# Probing Supermassive Black Holes with Pulsar Timing Arrays

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# Gravitational Wave Spectrum

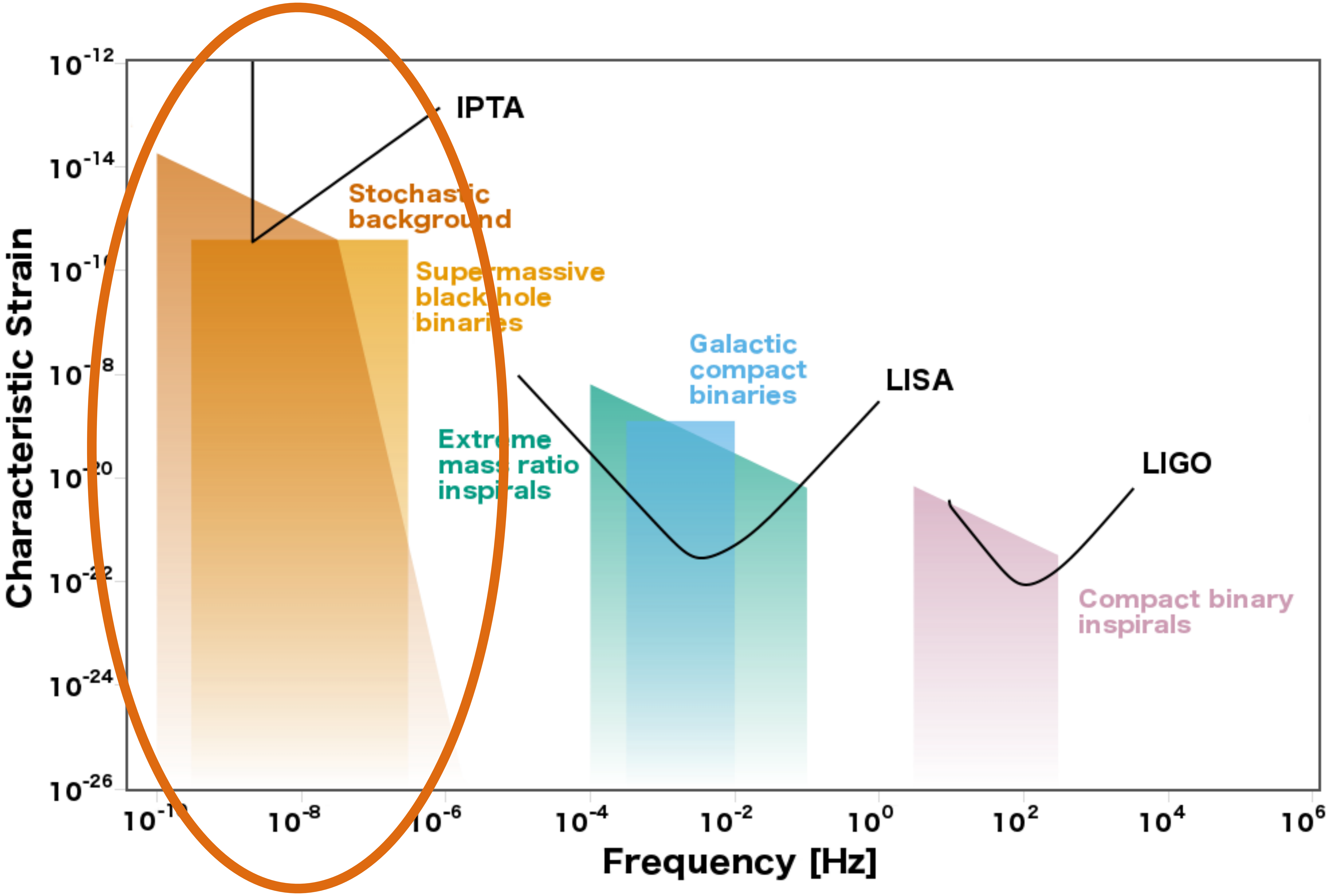


Figure credit: Moore, Cole, Berry 2014 (modified).

# Supermassive Black Hole Binaries

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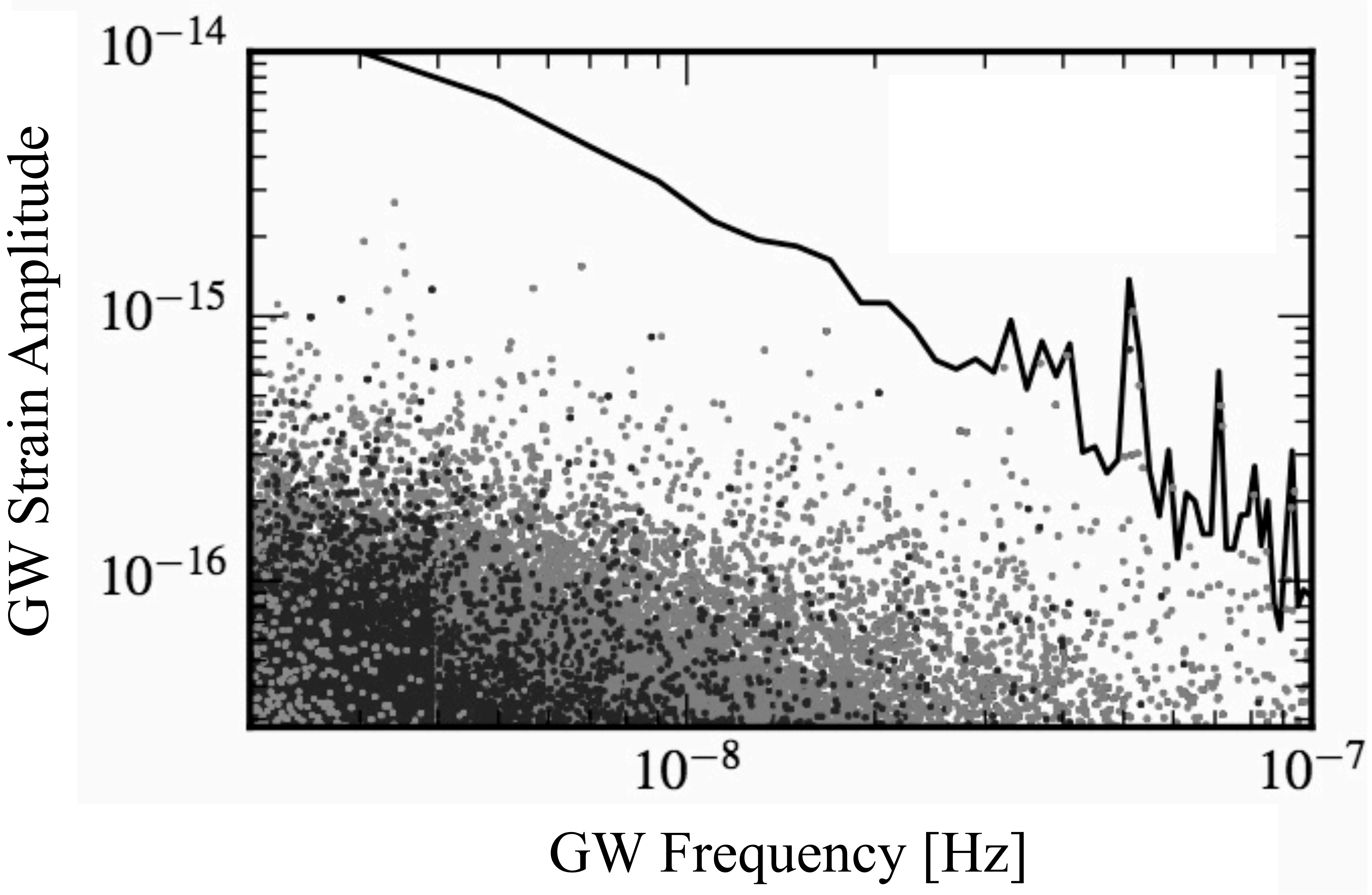



Figure credit: J. Simon

# Stochastic GW Background

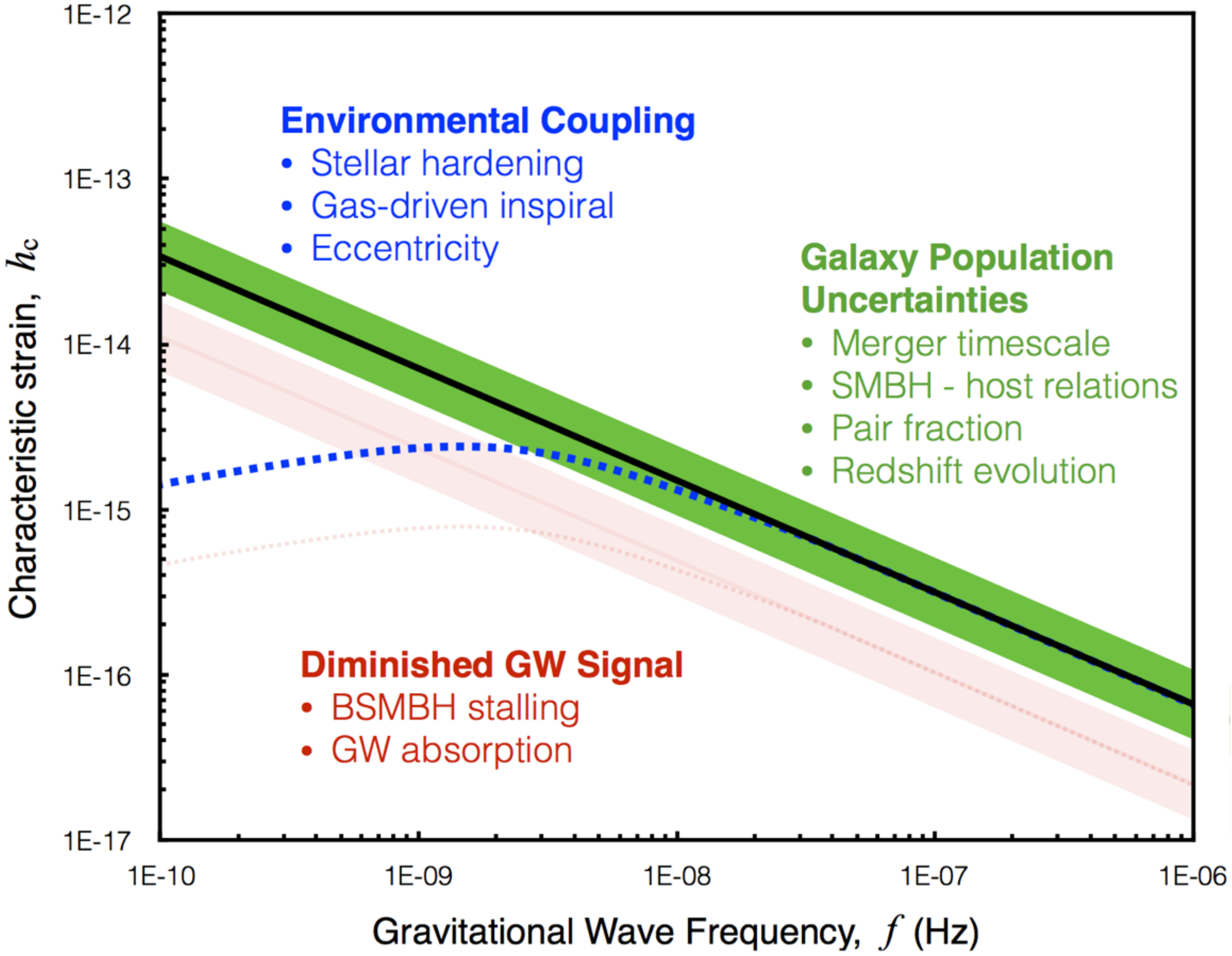


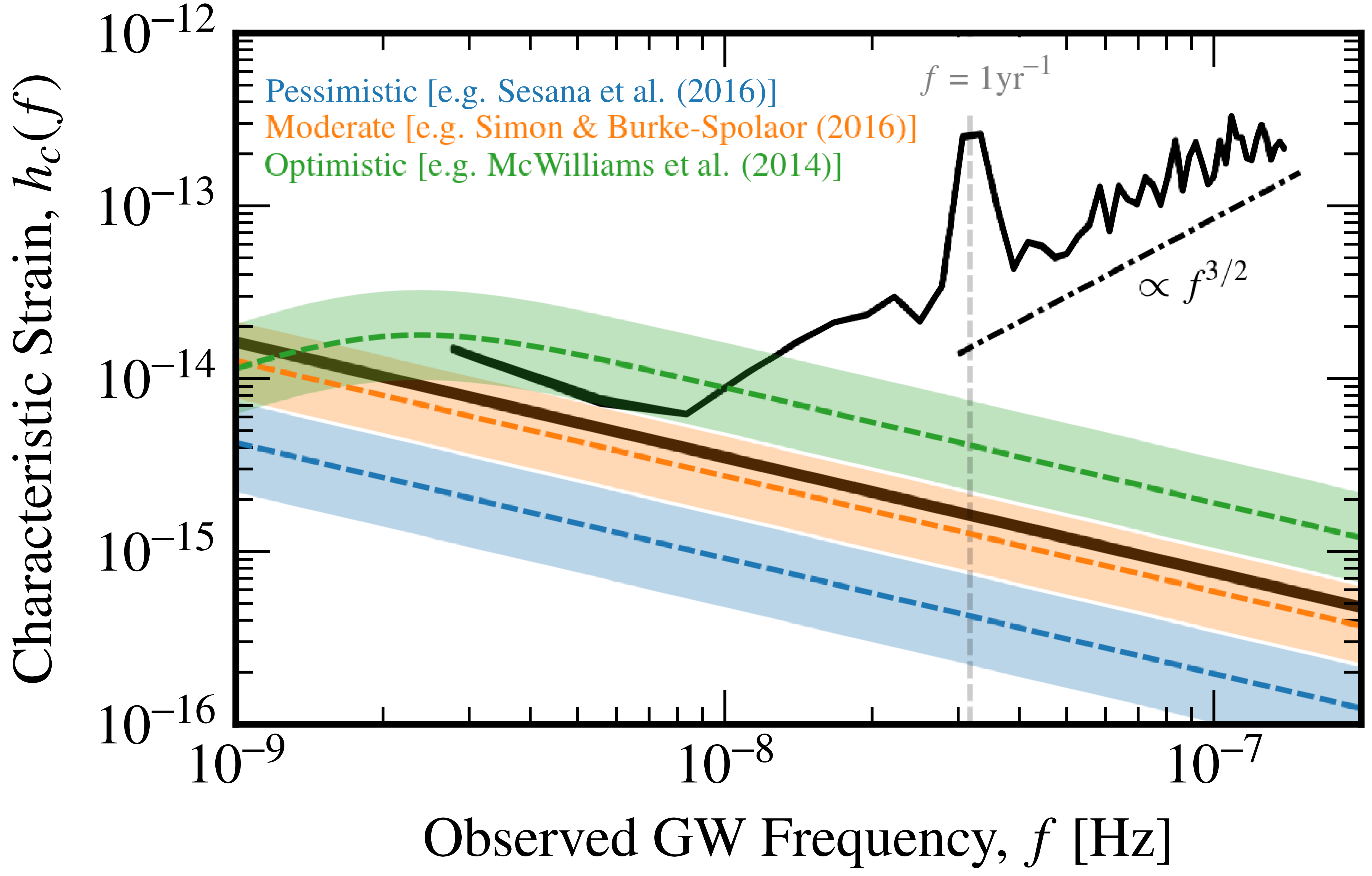

Figure credit: S. Burke Spolaor 2015

Assuming circular binaries evolving only due to GW emission,

$$h_c(f) = A_{\rm gw} \left( \frac{f}{f_{1\,{\rm yr}}} \right)^{-2/3} .$$

If binaries evolve due to GW emission and environmental coupling, there may be a turnover in the spectrum at low frequencies.

