Title: Probing Supermassive Black Holes with Gravitational Waves

Speakers: Sarah Vigeland

Series: Strong Gravity

Date: March 19, 2020 - 1:00 PM

URL: http://pirsa.org/20030011

Abstract: Observations have shown that nearly all galaxies harbor massive or supermassive black holes at their centers. Gravitational wave (GW) observations of these black holes will shed light on their growth and evolution, and the merger histories of galaxies. Massive and supermassive black holes are also ideal laboratories for studying strong-field gravity. Pulsar timing arrays (PTAs) use observations of millisecond pulsars to detect low-frequency GWs with frequencies ~1-100 nHz, and can detect GWs emitted by supermassive black hole binaries, which form when two galaxies merge. I will discuss source modeling and detection techniques for PTAs, as well as present limits on nanohertz GWs from the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) collaboration.

Zoom Link: https://pitp.zoom.us/j/991014922

Supermassive Black Hole

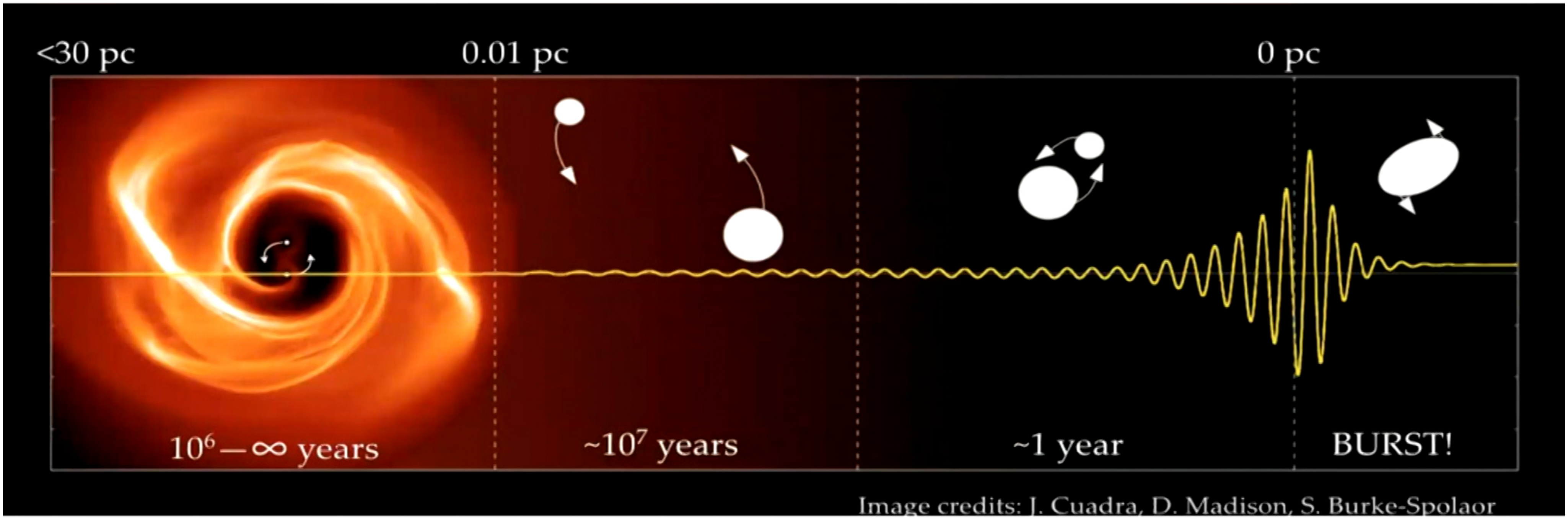
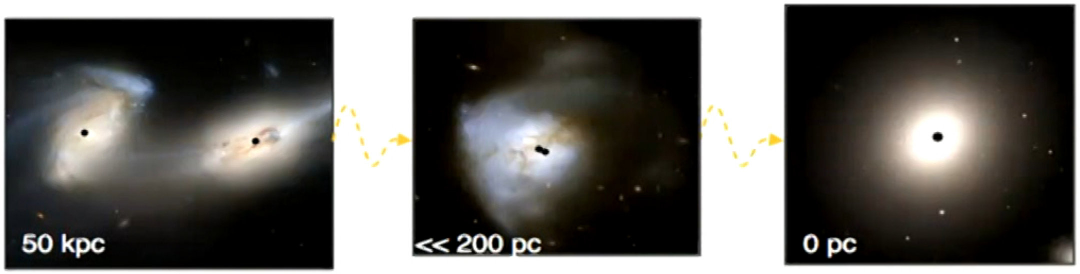
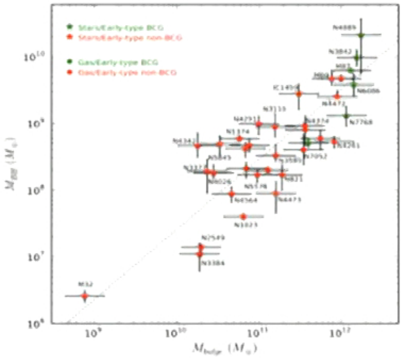


Image credits: J. Cuadra, D. Madison, S. Burke-Spolaor

Supermassive Black Hole

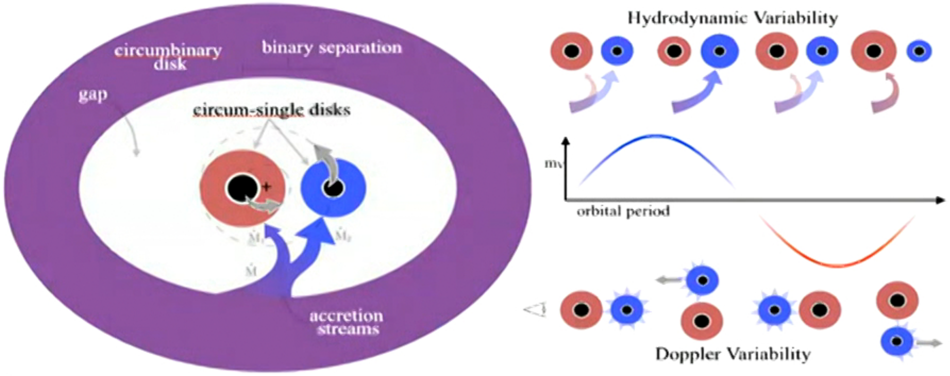




Form in galaxy mergers.

