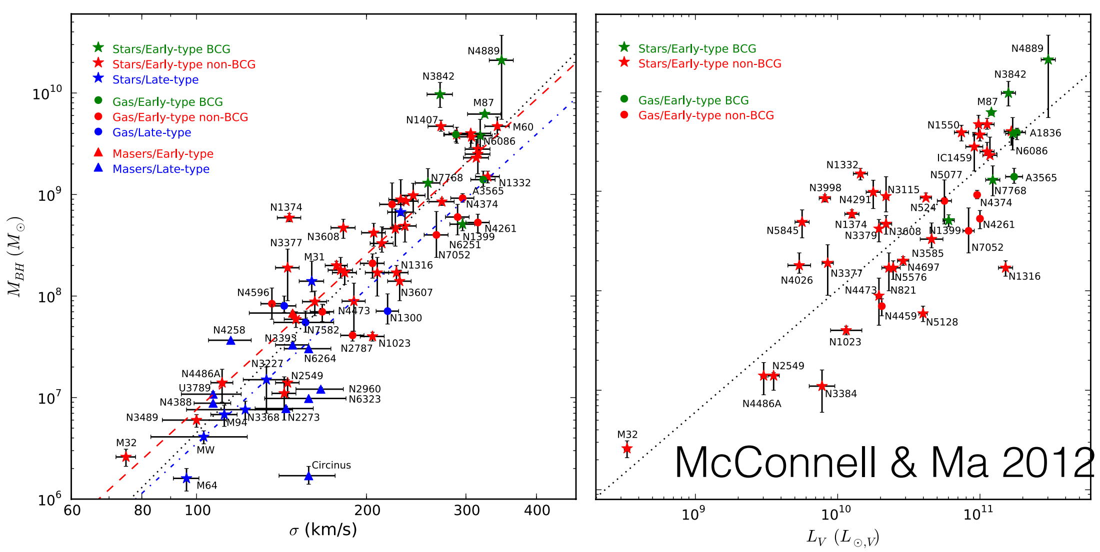
- Big picture overview of GWs from Supermassive Black Hole binaries
- Current predictions of GW background
- Environmental effects
- Search and upper limit results from NANOGrav 9-year data
- Inference of astrophysical parameters

Sources of GWs: SMBHBs

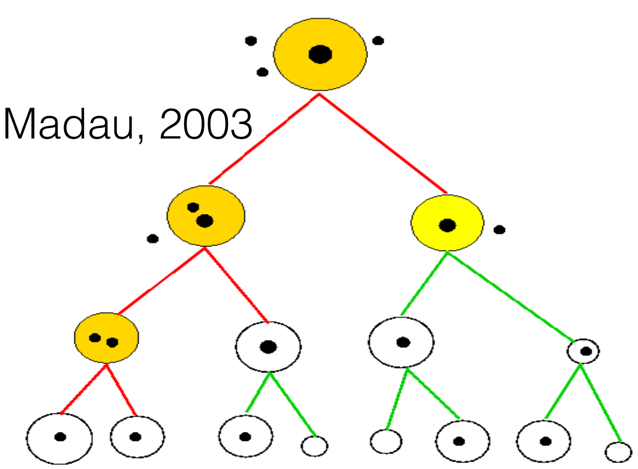


De Lucia et al, 2006

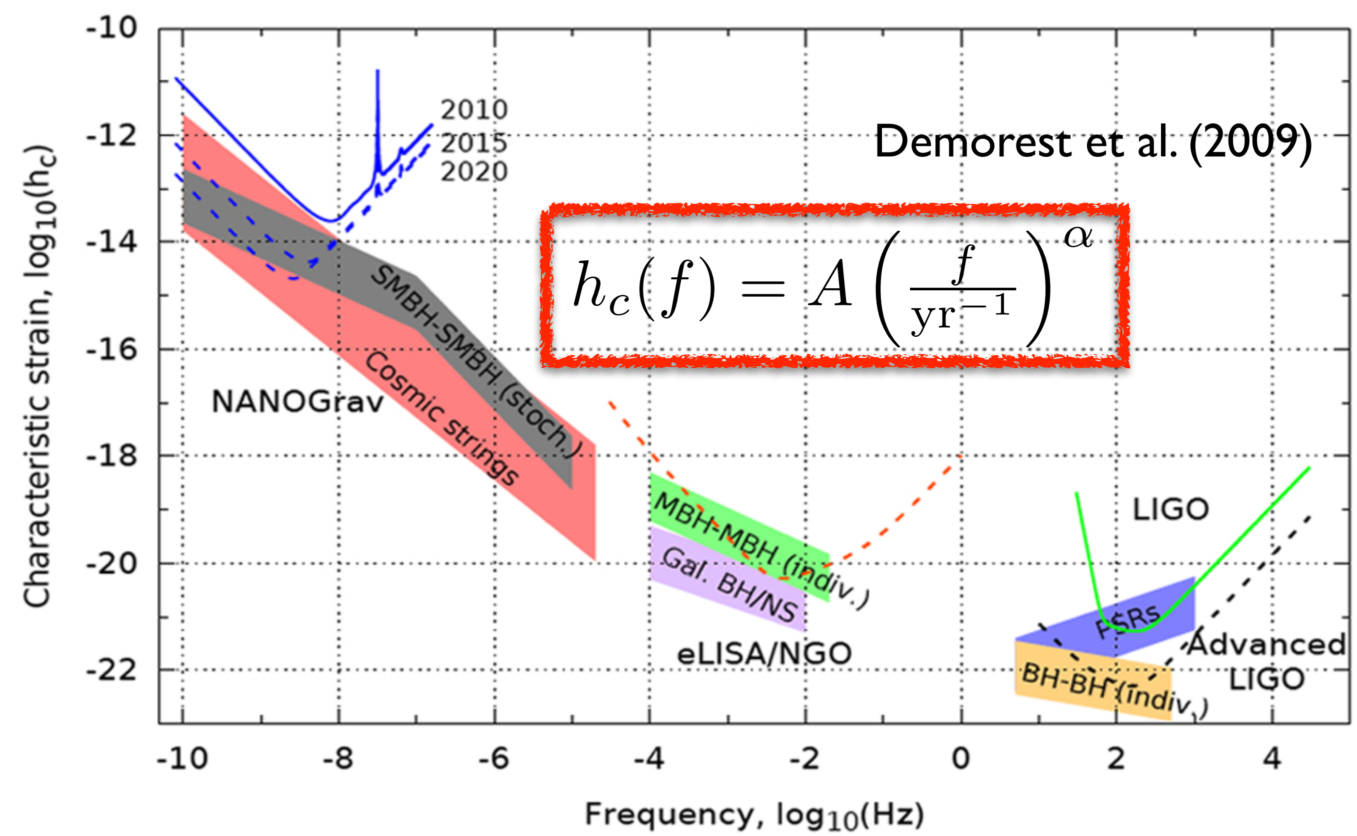




McConnell & Ma 2012

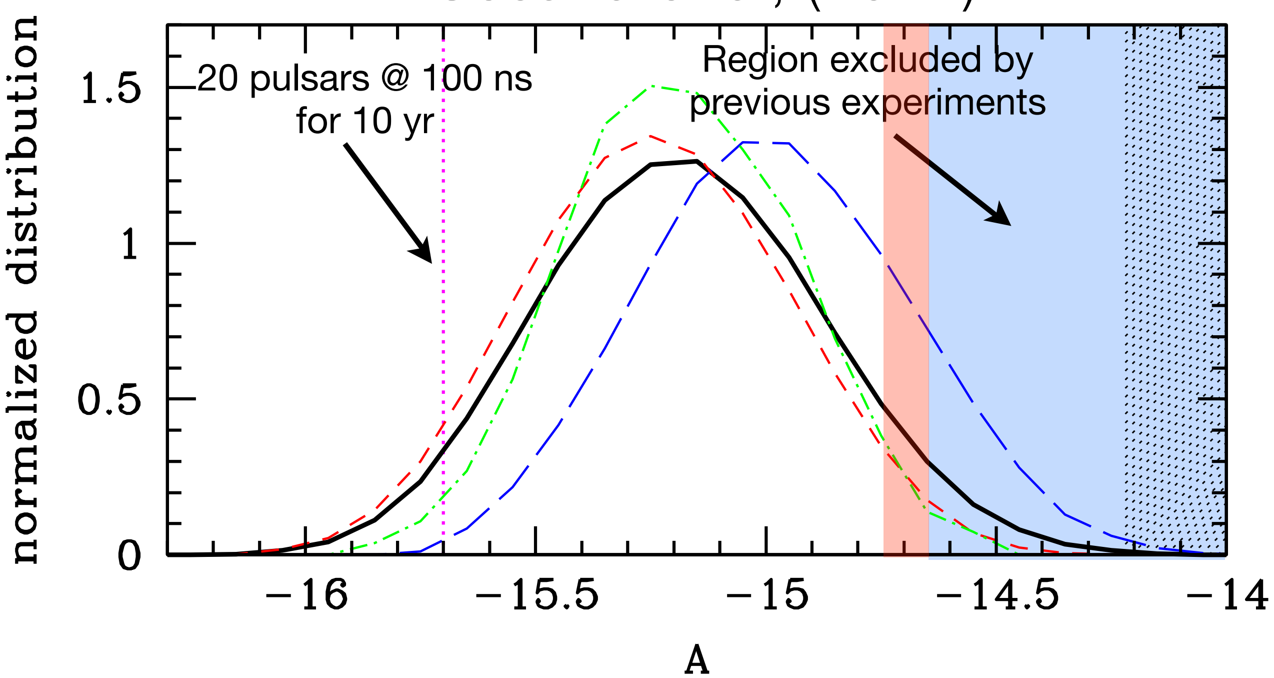


Vononteri, Hardt & Madau, 2003



Expected level of SMHB Stochastic Background

Sesana et al, (2012)