# Limits on the GWB



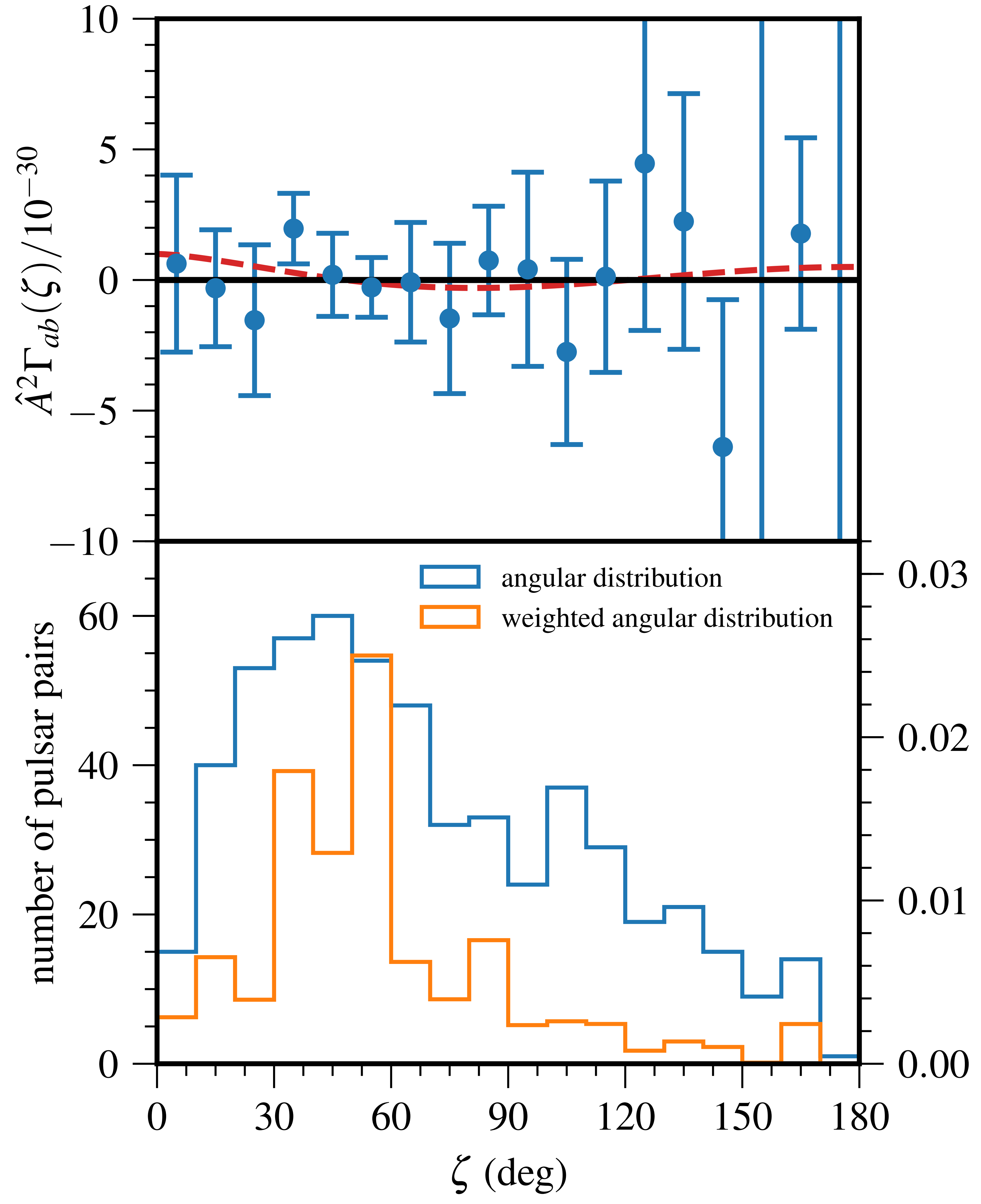




Figure credits: Z. Arzoumanian et al. (2018)

# Interpreting Limits on the GWB

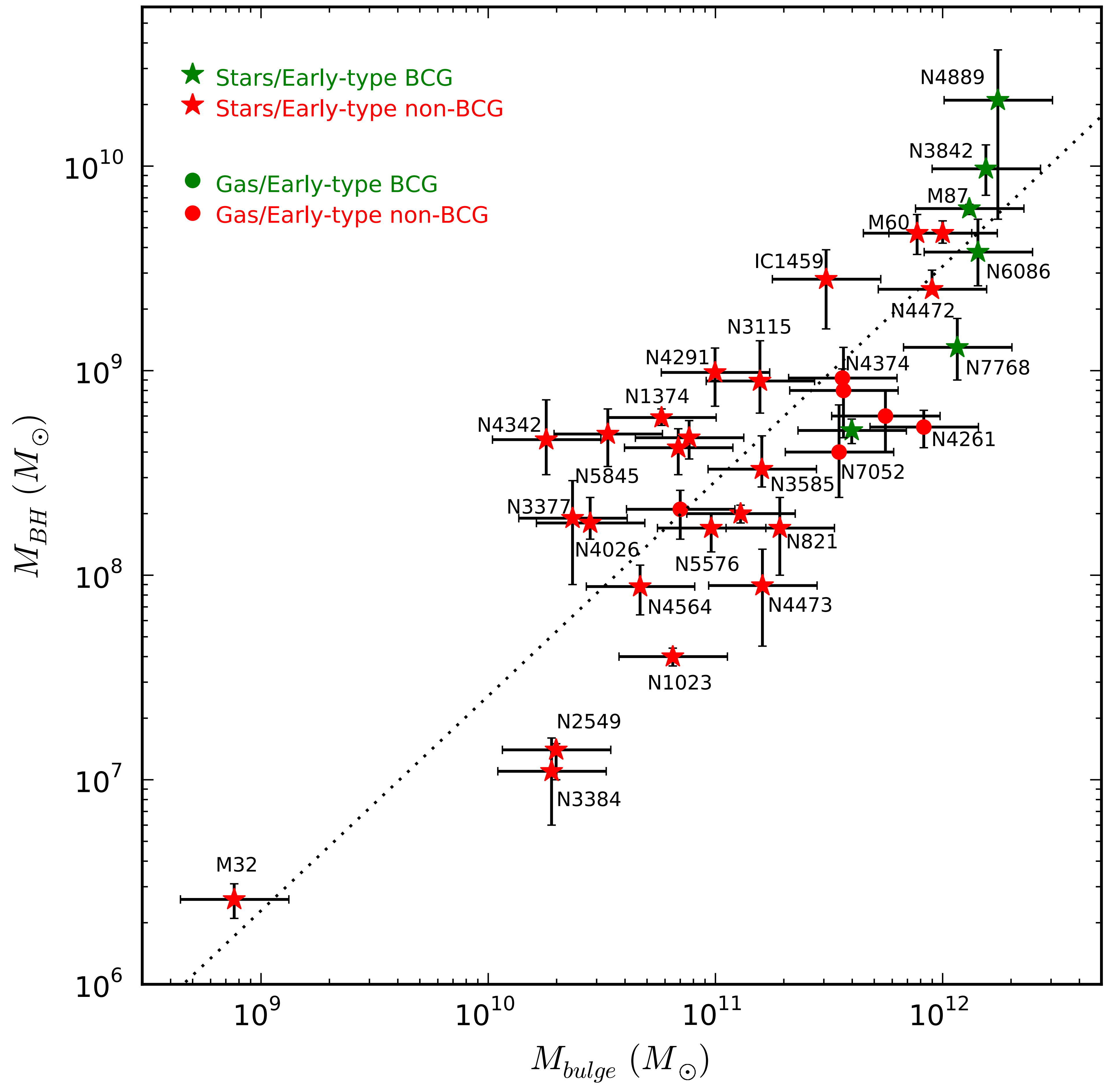



Figure credit: McConnell & Ma (2013)

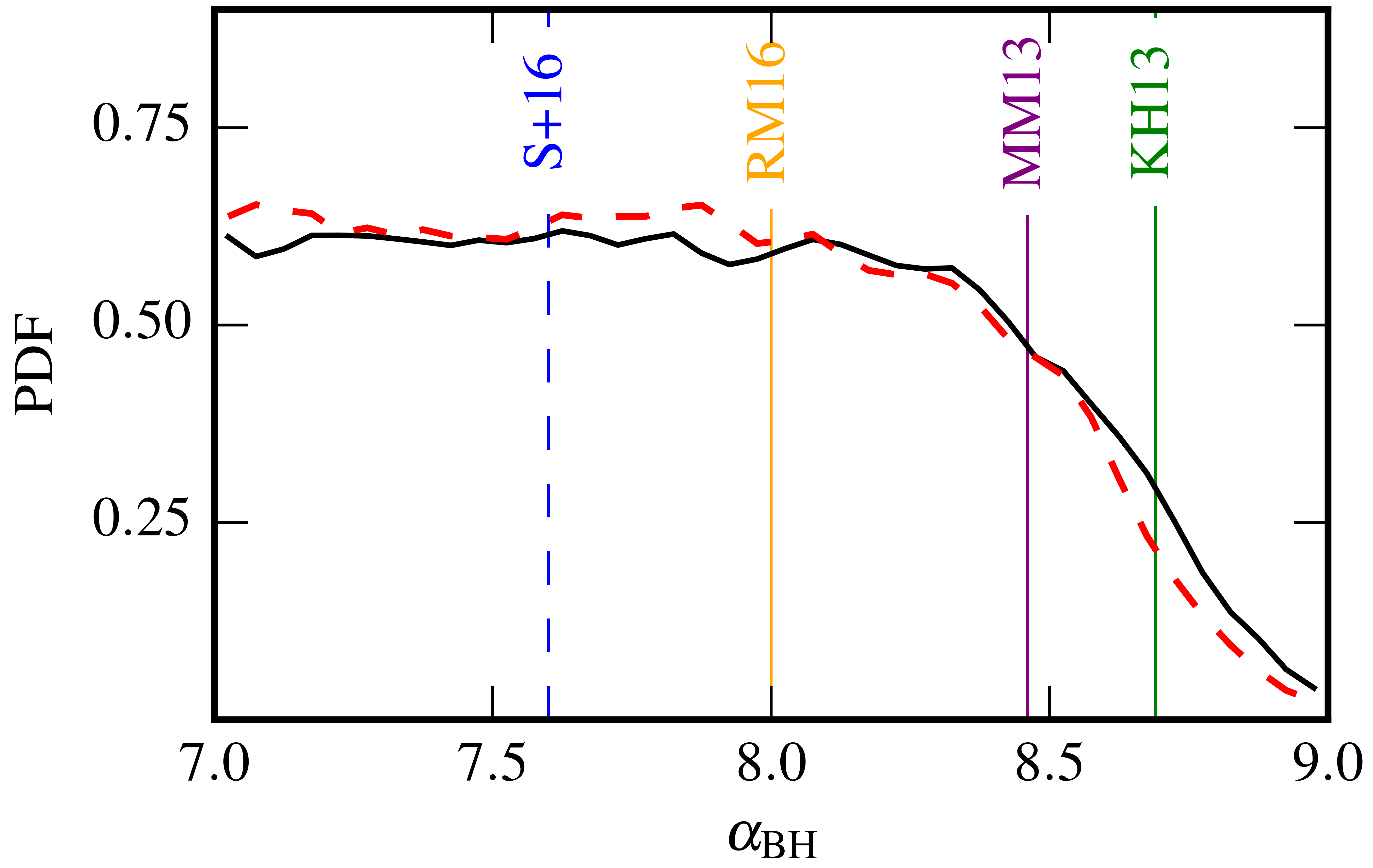



Figure credit: Z. Arzoumanian et al. (2018)