Precision masses for supermassive black holes only possible up to tens of Mpc away

Binary candidates can be identified by looking for light curve periodicities



Kelley et al. (2018), arXiv:1809.02138

Supermassive Black Hole B

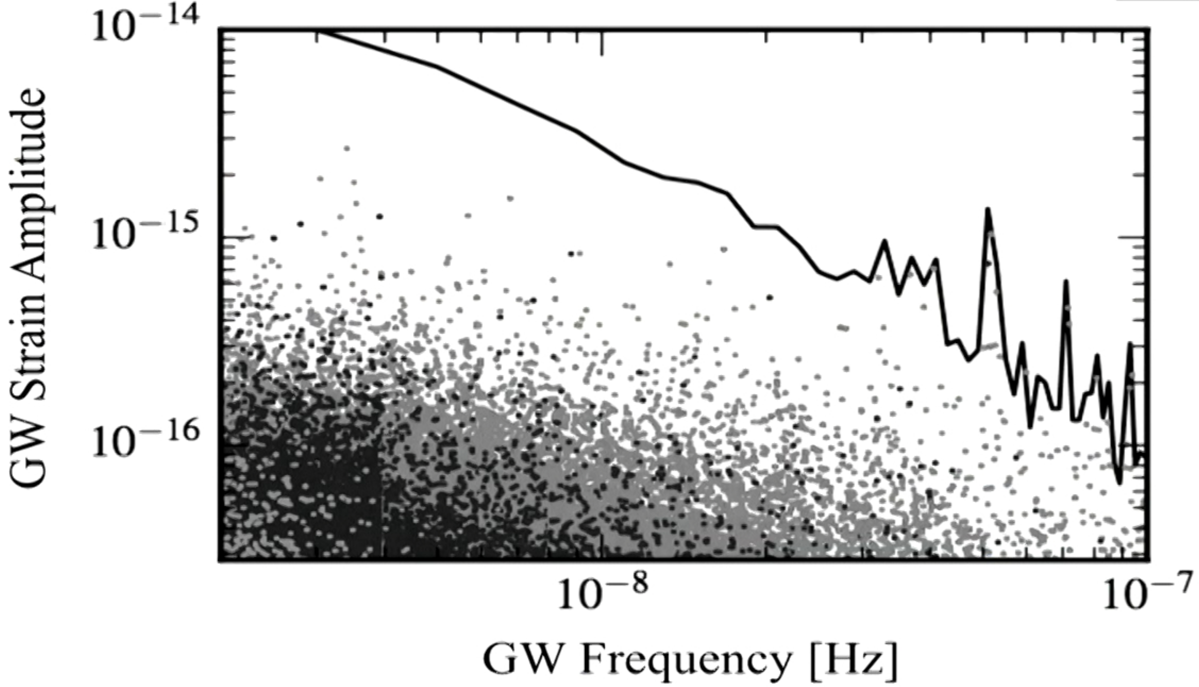
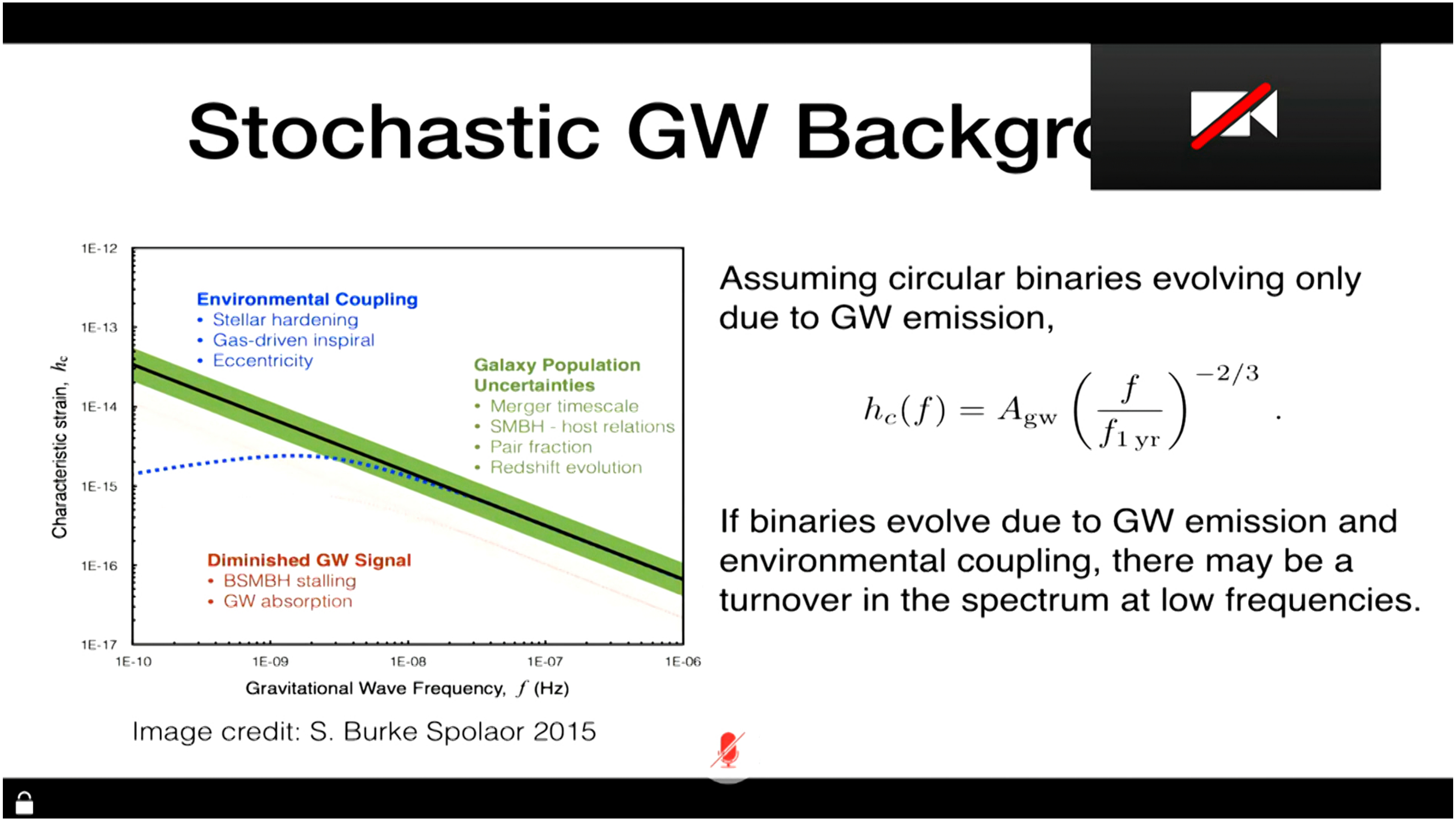


Figure credit: J. Simon



Stochastic GW Backgr

Image 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.