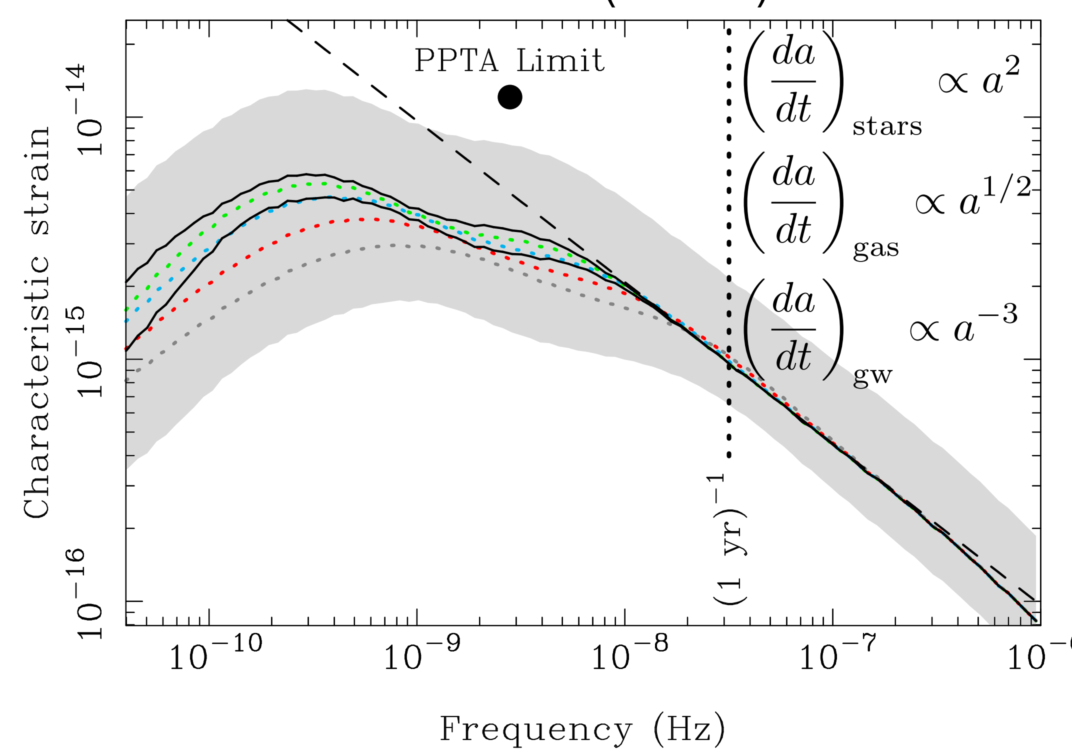


1-sigma bounds on amplitude are

$$5.6 \times 10^{-16} < A < 2 \times 10^{-15}$$

with a mean of $\langle A \rangle = 1 \times 10^{-15}$

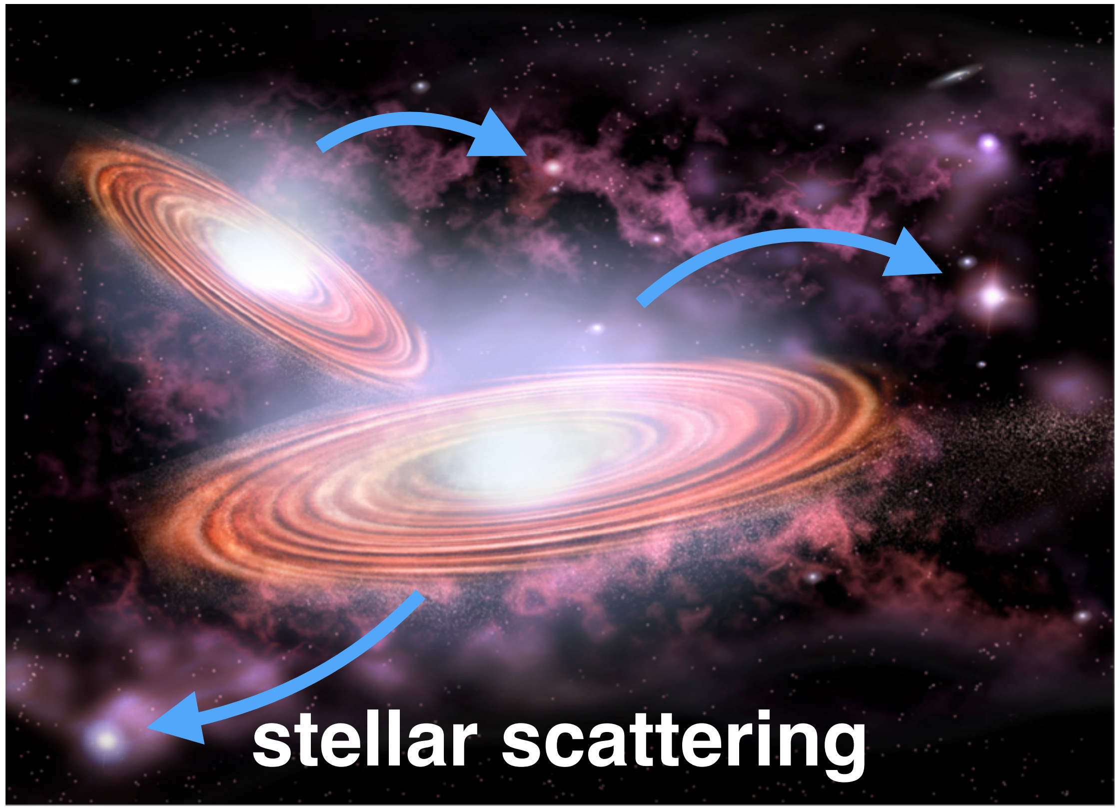
Ravi et al. (2014)