# Interpreting Limits on the GWB

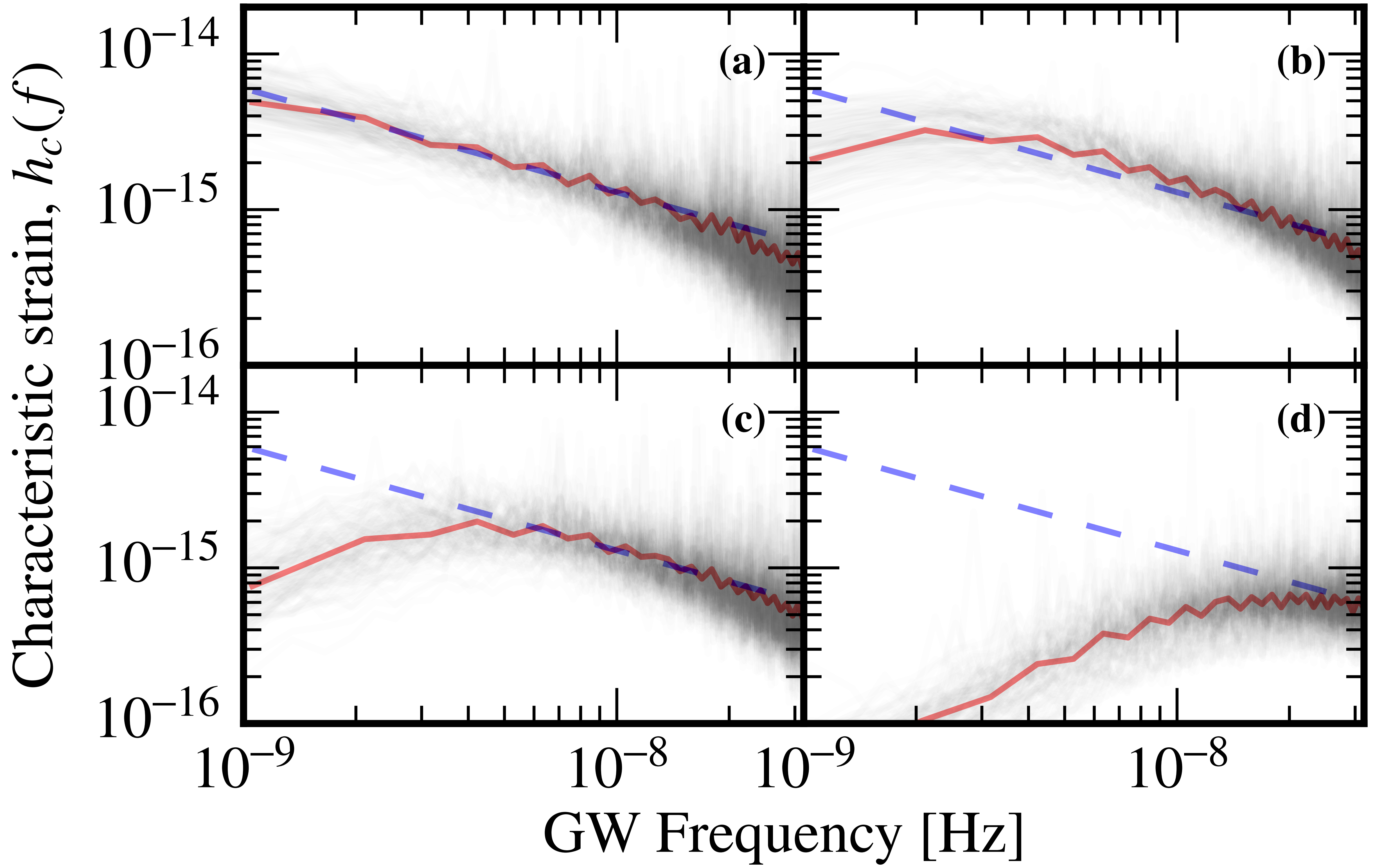
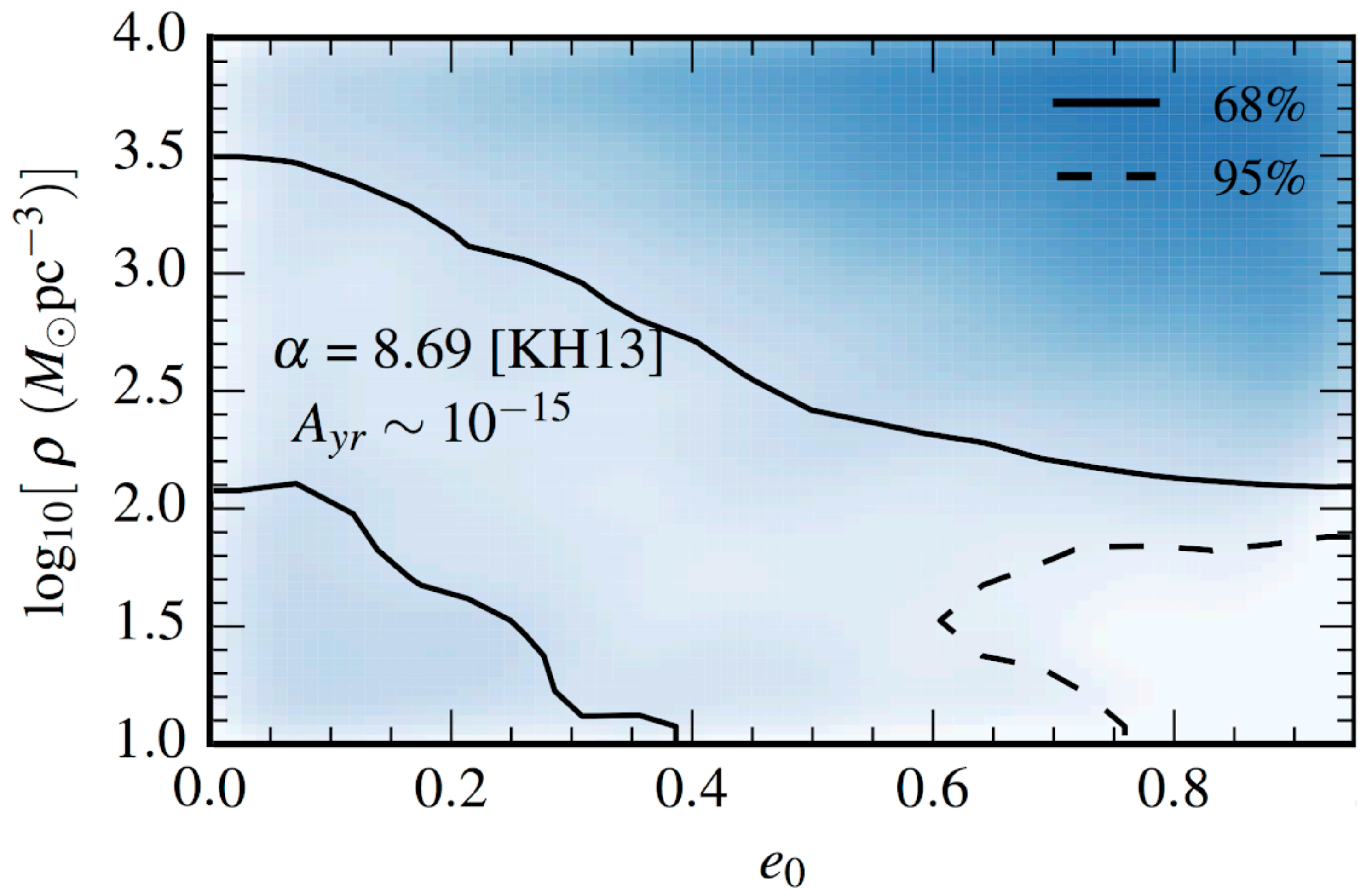



Figure credit: Taylor, Simon, Sampson (2017)



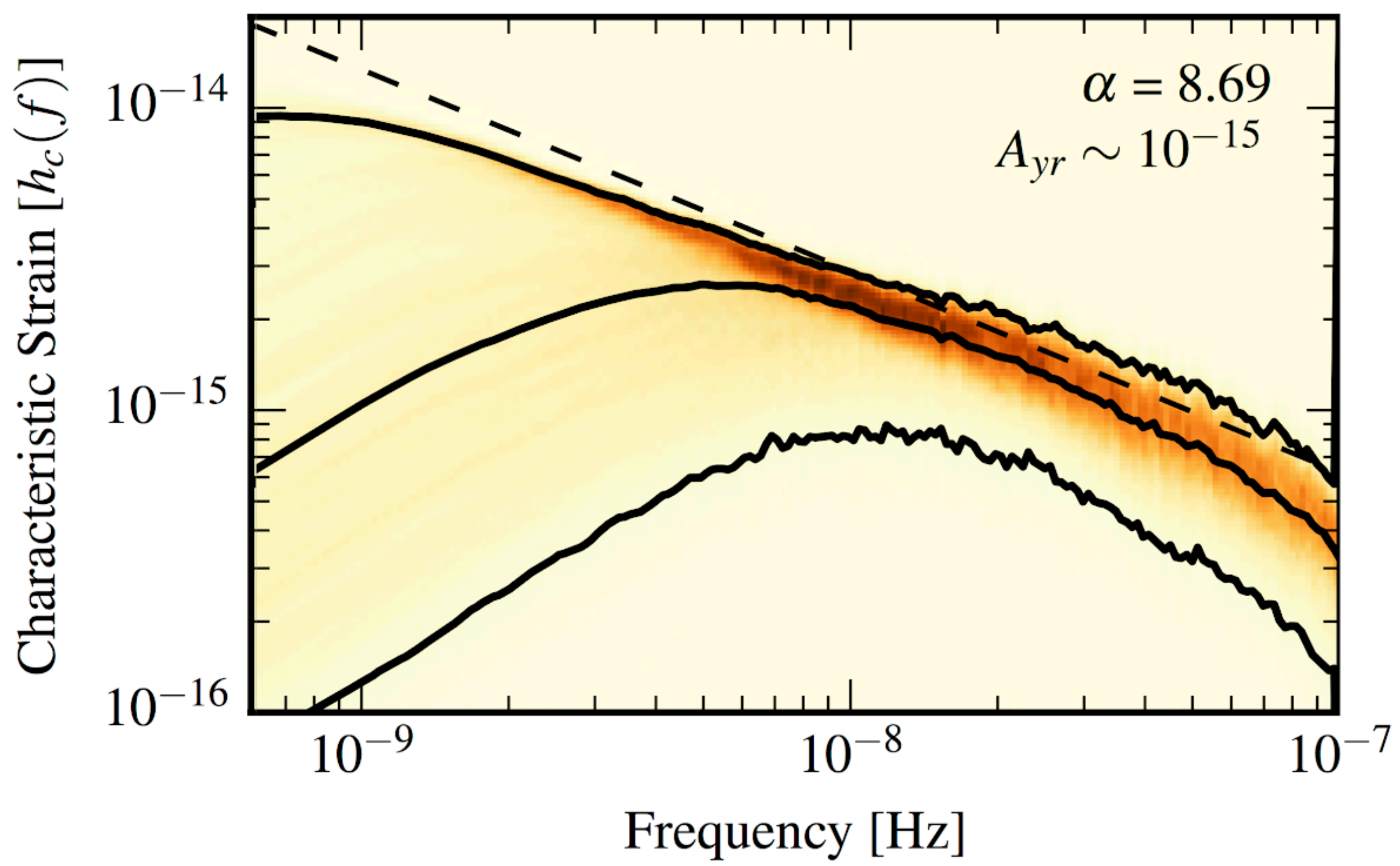
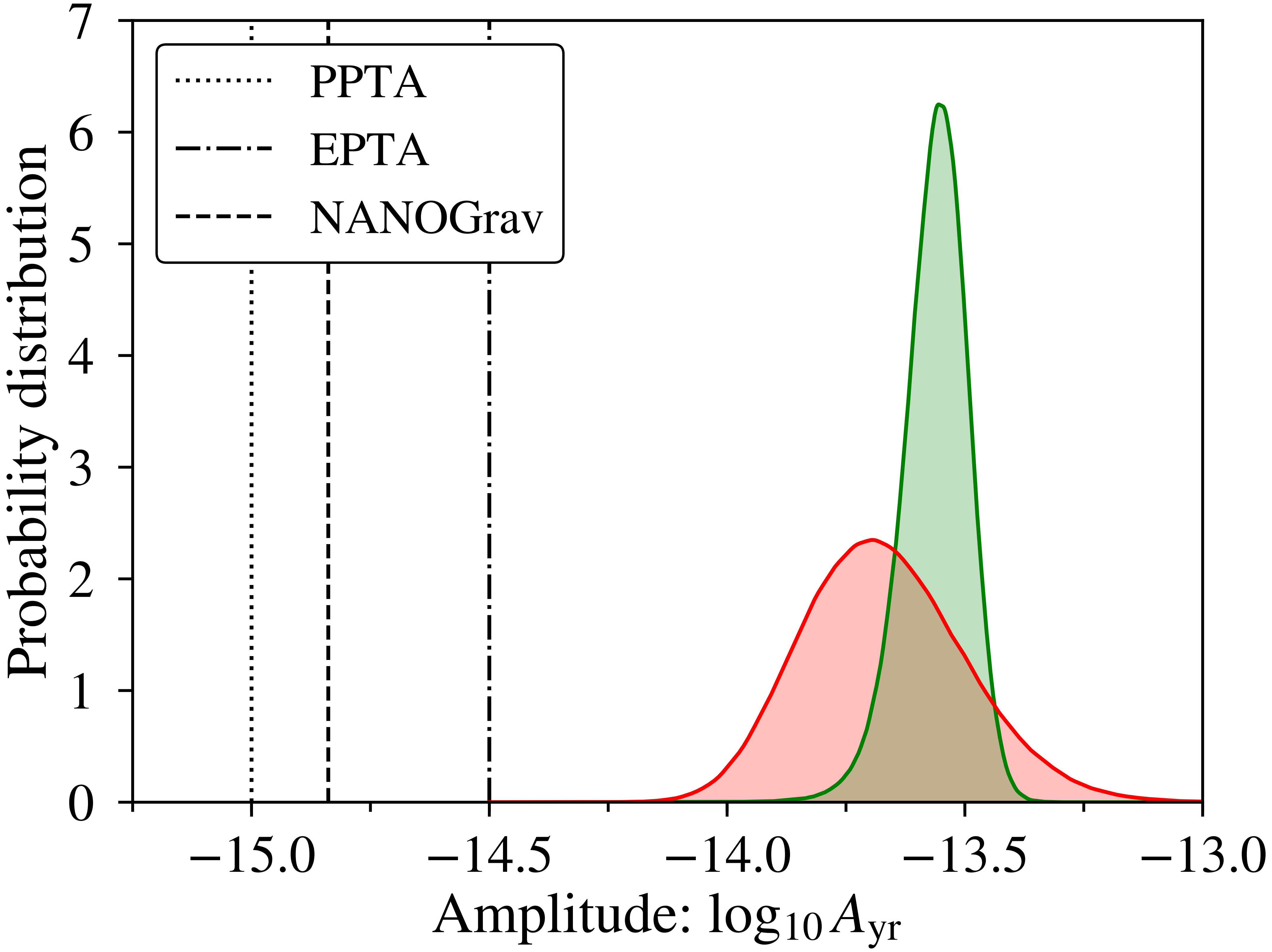






Figure credit: Z. Arzoumanian et al. (2018)

# Constraints on Candidate SMBHBs

Limits on the GWB can constrain the binary fraction quasi-period BL Lac objects.