11-year Upper Limit on the Stochastic nd

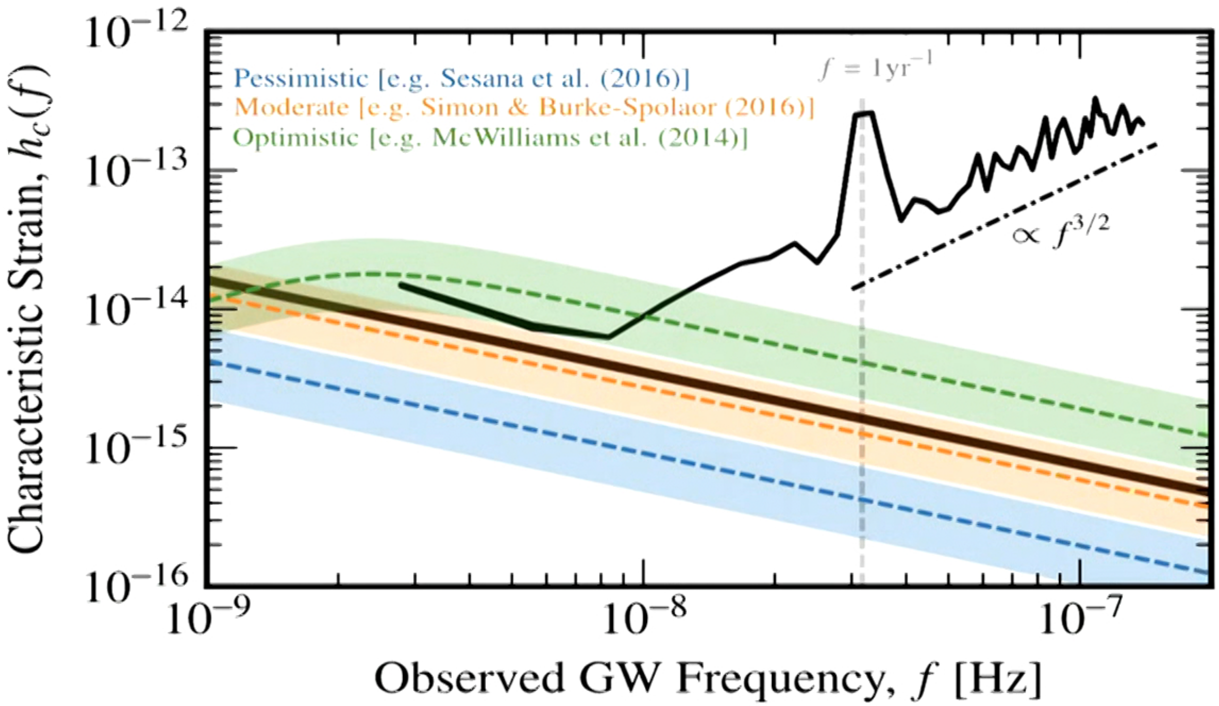
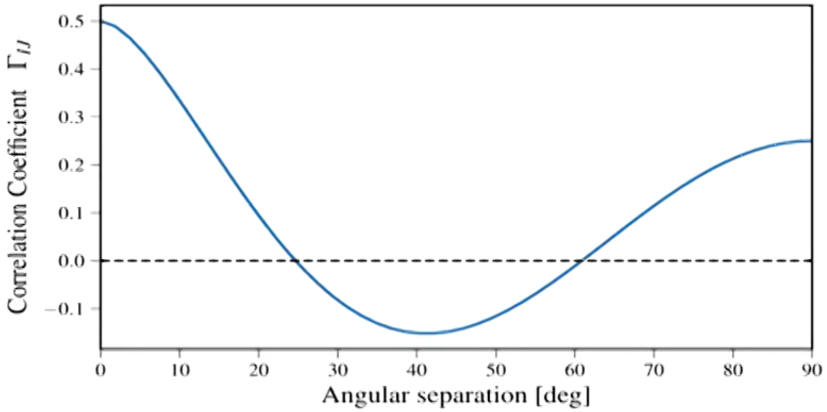


Figure credit: Z. Arzoumanian et al. (2018)

11-year Data Set Cross-Cor s

The optimal statistic $\hat{A}^2_{gw}$ can be found by fitting the correlated power to the cross-correlation coefficients (Anholm et al. 2009; Demorest et al. 2013; Chamberlin et al. 2015):



Hellings & Downs (1983)

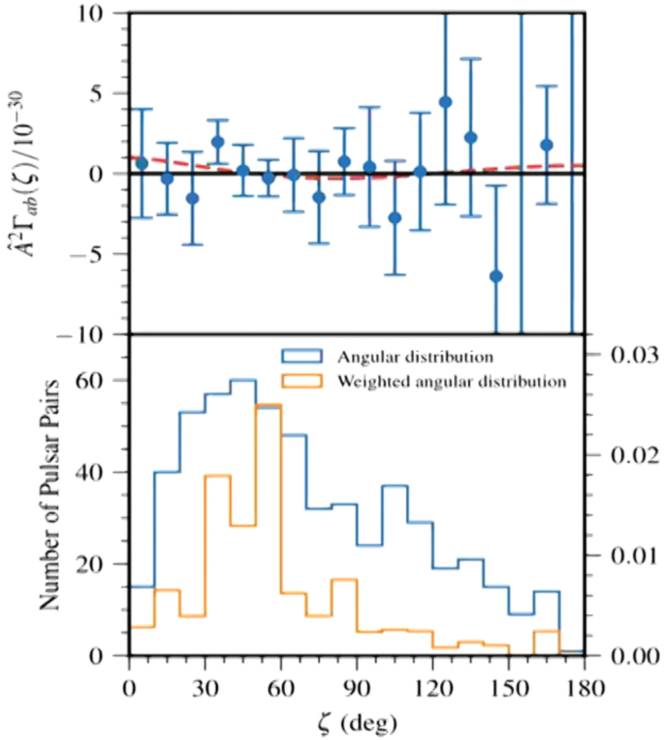
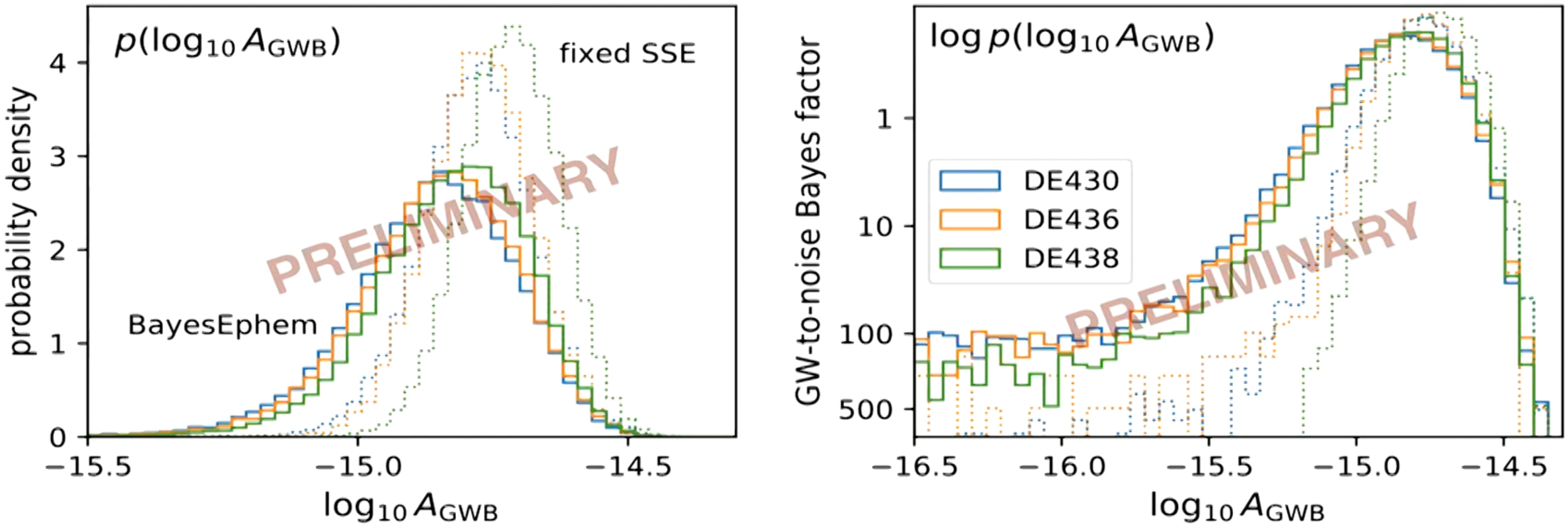