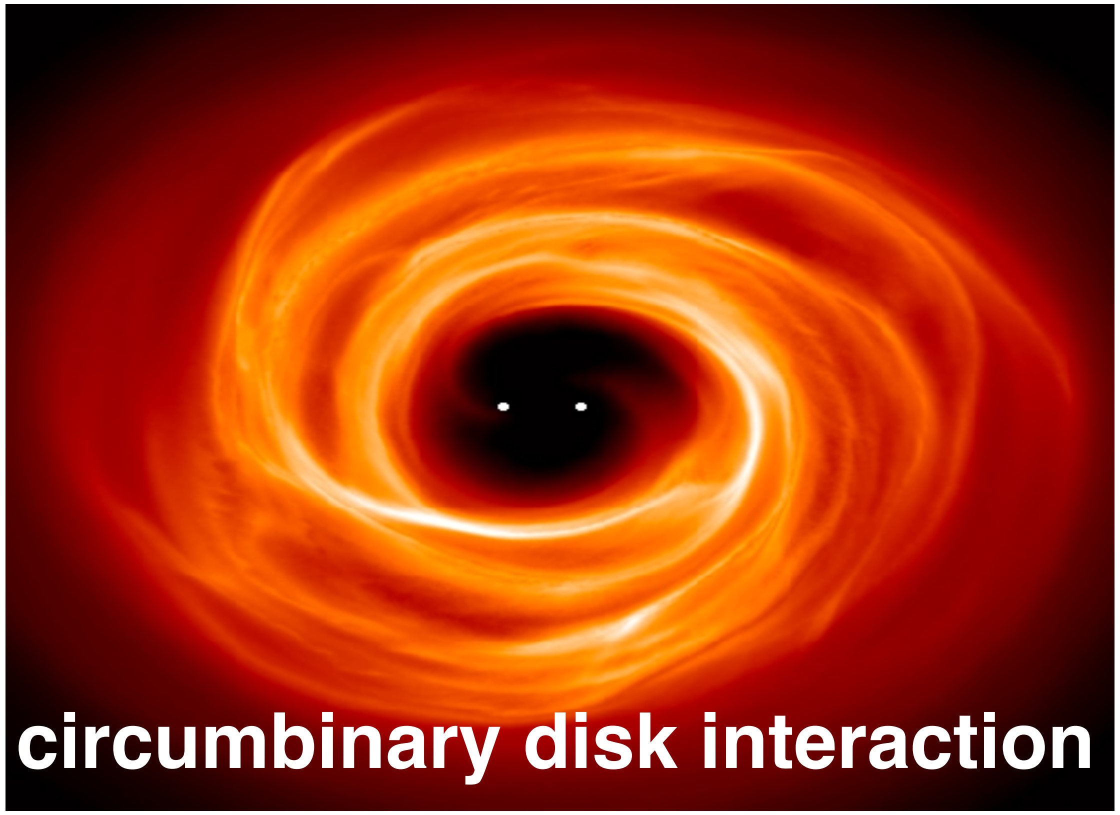


Large uncertainty in signal amplitude at low frequencies due to very poorly understood binary-environment interactions.

Bottom Line: Predictions of the SMBHB stochastic background amplitude based on observations and more reliable models are larger than previously thought, but there could be some depletion of the signal at low frequencies due to coupling with physical mechanisms that solve the final parsec problem.