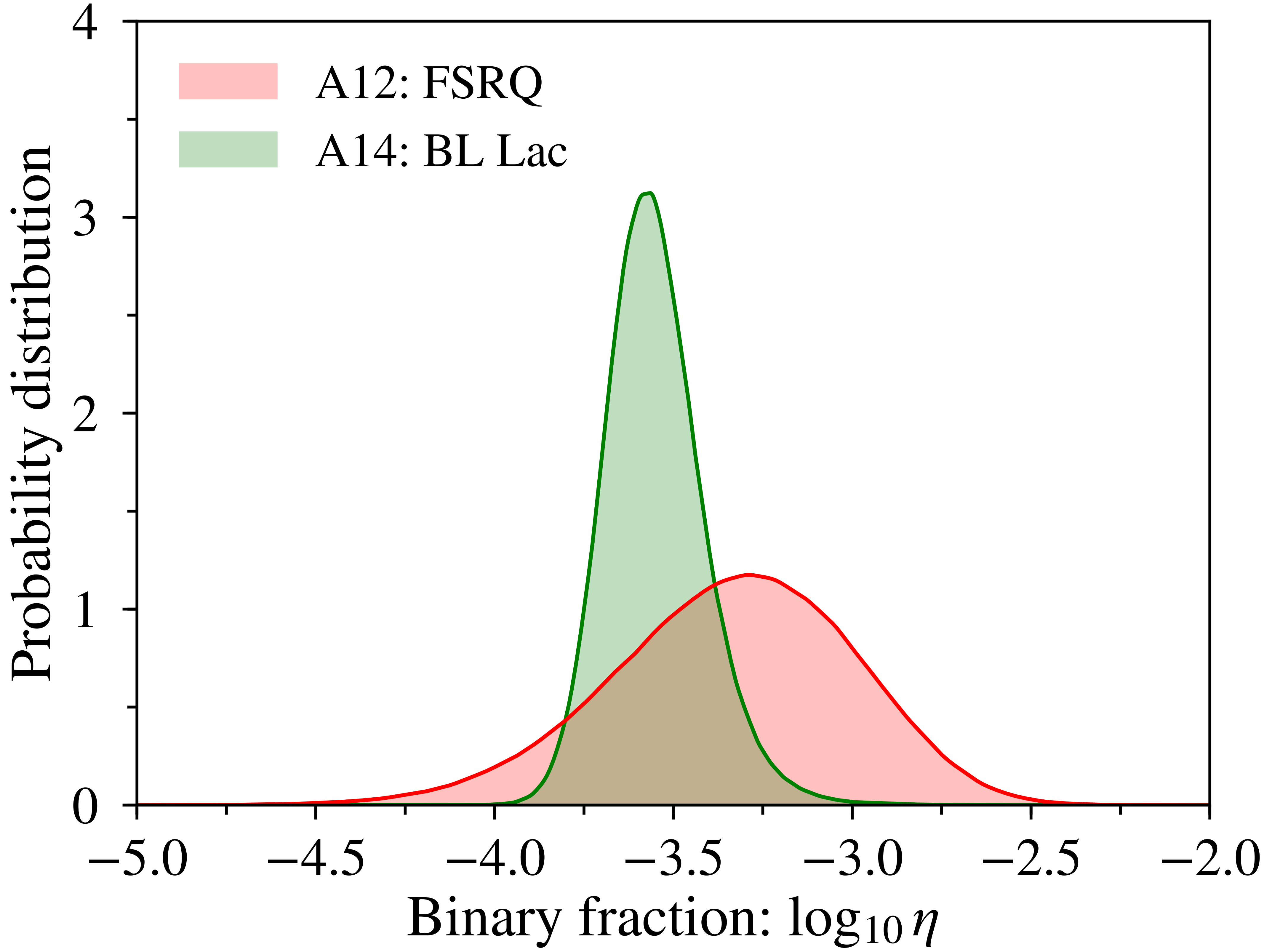




Figure credits: Holgado, Sesana, Sandrinelli, et al. (2018)

# Alternate Polarizations

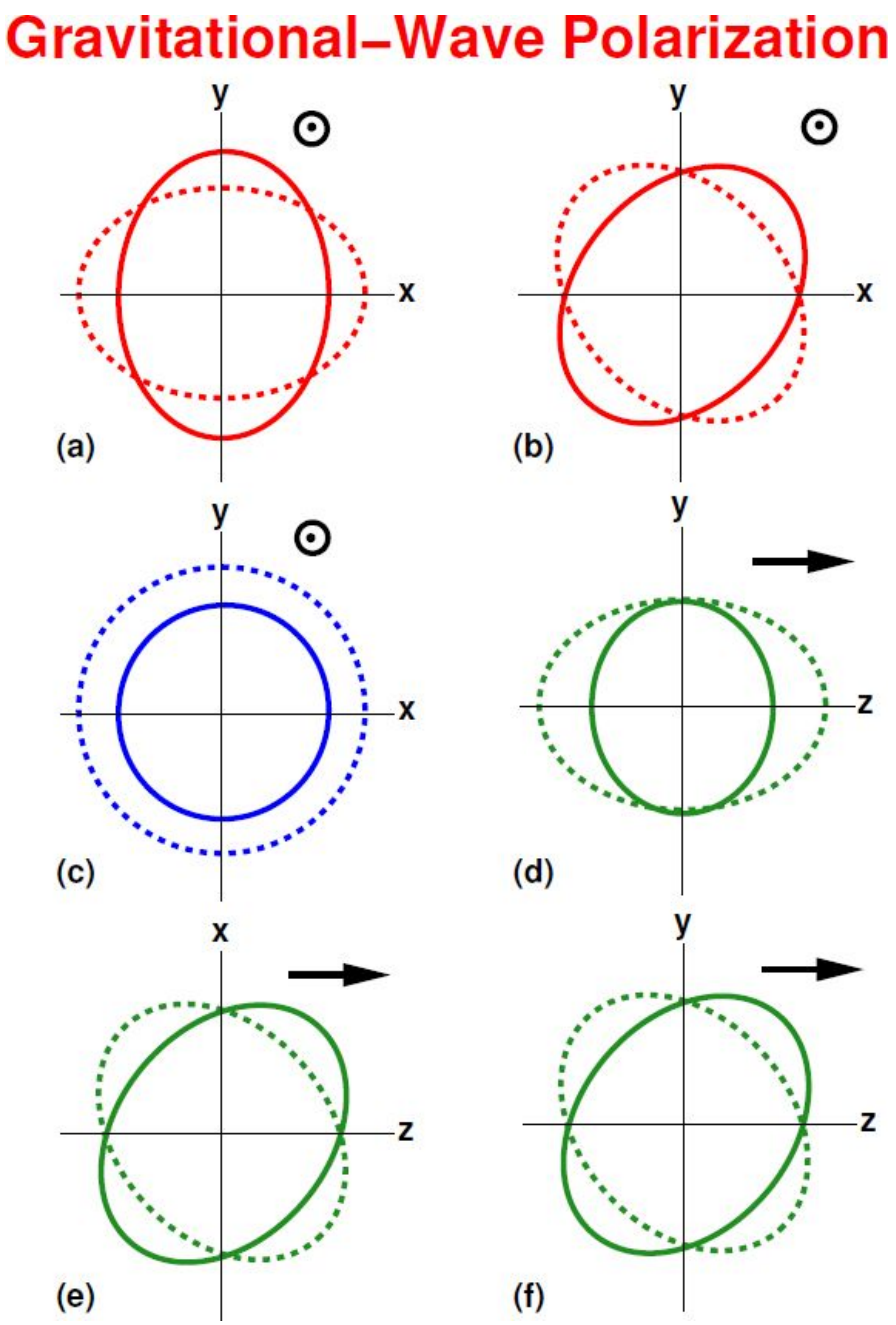
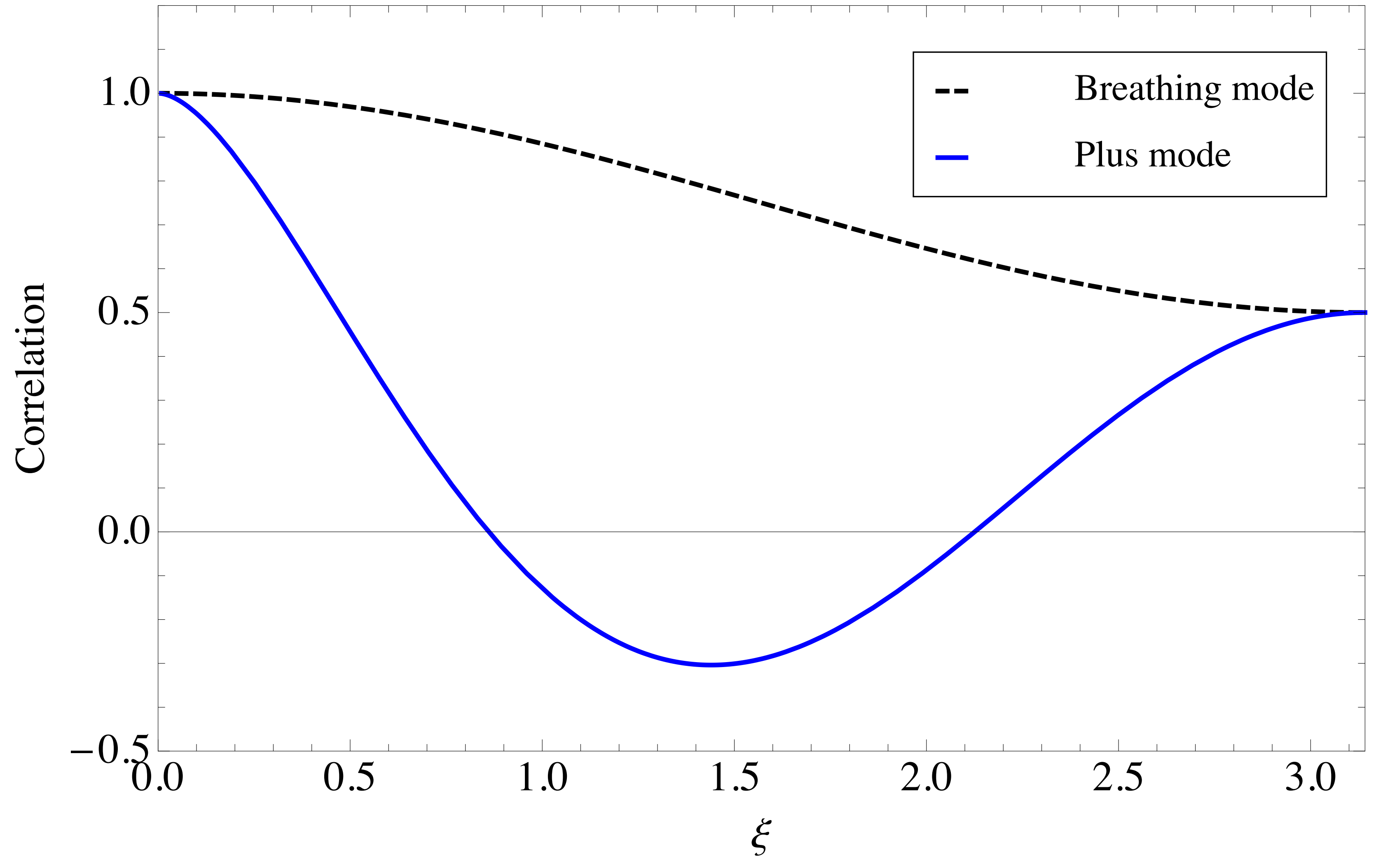



Figure credit: C. Will (2014)

In GR, there are only two GW polarizations. Alternate theories of gravity may allow other polarizations to exist.

PTAs can put constraints on the power in alternate polarizations (Chamberlin & Siemens 2012; Cornish, O'Beirne, Taylor, and Yunes 2018)




Chamberlin & Siemens (2012)