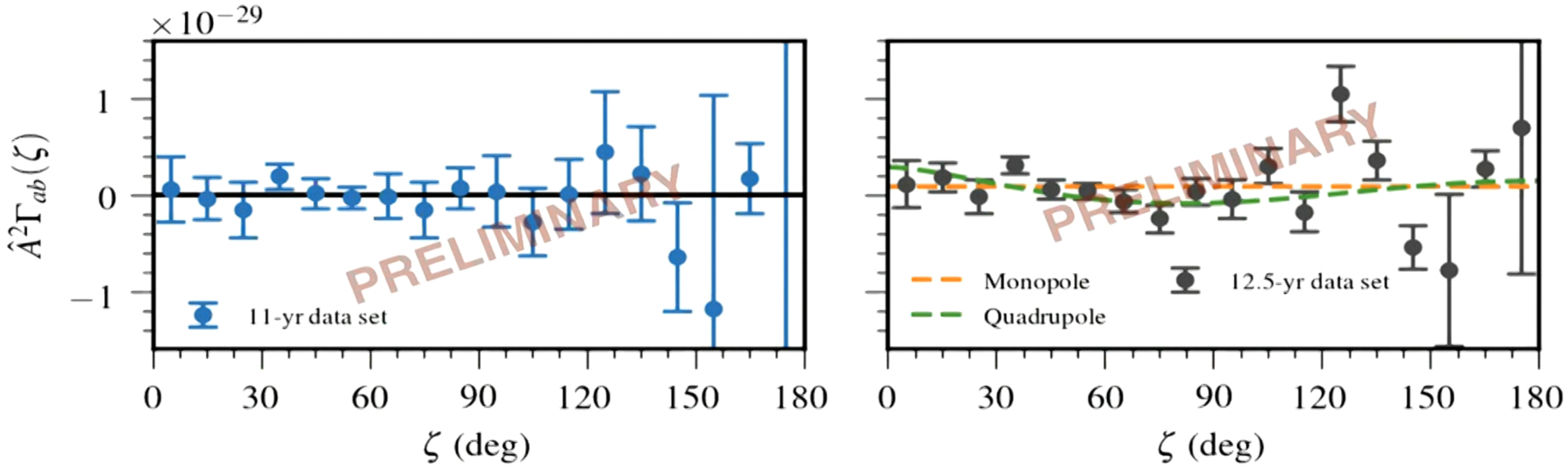
Figure credit: Z. Arzoumanian et al. (2018)

Preliminary 12.5yr GWB

12.5-yr Data Set: Posterior probability density of GW stochastic-background amplitude



Preliminary 12.5yr GWB F



Alternate Polarizatio

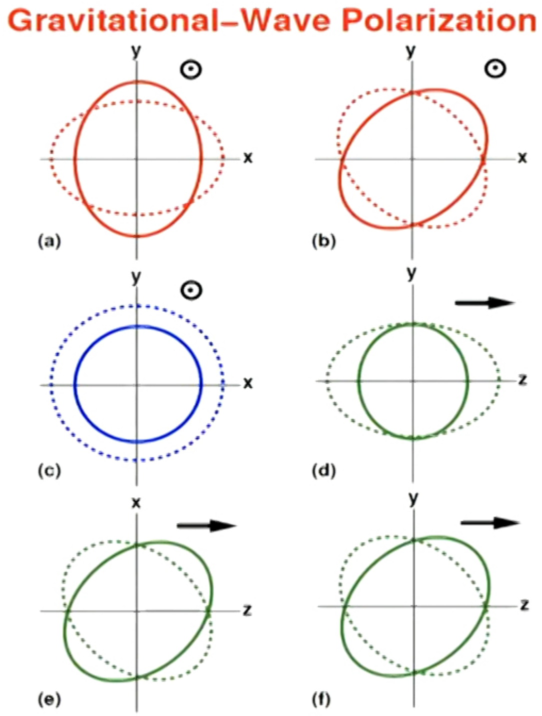
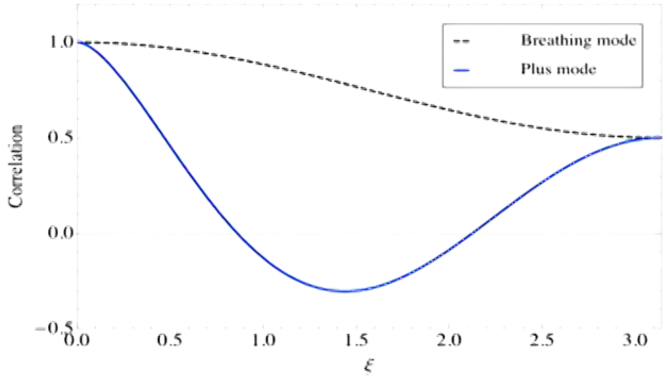


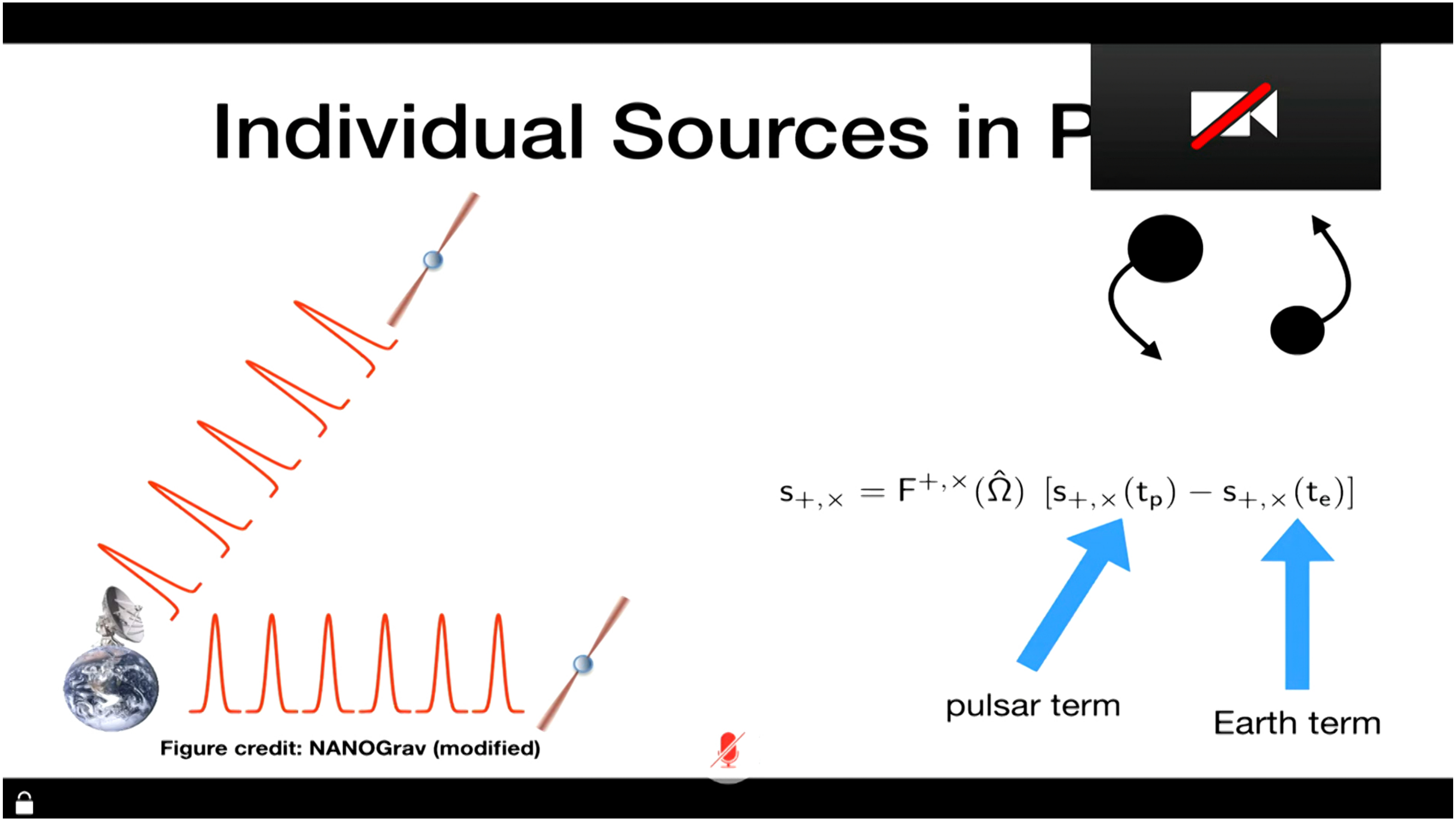
Figure credit: C. Will (2014)