SMBH Environmental Effects

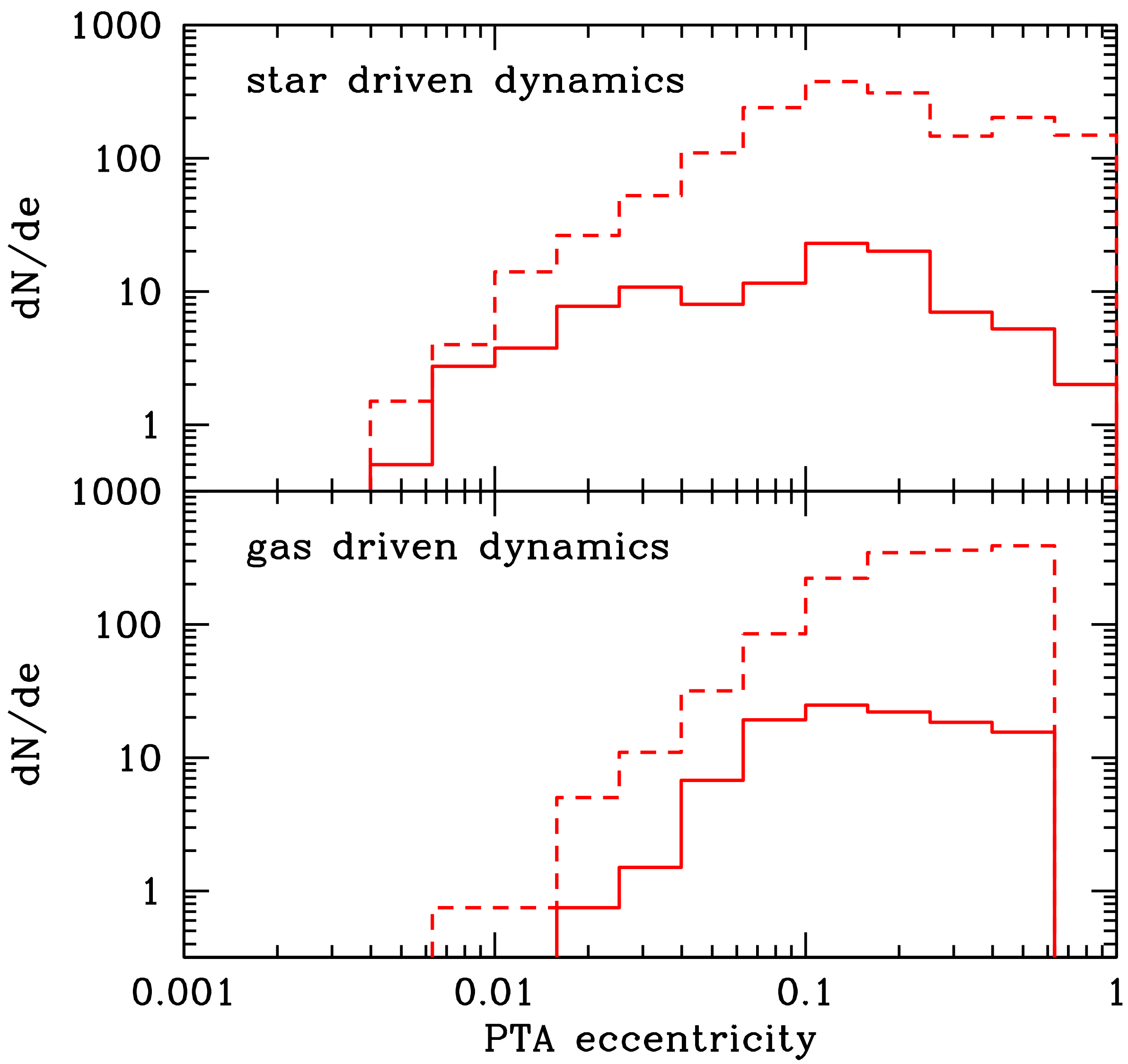




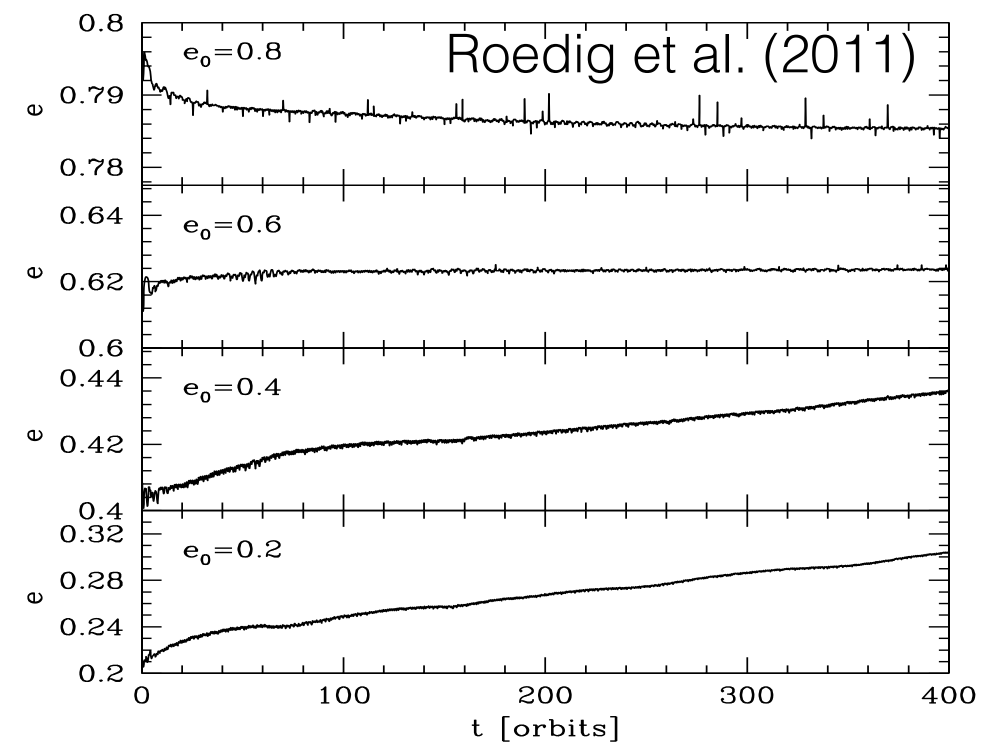
Courtesy: Steve Taylor

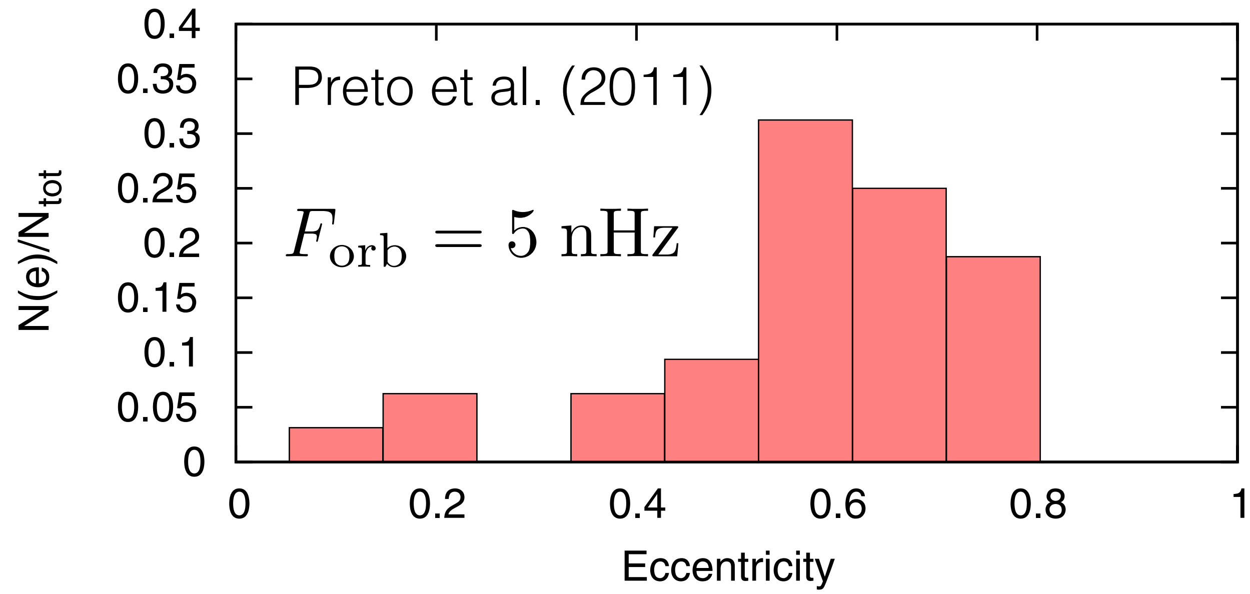
Orbital Eccentricity

stellar scattering or **circumbinary disk interaction** can *maintain or even increase eccentricity*

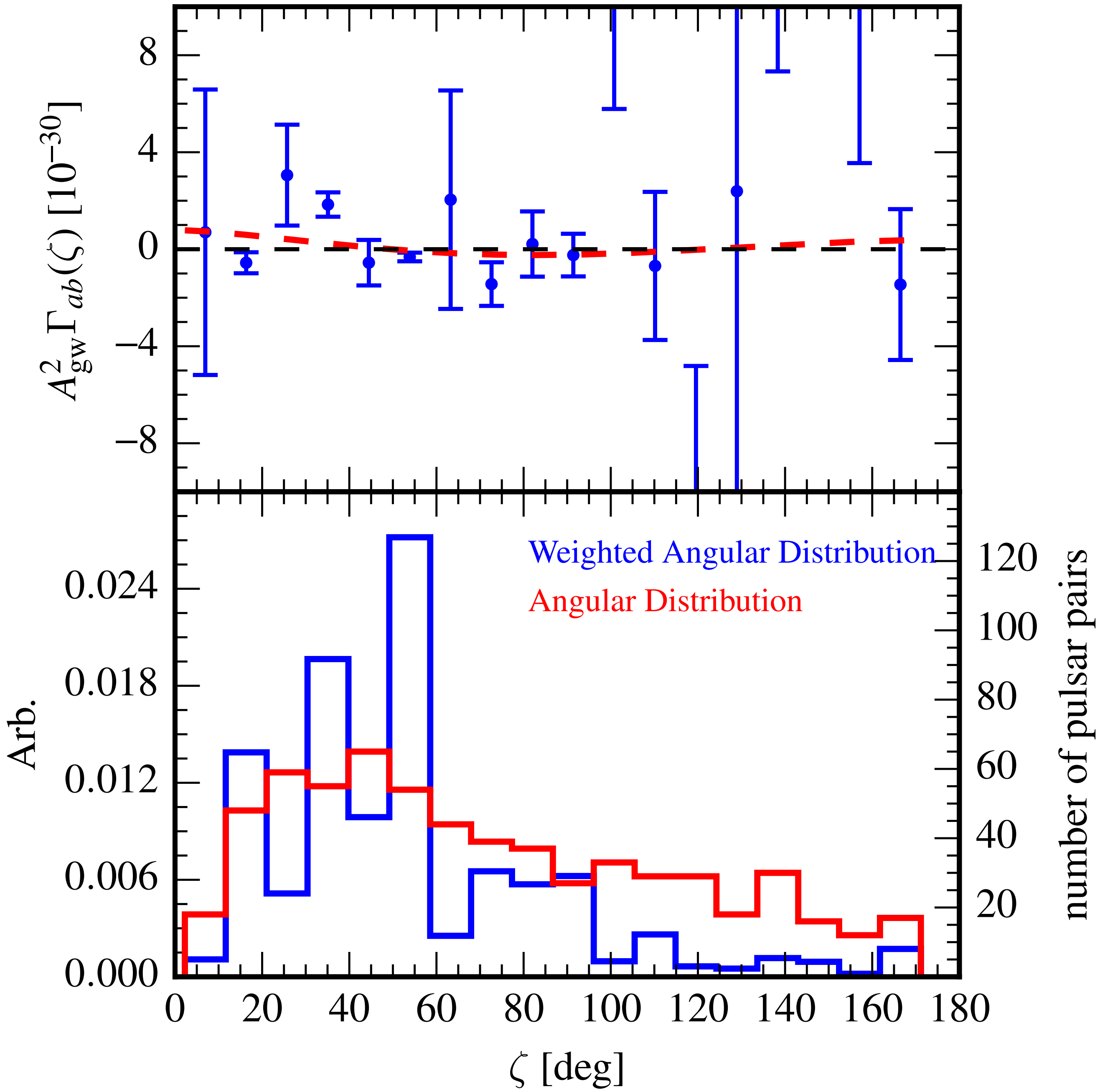


Roedig & Sesana (2012)