# Individual Sources

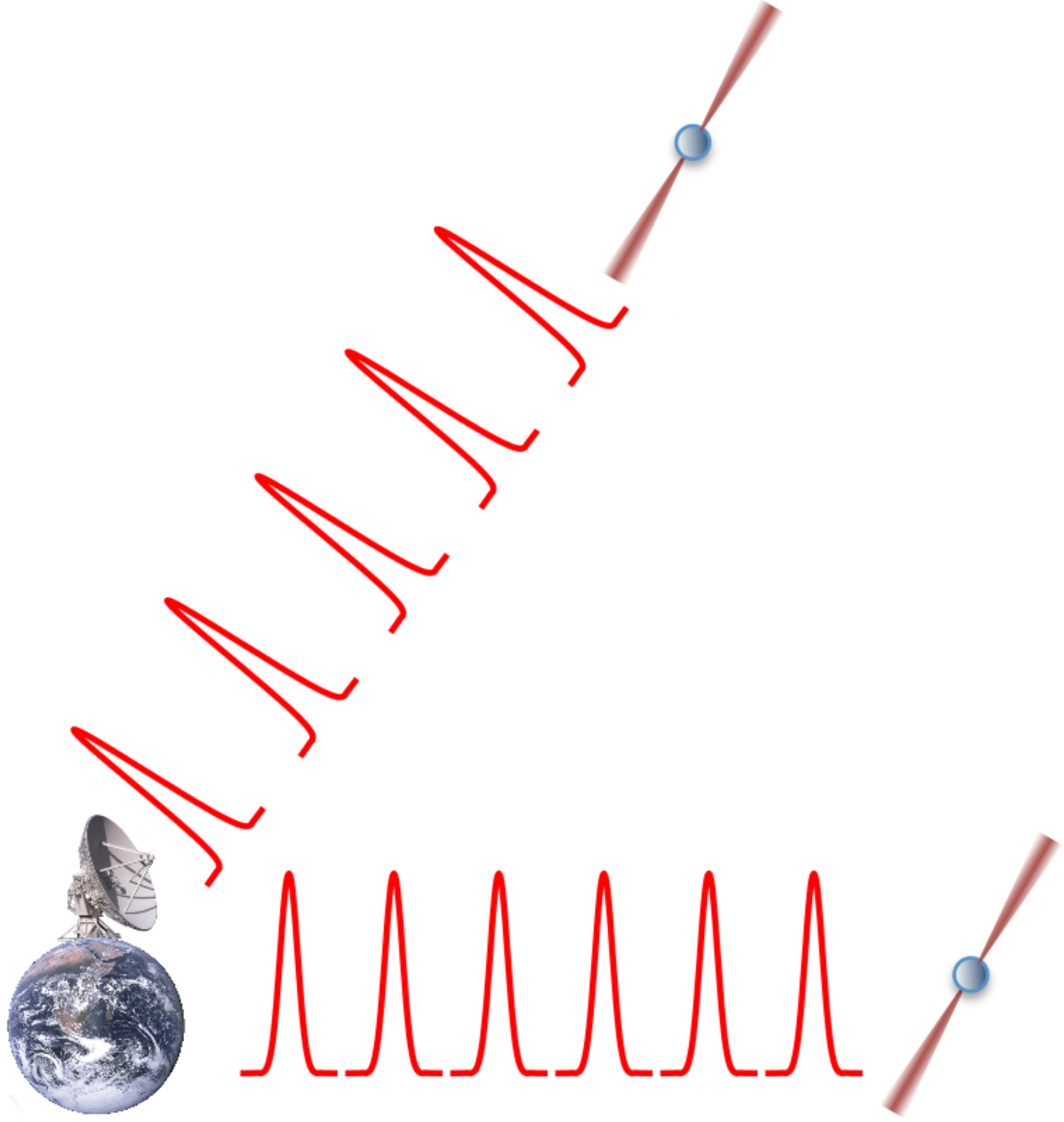
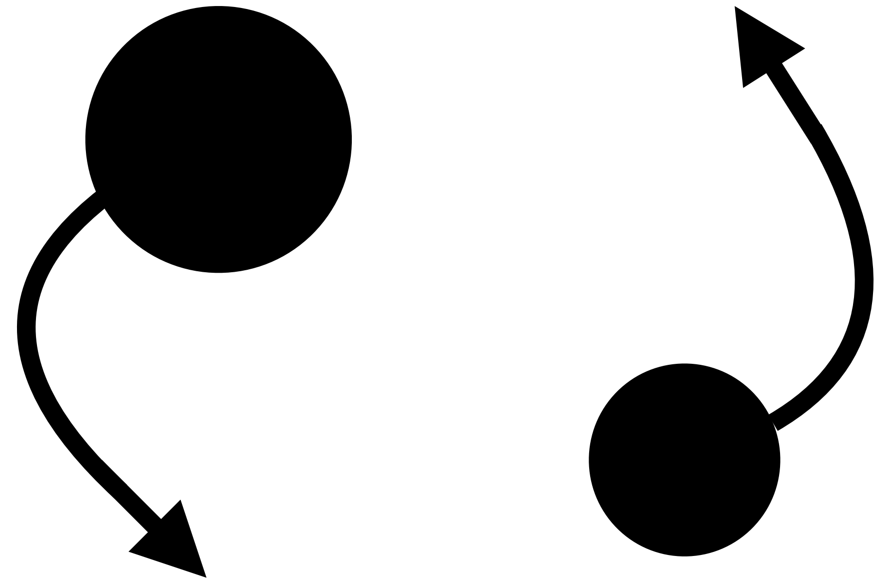


Figure credit: NANOGrav (modified)

$$h_0 = \frac{2\mathcal{M}^{5/3}(\pi f_{\rm gw})^{2/3}}{d_L}$$



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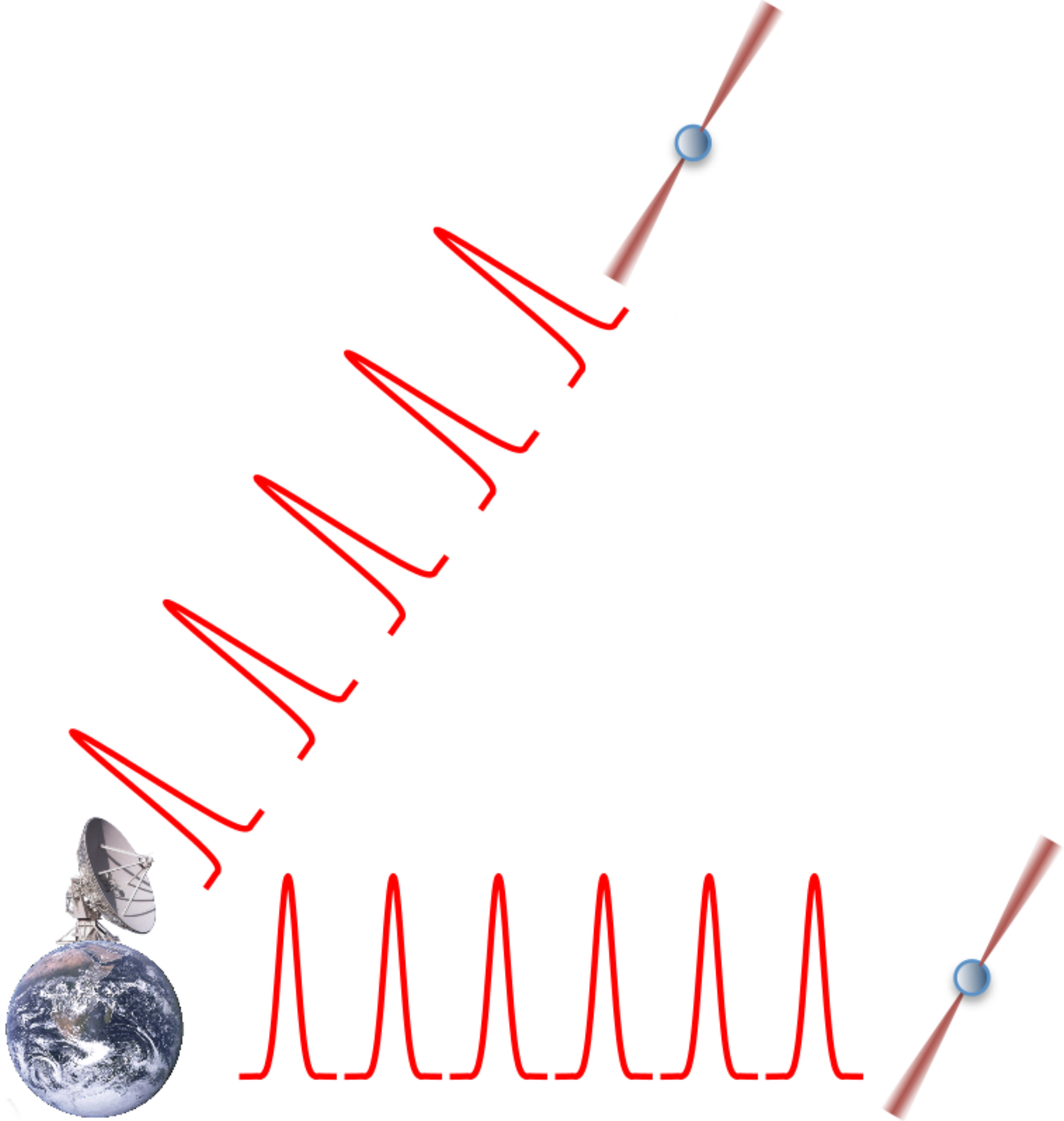

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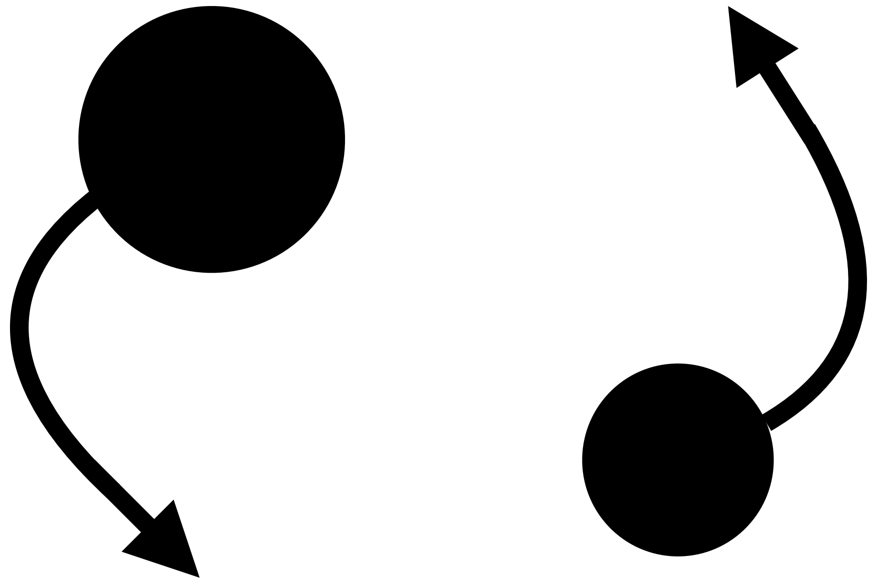
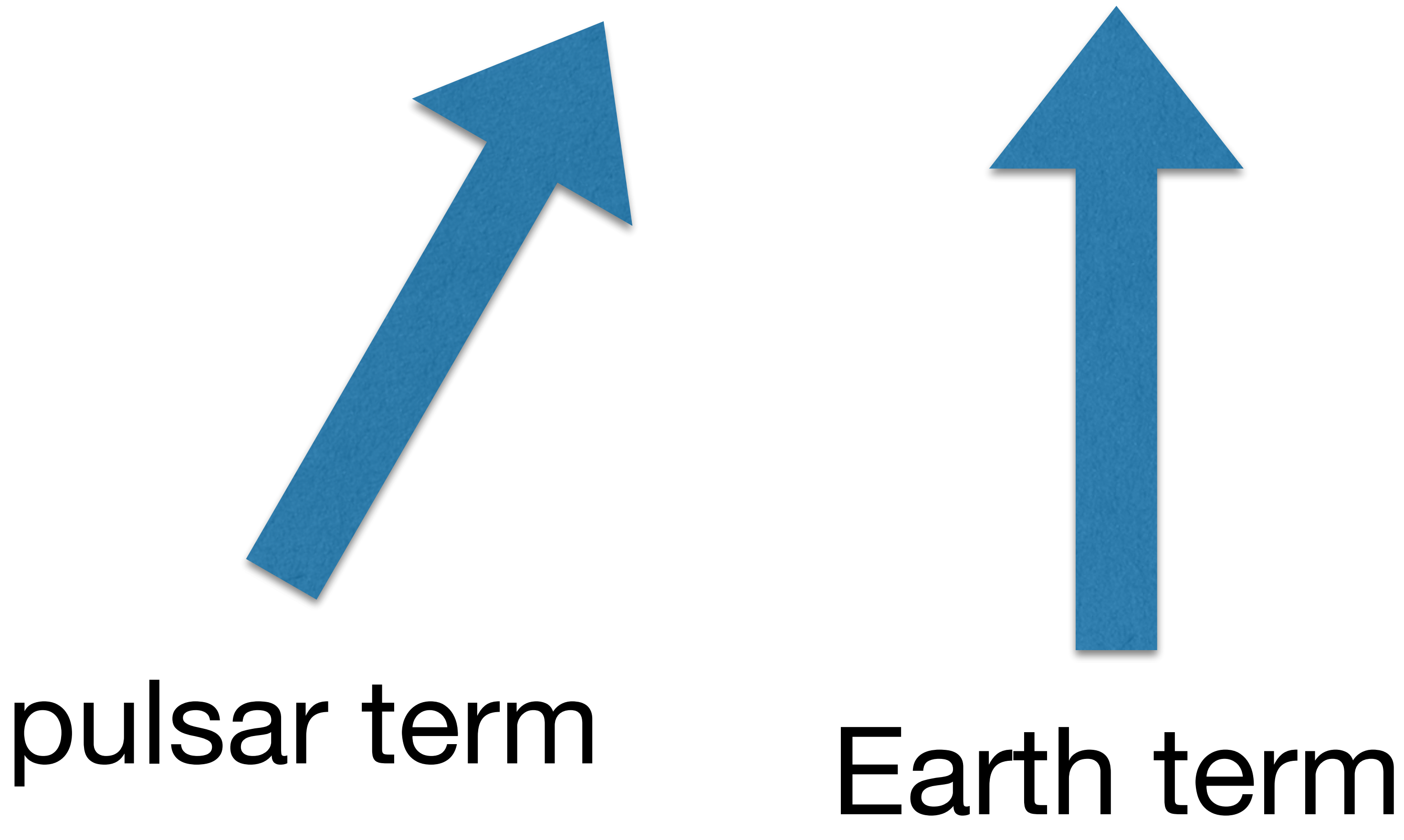
$$h_0 = \frac{2\mathcal{M}^{5/3}(\pi f_{\mathrm{gw}})^{2/3}}{d_L}$$



$$\mathsf{s}(\mathsf{t}, \hat{\Omega}) = \sum_{+,\times} \mathsf{F}^{\mathsf{A}}(\hat{\Omega}) \left[\mathsf{s}_{\mathsf{A}}(\mathsf{t}_{\mathsf{p}}) - \mathsf{s}_{\mathsf{A}}(\mathsf{t}_{\mathsf{e}})\right]$$