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)



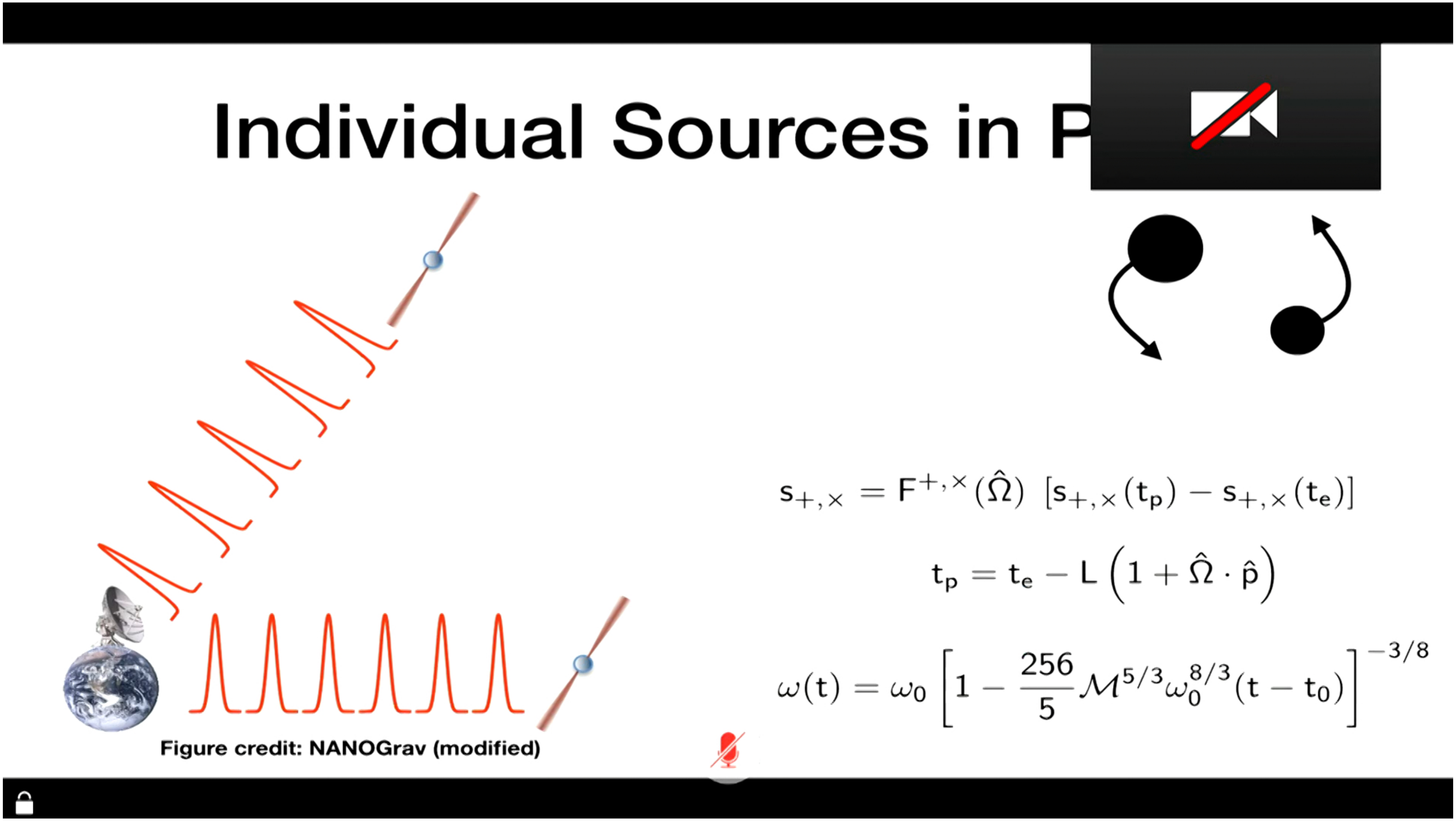
Individual Sources in P

$$s_{+,\times} = F^{+,\times}(\hat{\Omega})\ \left[s_{+,\times}(t_p) - s_{+,\times}(t_e)\right]$$

pulsar term

Earth term

Figure credit: NANOGrav (modified)



Individual Sources in P

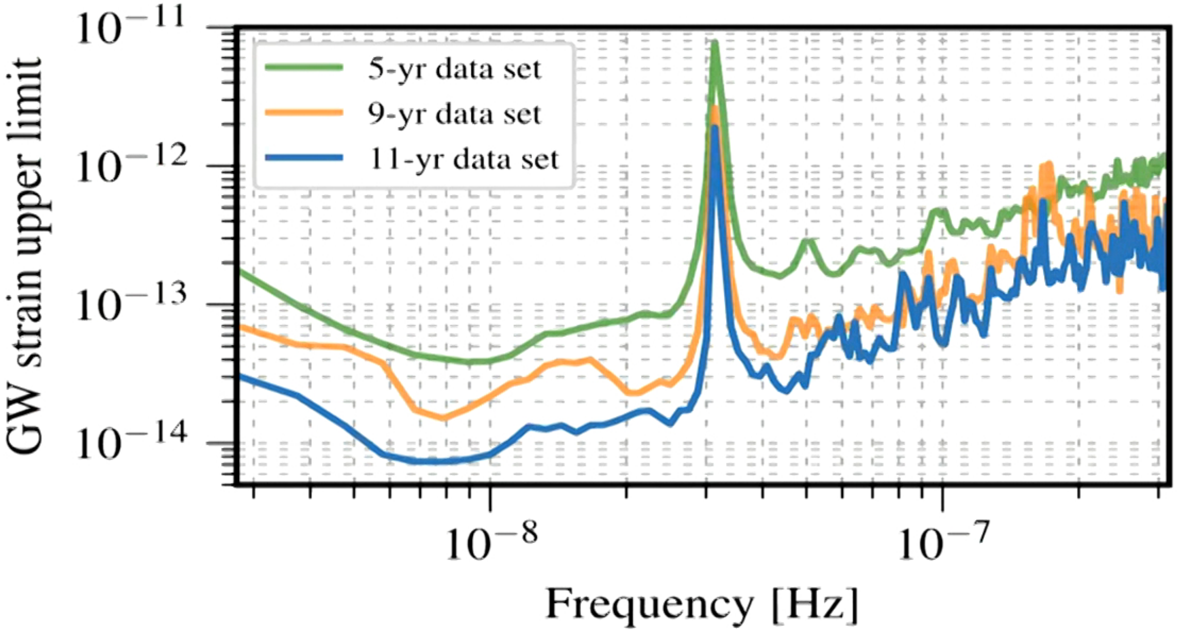
$$s_{+,\times} = F^{+,\times}(\hat{\Omega})\;\left[s_{+,\times}(t_p) - s_{+,\times}(t_e)\right]$$