GW Search Results

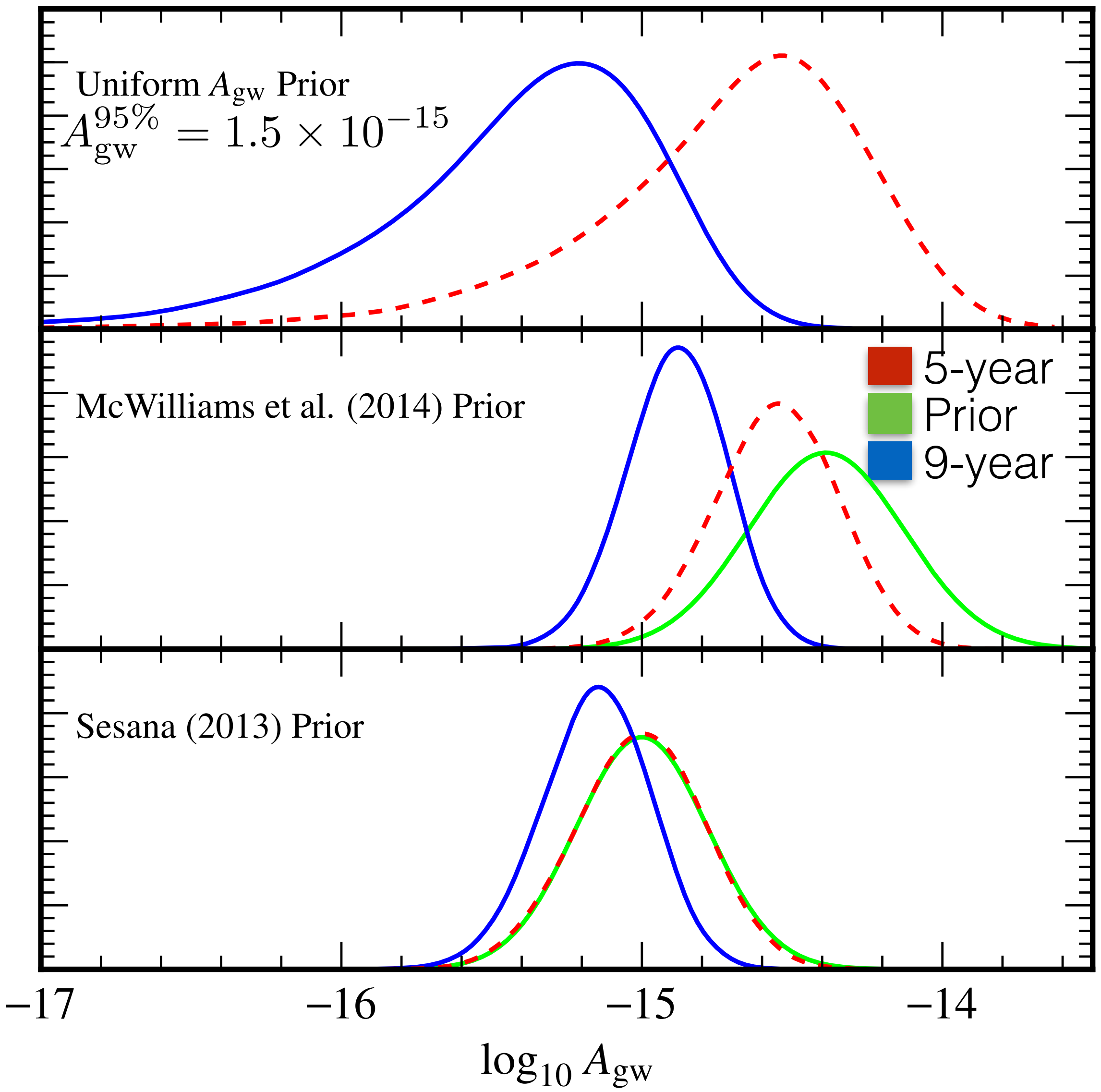


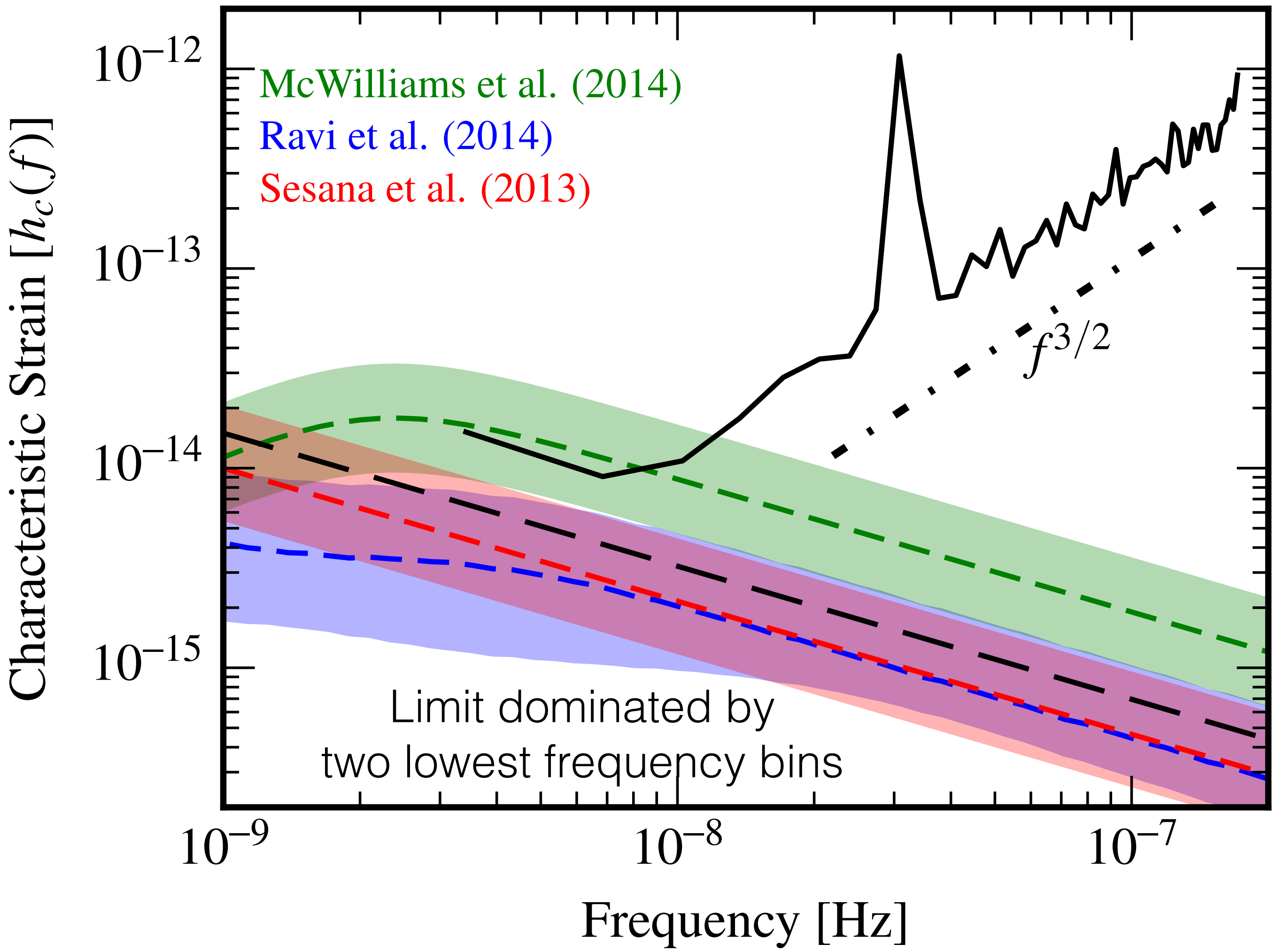
$$\xi_{ab} = \frac{\delta \mathbf{t}_a^{\rm T}\mathbf{P}_a^{-1}\hat{\mathbf{S}}_{ab}\mathbf{P}_b^{-1}\delta\mathbf{t}_b}{\mathrm{tr}\left[\mathbf{P}_a^{-1}\hat{\mathbf{S}}_{ab}\mathbf{P}_b^{-1}\hat{\mathbf{S}}_{ba}\right]}$$

$$\sigma_{0,ab} = \left(\mathrm{tr}\left[\mathbf{P}_a^{-1}\hat{\mathbf{S}}_{ab}\mathbf{P}_b^{-1}\hat{\mathbf{S}}_{ba}\right]\right)^{-1/2}$$

- Use full 37 pulsar data set.
- ML value $\hat{A}_{\rm gw} = 8.9\times 10^{-16}$
- SNR = 0.8
- Dominated by angular separation < 100 degrees
- 5.4 and 1.5 times more constraining than DFG13, LTM15

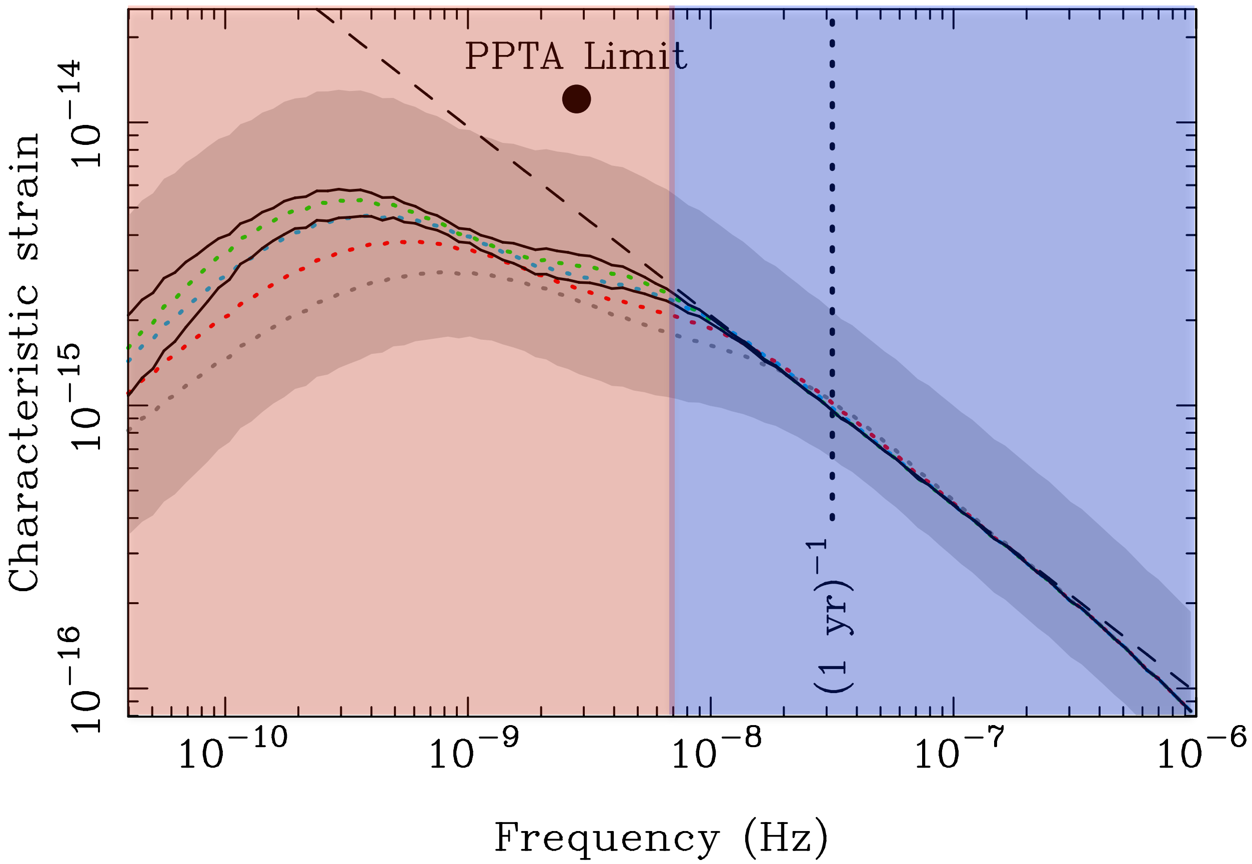
“Classic” Results





- Factor of ~5 improvement of 5-year dataset.
- Can update astrophysical prior based on Sesana (2013) and McWilliams et al (2014).
- McWilliams and Sesana models only 0.8% and 20% consistent with data