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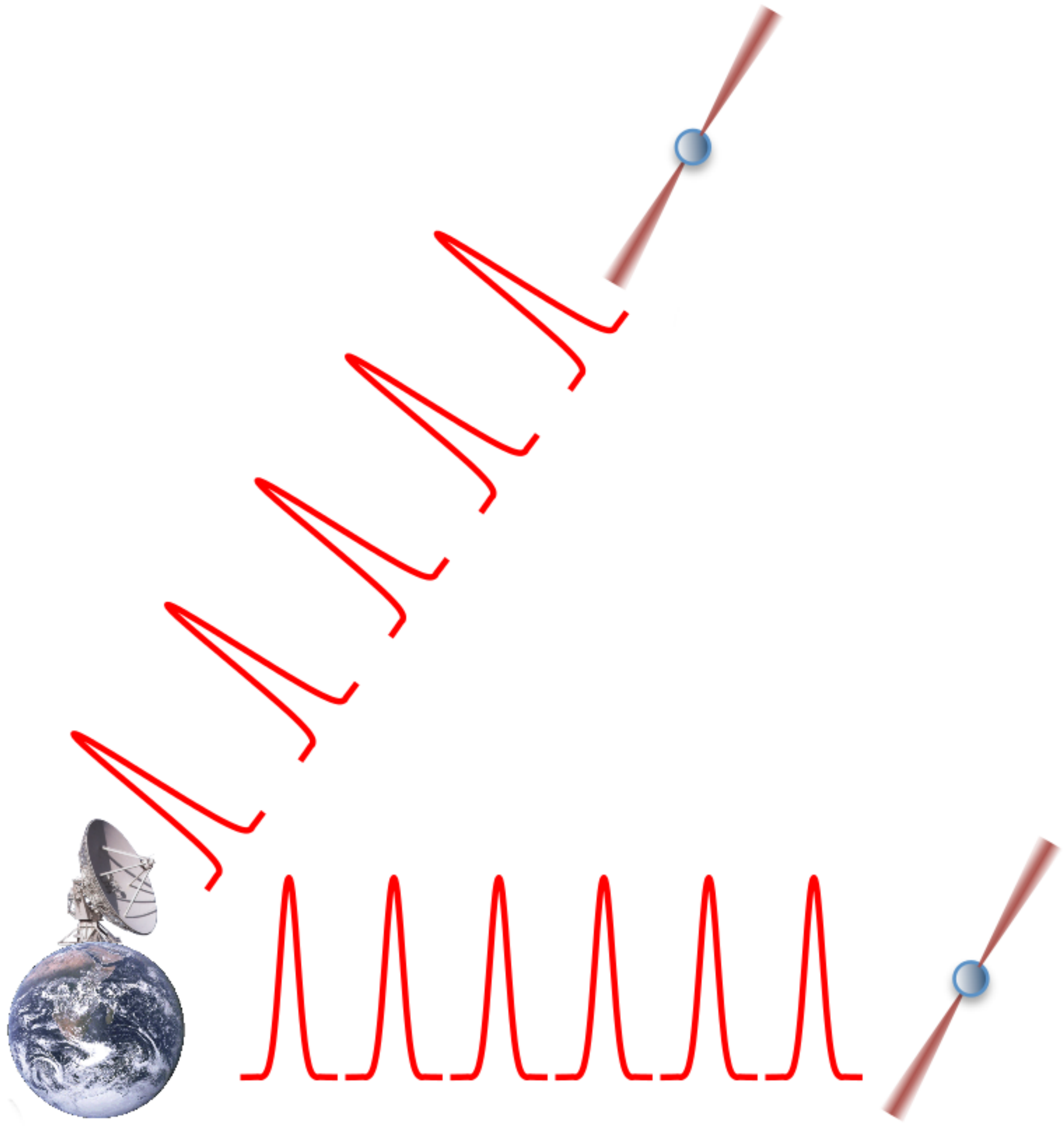
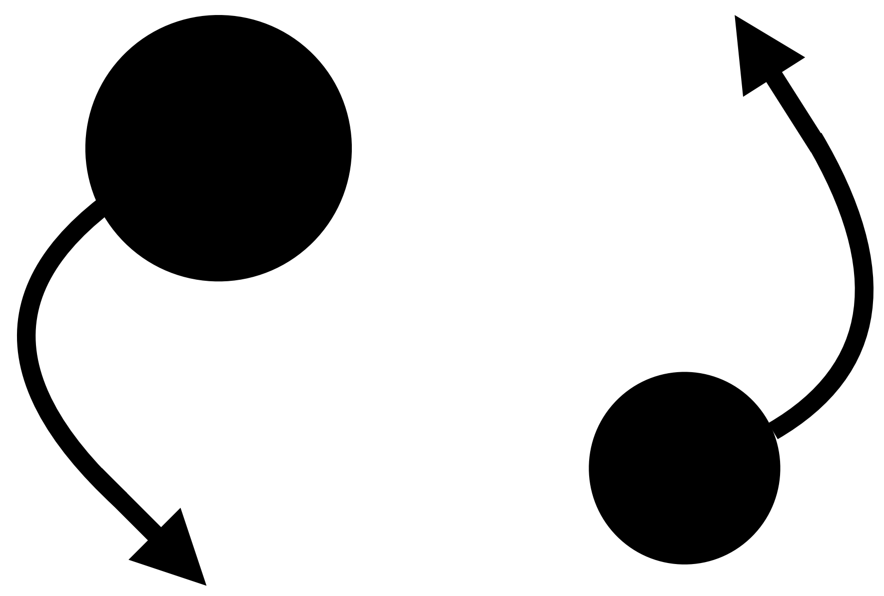


$$h_0 = \frac{2\mathcal{M}^{5/3}(\pi f_{\mathrm{gw}})^{2/3}}{d_L}$$



$$\mathsf{s}(\mathsf{t}, \hat{\Omega}) = \sum_{+,\times} \mathsf{F}^{\mathsf{A}}(\hat{\Omega}) \left[\mathsf{s}_{\mathsf{A}}(\mathsf{t}_{\mathsf{p}}) - \mathsf{s}_{\mathsf{A}}(\mathsf{t}_{\mathsf{e}})\right]$$

$$\omega(\mathsf{t}) = \omega_0 \left[1 - \frac{256}{5}\mathcal{M}^{5/3}\omega_0^{8/3}(\mathsf{t} - \mathsf{t}_0)\right]^{-3/8}$$

**Figure credit: NANOGrav (modified)**

# Limits on Individual SMBHBs

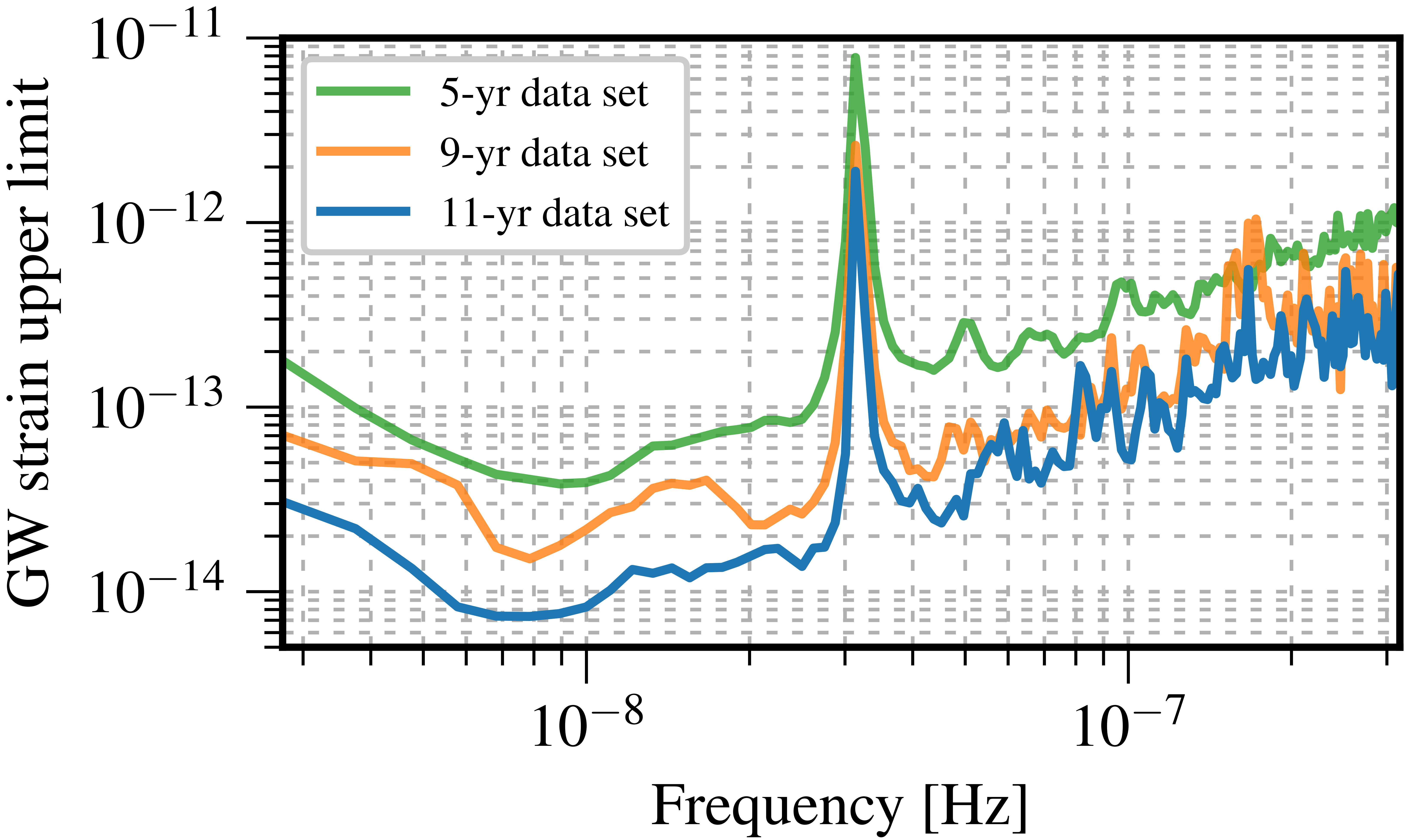



Figure credit: K. Aggarwal et al. (2019)