$$t_p = t_e - L\left(1 + \hat{\Omega}\cdot\hat{p}\right)$$

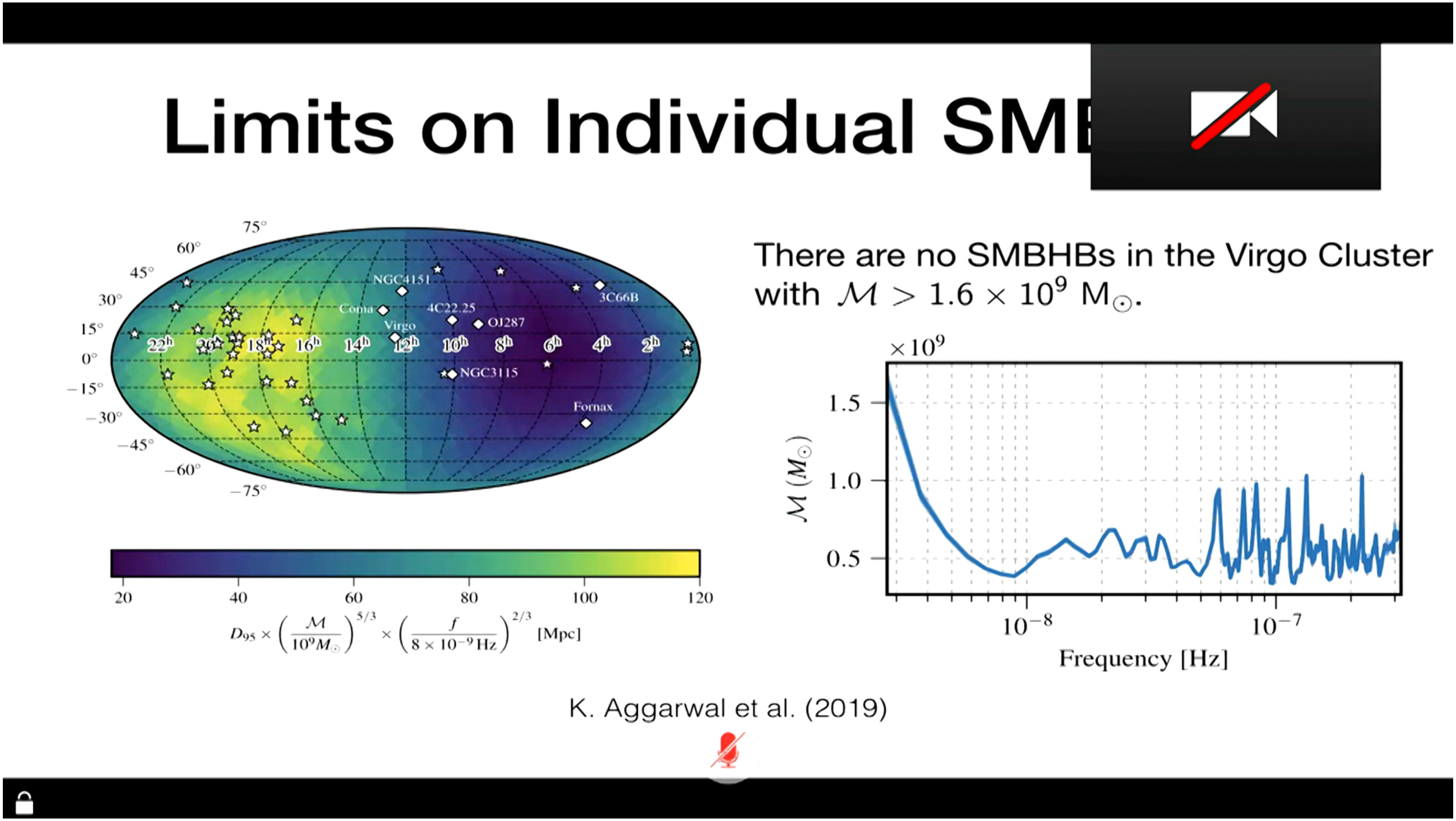
$$\omega(t) = \omega_0\left[1 - \frac{256}{5}\mathcal{M}^{5/3}\omega_0^{8/3}(t - t_0)\right]^{-3/8}$$

Figure credit: NANOGrav (modified)

Limits on Individual SM



K. Aggarwal et al. (2019)



Limits on Individual SM

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

K. Aggarwal et al. (2019)

Limits on Individual SM

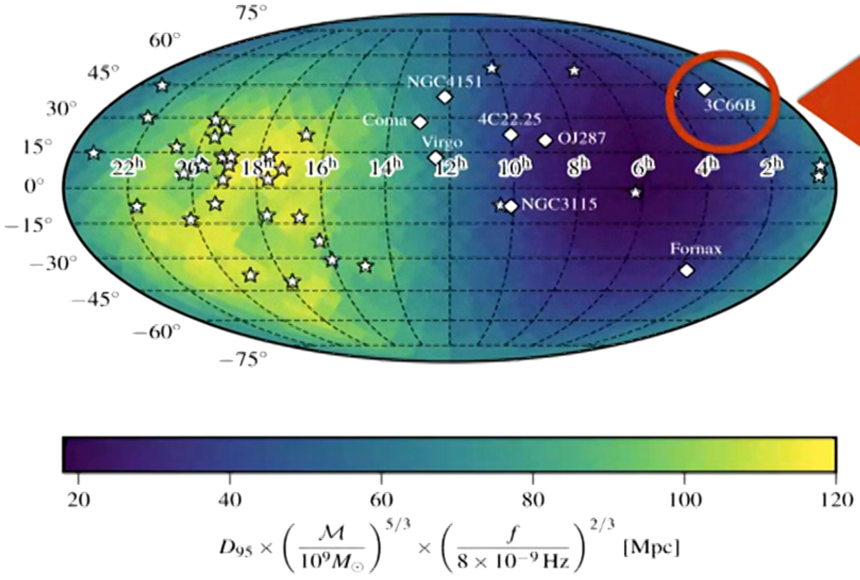
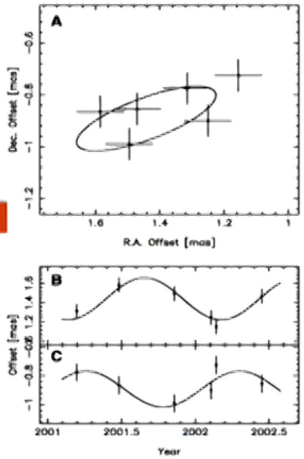
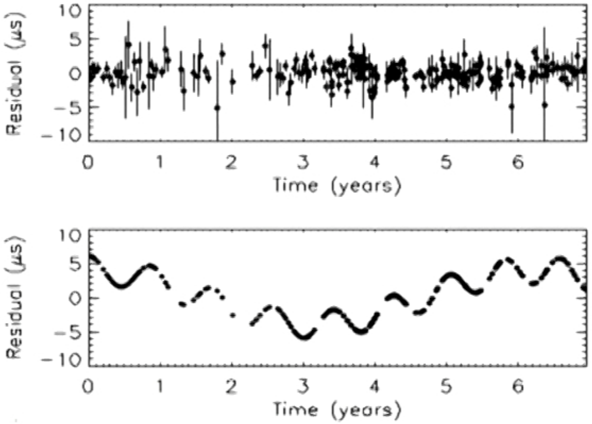