Astrophysical Inference



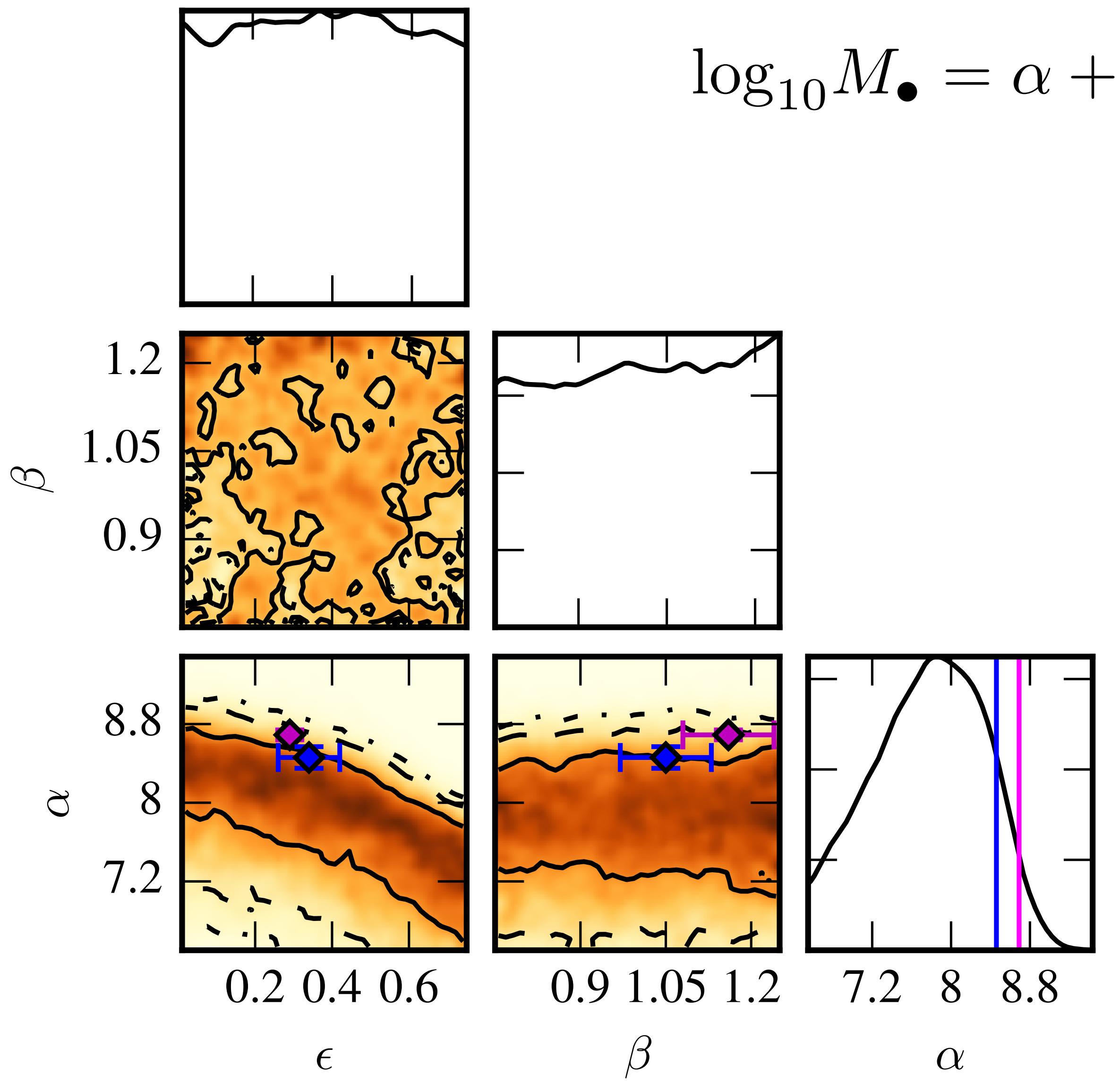
- Galaxy Merger Rates
- Black hole-host correlations (i.e., M-sigma, M-M_bulge)

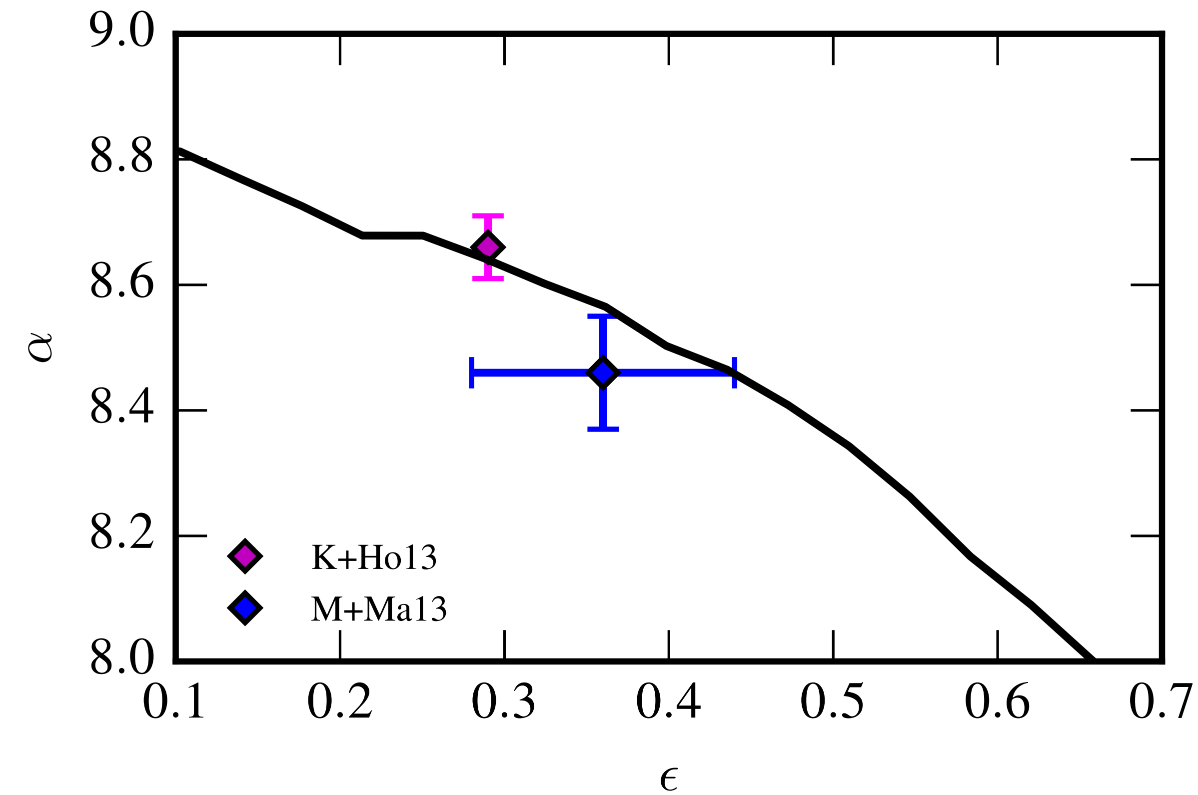
- Environmental effects:
  - Stellar Hardening
  - Circumbinary disk interaction
  - Orbital eccentricity

- Very large parameter space with many degeneracies
- Take a piecewise approach where each effect is investigated separately
- Parameters of interest: stellar density, mass accretion rate, initial eccentricity
- Cannot provide quantitative limits but can provide qualitative constraints that give us clues about the dynamic properties of SMBHBs