# Prospects for Detection

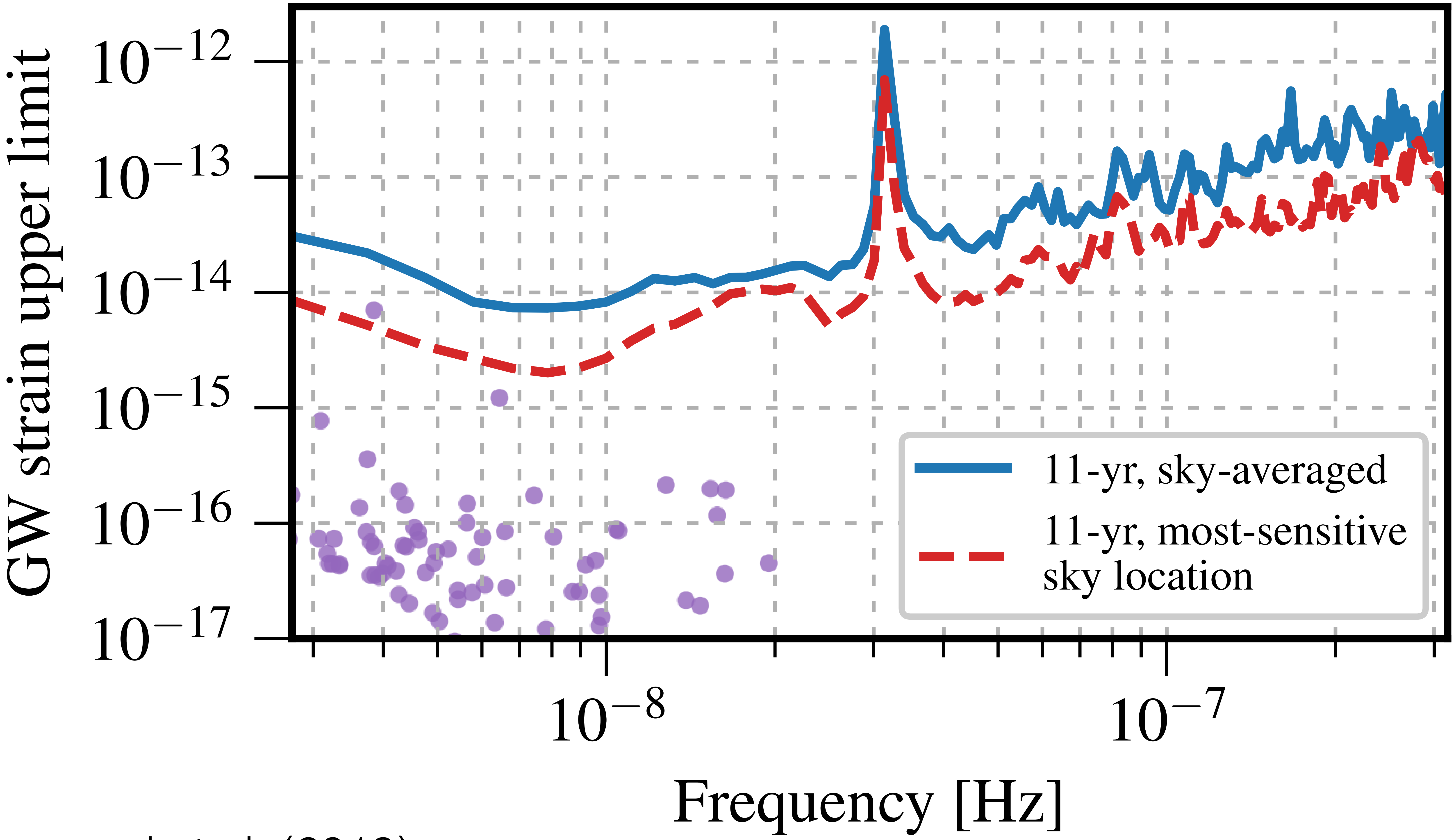
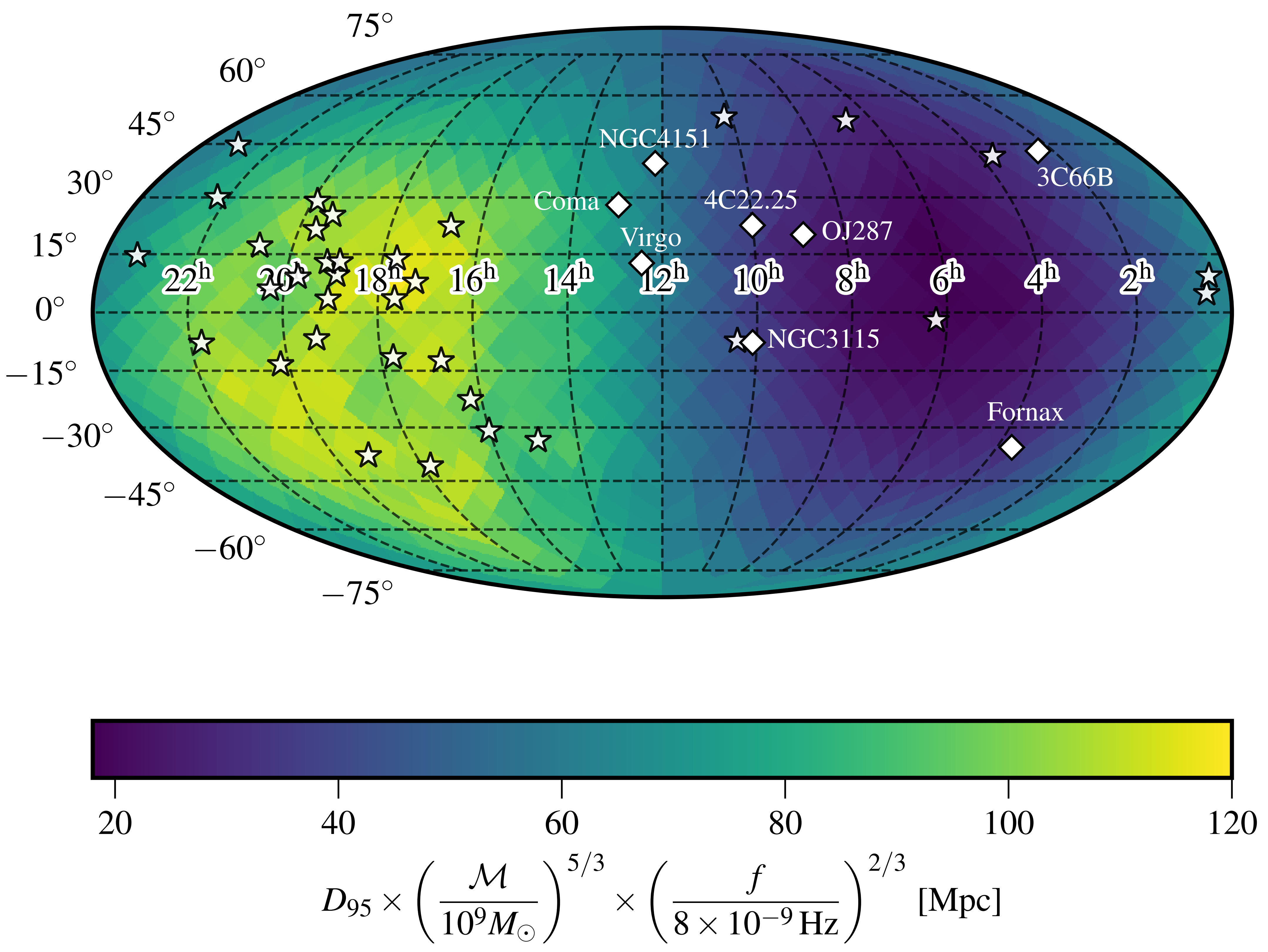
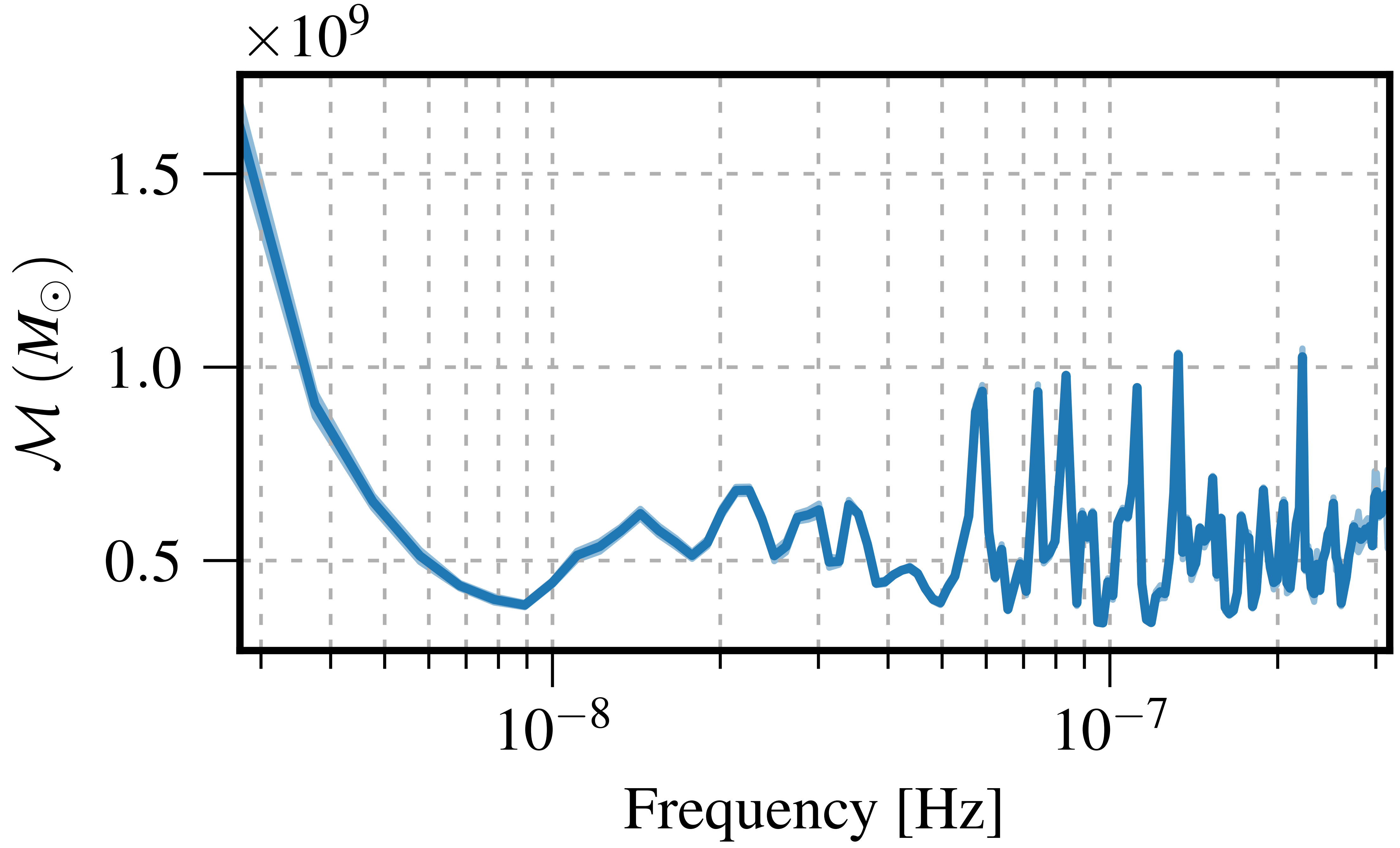



Figure credit: K. Aggarwal et al. (2019).
Simulated SMBHBs from Mingarelli et al. 2017.

# Limits on Individual SMBHBs

$$h_0 = \frac{2\mathcal{M}^{5/3}(\pi f_{gw})^{2/3}}{d_L}$$

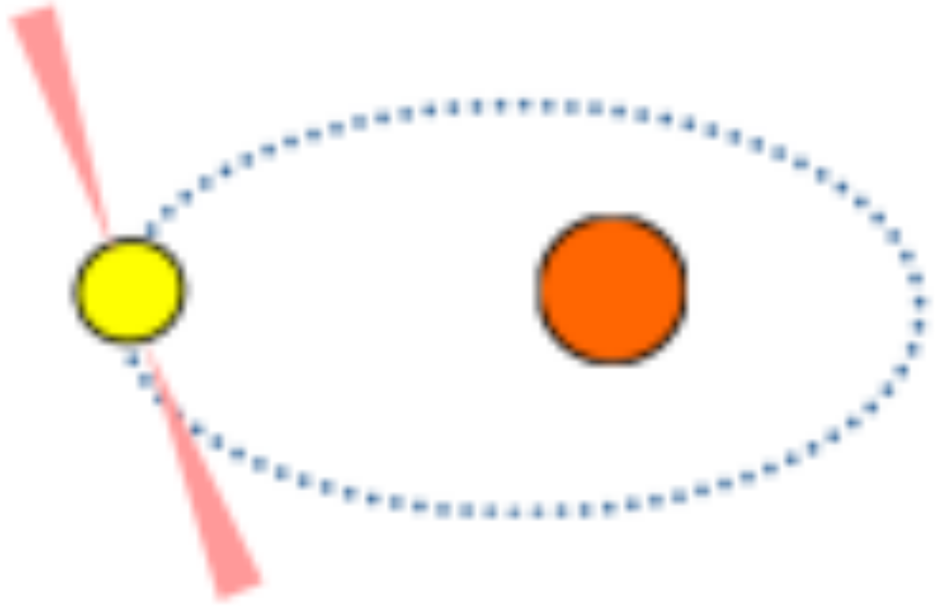


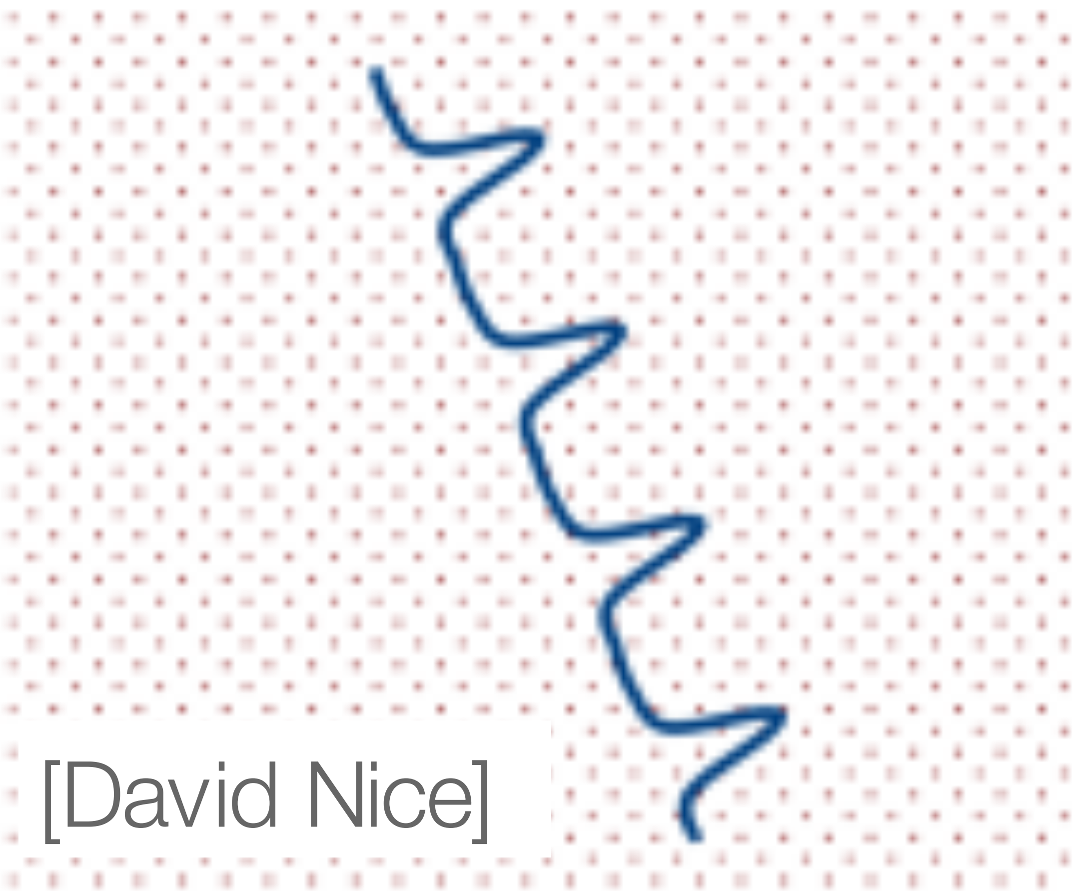



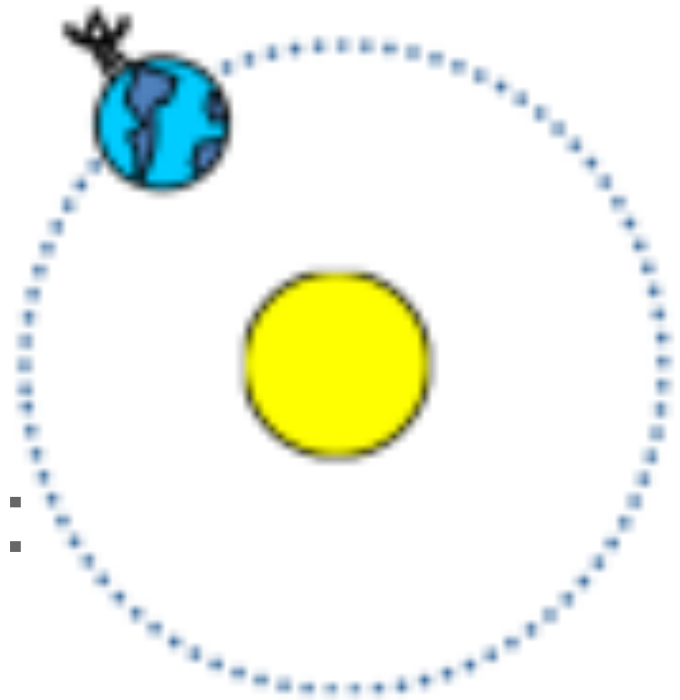

There are no SMBHBs in the Virgo Cluster with $\mathcal{M} > 1.6 \times 10^9$ $M_\odot$.