Figure credit: K. Aggarwal et al. (2019)



Sodou et al. (2003)



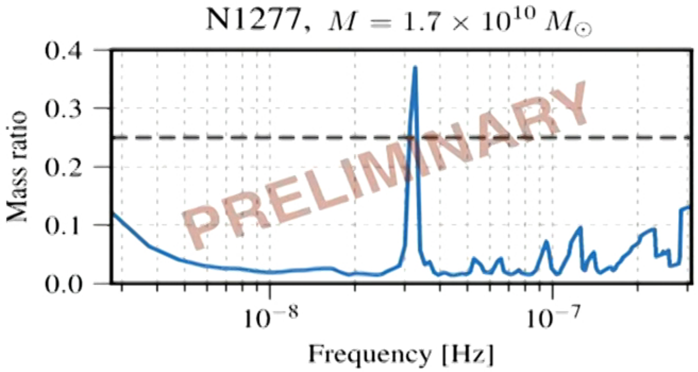
Jenet et al. (2004)

Upcoming paper will put updated constraints on 3C66B (C. Witt, S. Burke Spolaor, J. Simon)

Constraints on Galaxy M

NGC 4676 (Image credit: NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M.Clampin (STScI), G. Hartig (STScI), the ACS Science Team, and ESA)

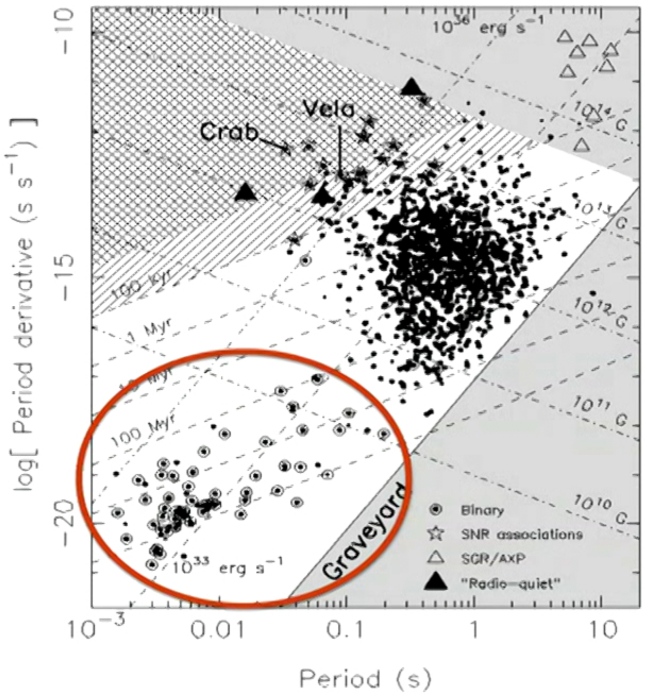
Major mergers involve two galaxies of similar masses. The resulting SMBBH will have a large mass ratio ($q > 0.25$).



N1277, $M = 1.7 \times 10^{10}\,M_\odot$

M. Charisi, S. Vigeland, J. Simon

Millisecond Pulsars



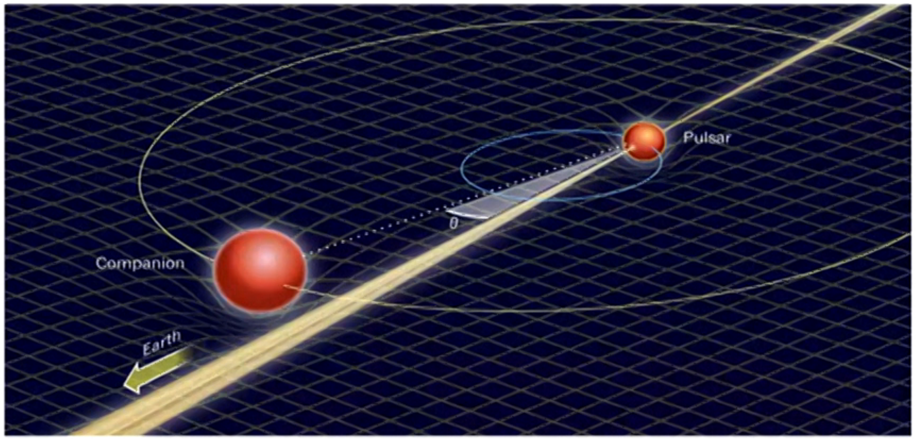
From the *Handbook of Pulsar Astronomy*
by Lorimer and Kramer

Millisecond pulsars have small spin periods (1 - 30 ms), weaker magnetic fields.

Most are found in binaries with a stellar remnant companion.

Thought to have been spun up via accretion in an X-ray binary.