Black hole-host constraints

$$\log_{10} M_\bullet = \alpha + \beta \, \log_{10} \left(M_{bulge} / 10^{11} M_\odot \right)$$



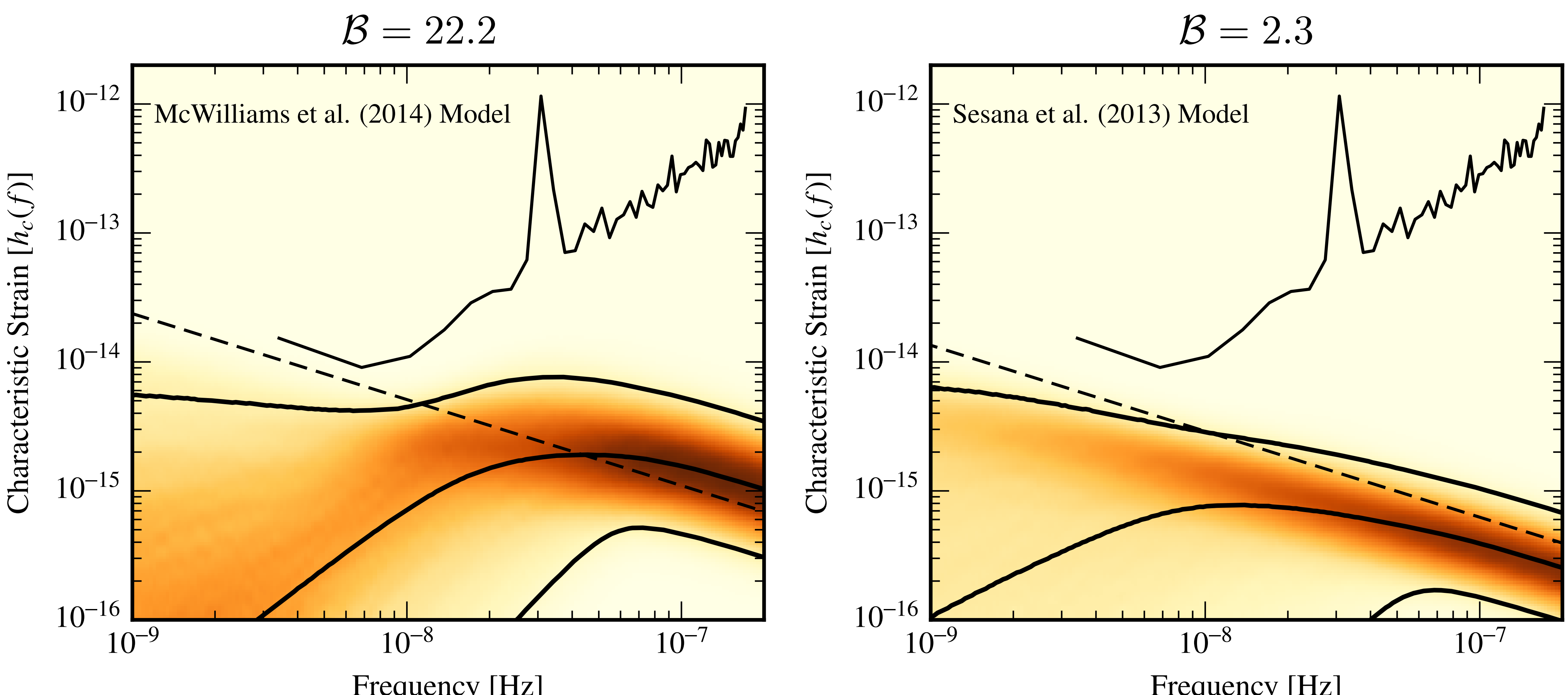


- Map $A_{\rm gw} \rightarrow (\alpha, \beta, \epsilon)$ by simulating GWB amplitude given values of $(\alpha, \beta, \epsilon)$ and given galaxy stellar mass functions and galaxy merger rates.
- Under assumption of GW driven (power-law) dynamics, we find that our upper limit is inconsistent with the Kormendy & Ho (2013) and in tension with the McConnel & Ma (2013) M - M_bulge relations

Parameterization of a "generic" SGWB

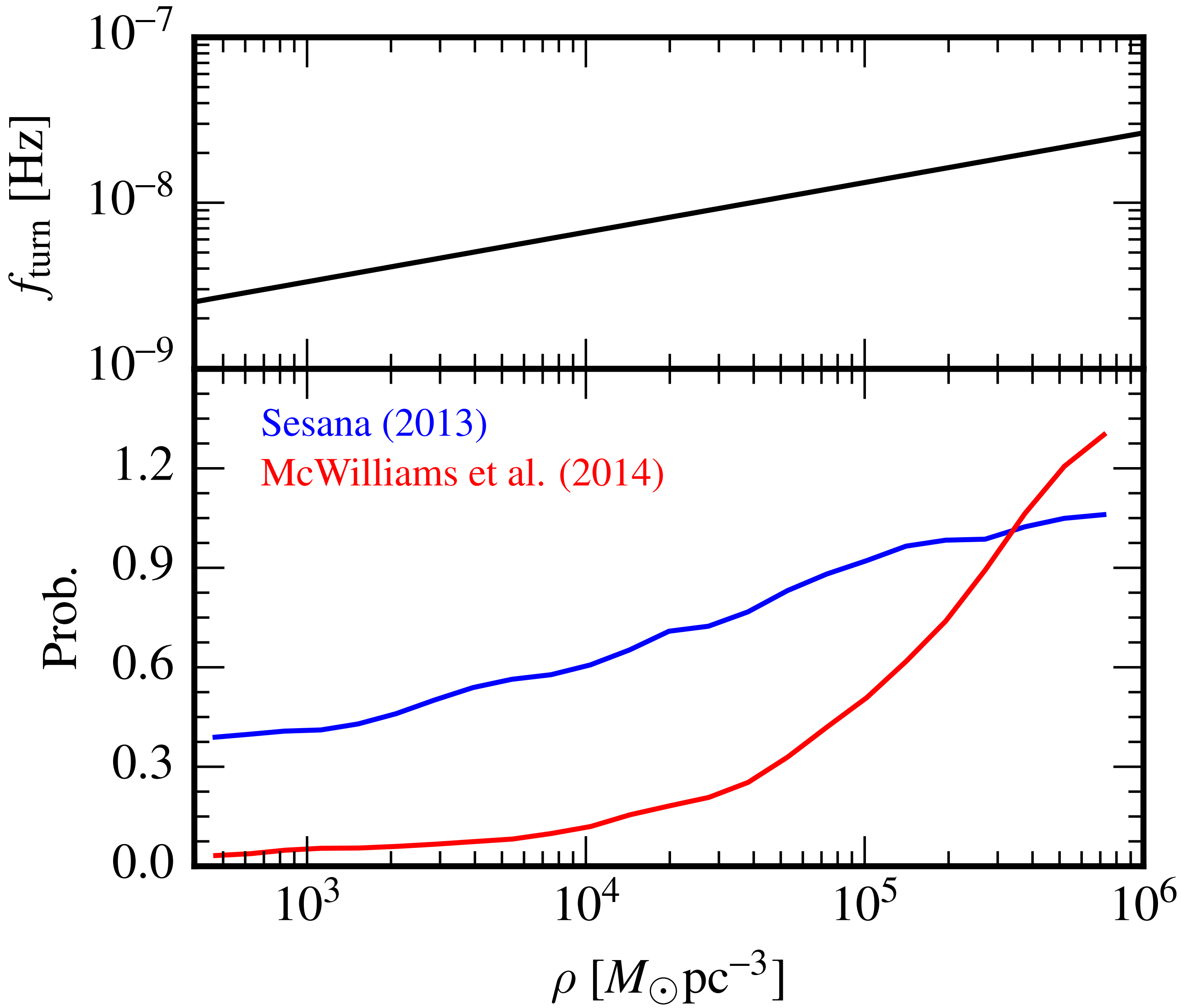
- Physics that drives binary to small orbital separations becomes very important in our most sensitive frequency band (f~10 nHz)

- Can be simply parameterized by: $$h_c(f) = A\frac{(f/f_{\rm yr})^{\alpha}}{(1+(f_{\rm bend}/f)^{\kappa})^{1/2}}$$