Figure credits: K. Aggarwal et al. (2019)

# The Solar System Ephemeris





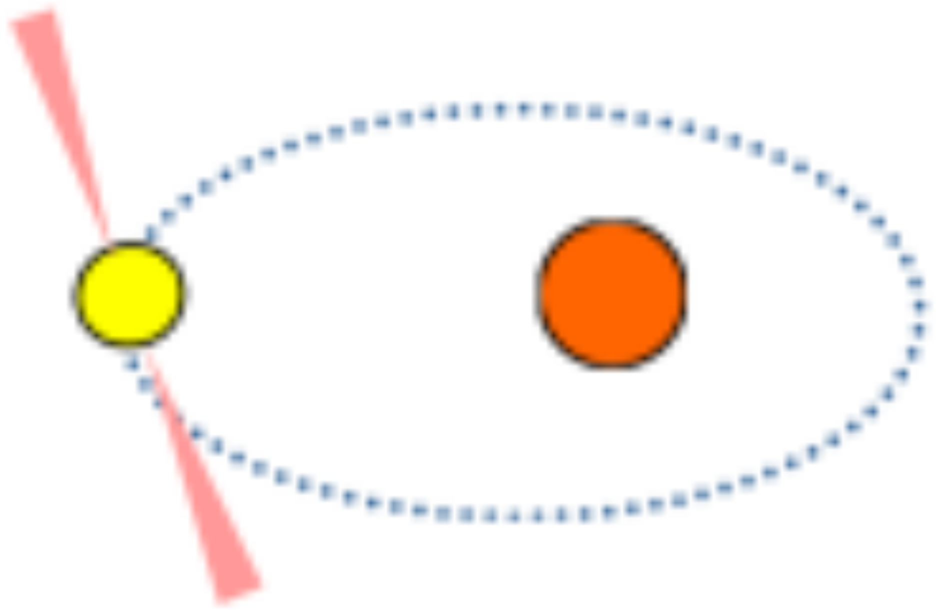
Roemer delay:
~ 500 s ± 1 us

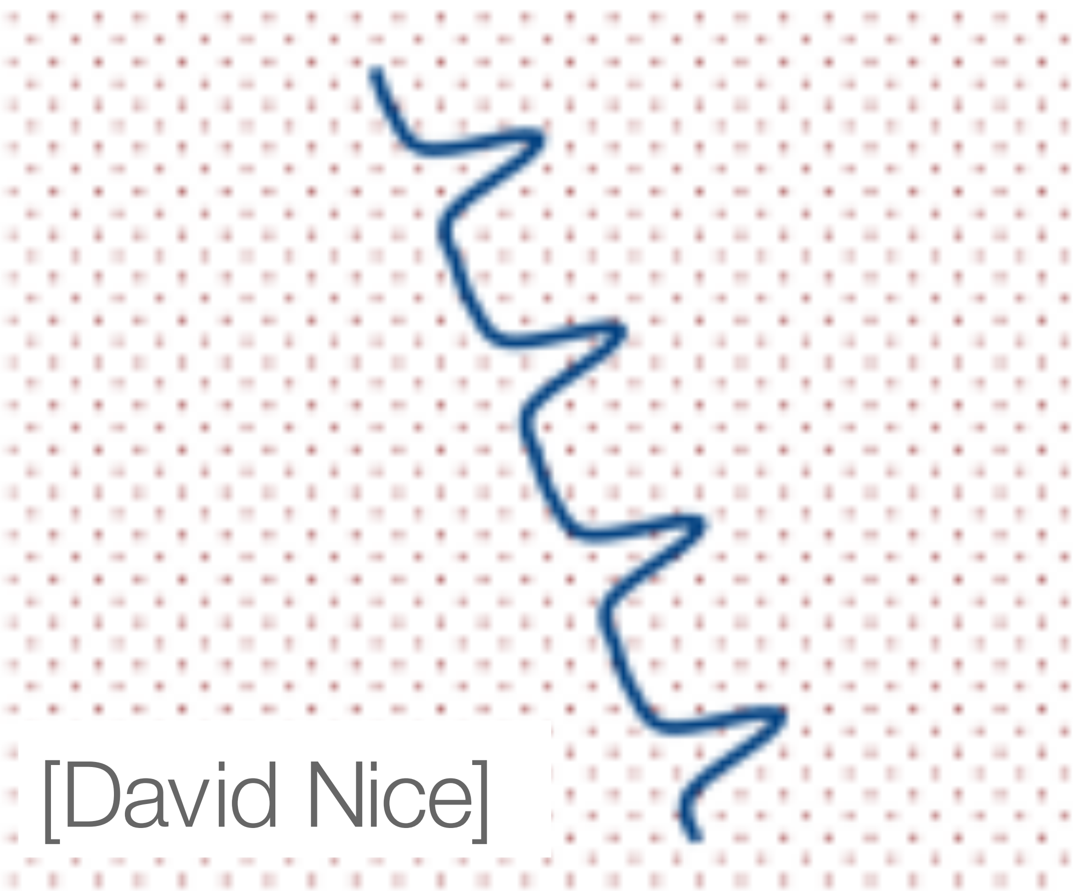
Pulse TOAs are referenced to the **Solar System barycenter (SSB)**. The **SSB** is the center of mass for the Solar System.

Pulse TOAs are recorded at particular observatories and then corrected to the SSB TOA.

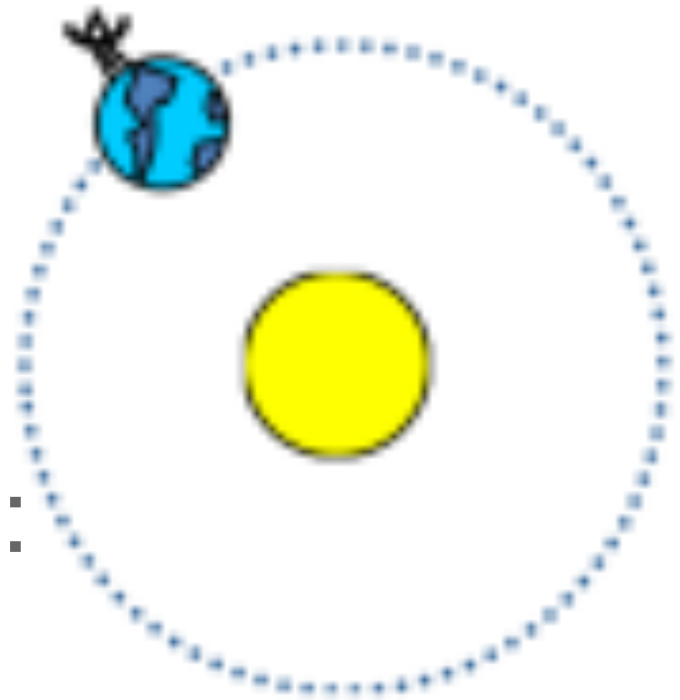
The **Solar System ephemeris (SSE)** is a model for the position of the SSB. We primarily use the one produced by JPL. It uses data from spacecraft and lunar laser ranging.

# The Solar System Ephemeris



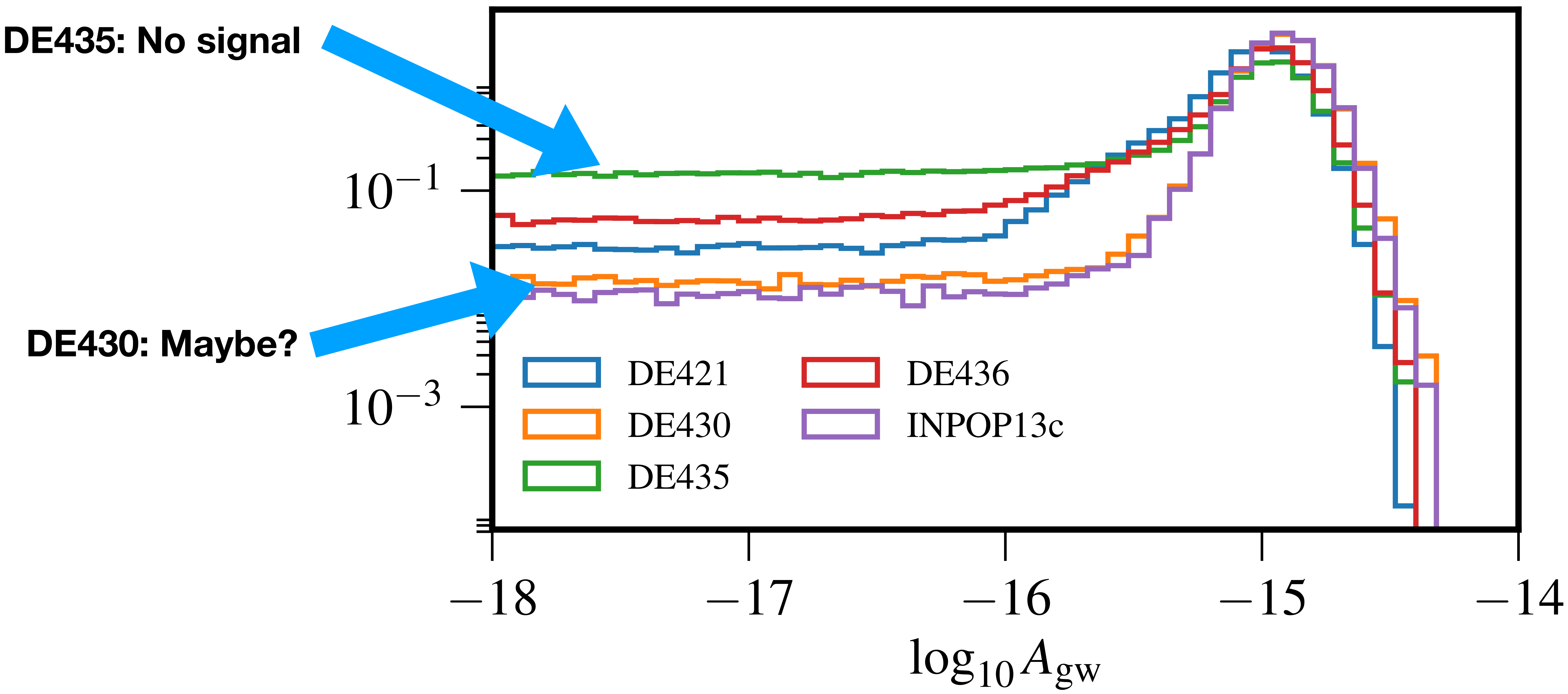


[David Nice]

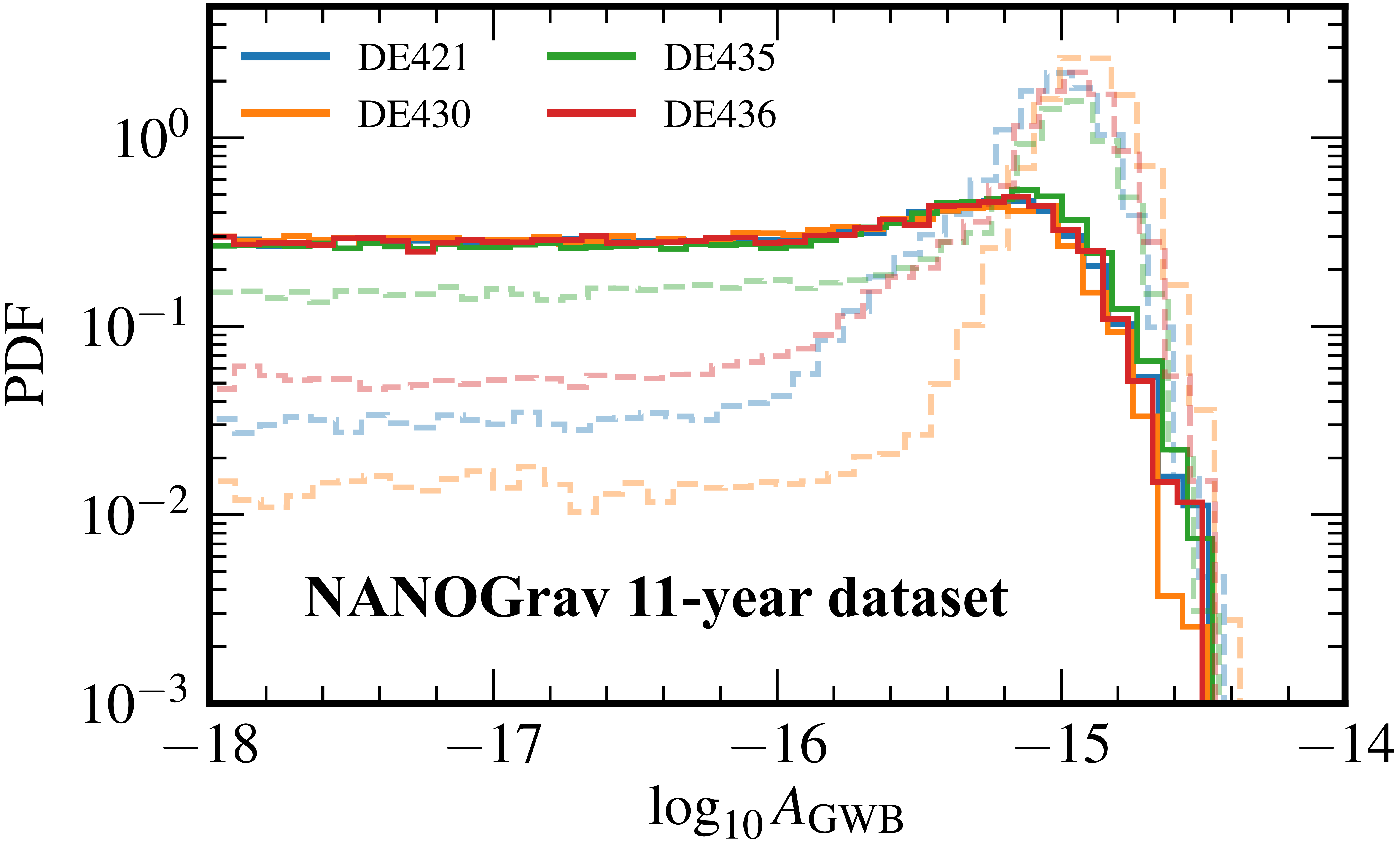


Roemer delay:
~ 500 s ± 1 us

Using different ephemerides, we find different significances for a common red process.



# Modeling Ephemeris Error with `BayesEphem`




From Arzoumanian et al., ApJ 859, 1 (2018)

With BayesEphem, all ephemerides give the same results for the significance of a common red process.

# Conclusions

- Pulsar timing arrays are sensitive to the stochastic background of SMBHBs, as well as individual binaries.
- Pulsar timing arrays are already putting constraints on the astrophysical properties of SMBHBs.
- Pulsar timing arrays can do targeted searches for GWs from individual binaries based on EM observations (periodicities in AGN light curves, massive galaxies, etc).