Shapiro Delay

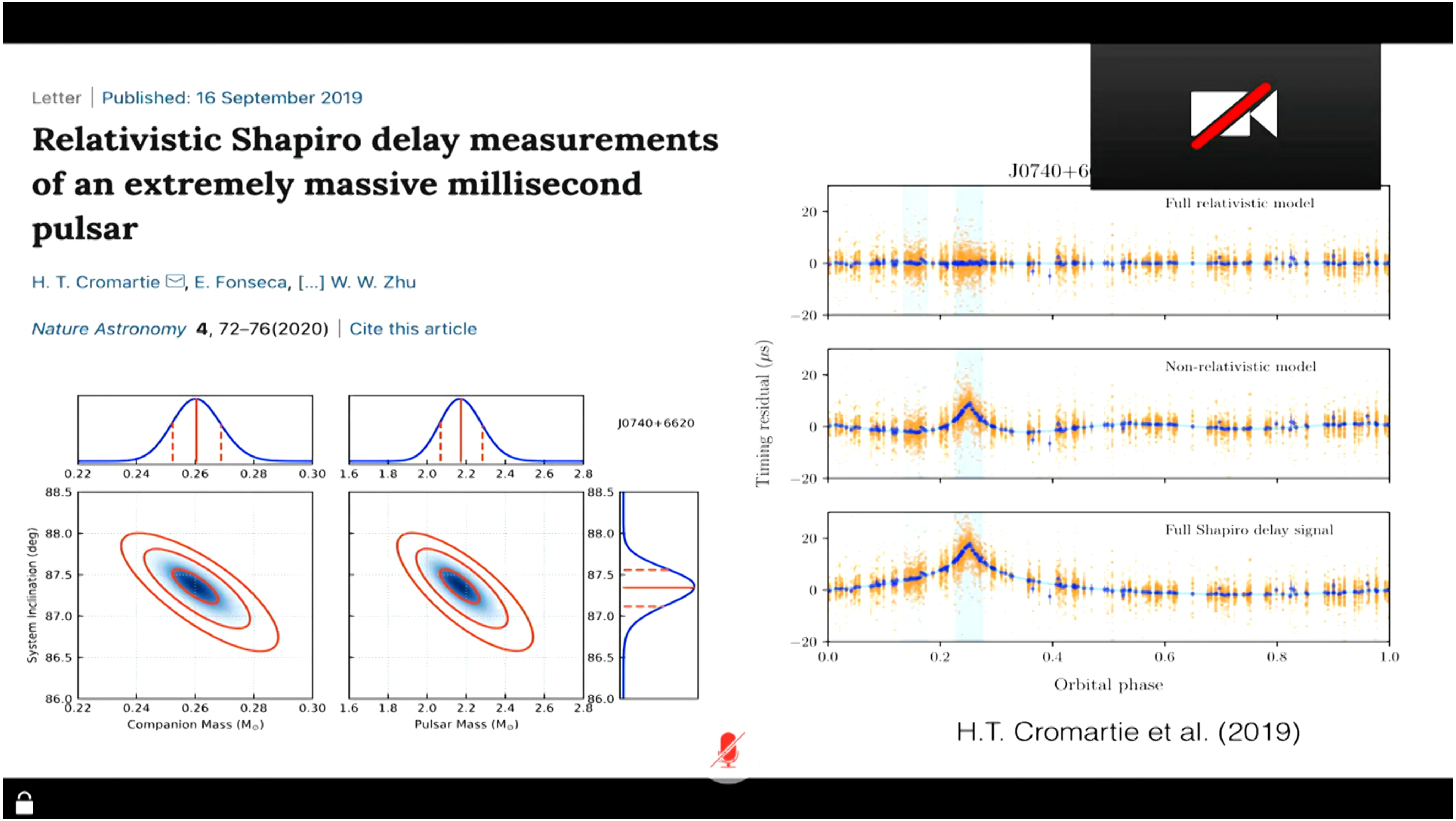


For some MSPs in binaries, the companion mass can be measured via detection of the **Shapiro delay:**

$$\Delta t = -\frac{2GM_\odot}{c^3} m_2 \ln\left[1 - \sin i \, \sin(\Phi - \Phi_0)\right]$$

If the companion mass can be measured, then the pulsar mass can be measured from the **binary mass function:**

$$\frac{4\pi^2}{G} \frac{(a \sin i)^3}{P_b^2} = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2}$$



Letter | Published: 16 September 2019

Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar

H. T. Cromartie ✉, E. Fonseca, […] W. W. Zhu

Nature Astronomy **4**, 72–76(2020) | Cite this article

H.T. Cromartie et al. (2019)

Neutron Star Equation of

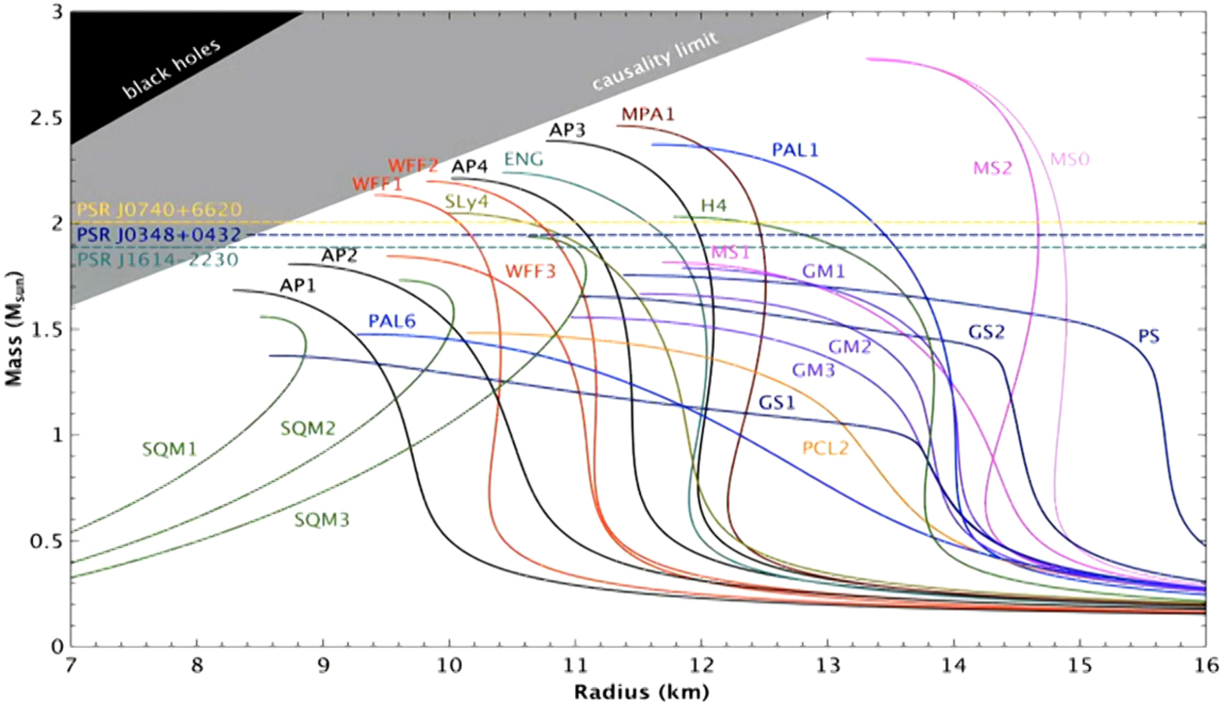


Figure credit: Norbert Wex

Conclusions

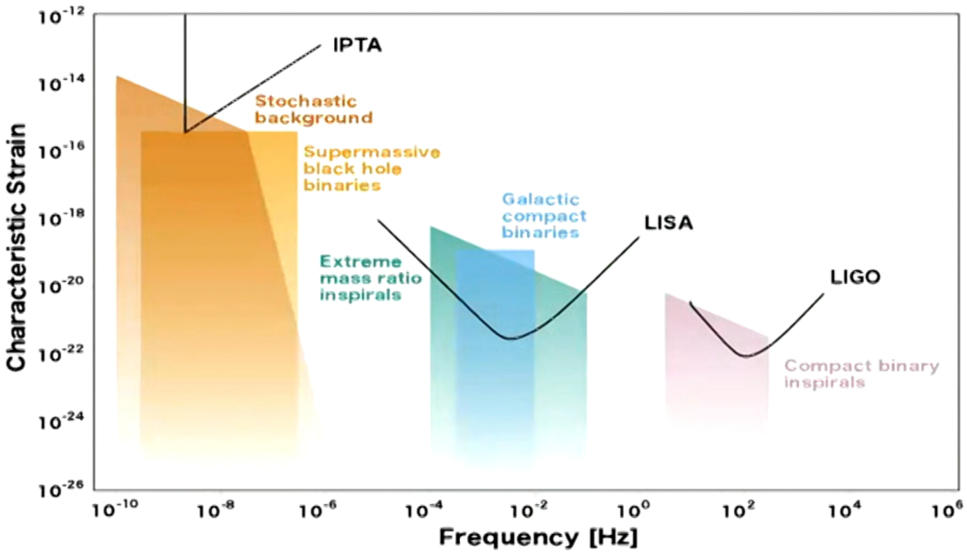


Figure credit: Moore, Cole, Berry 2014.

- Pulsar timing arrays are sensitive to nanohertz GWs, and are expected to detect GWs from SMBHBs within the next several years.
- PTAs are already putting constraints on the astrophysical properties of nearby SMBBHs.
- Constraints from PTAs on the binary chirp masses complement constraints from EM observations, which are sensitive to the total masses.
- Better measurements of the pulsars themselves improves the sensitivity of PTAs, and can be used to study the neutron star equation of state and binary evolution.