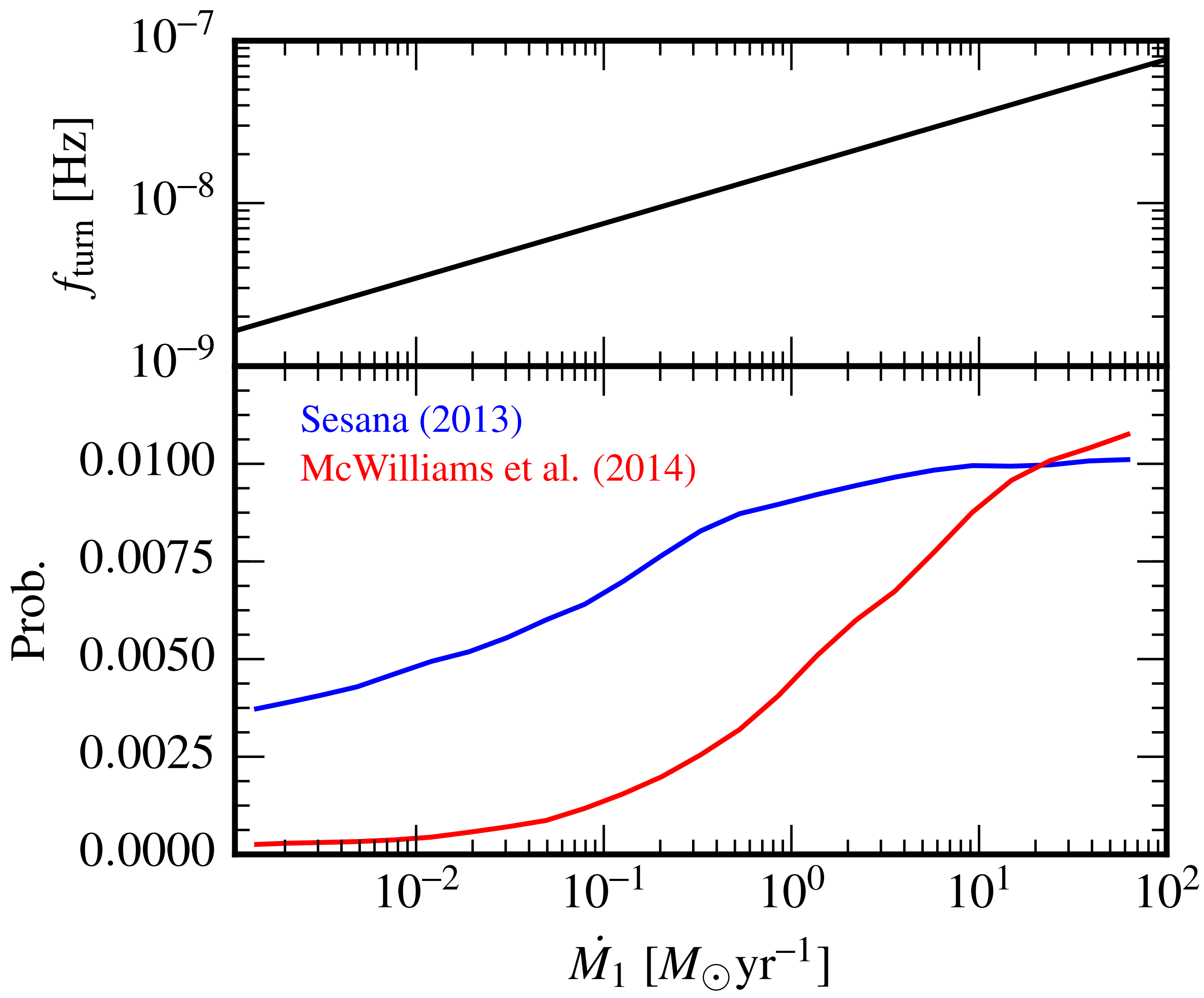
Sampson+2015

Stellar Hardening Constraints



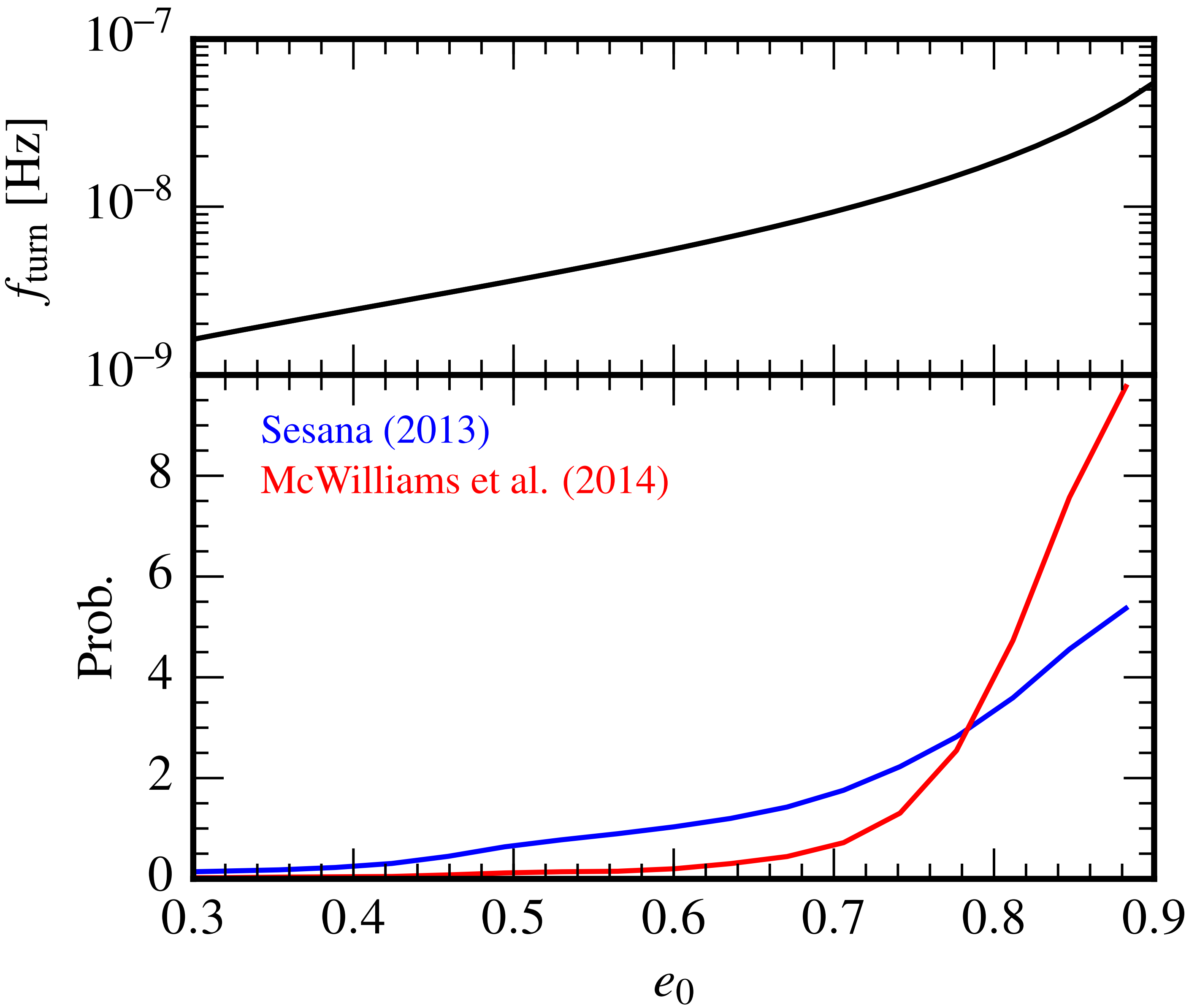
- Map $f_{\rm turn} \rightarrow \rho$
- Expected range $10 - 10^4\ M_\odot\ \mathrm{pc}^{-3}$
- McWilliams model in tension even if massive ellipticals have densities 2-3 higher than at z=0
- Sesana model unconstraining

Circumbinary Disk Interaction Constraints



- Map $f_{\rm turn} \rightarrow \dot{M}$
- Expected range 10^{-3} –1 $M_\odot$ yr^{-1}
- McWilliams model in tension with expected values but short episodic bursts could produce much higher rates
- Sesana model unconstraining

Orbital Eccentricity Constraints



- Map $f_{\rm turn} \rightarrow e_0$
- Expected range is unknown and hard to pin down with N-body simulations.
- McWilliams model favors large eccentricities
- Sesana model less constraining but does favor e>0.3

Conclusions

- “Classic” power law upper limits most constraining to date
- For the first time, our data can inform us on the shape of the GWB spectrum
- For the first time, our data can be used to place constraints on stellar hardening and circumbinary disk interaction parameters that play a critical role in solving the final parsec problem
- Can still do important astrophysics even without a direct detection!
- All of these limits and astrophysical inferences will be more constraining with upcoming International Pulsar Timing Array (IPTA) data.